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Bernhard Robert KLOIBER

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Broadcast Collision Mitigation in Vehicular Ad Hoc Networks

Directeur de thèse : **Jérôme HÄRRI**
Co-encadrement de la thèse : **Thomas STRANG**

Jury

M. Christian BONNET, Professor, Communications Mobiles, EURECOM	Président
M. André-Luc BEYLOT, Professor, Ingénierie Réseaux et Télécommunications, IRIT	Rapporteur
M. Falko DRESSLER, Professor, Distributed Embedded Systems, Universität Paderborn	Rapporteur
M. Javier GOZALVEZ, Professor, UWICORE, University Miguel Hernandez	Examinateur
M. Giovanni PAU, Professor, Networks and Performance Analysis, Sorbonne Universités	Examinateur
M. Riccardo SCOPIGNO, Ph.D., Multi-Layer Wireless Solutions, ISMB	Examinateur

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Résumé

Alors que les systèmes passifs atteignent leurs limites physiques, les systèmes actifs de sécurité routière ouvrent la voie vers une vision "zéro accident" de la route. Sur cette voie, les réseaux véhiculaires ad hoc, appelés VANETs montrent un grand potentiel. Ils sont capables de fournir une vision plus large de l'environnement immédiat, appelée 'conscience coopérative', que les systèmes basés sur des radars ou des caméras. Dans ce but, les véhicules doivent périodiquement diffuser des messages en broadcast contenant leur position et leur vitesse à leurs voisins immédiats grâce à une technologie WiFi adaptée à un environnement véhiculaire. Malgré sa flexibilité, cette technologie ne peut pas garantir la fiabilité des communications véhiculaires, et les collisions de paquets représentent un défis majeur au développement d'applications de sécurité routières fiables.

Dans cette thèse, nous développons une méthodologie en trois phases pour analyser la problématique des collisions broadcast dans un contexte d'applications de sécurité routière: premièrement, nous évaluons la source des collisions de paquets dans les réseaux VANETs. Ensuite, nous proposons de les atténuer en adaptant leurs politiques de transmission. Finalement, nous appliquons ces adaptations aux applications de sécurité routière et démontrons leur faisabilité et leur efficacité afin améliorer la performance de ces applications.

En particulier, nous identifions que les collisions de paquets sont corrélées dans l'espace et dans le temps, ce qui est particulièrement critique car cela tend à réduire de manière significative l'efficacité des applications de sécurité routière. À ce titre, un des objectifs de cette thèse est de proposer des adaptations de politiques de transmission afin de réduire cette corrélation de collisions de paquets dans l'espace et dans le temps.

Concernant l'aspect "temporel", nous proposons d'ajouter une gigue aléatoire sur la périodicité des transmissions des paquets afin d'éviter que deux véhicules tentent en même temps de transmettre. Concernant l'aspect spatial, nous proposons d'adapter la puissance de transmission de manière aléatoire, afin d'éviter que l'espace de collision n'englobe toujours les mêmes véhicules. In fine, ces mécanismes sont évalués dans le contexte

d'applications de sécurité routières. En particulier, nous mettons en évidence qu'il n'est ni possible, ni nécessaire, de fournir une qualité de conscience coopérative identique en tout point. Nous proposons donc une nouvelle approche appelée 'conscience coopérative fisheye' de par sa capacité d'adapter la qualité de conscience coopérative en fonction de la distance vis-à-vis danger. Nous démontrons la manière donc les mécanismes d'adaptation de transmission précédemment développés permettent d'obtenir et de contrôler une telle conscience coopérative. Nous mettons également en évidence l'amélioration notable de fiabilité de communications, mais également de fiabilité applicative issues de cette conscience coopérative "fisheye".

Le reste du manuscrit est rédigé en anglais. Un résumé détaillé est disponible en français en Annex B.

Abstract

Whereas passive safety systems more and more reach their physical limits, active safety systems are going to determine the road map towards a ”zero-accidents” vision. A big potential is seen in Vehicular Adhoc NETworks (VANETs). They are expected to go far beyond the capabilities of local radar- and vision-based sensors, by providing an enhanced view of the current environment, known as cooperative awareness. Therefore, vehicles are compelled to periodically broadcast safety-related information (e.g. position, speed, heading) to their neighbors. For that they use ITS-G5, a fully decentralized communications technology based on IEEE 802.11.

IEEE 802.11's PHYsical (PHY) and Medium Access Control (MAC) layer have been slightly adapted to support vehicular environments (e.g. multi-path delays, transient connections). However, VANETs introduce new cooperative safety applications, differing significantly in terms of communications policies and requirements. Especially the broadcast policy for safety-related information disables IEEE 802.11's collision avoidance mechanisms, like the exponential increase of the contention window, or the Request To Send / Clear To Send (RTS/CTS) handshake. Without them, the amount of packet collisions increases significantly under heavy communication loads, resulting in a distinct degradation of the communications performance. To support new cooperative safety applications, providing a high awareness quality is life critical. This issue raises the following research question: *How to transmit safety-related information with sufficient reliability by using a potentially undependable communications technology?*

From a MAC perspective, packet collisions are the main reason for undependable communications in VANETs. Hence, the first part of this work analyzes the sources of packet collisions, as well as their behavior in space and time. The results show, for instance, that a significant amount of packet collisions at close ranges are caused by vehicles, having chosen the same backoff counter (waiting time). Moreover, subsequent packet collisions reveal a (temporal) correlated behavior that may significantly degrade safety-related measures like

the update delay or inter-reception time.

Based on these results, three new broadcast collision mitigation strategies are introduced and evaluated in the second part: First, the *geo-backoff* concept aims at relocating packet collisions from near to far, as close ranges are much more critical than farther ones for vehicular safety. Therefore, position information is exploited in order to generate the backoff counter. Second, the *random transmit jitter* concept addresses correlated packet collisions in the time domain, by randomizing the periodic safety-broadcasts around the nominal transmission interval. Finally, the concept of *random transmit powers* alleviates the same issue by randomizing collision and interference areas in space.

From an applications perspective, the important question is more about whether applications requirements are fulfilled, and not about the how. Hence, in the final part the impact of the previously introduced broadcast collision mitigation strategies on application-specific requirements is investigated. Therefore, a new awareness control strategy is proposed. It implements a framework called *fish-eye awareness*, specifically, it allows to adapt the awareness quality as a function of the range. In a first step, Random Transmit Power Control (RTPC) is proposed. It manages to provide different levels of awareness quality at different ranges, while mitigating correlated packet collisions by randomizing them in space. Because RTPC is able to reduce the channel load, the second step is to combine RTPC with Transmit Rate Control (TRC), and benefit from the gained channel resources by subsequently increasing the transmit rate, and by implication, the quality of the awareness. The Fish-eye Awareness Control (FAC) strategy is evaluated through simulations, with focus on cooperative driving applications, such as platooning. Finally, the geo-backoff and random transmit jitter are integrated as well, to benefit from these collision mitigation strategies in addition.

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List of Acronyms

AC	Access Category
ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance System
AIFS	Arbitration Inter-Frame Space
AR	Awareness Range
ASTM	American Society for Testing and Materials
ATB	Adaptive Traffic Beacon
BER	Bit Error Rate
CACC	Cooperative Adaptive Cruise Control
CAM	Cooperative Awareness Message
CBT	Channel Busy Time
CCA	Clear Channel Assessment
CCDF	Complementary Cumulative Distribution Function
CDF	Cumulative Distribution Function
CEN	Comité Européen de Normalisation
CFP	Constant Full transmit Power
CMP	Constant Mean transmit Power

CPL	Consecutive Packet Loss
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CW	Contention Window
D2D	Device-to-Device
DCC	Decentralized Congestion Control
DCF	Distributed Coordination Function
DENM	Decentralized Environmental Notification Message
D-FPAV	Distributed Fair Power Adjustment for Vehicular environments
DIFS	DCF Inter-Frame Space
DSRC	Dedicated Short Range Communications
DTRA	Dynamic Transmission Range Assignment
EDCA	Enhanced Distributed Channel Access
ETSI	European Telecommunication Standards Institute
FAC	Fish-eye Awareness Control
FSR	Fish-eye State Routing
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HMI	Human Machine Interface
IEEE	Institute of Electrical and Electronic Engineers
i.i.d.	independent and identically distributed
IP	Internet Protocol
ISO	International Organization for Standardization
ITS	Intelligent Transport System

LDM	Local Dynamic Map
LIMERIC	LInear MEssage Rate Integrated Control
LLC	Logical Link Control
LOS	Line Of Sight
LTE	Long Term Evolution
MAC	Medium Access Control
MANET	Mobile Ad-hoc NETwork
MS-Aloha	Mobile Slotted Aloha
NLOS	Non Line Of Sight
OCB	Outside the Context of a Basic service set
OFDM	Orthogonal Frequency Division Multiplexing
OP	Operating Point
PDF	Probability Density Function
PDR	Packet Delivery Rate
PER	Packet Error Rate
PHY	PHYsical
PULSAR	Periodically Updated Load Sensitive Adaptive Rate control
QoS	Quality of Service
RTP	Random Transmit Power
RTPC	Random Transmit Power Control
RTS/CTS	Request To Send / Clear To Send
SAC	Strict Avalanche Criterion
SAE	Society of Automotive Engineers

SBCC	Statistical Beaconing Congestion Control
SHA	Secure Hash Algorithm
SINR	Signal to Interference and Noise Ratio
SIR	Signal to Interference Ratio
SOTIS	Self-Organizing Traffic Information System
SPAV	Segment-based Power Adjustment for Vehicular environments
STDMA	Self-organized Time Division Multiple Access
TDMA	Time Division Multiple Access
TPC	Transmit Power Control
TRC	Transmit Rate Control
UD	Update Delay
UMTS	Unviversial Mobile Telecommunications System
UTM	Universal Transverse Mercator
VANET	Vehicular Adhoc NETwork
WAVE	Wireless Access in Vehicular Environments
WLAN	Wireless Local Area Network

Chapter 1

Introduction

1.1 Vehicular Ad-hoc Networks

The year is 2020. Joe Public is one of 460,000 *commuters in the metropolitan area of Munich. He lives in the city center and works at the German Aerospace Center (DLR) in Oberpfaffenhofen. As the connection via public transport leaves much to be desired, he always goes by his new electric car. As soon as he has entered the highway, he presses a button labeled "Autonomous Driving". Then, he releases the steering wheel and starts to have a focus on his tablet. First, he checks the latest news to be up-to-date for political and social discussions during coffee and lunch break. In the meantime his car has aligned automatically in a platoon of several vehicles. The distance between the vehicles is kept quite short to reduce energy consumption, by making use of the slipstream effect. Then, Joe checks his business emails to identify possible urgent issues, which have to be discussed with his colleagues today.*
Half an hour later he arrives safely and already well prepared at work. ...

This is just one of many visions on Intelligent Transport Systems (ITSs), to enable safer, cleaner, and more efficient transportation in the future. Especially with respect to traffic safety, a significant contribution is seen in Vehicular Adhoc NETworks (VANETs) [61], where vehicles and even infrastructure sites are equipped with a dedicated communications technology, known as ITS-G5 [8]. The communications scheme is based on IEEE 802.11 [9], which is used in current Wireless Local Area Networks (WLANs), with slight modifications to support immediate ad-hoc communications between the VANET entities. The ability, to exchange rapidly relevant information (e.g. position, speed, heading) between each other, goes far beyond the capabilities of current on-board radar- and vision-based sensors. Therefor, vehicles are compelled to periodically broadcast information about their current status, like position, speed, and heading, to other ones in the vicinity. By receiving this information, vehicles are able to generate an enhanced view of the current environment called cooperative *awareness* [91, 108, 17, 38, 93]. It allows to track other vehicles in the surrounding, which is the basic functionality for many new cooperative safety systems. One example for such a system is Cooperative Adaptive Cruise Control (CACC) [43], where vehicles are able to automatically follow each other in a safe and efficient manner. While radar-based Adaptive Cruise Control (ACC) is only able to track the preceding vehicle, which even may fail within sharp bends or road humps, CACC is able to track all cooperative vehicles within communication range. This allows to significantly speed up the reaction time in case of dangerous events within the platoon, as well as a better adaptation of the control loop to mitigate the shock wave effect in case of hard breaking [107, 81].

For CACC to be able to track the corresponding vehicles with sufficient reliability and accuracy, a highly dependable communications technology is required, especially in the context of vehicular safety. As all cooperative vehicles have to share a common radio channel (medium), therefore, the use of efficient and scalable Medium Access Control (MAC) strategies plays a decisive role. Instead of a dedicated communications technology, which would be able to exactly address the challenges of vehicular safety communications, various standardization bodies (e.g. ASTM, IEEE, ETSI, ISO) have selected the well known WLAN standard IEEE 802.11 [9] as the basic communications technology. In the context of VANETs, it is usually referred to as ITS-G5 in Europe, or Dedicated Short Range Communications (DSRC) in other countries.

The major advantage of the WLAN standard, and the reason for its success, comes from its flexibility and adaptability. For instance, the challenging vehicular environment (e.g. highly transient connections) justified a new amendment to the IEEE 802.11 baseline: a new operation mode called Outside the Context of a Basic service set (OCB)[1]. This mode activates genuine decentralized ad-hoc communications between vehicles, without any association and authentication procedures towards any WLAN access point. Hence, the OCB mode makes the VANET connectivity quite flexible and fail-safe.

[1] Formerly known as IEEE 802.11 p.

1.2 Challenges for Cooperative Awareness

Trustworthy cooperative safety applications require the awareness of each vehicle to be highly up-to-date. This in turn requires safety-related single-hop broadcast transmissions being received regularly with high reliability. Although adapted, IEEE 802.11 is not able to provide reliable communications, which raised growing concerns about the capability of ITS-G5 to sustain traffic safety applications. One of the main reasons for this is the applied MAC protocol in IEEE 802.11.

The MAC layer coordinates the access on the shared wireless channel among several communication participants. The basic channel access scheme in IEEE 802.11 is implemented by Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) [9]. It is working in a fully decentralized manner, which makes the network quite flexible and robust. However, CSMA/CA is a contention- and random-based MAC protocol, which is not able to guarantee any deterministic access on the wireless channel. Furthermore, it may even cause the risk of granting access to the wireless channel for multiple nodes at the same time, which is usually referred to as a packet collision. This imperfection of the IEEE 802.11 MAC shows up in particular, if the number of transmitting nodes is increased [77]. Then, the CSMA/CA channel is going to be congested, which even increases the probability of causing packet collisions. As a result, the communication performance (throughput) degrades significantly [25]. Besides the issue of channel congestion, CSMA/CA also suffers from the so called hidden terminal problem [77]. Lets consider an ongoing transmission between two nodes. A hidden terminal is a third node that is in range of the receiver, but out of range regarding the corresponding transmitter. Consequently, the hidden terminal is not able to sense an ongoing transmission of the corresponding transmitter, and it may start to transmit as well, causing a packet collision at the receiver. To avoid such situations, a handshake protocol has been introduced called Request To Send / Clear To Send (RTS/CTS) [9]. In principle, the transmitter, first, indicates a reservation of the wireless channel (RTS) for a data packet, which is confirmed by the corresponding receiver (CTS). Unfortunately, the RTS/CTS handshake can be only applied for unicast communication. Thus, the hidden terminal problem still remains for broadcast transmissions.

Now lets consider IEEE 802.11-based VANETs and their properties. Especially in dense traffic scenarios there is a high number of transmitting vehicles, for instance, in a multi-lane highway scenario as depicted in Figure 1.1. The requirement of each vehicle to transmit regularly safety-related information at the maximum range on a wireless CSMA/CA channel with limited capacity, possibly brings congestion on the channel. Furthermore, most

Figure 1.1: Especially in highly dense traffic scenarios, each vehicle regularly transmitting safety-related information at the maximum range usually brings congestion on the wireless channel (Source: Wikimedia Commons)

of the safety-related transmissions are broadcast. Consequently, ITS-G5 suffers from severe hidden terminal conditions in addition, which significantly compound the problem of packet collisions [49]. Altogether, VANETs in particular have been shown to suffer from a significant degradation of the communications performance [75, 40, 84, 28, 35, 27, 113, 122, 74, 132, 37]. Indeed, broadcast delivery in VANETs is life critical, which brings ITS-G5 to a major conundrum: *How to transmit safety-related information with sufficient reliability by using a potentially undependable MAC technology?*

The most common approach to limit packet collisions during channel access is to avoid a congested channel. It has been the purpose of numerous studies, e.g. [54, 131, 18, 90, 21, 123, 99, 46, 49]. They regulate transmission parameters, like power or rate, to limit the load on the wireless channel. This is commonly known as *congestion control*. Instead of controlling the channel load, others adapt the same transmission parameters with focus on fulfilling the application's requirements, usually referred to as *awareness control*, e.g.

[102, 57, 63, 114, 108, 120, 115, 126].

Regardless of performing congestion or awareness control, almost all implementations either keep a constant transmit power, or make all nodes in the same vicinity to converge to a harmonized quasi-constant transmit power or rate. Due to this feature, the following VANET-specific issues still remain:

Correlated Packet Collisions

While current congestion control approaches aim at mitigating MAC-related packet collisions in general by operating the channel in a not congested state, they do not consider their causes as well as their spatial and temporal behavior. However, the primarily periodic communication patterns, combined with slow relative mobility between vehicles, e.g. in case of platooning on a highway, may result in recurring packet collisions at the same receiver. Such *correlated packet collisions* may quickly cause an outdated awareness of other vehicles in the surrounding, as no new status updates are received for a longer period.

Random repetition schemes, e.g. [140], are one solution to address that problem. However, as they randomly repeat the transmission of the same message for several times, they implicitly further increase the load on the wireless channel, which is rather a counterproductive approach, if the channel is already in a congested state.

Another part of the research community thinks that alternative technologies, like Self-organized Time Division Multiple Access (STDMA) [29], Mobile Slotted Aloha (MS-Aloha) [112], or even cellular solutions [86], may better suit the transmission policies for vehicular safety communications. Like WLAN, STDMA and MS-Aloha are fully decentralized approaches. As both are based on reserved time slots, they indeed better suit the periodic communication pattern of safety-related broadcast transmissions. However, in contrast to WLAN, they require a quite precise time synchronization between the nodes, which is even more challenging in decentralized networks. Whereas WLAN is a mature technology in the context of mobile ad-hoc networks, which have been studied and proved to be practicable for more than a decade, STDMA and MS-Aloha are relative new approaches. Hence, their supporters had difficulties to convince the standardization bodies about their practical suitability in the near future. The disadvantage of current cellular approaches, like Unviversial Mobile Telecommunications System (UMTS) or Long Term Evolution (LTE), is their centralized network layout. Relevant information, destined for neighboring vehicles, first has to be transmitted via the base station into the cellular backbone, before arriving at the final destination, which might be possibly located just a few meters ahead or behind. This increases the latency of safety-related information significantly [137]. Another issue of centralized cellular networks is the required coverage by base stations, which is not always given, especially in rural areas. However, the research activities in cellular networks are progressing significantly, also with respect to ad-hoc capabilities like Device-to-Device (D2D) communications in LTE-Advanced [83].

The Transmit Power/Rate Trade-Off Dilemma

Reducing packet collisions on the MAC layer by reducing the channel load is absolutely reasonable. The challenge is, however, to perform congestion control without violating the awareness range and quality requirements of cooperative safety applications. Therefore, an optimal trade-off between transmit power and rate has to be found, as both have a proportional impact on the awareness and the channel load. While increasing the transmit power may enhance the coverage, and by implication the awareness range, it also increases the channel load in space, as transmissions may occupy the shared channel up to higher ranges. Similarly, increasing the transmit rate may improve the awareness quality by providing updates of the vehicle's status more frequently, but it increases the channel load in time, as more messages are transmitted. This behavior may lead to the following *trade-off dilemma*: In order to reduce the channel load, one could reduce the transmit power, but may risk in not fulfilling the required awareness range anymore, or one could decrease the transmit rate, but may risk in not fulfilling the necessary awareness quality.

An interesting approach to find such transmit power/rate trade-off is provided, for instance, by Tielert *et al.* [127]. The authors propose, first, to map the desired target distance to the corresponding transmit power and then to adapt the transmit rate to maintain a certain target channel load. Although such target-distance-to-transmit-power mapping might be possible under specific conditions, it is quite unreliable in more general conditions, due to the unpredictability of wireless radio propagation, especially in vehicular environments. Additionally, fixing the transmit power in order to cover a certain target distance still preserves the issue of correlated packet collisions as described in the previous subsection.

Furthermore, future vehicles will not only run one cooperative safety application, but several at the same time. Then, finding a single power/rate pair, which is able to fulfill the awareness range and quality requirements of all applications, becomes even more challenging.

1.3 Objectives and Methodology

Regardless of whether alternative technologies might show better suitability for vehicular safety communications, the standardization bodies have decided for IEEE 802.11 as the first generation technology for ITS-G5. Hence, this work aims at remaining compatibility with current ITS-G5 and addresses the great challenges on MAC layer to support cooperative safety by single-hop broadcast transmissions. Based on that, the *objectives* of this work are as follows:

- *Understanding packet collisions:* While current congestion control schemes simply reduce the load on the wireless channel in order to mitigate packet collisions on the MAC layer, this thesis aims at investigating their different reasons, as well as their occurrence in space and in time.

- *Mitigation of nearby packet collisions:* As nearby vehicles are much more critical than farther ones, another objective is to mitigate in particular nearby packet collisions.

- *Decorrelation of correlated packet collisions:* Especially correlated packet collisions significantly degrade the awareness quality. For that reason, this thesis aims at decorrelating correlated packet collisions.

- *Relaxation of the transmit power/rate trade-off dilemma:* Mitigating packet collisions without violating the application's range and quality requirements is very challenging. Hence, the final objective of this work is to relax the transmit power/rate trade-off dilemma.

In order to achieve these goals, the following methodology is proposed:

Investigation of packet collisions

MAC-related packet collisions are probably the most performance limiting factor of ITS-G5 in dense traffic scenarios. The majority of current transmission control approaches aim to reduce packet collisions in general by simply reducing the load on the wireless communications channel. However, they do not explicitly address the source of packet collisions caused by the MAC.

Especially in VANETs the vehicles mobility and their transmission policy may have a significant impact on the MAC performance. Hence, the first step is to analyze packet collisions regarding their causes, as well as their spatial and temporal occurrence behavior. To obtain a MAC-challenging scenario, a multi-lane highway scenario with highly dense traffic is selected. As a real-world experimental setup of such a scenario is hardly possible in practice, the analysis is conducted by means of simulations. Furthermore, the focus of this work is on MAC-related packet collision caused by the MAC protocol. While in real-world experiments PHY layer effects like fading are automatically included, simulations allow to intentionally neglect them in order to limit their impact on the MAC protocol's performance. The investigation of the different causes for packet collisions and their spatial behavior is based on a receiver-based decision algorithm, which evaluates the spatial distribution between the collision participants, as well as the different states of the corresponding MAC scheme. To analyze the (temporal) correlation behavior of packet collisions on the MAC, the simulation results are evaluated by means of two distinct theoretical models, with a strict focus on the receiver-based metric *update delay*, measured in units of packets. While the Gilbert-Elliott model is used to confirm the (temporal) correlation behavior of MAC-related packet collisions, the geometric distribution model serves as a benchmark, as it assumes perfect independence between subsequent reception events by definition. In order to determine the model's parameters, curve fitting is applied by means of the Levenberg-Marquardt algorithm.

The expectation is to get a sufficient understanding of MAC-related packet collisions. Only if the problem of packet collisions is well understood, appropriate countermeasures can be taken in order to mitigate them accordingly.

Identification of collision mitigation concepts

Based on the results from the packet collisions analysis, in this step, possible collision mitigation concepts are identified. It should be noted that the solution space is limited as this work aims at remaining compatibility with the current standard. Consequently, alternative TDMA-based approaches are not considered as a possible solution in this thesis. Maintaining compatibility with the current standard also includes the fact that cooperative awareness is still provided by safety-related single-hop broadcast transmissions. That means, the problem of hidden terminal collisions still remains. Hence, the methodological approach in this part is twofold:

1. *Packet collision mitigation in space:* Especially in the context of traffic safety, nearby vehicles are much more relevant than farther ones. The reason is that only nearby vehicles may pose an imminent danger regarding a physical collision between vehicles.

Thus, one objective is to reduce packet collisions in the nearby region. For that purpose the idea is to play with a MAC parameter named Contention Window (CW) as well as the backoff generation procedure, as both have a direct impact on packet collisions within the contention area.

2. *Packet collision mitigation in time:* With focus on safety-related broadcasts, (temporal) correlated packet collisions in particular degrade the cooperative awareness of other vehicles in the surrounding. They are caused by the primarily periodic transmission pattern for safety-related broadcasts, combined with slow relative mobility between neighboring vehicles, e.g. in case of platooning on a highway. Possible countermeasures may either rely on making safety-related broadcasts less periodic, or making the vehicles relative mobility more dynamic or even random. For that purpose the idea is to play with transmission parameters like rate (interval) or power. While the transmission interval is directly linked with the periodicity of safety-related broadcasts, the transmission power impacts the radio propagation, which can be exploited to simulate a more dynamic relative mobility between the vehicles.

Impact on MAC

After new collision mitigation strategies have been identified, their impact on the MAC is analyzed. For this purpose simulations are performed by means of the network simulator ns-3 [3] modified to support ITS-G5 communications, and the results are compared with the ones from the beginning. At that stage application requirements are still ignored, which allows to really focus on MAC issues.

The impact on MAC-related packet collisions in space is analyzed by determining the packet collision rate and evaluating it with respect to distance. To get a first indication on the temporal correlation of packet collisions, the recurring packet collision rate as well as its ratio with respect to the total amount of packet collisions is discussed. A more detailed investigation of correlated packet collisions is performed by evaluating the receiver-based update delay metric. But as the focus here is on packet collisions on the MAC, it is measured in units of packets instead of time. The reason is that the time-based update delay does not distinguish between different transmission rates. Hence, it cannot be used to analyze consecutive packet losses, if the transmission rate is not clearly defined. The packet-based update delay, instead, directly accumulates the number of subsequent lost packets up to and including the next successful reception from the same transmitter.

Besides the packet collisions behavior, the communications performance is analyzed as well. For that purpose the conventional update delay metric is used, i.e. the update delay with respect to time. Especially in the context of periodic safety-related broadcasts, the time-based update delay evaluates the communications performance with respect to the duration between two consecutive successfully received updates from the same transmitter. This allows to make statements about how frequently safety-related information is updated.

While an adaptation of transmission parameters like power or interval has no significant effect on the end-to-end latency, playing with the CW of the MAC has. Thus, for the latter one the latency behavior is analyzed as well, and compared with the requirements claimed in [43].

Impact on applications

While in the previous part the identified collision mitigation concepts are investigated with respect to packet collisions caused by the MAC protocol, in the final part their impact on the applications is analyzed. Eventually, it is the safety application that has to work with sufficient reliability. In the context of cooperative safety, an application's reliability usually relies on the cooperative awareness. Especially the transmit interval and power have a significant impact on the awareness quality and range, respectively. Whereas the transmit power defines up to which range safety-related information is transmitted, the transmission interval specifies how frequently safety-related updates are provided to other vehicles in the surrounding. Due to this observation, adapting the transmit power or interval may provide the key in order to adapt the cooperative awareness according to the application's needs, in space as well in time.

The impact of the proposed collision mitigation strategies on applications is evaluated by means of simulations again. But in contrast to the previous part, the results are discussed in the context of a concrete example cooperative safety application named CACC. Unfortunately, no authentic requirements on receiver-based metrics like the update delay could be found for CACC. Hence, the approach here is to reduce CACC to its basic task, that is tracking of the preceding vehicles. By means of simple constant velocity kinematics, update delay values are mapped to distance errors in order to determine the tracking accuracy with ITS-G5 communications.

1.4 Contribution

Following the proposed methodology above outlines the main contribution of this thesis:

Packet collisions analysis

In order to take appropriate countermeasures, first, the problem of MAC-related packet collisions has been analyzed in detail by means of extensive simulations. Please note that the focus here is on the MAC and its packet collisions caused by the CSMA/CA protocol. Hence, in this work a packet collision is defined by two simultaneous (overlapping) transmissions, detected at the corresponding receiver, which is located within the transmission range of both transmitters.

Packet collisions have been analyzed regarding their causes as well as their spatial and temporal behavior. The results show that in the nearby region a significant amount of approximately 45 % of the packet collisions are caused because the two transmitters have chosen the same backoff counter. Additionally, more than 70 % of the packet collisions recur from 450 m on and more than 90 % recur from 650 m on. In order to further validate the temporal correlation of packet collisions on the MAC, the simulation results have been also compared with two theoretical models. While the geometric distribution model assumes perfect independence between consecutive packet losses, and by implication is not able to consider correlated packet collisions on the MAC layer, the Gilbert-Elliott model is widely used to model correlated burst errors. Indeed, the simulation results show that the temporal behavior of packet collisions rather matches the Gilbert-Elliott model than the geometric distribution model. This observation confirms the hypothesis of a correlated behavior of packet collisions on the MAC layer.

Collision mitigation strategies - Impact on MAC

Based on these results, three new packet collision mitigation strategies are proposed. They are designed to address the following issues:

- **Geo-backoff:** The backoff generation procedure is an essential part of IEEE 802.11's MAC mechanism. In case of contention, it introduces an additional random waiting time before access on the wireless channel is granted, and by association has a direct impact on the occurrence of packet collisions. Indeed, the results above have shown that a significant amount of nearby packet collisions is caused by vehicles having chosen the same backoff counter. To mitigate this type of packet collisions is the objective of the *geo-backoff* concept. It aims at improving the backoff counter selection by exploiting the vehicle's current position, in order to relocate same backoff collisions to vehicles, which are geographically located as far as possible. This idea, however, implicitly requires to increase the CW as well, because packet collisions cannot be effectively mitigated as long as the number of available backoff counters is too small compared with the number of contending vehicles, even if the geographic information is used to select the backoff counter.

While the first step is state-of-the-art, this work is mainly focusing on the second one. Two implementation approaches for the geographic-based backoff counter generation have been investigated: Whereas the crypto-based approach makes use of the property of cryptographic hash-functions, the grid-based approach requires a grid-layout along the road in order to determine the corresponding backoff counter. Although the grid-based approach is able to reduce the same backoff collisions completely up to a certain range, the results show that the most significant improvement is coming from the CW increase, and the impact of the grid-based backoff counter generation is negligible.

The obtained results are in line with related work, but in this work the evaluation of the communications performance is based on the receiver-based metric update delay. The results show that an appropriate increase of the CW may improve the update delay performance approximately by a factor of 10.

- **Random Transmit Jitter:** Particularly correlated packet collisions significantly degrade the awareness of other vehicles in the surrounding. One of the reasons for correlated packet collisions on the MAC is the strict periodic transmission pattern for safety-related broadcasts. Although an up-to-date cooperative awareness requires to receive safety-related broadcasts in a regular manner, it is not necessary to receive them exactly at a certain fixed periodic rate. It might be sufficient to receive safety-related broadcasts at a certain rate on average, and accepting some variation around the nominal broadcast interval. Hence, the *random transmit jitter* concept aims at braking up the strict periodicity of safety-related broadcast transmissions by simply adding an artificial random jitter to the nominal broadcast interval. As a consequence, overlapping transmissions in time (i.e. packet collisions) are more unlikely to overlap again for the next transmission, as both transmitters are likely to choose different transmission times. Please note that this does not necessarily mean that packet collisions are reduced in general. If a packet collision between two transmitters does not recur again, one of the two transmitters may collide with another transmitter. However, the important point here is that correlated packet collisions become more uncorrelated.

The simulation results have indeed shown that for low channel load scenarios recurring packet collisions can be reduced by a factor of 10 at short distances. With increasing load, however, the randomization of the transmission times at higher layers is going to be absorbed again by the contention procedures of the MAC protocol.

- **Random Transmit Power:** The second reason for correlated packet collisions on the MAC is the quasi-static relative mobility between neighboring vehicles. However, simply altering vehicular mobility is not possible in practice. Thus, the proposed solution is to 'fake' an alternating mobility by adapting the transmit powers accordingly. Specifically, the concept of using *random transmit powers* is based on selecting the current transmit power randomly for each transmission and vehicle. Considering two static vehicles, high power transmissions may indicate a close distance between them, while low power transmissions may indicate a long distance. Thus, the concept of random transmit powers is able to provide a 'perceived' random mobility between neighboring vehicles. The benefit of random transmit powers is that it results in a randomization of collision and interference areas in space for consecutive transmissions. Consequently, a packet collision is unlikely to recur again at the same receiver (distance) for subsequent simultaneous transmissions.

  Whereas without random transmit powers a maximum recurring collision ratio of 98 % is revealed, the simulation results show that with random transmit powers that ratio is reduced to a maximum of 62 %. Furthermore, the concept is also able to reduce the load on the channel approximately by a factor of 2.5, thus saving resources on the wireless channel as vehicles transmit with less power on average.

Fish-eye Awareness Control - Impact on applications

While the previously introduced packet collision mitigation strategies indeed show a beneficial impact on the MAC, the remaining question is if this is still valid for the applications. In the end it is the cooperative application, which has to work with sufficient reliability. Especially the concept of randomization might sound quite contradictory at first, considering *safety* applications are running on top.

Two aspects should be mentioned here: First, particularly the cooperative awareness concept in VANETs makes the proposed collision mitigation strategies applicable to cooperative (safety) applications. Whereas conventional networks usually require to establish a communication link, the cooperative awareness concept does not care about the lower layer communications, as long as the required awareness is provided. This fact provides some freedom in adapting transmission policies like power or rate. Second, it should be noted that the introduced randomness includes an important feature, that is controllability. While a natural transmit power randomization effect called fading is absolutely uncontrollable, the proposed concept is able to adapt the randomization accordingly by making use of different probability distributions, defined by their shape, mean, variance, etc.

The controllability feature just described enhances the basic random transmit power concept to Random Transmit Power Control (RTPC), which provides the following benefit to the cooperative awareness: As vehicles transmit with random, but controlled alternating powers, they implicitly transmit at different ranges. While low power transmissions can only reach the nearby vehicles, high power transmissions are able to cover the farther ones as well. Consequently, nearby vehicles experience a higher update rate than farther ones. This results in a distance-based awareness quality, which degrades with increasing range. Especially in the context of vehicular safety, this is an interesting effect, as nearby vehicles are more critical with respect to absolutely dangerous events like vehicle collisions.

Although with RTPC the awareness shows a higher quality at closer distances than at farther ones, for some (safety) applications the provided quality at close ranges still might be not enough. The full potential is revealed, if RTPC is combined with an additional Transmit Rate Control (TRC) strategy. As RTPC is able to reduce the load on the wireless channel, the transmit rate may be increased subsequently, which in turn increases the quality of the awareness along the entire range.

With this approach, a new framework called *Fish-eye Awareness Control (FAC)* is introduced. It allows to adapt the awareness quality as a function of the range. The proposed FAC strategy is not able to improve awareness everywhere, but it provides a better spatial utilization of the wireless resources in the context of cooperative safety. While most of the current transmission control strategies aim at finding a single harmonized power/rate trade-off, they might provide an optimal awareness on average, but may risk in being over-designed at high ranges and under-designed at close ranges. With FAC, a trade-off has been found by exploiting the distance-dependent criticality/relevance in the context of traffic safety. Altogether, FAC provides a significant improvement by approximately a factor of 10 to 70 at close ranges, however, traded against reduced performance at farther but also much less critical distances.

The fish-eye concept has been already applied earlier to wireless ad hoc networks, but in the context of routing [95]. Also in VANETs research the distance-dependent relevance of information has been already considered in [138]. However, in this work the fish-eye concept is first applied to the cooperative awareness in VANETs, and is implemented for single-hop broadcast transmissions.

1.5 Outline

This thesis is organized as follows: Chapter 2 introduces the fundamentals of VANETs and its application to cooperative traffic safety. It emphasizes the specific communications requirements of cooperative safety applications, which pose a real challenge to IEEE 802.11 networks. Moreover, it surveys the relevant transmission control approaches, which aim to address these issues. Finally, the remaining open issues and challenges of current transmission control approaches are discussed.

A detailed analysis of packet collisions, which are the main reason for undependable ITS-G5 from a MAC perspective, is provided in Chapter 3. Therefore, packet collisions are detected and classified with respect to their causes, as well as their occurrence in space and in time. The correlated behavior of packet collisions is validated by the comparison with two distinct theoretical models.

Chapter 4 still focuses on the MAC perspective. Based on the observations from Chapter 3, it proposes three new mechanisms to mitigate MAC-related packet collisions. It introduces the concepts of geo-backoff, random transmit jitter, and random transmit powers, and analysis them regarding their impact on packet collisions, as well as on RX-centric communication performance metrics, like the update delay.

Chapter 5 focuses on the applications perspective, in particular on the impact of the previously proposed mechanisms according to application-specific requirements. It introduces the concept of fish-eye awareness, followed by a practical implementation approach, based on combining RTPC with TRC. The new fish-eye awareness control strategy is evaluated by simulations, with focus on platooning as an example for cooperative safety applications.

Finally, Chapter 6 summarizes the presented work and motivates for future research.

Chapter 2

Cooperative Safety by VANETs

With the deployment of VANET-technology in the near future, a significant contribution to traffic safety is seen in new cooperative safety applications. Hence, this chapter will introduce Vehicular Adhoc NETworks (VANETs) and their vision to support cooperative safety applications, as well as existing issues and current approaches.

2.1 VANETs - An ITS Subset

In principle, a VANET is a network of vehicles and even infrastructure sites, which are equipped with a fully decentralized communications technology called ITS-G5 [8] in Europe, or DSRC in other countries [68], like the USA or Japan. Similar to all modern communications systems, the VANET communications architecture also mainly follows a layered approach, based on the model proposed in [6]. Figure 2.1 shows the European reference communications architecture of a general ITS station. Whereas an ITS station may also include other wireless technologies, like cellular communications, VANETs can be seen as a subset of ITSs, which are focusing on the ITS-G5 Profile Standard [8] for direct inter-vehicle communications. Although some terminologies may differ from the ITS activities in the USA and other countries, the various (international) standardization organizations, like ETSI, CEN, ISO, IEEE, and SAE, are working closely together in order to "ensure a global harmonization of ITS deployment in different regions" [12]. For the purpose of uniformity, the European notations and terminologies will be used throughout this thesis, without becoming less important for ITS in other countries.

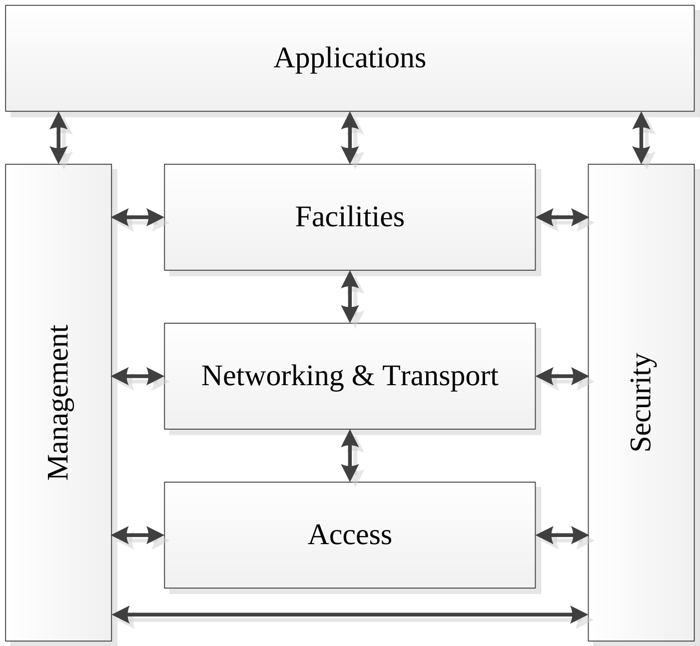


Figure 2.1: Reference communications architecture of an ITS station (based on [7]).

Access Layer

Following a bottom-up approach, the lowest layer is usually referred to as *access layer*. As this thesis is focusing on VANETs, the access technology of interest is specified by the European profile standard ITS-G5 [8], which is based on the well-known Wireless Local Area Network (WLAN) standard named IEEE 802.11 (a.k.a. Wi-Fi) [9]. To avoid interferences from other communications systems, ITS-G5 is operating in a dedicated frequency band, located around 5.9 GHz and exclusively reserved for ITS communications. The frequency band is divided into several channels of 10 MHz bandwidth. Safety-related information is foreseen to be transmitted on ITS-G5A, a group of three channels, built up by two service channels and one control channel. More details on the frequency and channel allocation can be found in [10].

The access layer in Figure 2.1 basically consolidates the PHYsical (PHY) layer and the data link layer from [6]. Starting with the PHY layer, a technique called Orthogonal Frequency Division Multiplexing (OFDM) [50] is used for physical transmissions on the wireless channel. Whereas in ordinary WLAN the default channel bandwidth is 20 MHz, for ITS-G5 it has been halved, which makes physical transmissions more robust against multi-path delays. More details on the PHY layer part of ITS-G5 are given in [9].

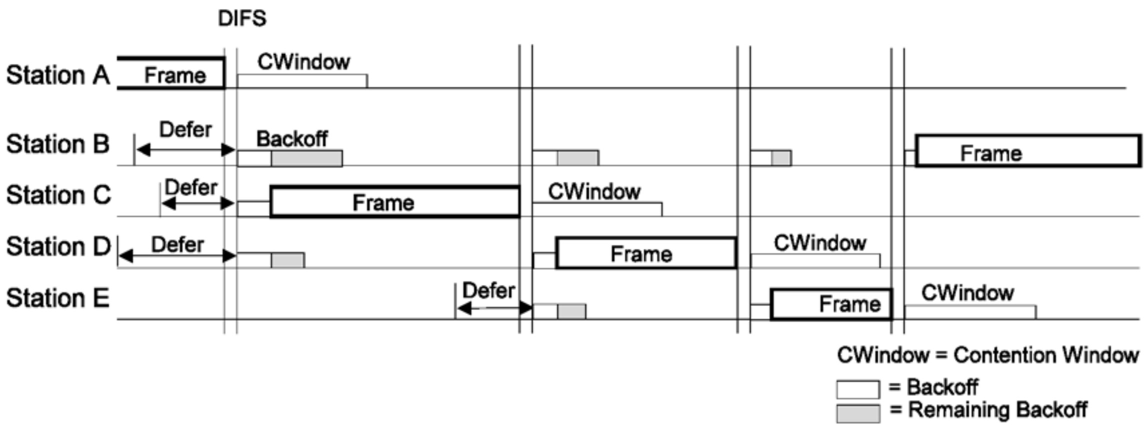


Figure 2.2: An example with five different stations, each performing DCF for accessing the shared channel (Source: [9]).

In IEEE 802 networks, the data link layer is usually split up by two further sublayers, the Logical Link Control (LLC) layer and the Medium Access Control (MAC) layer, where the latter one is the most relevant within this work. To coordinate the access on the shared communications medium among multiple vehicles in a decentralized manner, the fundamental MAC scheme is Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) [77]. It is implemented by the Distributed Coordination Function (DCF) in IEEE 802.11, and is working as follows: If a vehicle has a packet to transmit, it first listens to (senses) the channel for a certain time interval called DCF Inter-Frame Space (DIFS). If the channel was idle for the entire DIFS, the vehicle starts immediately to access the channel for transmission. But if the channel was sensed busy, the DCF generates a backoff counter, randomly chosen from the integer interval $[0;\ CW - 1]$, with the Contention Window (CW) specifying the size of the interval. The vehicle waits until the channel is idle again for an entire DIFS, but in addition, it waits for subsequent idle slot times, with each decrementing the current backoff counter by one. In case the current backoff counter has reached zero, the vehicle instantly accesses the channel for transmission. An example with five stations performing DCF is depicted in Figure 2.2.

While DCF implements the basic CSMA/CA protocol, ITS-G5 MAC uses an enhanced access mechanism called Enhanced Distributed Channel Access (EDCA) [9], which provides differentiated distributed medium access. For this purpose, EDCA defines four different Access Categorys (ACs), each of them implementing an enhanced version of DCF with different settings of the EDCA parameters, e.g. the Arbitration Inter-Frame Space (AIFS) or the CW. In principle, different ACs provide different waiting times on average for channel access. Thus, EDCA allows to assign different priorities to data frames by assigning them to different ACs. As the coordination functions in each of the ACs are working independently from each other, it may happen that two of them are contending with each other, causing an internal collision. In that case the data frames from the higher priority AC are granted to access the medium, while the others switch to the backoff procedure.

Regarding the MAC part, the basic difference to ordinary WLAN is a new mode of operation called Outside the Context of a Basic service set (OCB)[1]. This mode is essential for short-living connections typical for VANETs, as it allows fast communication between vehicles by operating in pure ad-hoc mode, that means, no access point and no association and authentication procedures are required.

Networking and Transport Layer

In the context of VANETs, *networking and transport* issues are regulated by the geo-networking functionalities [45, 47, 48]. Geo-networking enables to address vehicles within a certain geographical area. Three different types of forwarding schemes are considered:

- *GeoUnicast:* It describes the packet delivery method between two nodes via multiple hops. The sending node, first, determines the destinations position, which is used then to forward the packet towards the destinations direction via multiple intermediate nodes, until the destination has been reached.
- *GeoBroadcast:* The packet is forwarded via multiple hops until the destination area (specified by the packet) has been reached. Nodes located within the destination area rebroadcast the packet there.
- *Topologically-scoped Broadcast:* Packets are re-broadcasted to all nodes within the n-hop neighborhood.

Facilities Layer

The *facilities* layer is mainly responsible for application, information, and communications support. The latter also includes the definition of various message types, to be able to exchange different kind of information between vehicles. As the focus of this work is on cooperative safety, the most relevant message types are as follows:

[1] Formerly defined in the amendment IEEE 802.11p. However, in the meantime all amendments, including 802.11p, have been merged into the IEEE 802.11-2012 standard.

- *Cooperative Awareness Message (CAM) [11]:* The CAM is foreseen to be transmitted on the control channel. It contains information describing the current status of the transmitting vehicle. The most common information is position, speed, heading, etc. Due to the vehicle's absolute dynamics, the information provided by CAMs only has a short validity (in the range of hundreds of milliseconds to a few seconds). Thus, vehicles are required to regularly broadcast CAMs towards their neighbors. By receiving CAMs from other vehicles, the receiver is able to be aware of their current status, and to use this information for several cooperative (safety) applications.

- *Decentralized Environmental Notification Message (DENM) [44]:* The DENM typically describes a certain event, by specifying its type, location, relevance area, duration and much more. In contrast to CAMs, the validity of the information provided by DENMs is in the range of minutes, hours or even days. If a DENM is received, vehicles typically store it for the specified duration, and warn the driver in case of relevance.

Whereas DENMs are typically forwarded to all vehicles within a certain relevance area (GeoBroadcast), CAMs are mainly destined to the immediate vicinity (one-hop broadcast). All the information gathered from these messages is processed and used to update a geographical database, called Local Dynamic Map (LDM) [13]. The LDM contains current information (position, speed, heading, etc.) about other vehicles in the surrounding and certain events (e.g. road works, traffic jam), and provides the required information to the cooperative (safety) applications.

Application Layer

On top of the communications stack various ITS *applications* provide different services by requesting the necessary information from the LDM. A Human Machine Interface (HMI) allows the user to access the different services. To limit the drivers interaction with the HMI and distracting him from his main task (i.e. driving), the applications typically push the service automatically to the driver by displaying a warning or an advice only in case of relevance. Since the trend for future vehicles is going towards autonomous driving, applications do not necessarily have to interact with the driver, but can also act and make decisions by their own.

To have a common understanding of ITS applications, ETSI started to provide a basic set of applications, by means of a catalog, which defines some basic applications and their corresponding use cases [43]. Basically, ITS applications can be classified into three categories: traffic safety, traffic efficiency, and infotainment. However, this work will exclusively focus on *traffic safety*, provided by a new feature called *cooperative awareness*. It allows to track other vehicles in the surrounding and to determine if vehicles are heading for a collision. This is the basic functionality for many new cooperative safety applications, like platooning, where vehicles automatically follow each other in a safe and efficient manner by implementing Cooperative Adaptive Cruise Control (CACC)[98].

Cross-Layer Support

Beside the classic horizontally layered approach, the ITS communications architecture also provides two vertically arranged planes: On the one hand, there is the *management* plane, which allows to exchange relevant information across several layers. On the other hand, there is the *security* plane, which accounts for security and privacy issues on each of the layers.

2.2 Cooperative Awareness Enhancing Traffic Safety

VANETs are expected to go far beyond the capabilities of local radar- and vision-based sensors, by providing an enhanced perception of the current environment, which is usually referred to as cooperative *awareness* [90, 108, 105, 11, 17, 38, 72]. In order to provide such cooperative awareness, CAMs and DENMs are the most important messages in the context of traffic safety.

2.2.1 Communications Impact on Cooperative Awareness

As the validity period of CAMs is usually very short-living, vehicles are required to broadcast CAMs in a frequent and regular manner. Hence, CAMs are expected to comprise most of the generated load on the wireless channel (control channel) [31]. This thesis, therefore, exclusively focuses on the challenges of broadcasting CAMs in order to support cooperative safety in vehicular networks. The role of one-hop broadcast is indeed a hot topic in the community, and has been extensively discussed during the Dagstuhl Seminar in 2010 [36].

Initially, CAMs have been expected to be periodically transmitted at a fixed rate between 1 Hz and 10 Hz. However, it has been observed that the relevance of a CAM heavily depends on how much the vehicles status (position, speed, heading) has changed since the last CAM transmission. Accordingly, in [11], the European Telecommunication Standards Institute (ETSI) has specified that a CAM transmission should be triggered with a minimum rate of 1 Hz *and* if

- the position has changed by more than 4 m.
- the speed has changed by more than 0.5 m/s.
- the heading has changed by more than 4 degrees.

To limit the transmit rate to a maximum of 10 Hz, the latter conditions are only checked every 100 ms.

In the context of traffic safety, cooperative awareness of neighboring vehicles provided by CAMs is critical. It enables to estimate and predict the trajectory of other vehicles in the surrounding. Compared with the own predicted trajectory, possible collision courses can be determined and, if necessary, appropriate countermeasures, e.g. automatic braking, may be taken to avoid or mitigate an imminent collision. Thus, awareness is an essential feature, which supports the basic functionality of traffic safety applications, specifically, to avoid collisions between vehicles. However, to work with sufficient reliability, cooperative safety applications have certain requirements on the awareness and its quality.

Röckl [105] compared the behavior of the (situation) awareness in ITSs with the behavior of an information fusion filter. Let S_k denote the state of a vehicle at time step k, and let M_k denote the corresponding measurements (contained in the CAMs) received at time step k. Then, the behavior of the awareness can be described by the following two steps [104, 105]:

1. *Prediction Step:* As long as no CAM is received (e.g. due to packet collisions), the vehicle's state S^{k+1} at time step $k+1$ is predicted by using an appropriate prediction (movement) model $P(S^{k+1}|S^k)$, applied to the current state estimate $P(S^k|M^{1:k})$. Mathematically, the predicted state $P(S^{k+1}|M^{1:k})$ for time step $k+1$, given all the measurements $M^{1:k}$ from the past, is described by the following equation:

$$P(S^{k+1}|M^{1:k}) = \sum_{S^k} \underbrace{P(S^{k+1}|S^k)}_{\text{Prediction model}} \cdot \underbrace{P(S^k|M^{1:k})}_{\text{State estimation at time step k}} \tag{2.1}$$

2. *Update Step:* When finally a CAM with new up-to-date measurements M^{k+1} is received, the state prediction $P(S^{k+1}|M^{1:k})$ is updated accordingly, resulting in a new

state estimation $P(S^{k+1}|M^{k+1})$ for time step $k+1$. From a mathematical point of view, the update step is described by the following equation:

$$P(S^{k+1}|M^{1:k+1}) = \underbrace{\alpha}_{\text{Normalization coefficient}} \cdot \underbrace{P(M^{k+1}|S^{k+1})}_{\text{Measurement model}} \cdot \underbrace{P(S^{k+1}|M^{1:k})}_{\text{Prediction}} \tag{2.2}$$

Assuming Gaussian distributed errors, then the prediction model (PM) and the measurements (MM) are Gaussian as well, denoted by $\mathcal{N}_{PM}(\mu_{PM}, \sigma_{PM})$ and $\mathcal{N}_{MM}(\mu_{MM}, \sigma_{MM})$, respectively. If applied within the two steps described above, the predicted states (PS) and the updated states (US) are also Gaussian, denoted by $\mathcal{N}_{PS}(\mu_{PS}, \sigma_{PS})$ and $\mathcal{N}_{US}(\mu_{US}, \sigma_{US})$, respectively. Starting with the latest state update $\mathcal{N}_{US}^{k}(\mu_{US}^{k}, \sigma_{US}^{k})$ at time step k , the prediction step results in the predicted state $\mathcal{N}_{PS}^{k+1}(\mu_{PS}^{k+1}, \sigma_{PS}^{k+1})$, with

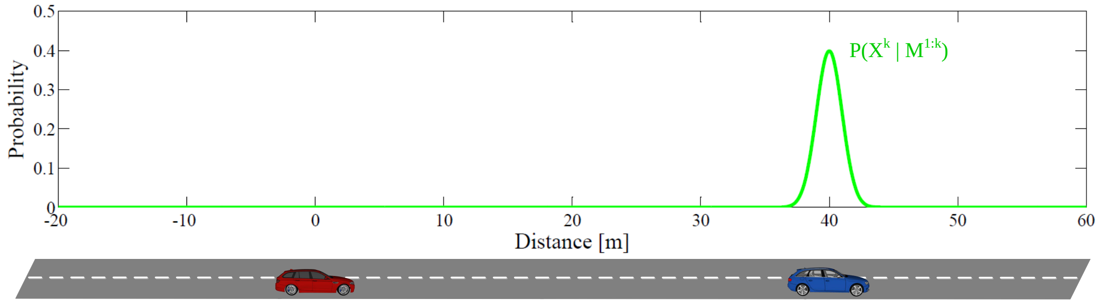
$$\begin{aligned} \mu_{PS}^{k+1} &= \mu_{US}^{k} + \mu_{PM} \\ \sigma_{PS}^{k+1} &= \sigma_{US}^{k} + \sigma_{PM} \end{aligned} \tag{2.3}$$

Obviously, error-prone prediction usually widens the Probability Density Function (PDF), that means, prediction typically adds uncertainty. Only if the predicted state is updated by the measurements, the updated state is described by $\mathcal{N}_{US}^{k+1}(\mu_{US}^{k+1}, \sigma_{US}^{k+1})$, with

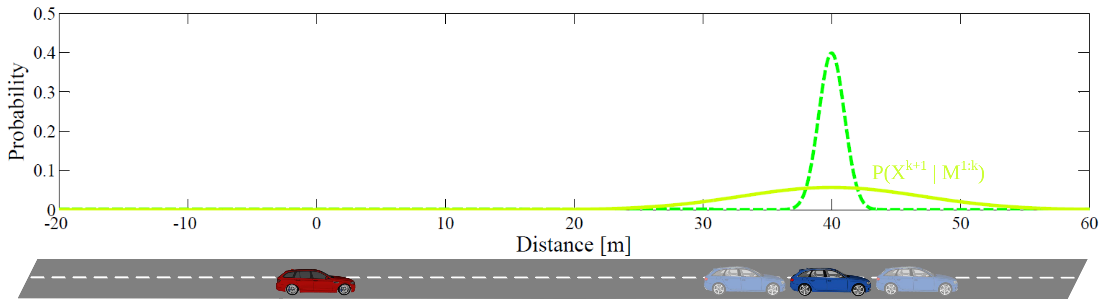
$$\begin{aligned} \mu_{US}^{k+1} &= \frac{(\sigma_{MM})^2 \cdot \mu_{PS}^{k+1} + (\sigma_{PS}^{k+1})^2 \cdot \mu_{MM}}{(\sigma_{PS}^{k+1})^2 + (\sigma_{MM})^2} \\ \sigma_{US}^{k+1} &= \frac{(\sigma_{PS}^{k+1})^2 \cdot (\sigma_{MM})^2}{(\sigma_{PS}^{k+1})^2 + (\sigma_{MM})^2} \end{aligned} \tag{2.4}$$

Obviously, an update usually narrows the PDF, which corresponds to a reduction of the uncertainty again. A more detailed derivation and explanation is given in [104] and [105].

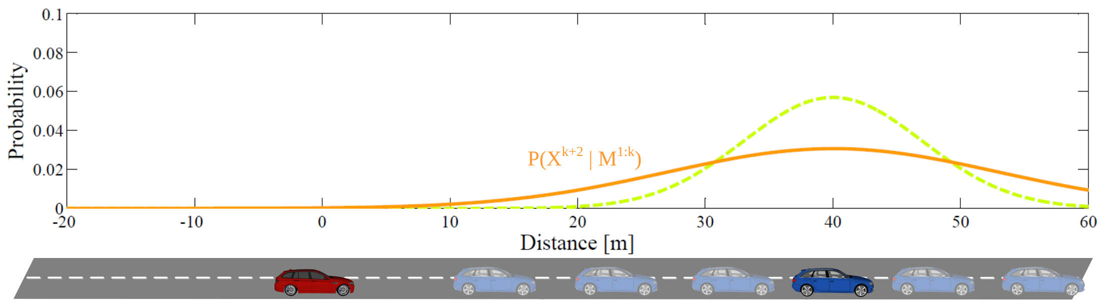
To provide a better understanding of the cooperative awareness and its quality behavior, a simple CACC example of only two vehicles, driving at a distance of 40 m, will be considered, by making use of Equation (2.3) and (2.4). The corresponding scenario is depicted in Figure 2.3. Without loss of generality, the awareness is simplified to the position awareness X, that means, the knowledge about the status of the neighboring vehicle corresponds to the knowledge X^k about its position at time step k. For better illustration, the position awareness is reduced to the one-dimensional space, and it is shown from the perspective of the ego vehicle (left). Hence, the position awareness corresponds to the distance estimate towards the target vehicle (right). The current quality of the position



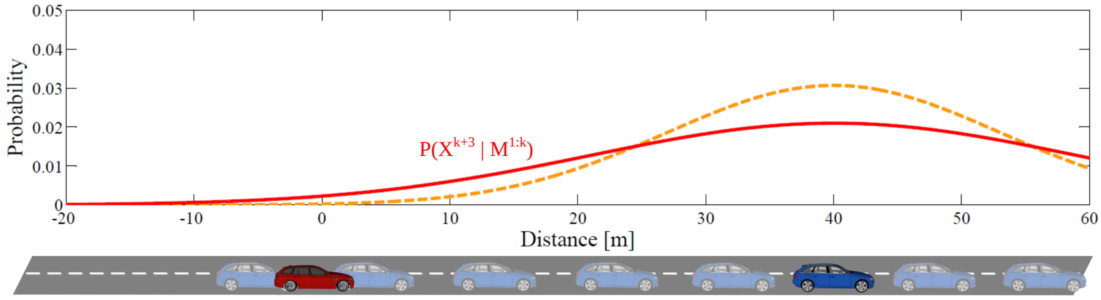
(a) Distance estimate $P(X^k|M^{1:k})$ after update at time step k: The ego vehicle (left) has just received a CAM from the target vehicle (right). Thus, the ego vehicle's awareness of the target's current position is highly up-to-date. The only uncertainty is induced by the measurement accuracy of the sensors (GPS receiver) and their processing (e.g. smoothing filter) at the transmitter side.



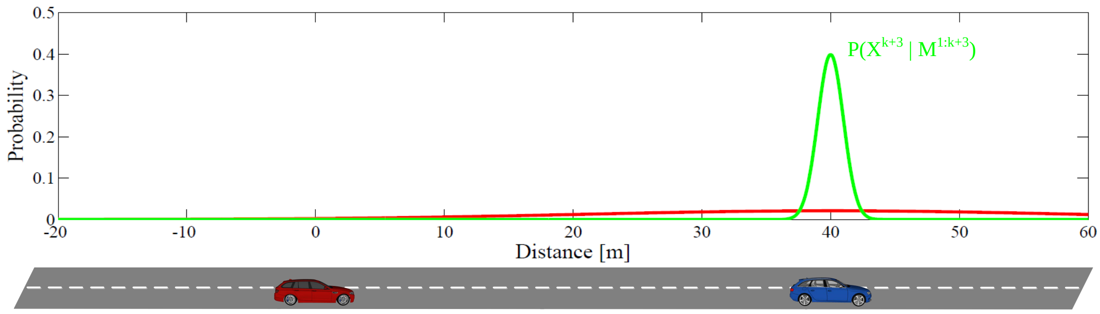
(b) Distance estimate $P(X^{k+1}|M^{1:k})$ after prediction at time step $k+1$: The ego vehicle (left) has not yet received a CAM update from the target vehicle. Thus, the current distance to the target is estimated by prediction, which typically introduces uncertainty, as illustrated by the semi-transparent target vehicles. Due to the spreading of the distance PDF, it is more likely now that the target vehicle is at a shorter or longer distance than before.



(c) Distance estimate $P(X^{k+2}|M^{1:k})$ after prediction at time step $k+2$: As in the previous time step, no CAM has been received yet from the target vehicle. The current distance is still estimated by prediction, and by implication its quality has further reduced, as the distance PDF has widened again.



(d) Distance estimate $P(X^{k+3}|M^{1:k})$ after prediction at time step $k+3$: Now, the prediction poses already a critical situation. The uncertainty of the distance estimate is high enough that with a certain residual probability both vehicles already may have been crashed with each other.



(e) Distance estimate $P(X^{k+3}|M^{1:k+3})$ after received CAM update at time step $k+3$: Only the reception of another CAM is able to reduce the uncertainty again, by updating the previous predictions.

Figure 2.3: Consideration of a CACC example with two vehicles: The quality behavior of the position awareness of the target vehicle (right) over time is comparable with the behavior of an information fusion filter. As long as the ego vehicle (left) does not receive any CAM from the target vehicle, the distance is estimated by prediction.

awareness is reflected by its PDF, which is assumed to be Gaussian.

In Figure 2.3a, the ego vehicle has just received a CAM from the target vehicle at time step k. Thus, its current knowledge about the position of the target is highly up-to-date. Although up-to-date, it contains already some uncertainty ($\sigma_X^k > 0$), due to the limited sensor accuracy (e.g. error-prone position measures) at the transmitter side. Figure 2.3b and Figure 2.3c show the position awareness at time step $k+1$ and $k+2$, respectively. As no CAM has been received yet, the target's current position is predicted by applying a certain prediction model (prediction step). To keep complexity manageable, typical prediction models are simplifications, e.g. constant velocity model or constant acceleration model, which do not exactly map the real world vehicular maneuvers. Thus, prediction usually adds uncertainty, that means, the PDF representing the current position awareness is typically widened with each prediction. In Figure 2.3d, prediction is getting critical for time step $k + 3$. The position awareness of the target vehicle is too much outdated, as the uncertainty of the distance estimate is already high enough to provide a certain residual probability of both vehicles having a crash. Only a successful CAM reception may relax the situation for time step $k + 3$ as depicted in Figure 2.3e. Then, the current distance estimate can be updated by new up-to-date position information about the target vehicle, and the uncertainty of the position awareness may be reduced again (update step).

The behavior of the position awareness just described, also reveals the two main influencing factors regarding its quality:

- *Measurement accuracy:* As CAMs usually contain position information, which is obtained from Global Navigation Satellite System (GNSS) measurements at the transmitter side, the measured values typically are error-prone. Hence, they do not represent the exact position of the vehicle. Instead, they are modeled by a probability distribution around the exact position. The uncertainty of the distribution can be improved by using sensor fusion approaches, that means, using additional measurements from additional sensors and/or information from the past. Moreover, the current position accuracy heavily depends on the current environment, e.g. satellite constellation, urban canyon, open sky view.

- *Up-to-dateness:* As the vehicles absolute movements in VANETs usually are highly dynamic, the measured positions are only valid for the corresponding point in time. As long as time goes by without any new position update, the current position information gets more and more outdated. Predictions may help, however, the applied models are usually simplifications of the true mobility of real world vehicles. Thus, they introduce errors as well, which are increasing with time.

The measurement accuracy is an influencing factor, which is completely independent from the communications, as it is already assigned at the transmitter side (see Figure 2.3a). It rather depends on the sensor capabilities, the environmental conditions during the measurements, and the applied information processing approaches, like multi-sensor fusion. As the focus of this work is on the cooperative aspects of the awareness, this thesis will concentrate on the communications dependent influencing factor *up-to-dateness*.

2.2.2 Assessing Cooperative Awareness

Based on the observation from the previous subsection, it is the time between two subsequent CAMs from the same transmitter, which has a significant impact on the quality of the current position awareness. If too long, the current position awareness of neighboring vehicles might be too much outdated. A cooperative safety application, working with outdated information, is expected not providing the required reliability.

Many current studies, investigating the ITS-G5 communications performance, are focusing on traditional end-to-end metrics like throughput, Packet Delivery Rate (PDR), or latency (e.g. [141, 84, 40, 134, 111, 122]). However, throughput and PDR only provide average values over time. Hence, they are not able to consider the up-to-dateness of the current position awareness. A more detailed discussion on that issue is given in Section 2.5.1.

Only a few publications try to define appropriate metrics in order to assess the cooperative awareness with sufficient reliability: Mittag *et al.* [91], for instance, introduced the *Neighborhood Awareness*, as the probability that node i is aware of its neighboring nodes, while being aware means having received at least one beacon message within the last second. Schmidt *et al.* [108] defined a binary awareness metric by forming the quotient between the number of detected vehicles and the number of all vehicles within a certain distance and comparing it with a desired threshold value.

Already a century ago, a metric named *inter-arrival time* has been used in the field of queuing theory to describe the arrival process of events, or the waiting time in between. ElBatt *et al.* [41] started to apply that pure receiver-based metric to VANETs in order to analyze the time elapsed between two consecutive successful packet receptions (packet *inter-reception time*). Whereas initially this receiver-based metric was quite uncommon, it got more and more attention the last years (e.g. [49, 126, 101, 88]). Rico García *et al.* [103] used the same metric, but named it *update delay* to emphasize its application to periodic status updates. Furthermore, the authors introduced a special representation called Complementary Cumulative Distribution Function (CCDF), which provides the probability for the update delay of exceeding a certain time value. This representation has the following two advantages: First, the distribution keeps all the measured information, which is not the case by focusing on average values and/or confidence intervals. Second, especially with focus on cooperative safety, the probability values of interest are very close to 1. Although using a log-scaled probability axis, the Cumulative Distribution Function (CDF) does not provide the necessary resolution around 1. By using the CCDF $= 1 - \text{CDF}$, a (theoretically) infinite resolution around the value of interest can be obtained.

However, regardless of the different naming, the metrics basic definition is the same. As they measure the time between two consecutive successfully received CAMs from the same transmitter, they are perfectly suited to assess the up-to-dateness of the (position) awareness from a communications perspective.

In this thesis, the *update delay* metric is selected, including its representation as CCDF. In order to assess the measured update delays with respect to certain requirements, the *T-window reliability* metric will be applied in addition. It has been introduced by Bai and Krishnan [20], and is defined as the probability of a successful CAM reception within a certain tolerance time window T. Let T denote the maximum allowed update delay, which guarantees the correct functionality of an application. Then, the update delay CCDF delivers the probability of exceeding T (corresponds to the complement of the T-window reliability), which basically represents the probability of application failure. Whereas Chapter 3 and Chapter 4 mainly use the update delay metric for relative performance comparisons, Chapter 5 discusses its application to evaluate a concrete cooperative safety example by mapping the update delay to position errors.

2.3 The VANET-Paradox

The major advantage of the WLAN standard, and the reason for its success, comes from its flexibility and adaptability. Likewise, the challenging vehicular environment, e.g. high mobility, Doppler effect, or transient connections, justified a new amendment to the WLAN baseline called IEEE 802.11 p[2].

2.3.1 From Internet- to Safety-Applications

While previous WLAN amendments assume the same *Internet-type applications*, VANETs introduce novel *cooperative safety applications*, which differ significantly in terms of communication policies and requirements. The salient characteristics differing between traditional WLANs and VANETs are described as follows:

- **Mode of operation:** The typical service within traditional WLANs is to provide wireless access to the Internet or other network services. Therefore, the user nodes

[2] In the meantime all amendments, including 802.11 p, have been merged into the IEEE 802.11-2012 standard

mainly operate in *infrastructure mode*, that means, they communicate with a centralized access point, which is connected to the Internet via a backbone network. In VANETs, however, vehicles typically communicate with each other in pure *ad-hoc mode* (OCB), to exchange safety-related information without making a detour.

- **Network topology:** Typical user nodes in traditional WLANs are quite static, when they use the corresponding services provided by the access points. For example, students on a campus, that is equipped with WLAN access points at fixed locations, are moving with walking speed maximum, when they surf the Internet or check emails. Consequently, the network topology in traditional WLANs is quite *static* as well. In VANETs, however, the network topology may vary significantly, from almost static to highly dynamic, depending on the current traffic scenario. Considering vehicles driving in the same direction, their network topology is rather static due to their slow relative speeds. Examples include platooning scenarios on highways, or vehicle flows in urban areas, which are usually controlled by traffic lights. A completely different topology behavior is shown, if vehicles are driving in the opposite direction, or stationary road side units are considered as well. Then, the high relative speeds may cause very short-lived connectivity. Both, flow and contra-flow scenarios, result in *highly changeable* network topologies.

- **Communications mode:** In traditional WLANs, nodes are mainly communicating with single destinations, e.g access point. Hence, the communications mode is predominantly *unicast*, which allows connection-oriented communications. In VANETs, however, vehicles aim to disseminate the same safety-related information to all vehicles in the same vicinity at once. For that purpose, *broadcast* mode is used. Although connection-less, the broadcast mode increases the flexibility of the network, and avoids additional delays caused by connection-oriented procedures.

- **Data traffic pattern:** Due to the functionality of typical Internet-type applications, e.g. web-surfing, email, in WLANs, the resulting data traffic pattern is predominantly *bursty*. In order to provide regularly safety-related information to neighboring vehicles, cooperative safety applications require CAMs to be transmitted in a periodic manner. As CAMs comprise the majority of generated messages in VANETs [31], the resulting data traffic pattern is predominantly *periodic*.

- **Communications requirements:** In traditional WLANs, users are mainly interested in *high throughput* and *low packet jitter*, for example, in the case of streaming

CHARACTERISTICS	**WLAN (Internet-type)**	**VANET (Cooperative Safety)**
Network topology	solely stationary	highly changeable
Mode of operation	Infrastructure mode	OCB mode (pure ad-hoc)
Communications mode	mainly unicast	mainly broadcast
Data traffic pattern	bursty data traffic	periodic data traffic
Communications requirements	high throughput, low packet jitter	high awareness quality, low update delays

Table 2.1: Comparison of the salient characteristics between Internet-type applications in WLANs and cooperative safety applications in VANETs.

applications. Cooperative safety applications in VANETs, however, require a *high awareness quality* by highly up-to-date information. For the communications, that means, short delays between consecutive updates from the same source, i.e. *low update delays*.

The differences between traditional WLANs and VANETs just described are summarized again in Table 2.1.

2.3.2 From CSMA/CA to CSMA without CA

Although the WLAN technology has been slightly adapted for operation in VANETs (e.g. by introducing the OCB mode), its application to cooperative traffic safety brings it away from its original design framework: On the one hand, random channel access schemes, like CSMA/CA, have been originally designed for bursty data traffic patterns [77] instead of periodic ones. On the other hand, broadcast transmissions implicitly deactivate IEEE 802.11's packet collision avoidance mechanisms, like the exponential increase of the CW, as well as the RTS/CTS handshake [9]. As a result, IEEE 802.11 based VANETs reveal a significant degradation of the communications performance, especially if the number of transmitting vehicles is increased [40, 113, 122, 119, 74, 34, 132]. This issue is usually referred to as the *scalability problem* [75, 27]. The main reason for that behavior is an increasing number of packet collisions caused by the CSMA/CA protocol, which in turn result in increasing packet losses.

In general, packet collisions accumulate as the more vehicles participate in communications. Then, more vehicles contend for accessing the same shared communication channel, and more data traffic is generated. However, the CW size for CAM transmissions only consists of 8 slots[3]. As the exponential increase of the CW does not apply for broadcast transmissions, the CW will remain at 8 slots, even if contention is increased. Consequently, each vehicle may have collision-free contention with at most 7 of its neighbors. Considering highly dense traffic scenarios, like multi-lane highways as depicted in Figure 1.1, each vehicle is expected to have more than 7 contending neighbors, which is a recipe for packet collisions.

But things get even worse. Without RTS/CTS, so called hidden terminal collisions [128] cannot be avoided anymore. This type of packet collisions may happen, if two transmitters are not able to sense each other, because both are outside of each others carrier sensing range. Then, a receiver, which is in the transmission range of both at the same time, experiences a packet collision, if both transmitters access the channel at the same time. Also in this case, an increasing number of vehicle/data traffic may increase the probability of simultaneous transmissions between hidden nodes.

Considering all the facts mentioned above, the idea of disseminating safety-related information via an IEEE 802.11-based communications technology might remind of a paradox.

2.4 Transmission Control Policies

The most common approach in current VANETs to support cooperative safety applications on top of an undependable communications technology, is based on congestion and awareness control techniques. While *congestion control* approaches regulate transmission parameters to limit the load on the wireless channel, *awareness control* mechanisms aim at fulfilling the application's requirements by adapting transmission parameters accordingly [116]. Typical transmission parameters used for various control schemes are transmit power, transmit rate, transmit data rate, contention window, and Clear Channel Assessment (CCA) [46, 121]. The most relevant control mechanisms in the context of this thesis are summarized hereafter.

2.4.1 Transmit Rate Control

The transmit rate (packets per second) is probably the most intuitive parameter to control the load on the wireless channel, as it directly affects the amount of transmitted messages. Halving the transmit rate, also halves the channel load. However, halving the transmit

[3]Currently, CAMs are foreseen to be transmitted on the AC_VI queue representing the second access priority according to EDCA in [9].

rate, also doubles the time interval between two subsequent CAM transmissions, which may have a significant impact on the awareness quality as described in Section 2.2. Hence, Transmit Rate Control (TRC) strategies have to be designed carefully.

Fukui *et al.* [54] proposed a TRC mechanism, based on the vehicle's mobility. Specifically, a CAM is transmitted, if it's position has changed by a certain distance. Although the proposed scheme is in line with certain results from traffic theory, it may cause trouble for some stationary scenarios.

A more complex approach is proposed by Rezaei *et al.* [102]. There, each vehicle is expected to run the same position estimator, which is able to estimate its own position. Then, a CAM is transmitted, if the own position estimate exceeds the actual position by a certain threshold. Although this approach corresponds to an efficient strategy regarding the behavior of the (position) awareness as described in Section 2.2, it does not consider the fact that CAMs might get lost, e.g. due to packet collisions. Hence, Huang *et al.* [63] enhanced this idea by predicting the packet loss for neighboring vehicles as well, based on measuring the packet error rate.

Seo *et al.* [114] applied the coupon collector's problem to safety beaconing in VANETs. Therefore, they introduced an acknowledgment at application level, piggybacked on the safety beacons. As long as an acknowledgment is received, the interval between two subsequent CAMs is increased with each transmission, which automatically results in a reduction of the transmit rate.

Sommer *et al.* [120] introduced Adaptive Traffic Beacon (ATB), a TRC mechanism, which calculates the current beacon interval based on two metrics: the channel quality and the message utility. The basic idea is to save beacon transmissions depending on their importance (utility), in case of network congestion.

Tielert *et al.* [126] introduced a rate adaptation oriented congestion control protocol named Periodically Updated Load Sensitive Adaptive Rate control (PULSAR). It takes the transmission range, required by the safety application as input, and adapts the transmit rate according to a well-defined target channel load [127].

A service-oriented approach for safety beacons is proposed by Lasowski and Linnhoff-Popien [79]. While vehicles transmit beacons with a basic rate of 2 Hz by default, they can request beacon updates from their neighbors in addition. For the corresponding service responses, they use multiple channels in order to avoid addressing vehicles, which are not interested in that update.

Bansal *et al.* [23] designed a LInear MEssage Rate Integrated Control (LIMERIC) algorithm. It avoids the limit cycle behavior that is inherent to other binary control approaches, and thus, provides a fair and efficient channel utilization.

A comprehensive overview of various adaptive beaconing approaches can be found in [109].

2.4.2 Transmit Power Control

In principle, most of the Transmit Power Control (TPC) mechanisms for VANETs have their origins in topology control solutions for Mobile Ad-hoc NETworks (MANETs). However, the requirements and objectives of both networks are completely different. Whereas topology control in MANETs aims at minimizing power consumption, while remaining the full connectivity of the network [106], TPC in VANETs is used to adapt to a target range for cooperative safety applications [59], while minimizing the interference to farther vehicles.

The mechanism proposed by Guan *et al.* [59] is based on a special feedback field contained in the CAM. The feedback information is used to determine the number of vehicles outside the target range, even so covered by the own transmission. The control loop tries to keep this number within certain limits.

Torrent-Moreno *et al.* [131] developed the Distributed Fair Power Adjustment for Vehicular environments (D-FPAV) strategy, which adapts optimal transmit power levels regarding the maximum beaconing load constraint. Therefor, D-FPAV requires to provide the power levels via piggybacking to all two-hop neighbors. In [129], they further adapted their approach to safety-critical information.

Segment-based Power Adjustment for Vehicular environments (SPAV) is a TPC strategy proposed by Mittag *et al.* [90]. Although it does not provide an optimal assignment of transmit power levels like D-FPAV, it is able to significantly reduce the protocols overhead, as it does not require full knowledge of the two-hop neighbor's power levels. Instead, it is based on an estimation of the local density.

Rawat *et al.* [100, 99], likewise, used an estimation of the local density by received CAMs, to assign transmit powers accordingly. In contrast to [90], their assignment strategy is based on traffic flow theory.

In [69], Khorakhun *et al.* adapted either the transmit power or rate, depending on the current channel load, measured by the Channel Busy Time (CBT). To provide a higher level of fairness, information about the local measures is exchanged among neighboring vehicles. Based on that, the current transmit power or rate is adapted in order to converge to a given target channel load.

Artimy [18] developed the Dynamic Transmission Range Assignment (DTRA) algorithm, which assigns the vehicle's transmission range according to the local traffic conditions. To estimate the local density, he only uses on-board sensors and traffic flow theory, which allows to completely remove the communications overhead for TPC.

An opportunistic-driven adaptive radio resource management control strategy was proposed by Gozalvez and Sepulcre [57]. The transmission control scheme adapts both, the transmit power as well as rate, based on the vehicle's position and its proximity to a potential hazardous area. The proposed mechanism focuses on safety application requirements, while it takes care of an efficient use of the wireless resources.

In [63], Huang *et al.* exploit information provided by the CCA mechanism in order to determine the channel occupancy, that is used to adapt the transmission powers accordingly. The advantage of that approach is that it can cope with security requirements, like pseudonyms, in VANETs. In their follow-up work [49], Fallah *et al.* presented an enhanced feedback control scheme for transmission range adaptation, which is robust to variations of the road and network traffic.

Similar to [57], Baldessari *et al.* [21] also proposed a combined transmit power and rate control scheme. In a first step, a mapping of transmit power and rate pairs is determined, based on the estimated node density in the surrounding. Then, inter-arrival time measures are used to estimate the current transmit rate of neighboring vehicles, which in turn is applied to determine an appropriate transmit power/rate pair.

A context-based congestion control approach was introduced by Sepulcre *et al.* [115]. Therefor, information about the traffic context of each vehicle is used in order to reduce the channel load, while the application requirements are still fulfilled.

Egea-Lopez *et al.* [39] proposed a statistical approach called Statistical Beaconing Congestion Control (SBCC), which is based on local information, and uses limited feedback in addition. In SBCC, each vehicle determines the current transmit power, which is required to satisfy a given maximum beacon load, based on an estimation of radio channel parameters, vehicle density, and beaconing rate.

2.4.3 Contention Window

Several studies have been published by the VANET research community, which dynamically adapt the Contention Window (CW):
Already in 1996, Bianci *et al.* [26] demonstrated that the optimal CW in a general IEEE

802.11 network depends on the number of nodes. Specifically, he showed that the throughput is maximized, if the following condition holds:

$$\mathrm{CW} \approx \tilde{n}\sqrt{2T} \tag{2.5}$$

where $\tilde{n}$ is the number of contending nodes and T is the total packet transmission time (in slots). Based on their results, Mertens *et al.* [89] proposed the following two-step approach to adapt the current CW: First, they estimate the vehicle density and apply Equation (2.5). Then, they refine the CW based on an estimated packet error rate.

In [135], Wang *et al.* proposed two solutions. Whereas the first centralized approach assumes that the exact number of concurrent vehicles is known to calculate the optimal CW using Equation (2.5), the second decentralized approach linearly increases or decreases the current CW, dependent on the difference between two consecutive measures of the channel busy proportion (corresponds to the CBT).

Balon *et al.* [22] increased the reception probability of safety broadcast transmissions, by dynamically adapting the CW based on analyzing the sequence number of packets. In [99], Rawat *et al.* applied Balon's CW adaptation approach, and combined it with a TPC strategy based on the vehicle density. As a result, they could improve the throughput and the average end-to-end delay.

Jang and Feng [65] adapt the CW based on a network status detection scheme, and the prediction of competing nodes. However, their detection scheme relies on unicast communications by using RTS/CTS control messages.

Alapati *et al.* [16] proposed an algorithm, which is based on testing different CW sizes, in order to find the optimal size, which maximizes the measured throughput.

In [124], Stanica *et al.* also investigated the problem of small contention windows in current VANETs. The authors proposed to adapt the CW as a function of the vehicle density and another parameter, derived from their simulations, to improve the beacon reception probability.

2.4.4 Standardization Activities

While an adaptation of the contention window seems to be a promising approach [124], at the moment, it is not taken into consideration by the standardization bodies for Day one Decentralized Congestion Control (DCC) [46]. Instead, CAM transmissions are based on a fixed CW of 8 slots[4], regardless of the current congestion state of the network. The reason for keeping such a small CW in VANETs might be explained by the traditional end-to-end perspective, that means, aiming to keep the end-to-end delay (latency) as low as possible. But as explained in Section 2.2, CAMs are dedicated to provide regular awareness updates to the corresponding receivers. Hence, the performance of cooperative safety applications rather depends on RX-centric metrics like the update delay or inter-reception time instead of latency, which allows more freedom for the adaptation of the CW. A first approach to analyze the effects of the CW in beaconing vehicular networks from an RX-centric perspective is provided by Reinders *et al.* [101]. In addition to the traditional metrics, they measured the inter-arrival time as well.

TRC and TPC, however, formed the basis for the standardization of DCC [46]: It implements a simple state machine based on three states (RELAXED, ACTIVE, RESTRICTIVE). The control input is a parameter called *channel load*, which specifies the fraction of time the received signal strength is above a certain threshold (equivalent to CBT). The channel load is measured by channel probing. Dependent on the observed channel load, DCC switches to the corresponding state, which adapts a fixed transmit power and rate accordingly.

Although an advantage on the one hand, the simplicity of ETSI's DCC comes along with important disadvantages:

1. It can lead to severe instability and unfairness between vehicles [125, 19].

2. Fixing the transmit power does not necessarily consider application requirements, for instance, if the required awareness range is larger than the transmission range.

2.5 Open Issues

Regardless of using ETSI's simple three-state DCC or one of the more sophisticated transmission control approaches, all of them have one important property in common: They *either use, or tend to converge to a reduced, harmonized, quasi-constant transmit power and rate*. However, this property may have a significant impact on the MAC communications, as well as on the cooperative safety applications.

[4]Due to the broadcast communications mode, the CW will not be increased with increasing contention.

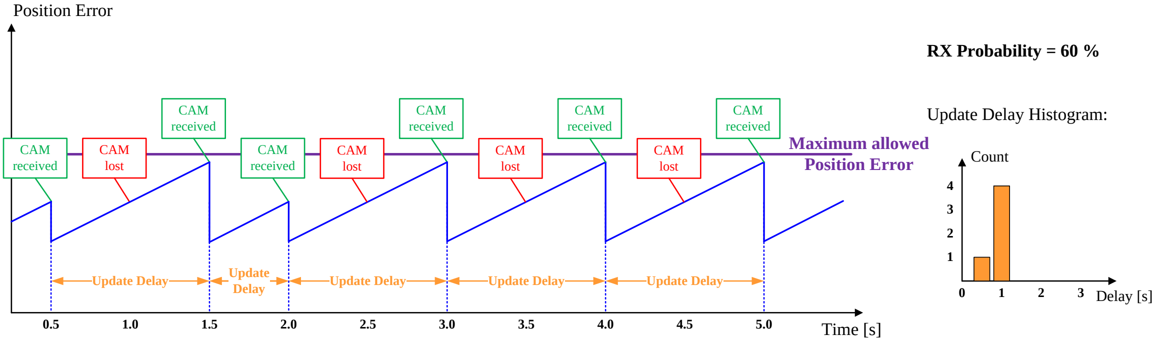
2.5.1 MAC Communications Issues

Indeed, packet collisions have a negative impact on the communications performance in general. However, not all packet collisions have the same negative impact on the awareness, as it makes a huge difference, if several messages are lost individually, or they are lost in bursts. Considering the cooperative awareness and its quality behavior from Section 2.2, cooperative safety applications require regular status updates from other vehicles within a certain range through CAMs. Whereas they may support the loss of individual messages, the loss of several subsequent CAMs may quickly lead to outdated status information about the corresponding vehicle, which significantly lowers the application's reliability.

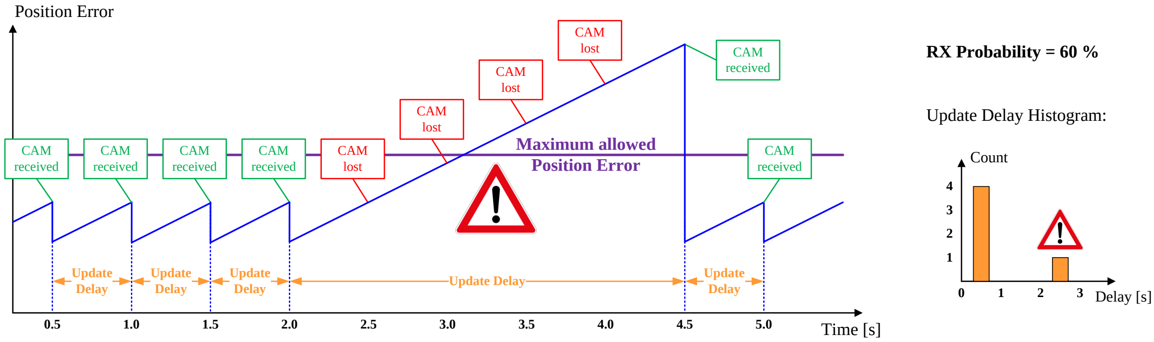
Although the term "awareness" provides a general description of the knowledge about other vehicles in the surrounding, it might be still quite abstract. Without loss of generality, lets focus on the position awareness again, that means, the only relevant information about neighboring vehicles is their current position. Then, the current position error is a decisive factor, which has a significant impact on the application's reliability. Figure 2.4 illustrates the impact of correlated packet collisions on the position error. If CAMs are lost individually, the position error may remain quite low, as the position information is still updated in a regular manner (see Figure 2.4a). However, if CAMs are lost in bursts, the position error may increase significantly, risking to exceed a maximum allowed threshold value (see Figure 2.4b).

The highlighted fact has an important consequence for the significance of current communication performance studies, which have only focused on the reception probability or PDR. In both cases, the reception probability is the same (60 %). However, with focus on the awareness quality, the first case provides a much better performance. This observation verifies again that the true performance of cooperative safety applications cannot be measured by traditional end-to-end metrics like throughput, reception probability or PDR. They do not consider correlations between subsequent transmissions/receptions. Instead, RX-centric metrics, like the update delay or inter-reception time, are required, as they are directly affected by the temporal behavior of packet collisions.

Although the additional trigger conditions (see Section 2.2) do not imply *periodic* CAM transmissions anymore, it may still be observed that certain mobility conditions may not vary as much as expected for vehicular scenarios. On highways, for instance, traffic volumes and capacity tend to make neighboring vehicles converging to constant and similar speeds per direction, especially in case of platooning. In urban scenarios, traffic-light controllers tend to generate synchronized flows of vehicles with similar speeds, too. Then, the vehicles



(a) Individual packet collisions and their impact on the position error, as well as the update delay.



(b) Burst packet collisions and their impact on the position error, as well as the update delay.

Figure 2.4: Whereas cooperative safety applications may support the loss of individual CAMs, the position error may increase too much, if CAMs are lost in bursts.

positions are changing constantly over time, again causing periodic CAM transmissions. The same scenarios indicate that in numerous contexts the relative speed between vehicles remains low as well, and by association, their relative mobility is quite static.

The resulting effect of both, quasi-periodic CAM transmissions at common transmit powers in combination with quasi-static relative mobility, is illustrated in Figure 2.5 by means of a space-time schematic. Lets assume three vehicles forming a platoon, and two of them (TX and IF) approximately transmit at the same time (simultaneous transmission). Then, a possible receiver RX in between may experience a packet collision. Due to the quasi-periodic nature of CAM transmissions in combination with quasi-static relative mobility, especially in case of platooning, the collision may recur for several subsequent transmissions at the same receiver RX, resulting in *correlated packet collisions*.

The problem of correlated packet collisions is particularly significant in hidden terminal situations. Due to the broadcast mode, and by implication, the disabled RTS/CTS mechanism, hidden terminals are not able to detect an ongoing transmission, despite carrier

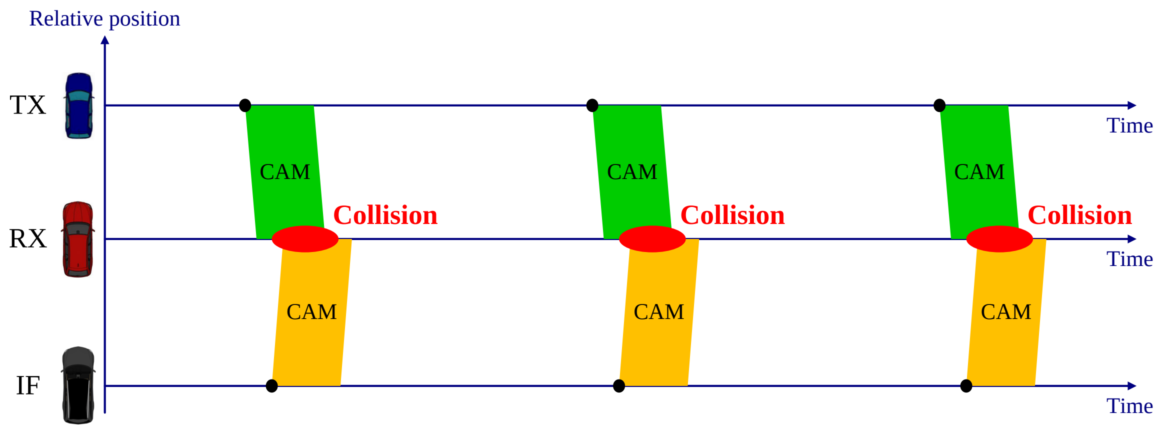


Figure 2.5: Space-time schematic of three vehicles TX, RX, and IF: Due to the periodic nature of CAM broadcasts in combination with slow relative speeds, a collision is likely to recur several times in a row at the same receiver RX.

sensing. Furthermore, no (negative) acknowledgments are provided, which would indicate a possible collision at the receiver, and the need of adapting the transmit policy to avoid the next transmission colliding again.

A potential approach to mitigate correlated packet collisions may be found in the class of random repetition-based MAC protocols (e.g. [140]). Although it is able to reduce correlated packet collisions, it also comes along with some drawbacks: On the one hand, it requires to modify the MAC, and on the other hand, it increases congestion on the channel. Both properties have not been desired by the standardization bodies. Hence, random repetition schemes have not been selected for Day one ITS communications technology.

Alternatively, Time Division Multiple Access (TDMA) approaches have been proposed (RR-ALOHA [30], MS-ALOHA [112], S-TDMA [29]), which have shown to be able to mitigate the correlated packet collision problem, too. However, in contrast to IEEE 802.11, they require a quite precise time synchronization between the nodes, which is even more challenging in decentralized networks. Whereas IEEE 802.11 is a mature technology in the context of mobile ad-hoc networks, which have been studied and proved to be practicable for more than a decade, STDMA and MS-Aloha may require a redesign of the transceiver chip-set, which is currently not accepted by the standardization bodies and industry.

2.5.2 Application-related Issues

Ideally, one would provide maximum awareness quality within the maximum awareness range, by simply transmitting at maximum rate (quality) and maximum power (range).

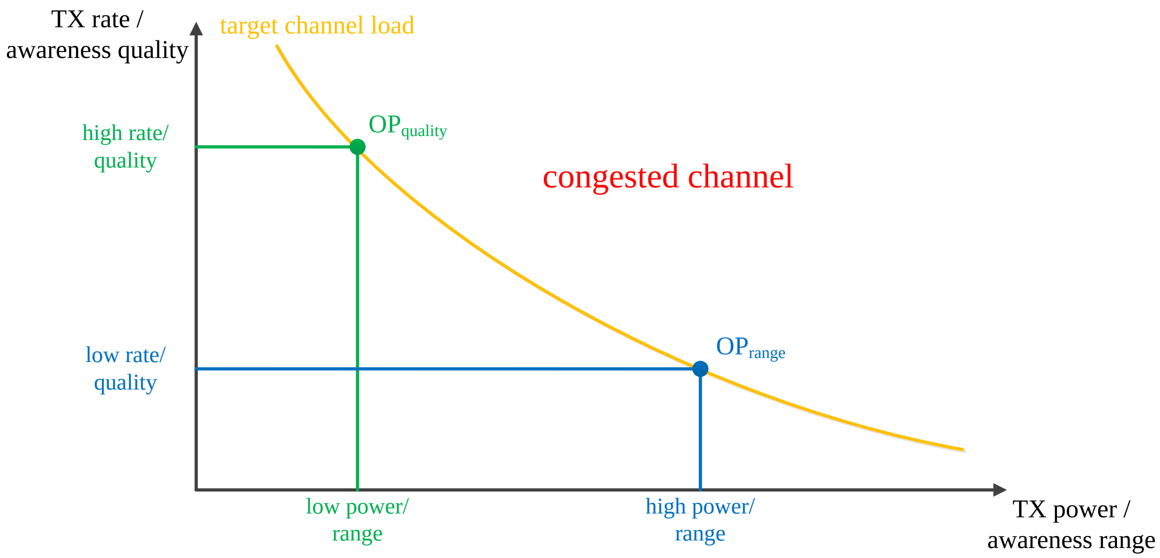


Figure 2.6: The trade-off dilemma by using constant transmit powers: Whereas the operating point $OP_{quality}$ provides a high quality (rate) but a short awareness range, the OP_{range} provides a high awareness range but at a low quality (rate).

However, in reality there is a crucial constraint called channel capacity, which has to be shared among several cooperating vehicles in addition. Hence, transmitting at maximum power and rate would probably work for isolated vehicles, but is far beyond the capacity of current ITS-G5 channels in real-world vehicular networks (e.g. multi-lane highways, urban intersections).

As indicated in [115], the control parameters transmit power and rate are inversely correlated at constant target load on the wireless channel: Reducing the transmit power allows an increase in the transmit rate, and reducing the transmit rate allows an increase in the transmit power. The fact that current transmission control approaches are only able to set one single power/rate pair, i.e. a single Operating Point (OP), at a time, may result in the *transmit power/rate trade-off dilemma* as illustrated in Figure 2.6: To fulfill the awareness range requirement (OP_{range}) by increasing the power, the rate has to be reduced, risking to fail achieving the required awareness quality. On the other hand, to fulfill the quality requirement ($OP_{quality}$) by increasing the rate, the power has to be reduced, risking to fail achieving the required awareness range.

In order to find an appropriate OP, Tielert *et al.* [127], for instance, start by mapping the required transmit range to the corresponding transmit power, and then adapt the transmit rate to maintain a certain target channel load. Although such transmit range to power mapping approaches might be possible under specific conditions, probably they are

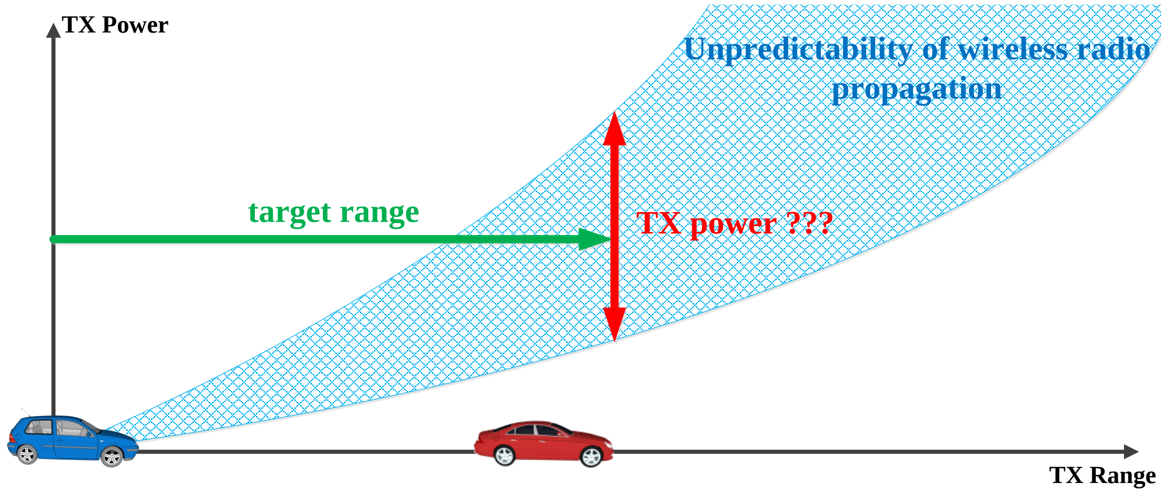


Figure 2.7: Illustration of the problem of mapping a target transmission range to the necessary transmit power, due to the unpredictability of wireless radio propagation in practice.

quite unreliable in more general conditions, due to the unpredictability of wireless radio propagation, as indicated in Figure 2.7, especially in vehicular environments. In their work, they provide mapping curves to obtain transmit power/rate pairs, optimizing the average packet inter-reception time (update delay) up to the required transmission range. Such optimal mapping is typically tested for a given environment (fading, street layout) via intensive simulations for various transmit powers. Yet, providing such mapping in more generalized environments, i.e. any road/street configuration and for most of the fading environments, remains very challenging, and is probably not feasible in practice.

Furthermore, future vehicles will not only run one cooperative safety application, but several in parallel. Assuming each application defines its own OP, then finding a global one, which is able to satisfy all applications, becomes even more challenging. For example, lets assume one application requires high range (power) but at a low quality (rate), and another application requires a short range (low power) but a high quality (rate). The channel, however, does not always provide both, especially in highly dense scenarios. So, which requirements should be satisfied?

2.6 Discussion

Although current ITS-G5 is known to suffer from certain safety-hostile issues as described in Section 2.3, it has been chosen by the corresponding standardization bodies for Day one ITS communications in VANETs. Especially in the context of cooperative safety applications, packet collisions are probably the most performance limiting factor of ITS-G5. As most of the safety-related transmissions are broadcast, the collision avoidance mechanisms of CSMA/CA are not working anymore.

To support cooperative safety applications in VANETs, reliable CAM delivery is life critical, which brings ITS-G5 to a major conundrum: *How to transmit safety-related information with sufficient reliability by using a potentially undependable access technology?*

Current transmission control approaches aim at reducing the probability of packet collisions in general by simply limiting the load on the wireless communication channel. However, this is not sufficient, because of the following reasons:

1. Simply reducing the channel load sounds like a backup plan. Apart from the CW adaptation approaches, packet collisions are not addressed directly.

2. Current approaches do not consider correlated packet collisions on the MAC, caused by transmissions with quasi-constant transmit power and rate, in combination with quasi-static relative mobility between neighboring vehicles. Especially with respect to cooperative safety, correlated packet collisions have a significant impact on the quality of the awareness.

3. The transmit power/rate trade-off dilemma strictly limits current approaches in adapting a single harmonized awareness operating point regarding range (power) and quality (rate). Although they might provide an optimal awareness on average, current transmission control approaches may risk in being over-designed at high ranges and under-designed at close ranges. However, in the context of traffic safety close ranges are much more critical than farther ones, because only nearby vehicles might pose an imminent danger with respect to vehicle collisions.

Addressing each of them is the basic objective of this thesis. Therefore, it continues by analyzing the issue of packet collisions on the MAC layer, as well as their occurrence behavior in space and in time. Based on the results, new broadcast collision mitigation strategies are introduced. Finally, the proposed concepts are investigated from an application's perspective, in order to relax the transmit power/rate trade-off dilemma by making use of the distance dependent relevance of neighboring vehicles.

Chapter 3

Investigating MAC-related Packet Collisions

To support cooperative safety applications in VANETs, reliable CAM delivery is life critical, which brings ITS-G5 to a major conundrum: *How to transmit safety-related information with sufficient reliability by using a potentially undependable access technology?*

3.1 MAC-related Packet Collisions

According to Section 2.3, MAC-related packet collisions are probably the most performance limiting factor of ITS-G5. Hence, the focus here is the problem of packet collisions caused by the MAC protocol, specifically CSMA/CA. Consequently, in this thesis a packet collision is defined as the detection of two overlapping packets on the shared wireless channel at a certain receiver RX.

The majority of current transmission control approaches aim to reduce the probability of packet collisions in general by reducing the load on the wireless communication channel. In this work, the first step is to analyze packet collisions regarding their causes, as well as their spatial and temporal occurrence behavior. Only if packet collisions are well understood, appropriate countermeasures can be taken.

3.1.1 The Framework

The problem of packet collisions has been analyzed by means of simulations, using the environment and metrics described in Appendix A. To obtain a MAC challenging scenario

Traffic scenario	10-km highway with 6 lanes in each direction
Evaluation section	5 km (from 2.5 – 7.5 km)
Vehicle generation process	Erlang distributed ($\mu = 2.25$ s)
Speed profile	From 20 to 40 m/s (4 m/s increase from outer to inner lane)
Access technology	ITS-G5 on control channel
Radio propagation model	Log distance (exponent 2.35)
Transmit power profile	constant at 33 dBm
CAM generation policy	1 Hz + trigger conditions
Metrics	normalized packet collision rate, packet collision ratio, update delay

Table 3.1: Default simulation scenario.

with respect to channel contention and resulting packet collisions, a multi-lane highway has been implemented. As the focus is on packet collisions caused by the MAC protocol, a simple log-distance path-loss model has been used, in order to restrain PHY layer effects like fading as much as possible, and to ensure a clean analysis of pure MAC-conditioned packet collisions. The default transmission scenario in this thesis employs a simple constant transmit power approach, which serves as a generalized representative of current transmission control policies. These predominantly tend to converge to harmonized quasi-constant powers. To cover the worst case, vehicles will mainly broadcast at the transmit power limit of 33 dBm on the control channel [10]. The most important simulation parameters are summarized in Table 3.1.

In this framework, a packet collision on the MAC layer is detected by a potential receiver RX, as illustrated in Figure A.4 in the Appendix. A packet collision is identified, if a new incoming packet is arriving, while the node is already processing an ongoing reception (RX state) or an ongoing transmission (TX state). In both cases, a packet collision is notified and the incoming packet is dropped. Although the packet has been dropped internally, a certain signal level will remain on the channel for the packet duration. Hence, after processing the current ongoing reception/transmission, it is checked if the remaining signal is above the CCA threshold and the channel has to be declared as busy (CCA_BUSY). In case there is no ongoing reception/transmission, the node switches to the RX state and processes the new incoming packet accordingly.

To classify different reasons for packet collisions, a specific classification scheme has

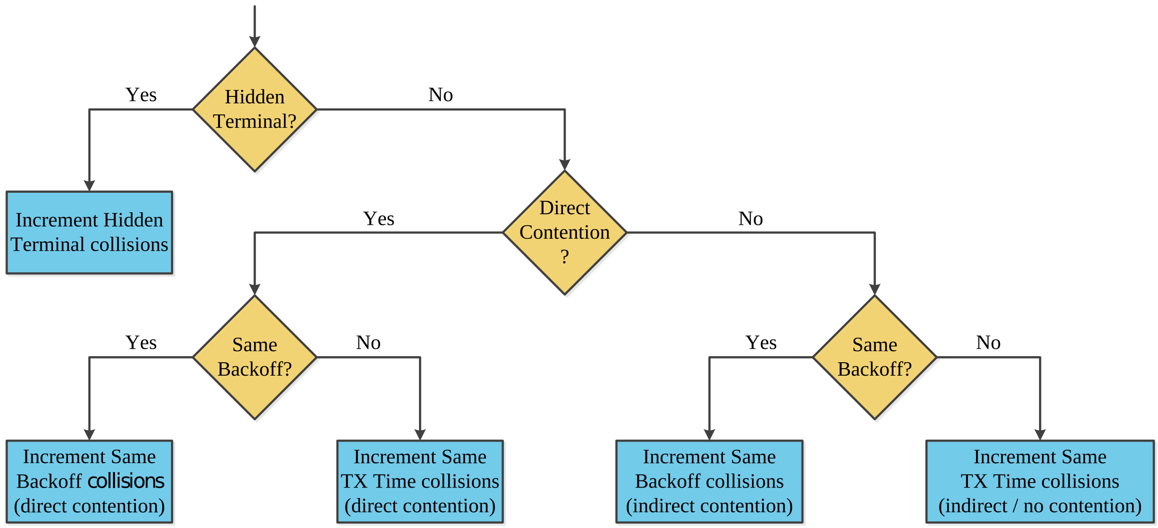


Figure 3.1: Decision tree, used to classify different situations causing a packet collision.

been implemented within the aforementioned simulation framework. The corresponding classification tree is illustrated in Figure 3.1. Once, a collision is detected, specific transmission conditions (e.g. transmitter ID, transmit power, position, backoff states) are checked in order to identify one of the following reasons:

- *Hidden terminal collision:* Both transmitters have been hidden to each other.
- Direct contention: Each transmitter attempted to access the channel, but each sensed a busy channel, which was currently occupied by the same transmitter.
  - *Same backoff collision (direct contention):* Both transmitters have chosen the same backoff counter during direct contention phase.
  - *Same TX time collision (direct contention):* Although not having chosen the same backoff counter, both transmitted at the same time.
- Indirect contention: Either the channel was currently occupied by different transmitters during their transmission attempt, or there was no contention at all.
  - *Same backoff collision (indirect contention):* Each of the two transmitters has been blocked by different other transmitters, however, both have chosen the same backoff counter.
  - *Same TX time collision (indirect / no contention):* Both transmitters have accidentally transmitted at the same time.

The classification scheme just described is used to analyze the spatial, as well as temporal occurrence of packet collisions in VANETs, as described next.

3.1.2 The Results

In order to get a better insight into the spatial occurrence of packet collisions, the following distance information has been evaluated, once a packet collision was detected:

- The distance between the actual transmitter (TX) and the receiver (RX), whereas TX is defined as the transmitter, whose signal has arrived at RX first.
- The distance between the collision inducing transmitter (IF) and the receiver (RX), whereas IF is defined as the interfering transmitter at RX with respect to a currently ongoing transmission by TX.
- The distance between the actual transmitter (TX) and the collision inducing transmitter (IF), whereas TX and IF are defined as for the previous items.

The spatial occurrence of packet collisions is presented in Figure 3.2. It shows the various normalized packet collision rates, dependent on the distance between the two collision inducing transmitters (TX-IF distance), and separated by the different causes as classified in Figure 3.1. The graph reveals very interesting effects, which are explained first:

- The probably most distinctive observation in this figure is the excessive increase at the transmission range ($\approx$ 970 m). It indicates the starting of the conventional hidden terminal collisions, as beyond that distance, TX and IF are outside of each others transmission range.
- Even below the transmission range, a significant amount of hidden terminal collisions is observable. This effect is caused by the Clear Channel Assessment (CCA) threshold [9]. By default it is 20 dB above the RX sensitivity threshold of -85 dBm, and is used to declare the channel as busy, only if the received signal strength is above -65 dBm. This is used in case the signal strength of an incoming packet is above the RX sensitivity threshold, but the terminal could not synchronize on the preamble, e.g. due to packet collision, and is not able to decode the rest of the packet. Although there is an ongoing packet transmission, thanks to the CCA threshold, the terminal is allowed to transmit its own packet, if the current signal strength is below -65 dBm. Otherwise, the channel would be declared as busy. Based on the

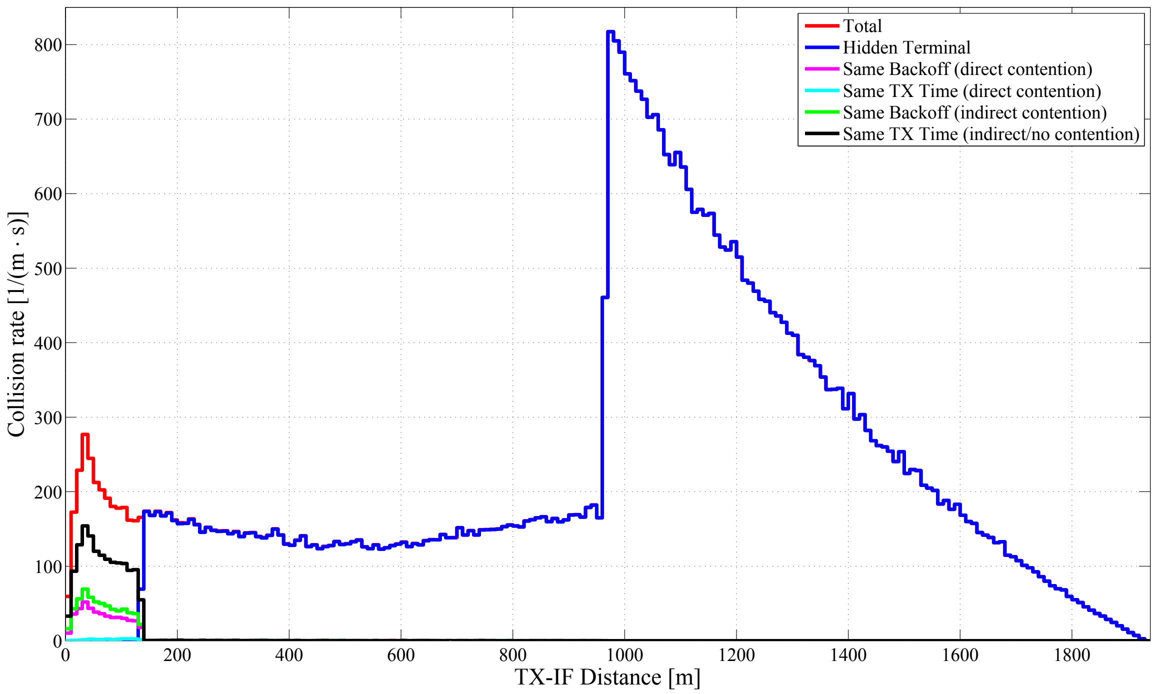


Figure 3.2: Packet collision rate (normalized in time and space) for the various collision types, plotted against the TX-IF distance.

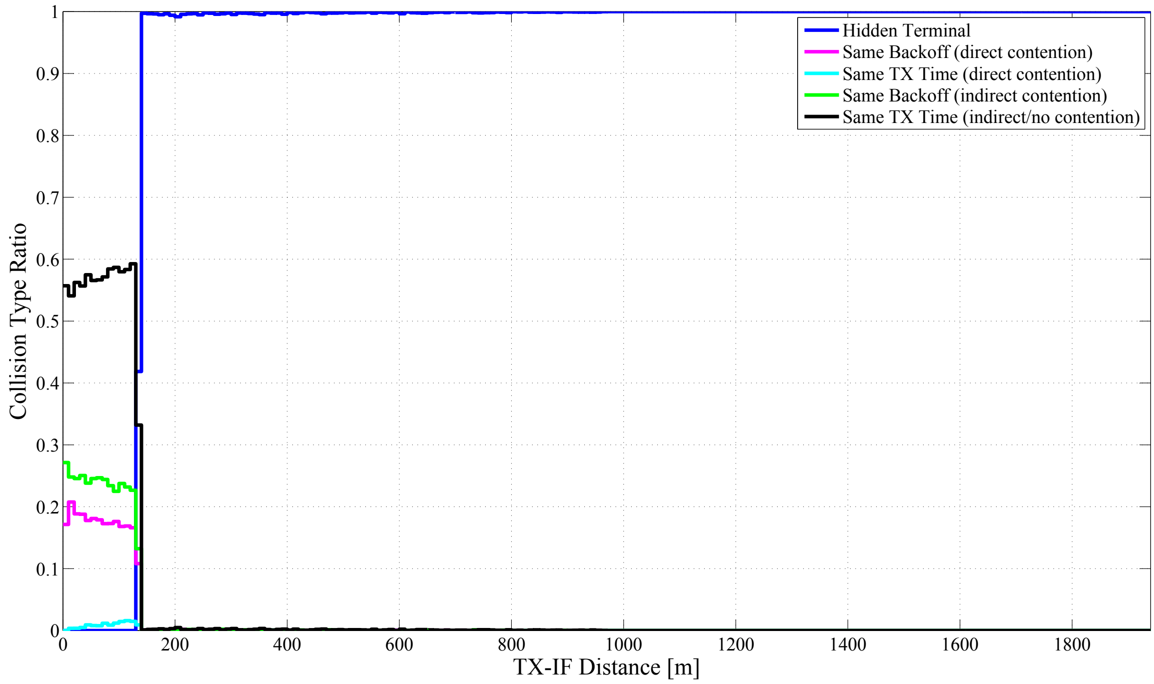


Figure 3.3: Relative amount of packet collisions for the various collision types, plotted against the TX-IF distance.

radio propagation model, used within the simulation framework, the CCA threshold of −65 dBm corresponds to a range of approximately 135 m.

- The peak at approximately 40 m is a side effect given by the highway scenario. As the highway has a width of approximately 40 m, up to this range the number of collisions is growing in lateral as well as longitudinal direction. Beyond that range, only the longitudinal direction still contributes to the number of collisions.

A more detailed view according to the shares of the different collision types is presented in Figure 3.3. It shows the ratio of the various collision types with respect to the total number of collisions, dependent on the TX-IF distance. Beyond the distance of approximately 135 m, the hidden terminal collisions clearly dominate all the other collision types with a relative amount of 99 % and more. However, especially in the context of cooperative safety, close ranges are much more critical, as nearby vehicles typically pose a higher risk than farther ones. Considering short TX-IF distances as well, the *same TX time* collisions are the dominating collision type. Nevertheless, the collisions due to the *same backoff* counter are still significant with approximately 45 %. These are probably more interesting, as they can be clearly identified with a single trigger event, namely both transmitters have chosen the same backoff counter. This fact allows to take appropriate countermeasures in order to mitigate this type of collision.

The existence of correlated packet errors on the PHY layer, has been already demonstrated by Martelli *et al.* [88]. Performing a measurement-based analysis with two IEEE 802.11p devices, the authors observed temporal correlated blackouts, due to persistent channel/link conditions. In contrast to [88], this work is focusing on the problem of correlated packet collisions on the MAC layer, caused by the quasi-periodic CAM transmission policy in combination with the quasi-static relative mobility between the vehicles.

The existence of MAC-related correlated packet collisions is presented in Figure 3.4. Detected collisions have been analyzed at RX, regarding their recurrence (temporal correlation) caused by the same initiator (IF). The figure compares the normalized packet collision rate of total packet collisions with the recurring ones, plotted against the IF-RX distance. Two main observations can be made from Figure 3.4: First, the number of total collisions increases significantly with increasing distance. Obviously, transmitting at high ranges all the time is a waste of resources, as a lot of information is lost there, due to packet collisions. Second, the amount of recurring collisions increases even faster.

On the first glance, it seems to be surprising that the amount of packet collisions is increasing with increasing IF-RX distance, as the interference from IF should become less

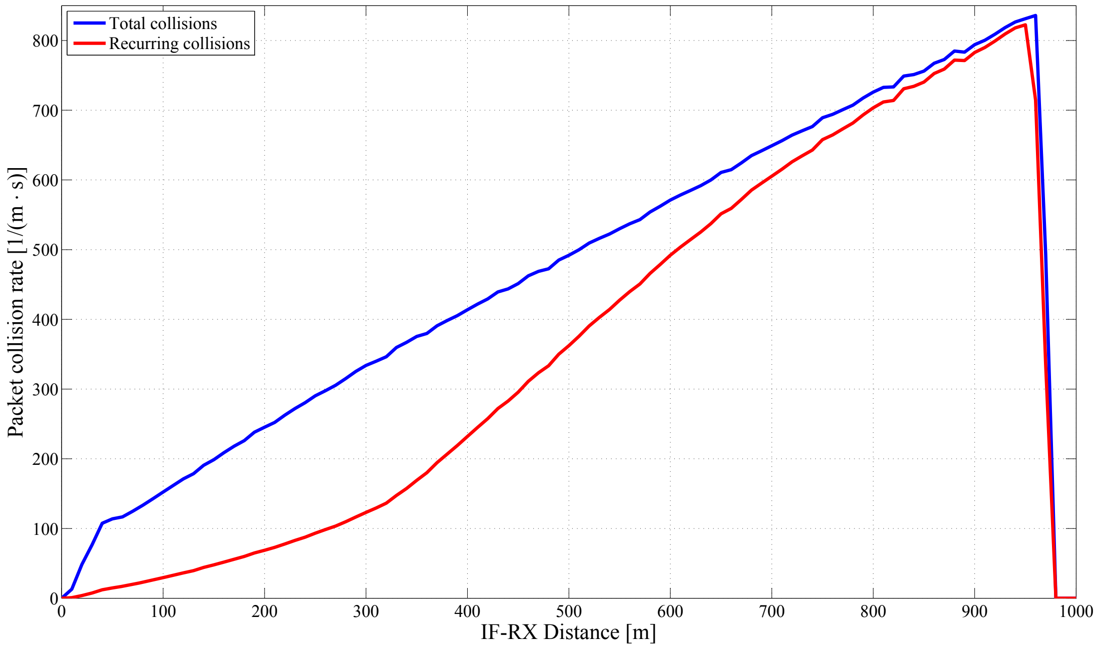
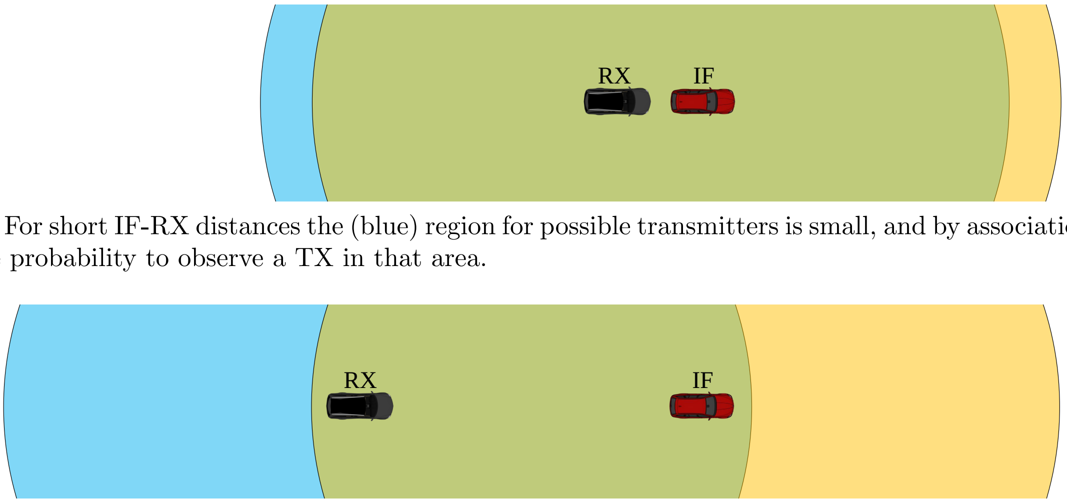


Figure 3.4: Total vs. recurring number of packet collisions (normalized in time and space), dependent on the distance between the collision-inducing transmitter (IF) and the receiver (RX).

significant. However, the focus here is on packet collisions caused by the imperfection of the MAC protocol, specifically, simultaneous transmissions detected at the receiver RX. Hence, the dominant impact factor here are not the conditions on the PHY layer, but on the MAC. In case of a hidden terminal situation, for instance, an increasing IF-RX distance increases the region for possible TX locations, which in turn increases the chance that a TX and an IF are transmitting at the same time, resulting in a packet collision. This fact is illustrated in Figure 3.5. The blue and the yellow area represent the transmission range of RX and IF, respectively. The green area indicates the overlap of both transmission ranges. Considering a packet collision caused by a hidden terminal situation between TX and IF, a receiver RX has to be inside the transmission range of both transmitters TX and IF, while both transmitters have to be outside of each others transmission range. Having this condition in mind, a short IF-RX distance leads to a small (blue) region for TX locations, which makes such hidden terminal collisions less likely. If the IF-RX distance is increased, the (blue) region for TX locations is increased as well. In that case, hidden terminal collisions are becoming more likely.

Figure 3.6 shows the ratio of recurring packet collisions, split up into their different causes. Whereas less than 20 % of the total packet collisions are recurring within the first



(a) For short IF-RX distances the (blue) region for possible transmitters is small, and by association the probability to observe a TX in that area.

(b) If the IF-RX distance is long, the (blue) region for possible transmitters is large, and by association the probability to observe a TX in this area.

Figure 3.5: Impact of an increasing IF-RX distance on hidden terminal collisions.

100 m, more than 70 % recur from 450 m on and even more than 90 % recur from 650 m on. The graph also reveals that the vast majority of recurring packet collisions is caused by *hidden terminal* situations. Whereas the hidden terminal collisions increase quite fast with distance, other collision types, like *same time* and *same backoff* remain quite constant. Hence, they show high relevance for nearby collisions, but become negligible with increasing distance.

Whereas Figure 3.4 and 3.6 just demonstrate the existence of recurring collisions, Figure 3.7 reveals the severity of the correlations as well. It shows the CCDF of the update delay in units of packets. Consequently, the plot provides the probability (y-axis) of exceeding a certain delay of n packets (x-axis) from the same transmitter. As the metric includes the number of $n-1$ consecutive lost packets from the same transmitter, it is very suitable to show the severity of (temporal) correlated packet collisions. Although plotted by a continuous line, it should be noted that the x-values are discrete, as the number of packets is an integer. To account also for spatial dependencies, the update delay CCDF is shown for three different ranges. A more detailed understanding and discussion of the packet-based update delay is provided in the next section.

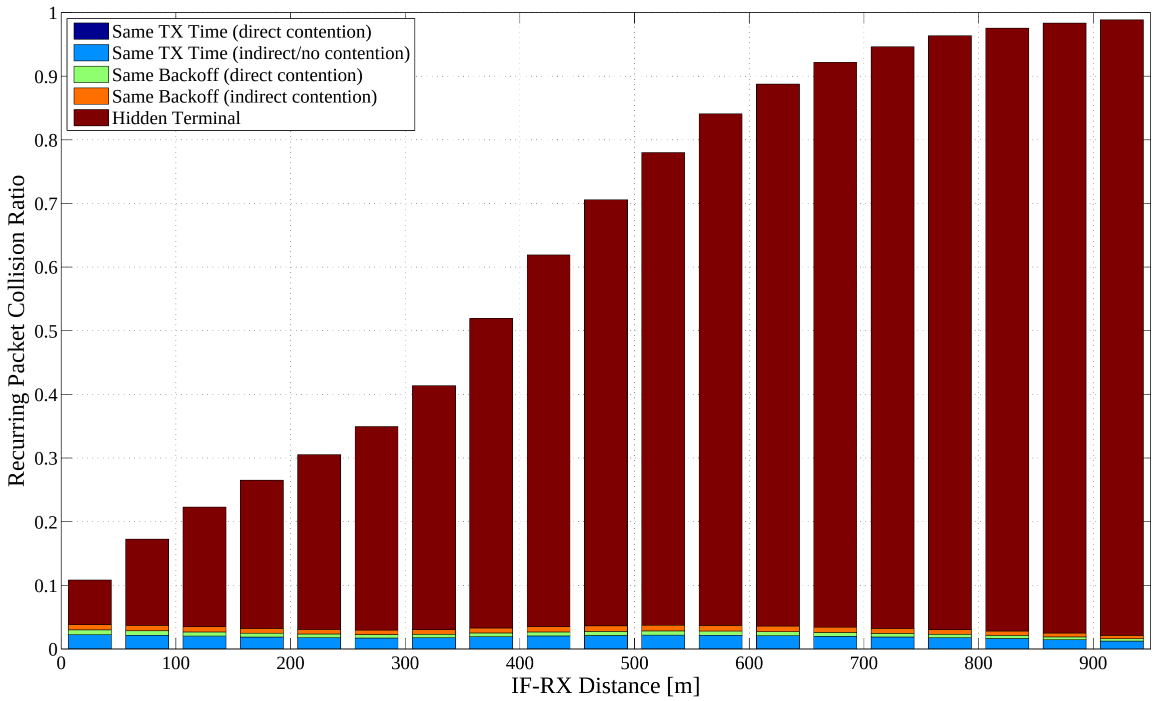


Figure 3.6: Recurring packet collision ratio, separated by the different types of packet collisions, and plotted against the IF-RX distance.

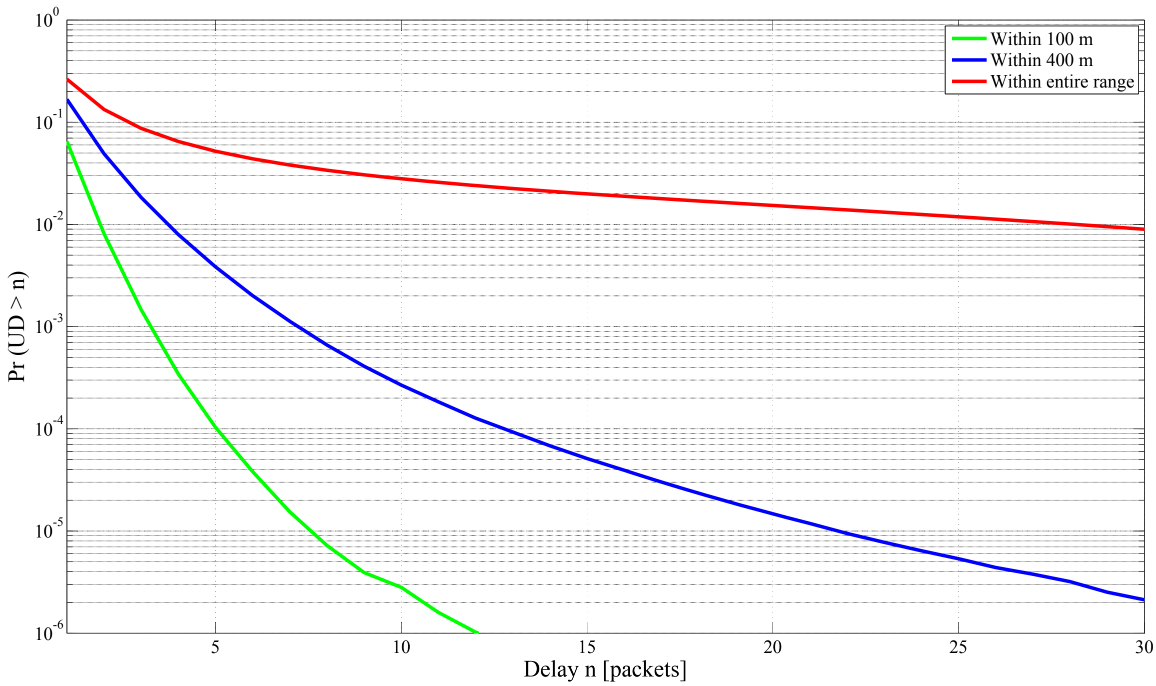


Figure 3.7: The CCDF of the update delay, measure in units of packets, for three different ranges.

3.2 Understanding Correlated Packet Collisions

While correlated packet errors on PHY layer have been already shown to play a significant role in VANETs [58, 88], correlated packet errors caused by correlated packet collisions on the MAC layer have not been investigated so far.

This section evaluates and validates the observation of MAC-related correlated packet collisions from the previous section. Therefor, the packet-based update delay obtained by the simulations is compared with with two distinct theoretical models. While the geometric distribution model assumes perfect independence between consecutive packet losses, and by implication represents a perfect decorrelation behavior, the Gilbert-Elliott model is widely used to model correlated burst errors.

3.2.1 Geometric Distribution Model

Some analytical studies, e.g. [127], derive the update-delay (inter-reception time) by means of a geometric distribution [52]. Therefore, the reception process of subsequent packets is compared with independent Bernoulli trials. Then, the probability $\mathbf{Pr}(\mathrm{UD} = n)$, for any $n \geq 1$, is calculated by

$$\mathbf{Pr}(\mathrm{UD} = n) = (1 - p_r)^{n-1} \cdot p_r \tag{3.1}$$

with p_r denoting the reception probability of an individual packet. The corresponding CDF is

$$\mathbf{Pr}(\mathrm{UD} \leq n) = 1 - (1 - p_r)^n \tag{3.2}$$

and the CCDF

$$\begin{aligned}\mathbf{Pr}(\mathrm{UD} > n) &= 1 - (1 - (1 - p_r)^n)) \\ &= (1 - p_r)^n \end{aligned} \tag{3.3}$$

Figure 3.8 compares the behavior of the geometric distribution model with the simulation results from Section 3.1.2, with focus on the packet-based update delay within the entire transmission range. It shows the update delay in units of packets represented as CCDF. Although varied by selecting different input parameters p_r, the geometric distribution is not able to match the curvature of the simulation data. By setting $p_r = 0.738$,

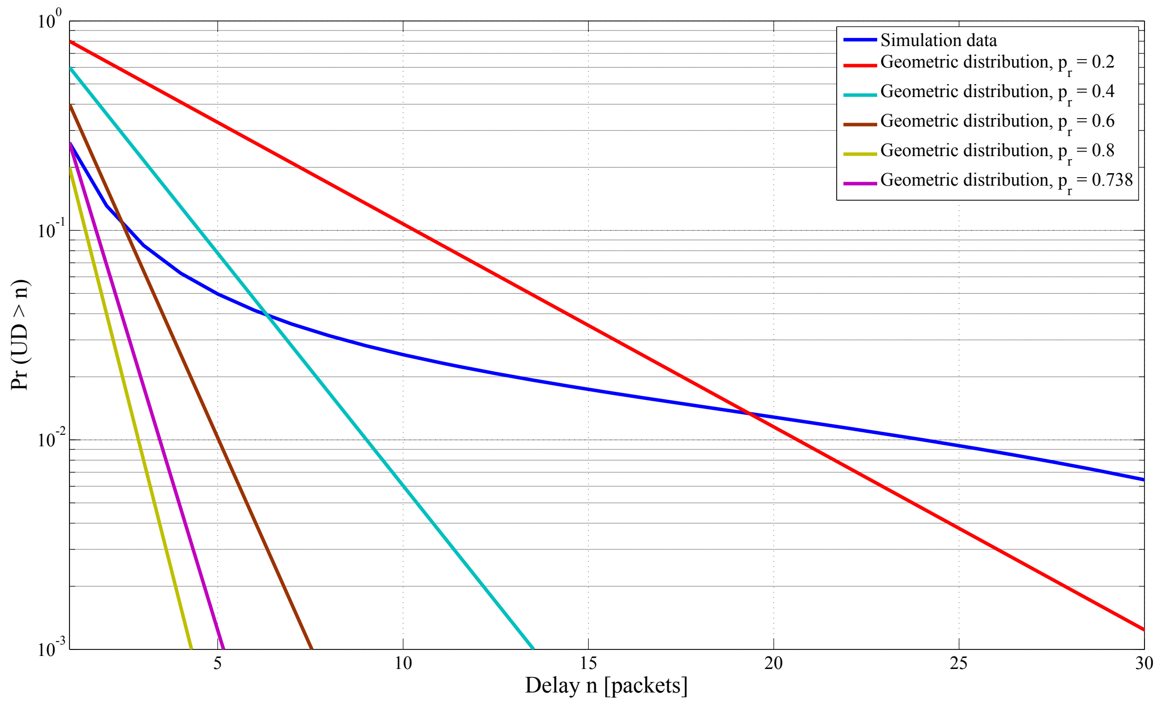


Figure 3.8: Comparison of different variations of the geometric distribution model with the update delay obtained by simulations.

which corresponds to the probability $\mathbf{Pr}(\mathrm{UD} = 1)$ from the simulations, the geometric distribution would indeed fit for $n = 1$, but starts to deviate significantly with increasing n.

The reason for this mismatch is that the geometric distribution model assumes perfect independence of the reception process for subsequent packets. Mathematically speaking, the sequence of independent Bernoulli trials corresponds to an independent and identically distributed (i.i.d.) sequence of random variables. Hence, this model is not able to consider (temporal) correlations between consecutive packet collisions. It rather represents the case where correlated collisions have been removed completely, that means, it specifies the desired behavior for consecutive packet losses and may present a lower bound.

However, the observation from Figure 3.8 does not yet confirm the hypothesis of correlated packet collisions caused by the MAC. There could be also other reasons for the mismatch. Therefore, the simulation results are additionally compared with a widely used model for correlated errors as described next.

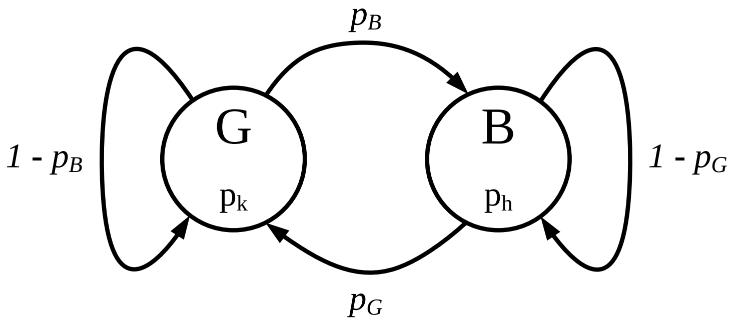


Figure 3.9: Correlated bit/packet errors modeled by a Markov process.

3.2.2 Gilbert-Elliott Model

Already in 1960, E. N. Gilbert [56] developed a bit error model to consider burst-noise channels. In 1963, this model was generalized by E. O. Elliott [42], and since then, it is known as the Gilbert-Elliott channel model for burst errors. It is based on a finite Markov chain, which consists of two states, G (for "good") and B (for "bad" or "burst"). The corresponding chain is illustrated in Figure 3.9. Beside the corresponding transition probabilities p_G and p_B, the two states G and B also specify a certain probability p_k and p_h, respectively, of correctly transmitting a bit. Dependent on the parameter setup, the model is able to account for a certain correlation between consecutive bit errors (burst errors). Low probabilities of p_G and p_B, for instance, make the model to remain in the same state with the same "good" or "bad" reception probability for a longer period.

In principle, correlated packet losses describe the same problem on frame-level, as correlated bit errors on bit-level. Consequently, the same model may be applied to determine the behavior of the update delay. This idea has been picked up and applied to VANETs by Martelli *et al.* [88]. Based on the Gilbert-Elliott model, the authors introduced the L/N model to consider (temporal) correlations of packet losses, caused by the persistent channel/link conditions on the PHY layer. Therefor, they focused on the two link conditions, Line Of Sight (LOS) and Non Line Of Sight (NLOS), which are represented by the two states L (corresponding to the G state) and N (corresponding to the B state), respectively. Although others already used the Gilbert-Elliott model to derive packet loss statistics, e.g. [62], Martelli *et al.* claimed of being the first, who characterize the distribution between two consecutive successful packet receptions [88], that means, the discrete packet-based update delay.

In this thesis, the Gilbert-Elliott model is used similarly to [88], but instead of correlated packet losses on the PHY layer due to persistent channel conditions, the focus here is on correlated packet collisions on the MAC layer, caused by the quasi-periodic CAM transmission policy in combination with the vehicles quasi-static relative mobility. While Martelli *et al.* completely neglected MAC effects like contention or hidden terminals by considering an experimental setup of only two communications devices, this work provides a complementary investigation by neglecting PHY layer effects like fading or capture as much as possible in order to isolate the MAC and its effects on packet collisions.

Following the derivation in [88], starting point is the Gilbert-Elliott model with the two states G and B, as illustrated in Figure 3.9. The corresponding transition probabilities are denoted by p_G and p_B, respectively. In addition, each of the states G and B specifies a certain probability of correctly receiving a packet, denoted by p_k and p_h, respectively. Based on these definitions, the corresponding transition matrix $\mathbf{T}$ is specified as

$$\mathbf{T} = \begin{array}{c} \\ G \\ B \end{array} \begin{array}{c} \begin{array}{cc} G & B \end{array} \\ \begin{pmatrix} 1-p_B & p_B \\ p_G & 1-p_G \end{pmatrix} \end{array} \tag{3.4}$$

The corresponding stationary distribution π provides the probabilities $\mathbf{Pr}(G)$ and $\mathbf{Pr}(B)$ of being in state G and B, respectively, after n transitions, if n tends to infinity, and is obtained as follows:

$$\pi = \left(\mathbf{Pr}(G) = \frac{p_G}{p_G + p_B} \;,\; \mathbf{Pr}(B) = \frac{p_B}{p_B + p_G} \right) \tag{3.5}$$

Let S denote the current state with $S \in \{G, B\}$. As mentioned above, the quantity of interest here is the delay in packets between two successful reception events RX. Hence, the first step is to derive the probability $\mathbf{Pr}(S|RX)$ of being in state S conditioned on the event RX of a successful packet reception. By making use of Bayes' Theorem [52], $\mathbf{Pr}(S|RX)$ can be obtained as follows:

$$\mathbf{Pr}(S|\mathrm{RX}) = \frac{\mathbf{Pr}(\mathrm{RX}|S) \cdot \mathbf{Pr}(S)}{\mathbf{Pr}(\mathrm{RX})} \tag{3.6}$$

Applied to the model introduced above, the corresponding probabilities can be computed by

$$\begin{aligned}\mathbf{Pr}(G|\text{RX}) =& \frac{\mathbf{Pr}(\text{RX}|G)\cdot\mathbf{Pr}(G)}{\mathbf{Pr}(\text{RX})} = \frac{p_k\cdot\mathbf{Pr}(G)}{\mathbf{Pr}(G)\cdot p_k + \mathbf{Pr}(B)\cdot p_h}\\ =& \frac{p_k\cdot p_G}{p_k\cdot p_G + p_h\cdot p_B}\end{aligned} \tag{3.7}$$

for $S = G$ and

$$\begin{aligned}\mathbf{Pr}(B|\text{RX}) =& \frac{\mathbf{Pr}(\text{RX}|B)\cdot\mathbf{Pr}(B)}{\mathbf{Pr}(\text{RX})} = \frac{p_h\cdot\mathbf{Pr}(B)}{\mathbf{Pr}(G)\cdot p_k + \mathbf{Pr}(B)\cdot p_h}\\ =& \frac{p_h\cdot p_B}{p_k\cdot p_G + p_h\cdot p_B}\end{aligned} \tag{3.8}$$

for $S = B$.

Let S_i denote the state at time step i. Then, the probability of $\mathbf{Pr}(\text{UD} = n)$, for any $n \geq 1$, can be determined by investigating all possible sequences of n state transitions $(S_1, S_2, ..., S_n)$. Let p_{S_i} denote the probability of successfully receiving a packet in state S_i. Then, $\mathbf{Pr}(\text{UD} = n)$ is determined by the probabilities $1-p_{S_i}$ of not receiving a packet in the states $S_1, ..., S_{n-1}$, and the probability p_{S_n} of finally receiving a packet successfully in state S_n. Conditioned on the occurrence of the sequence $(S_1, ..., S_n)$, $\mathbf{Pr}(\text{UD} = n|(S_1, ..., S_n))$ is calculated by

$$\mathbf{Pr}(\text{UD} = n|(S_1, ..., S_n)) = p_{S_n}\cdot\prod_{i=1}^{n-1}(1-p_{S_i}) \tag{3.9}$$

with $p_{S_i} = p_k$, if $S_i = G$, and $p_{S_i} = p_h$, if $S_i = B$.

Finally, to obtain $\mathbf{Pr}(\text{UD} = n)$ among all possible sequences $(S_1, ..., S_n)$, the corresponding occurrence probability of any sequence, with a successful reception event RX in state S_n, has to be taken into account. These occurrence probabilities $\mathbf{Pr}((S_1, ..., S_n))$ can be obtained as follows:

$$\mathbf{Pr}((S_1, ..., S_n)) = \mathbf{Pr}(G|\text{RX})\cdot\prod_{i=1}^{n} p_{G|S_i} + \mathbf{Pr}(B|\text{RX})\cdot\prod_{i=1}^{n} p_{B|S_i} \tag{3.10}$$

where

$$p_{G|S_1} = \begin{cases} 1-p_B & \text{if } S_1 = G\\ p_B & \text{if } S_1 = B\end{cases}$$

and

$$p_{G|S_i} = \begin{cases} 1 - p_B & \text{if } S_{i-1} = G \text{ and } S_i = G \\ p_B & \text{if } S_{i-1} = G \text{ and } S_i = B \\ 1 - p_G & \text{if } S_{i-1} = B \text{ and } S_i = B \\ p_G & \text{if } S_{i-1} = B \text{ and } S_i = G \end{cases}$$

for $i \in \{2, ..., n\}$.

Likewise

$$p_{B|S_1} = \begin{cases} 1 - p_G & \text{if } S_1 = B \\ p_G & \text{if } S_1 = G \end{cases}$$

and

$$p_{B|S_i} = \begin{cases} 1 - p_G & \text{if } S_{i-1} = B \text{ and } S_i = B \\ p_G & \text{if } S_{i-1} = B \text{ and } S_i = G \\ 1 - p_B & \text{if } S_{i-1} = G \text{ and } S_i = G \\ p_B & \text{if } S_{i-1} = G \text{ and } S_i = B \end{cases}$$

for $i \in \{2, ..., n\}$.

Finally, the probability $\mathbf{Pr}(\text{UD} = n)$ is determined by

$$\mathbf{Pr}(\text{UD} = n) = \sum p_{S_n} \cdot \prod_{i=1}^{n-1} (1 - p_{S_i}) \cdot \mathbf{Pr}((S_1, ..., S_n)) \tag{3.11}$$

As the computation of $\mathbf{Pr}(\text{UD} = n)$ by Equation 3.11 requires to iterate over all permutations of the sequence $(S_1, ..., S_n)$, the computational complexity is in the order of $\mathcal{O}(2^n)$. However, there is a more efficient computation, which is based on the following recursive definition [88]:

$$\mathbf{Pr}(\text{UD} = n) = \mathbf{Pr}(G|RX) \cdot p_G^n + \mathbf{Pr}(B|RX) \cdot p_B^n \tag{3.12}$$

where

$$p_G^i = p_B \cdot (1 - p_h) \cdot p_B^{i-1} + (1 - p_B) \cdot (1 - p_k) \cdot p_G^{i-1}$$
$$p_B^i = p_G \cdot (1 - p_k) \cdot p_G^{i-1} + (1 - p_G) \cdot (1 - p_h) \cdot p_B^{i-1}$$

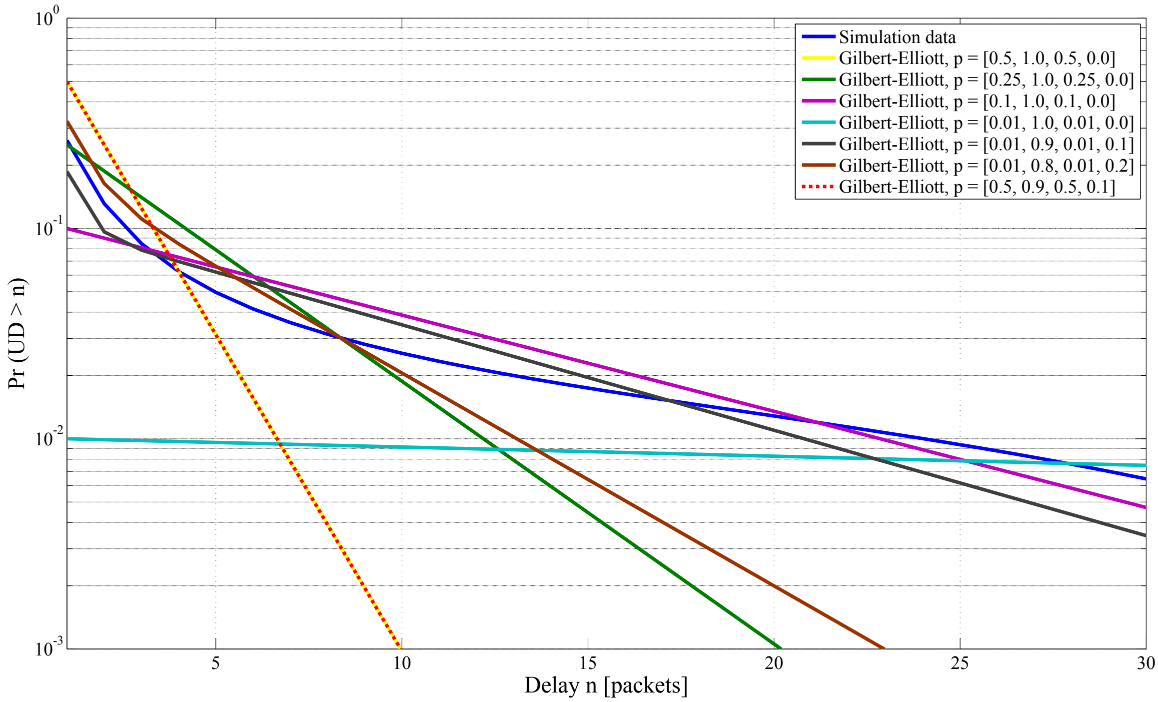


Figure 3.10: Comparison of the Gilbert-Elliott model with the simulation data, for different variations of the input parameters p_G, p_k, p_B, and p_h.

for $i \in \{2, ..., n\}$, and

$$p_G^1 = (1 - p_B) \cdot p_k + p_B \cdot p_h$$
$$p_B^1 = (1 - p_G) \cdot p_h + p_G \cdot p_k$$

To get a better understanding of the model's behavior, it is compared with the update delay obtained from simulations, for different input parameter settings. The corresponding CCDF curves, representing the update delay in units of packets, are shown in Figure 3.10. Similar to Figure 3.8, the simulation data serve as a reference again, and represent the update delay within the entire transmission range. The first four Gilbert-Elliott curves represent a simplified setup, by assuming that a packet is received in state G with probability 1, and in state B with probability 0. Whereas $p_G = 0.5$ and $p_B = 0.5$ correspond to a quite random, and by implication, non-correlated behavior of state transitions, decreasing them introduces a more correlated transition behavior, as the corresponding states show an increasing persistence. If p_k and p_h are varied as well, the resulting curve can be further adapted to the simulation data. Already a reduction/increase of the previous setting by

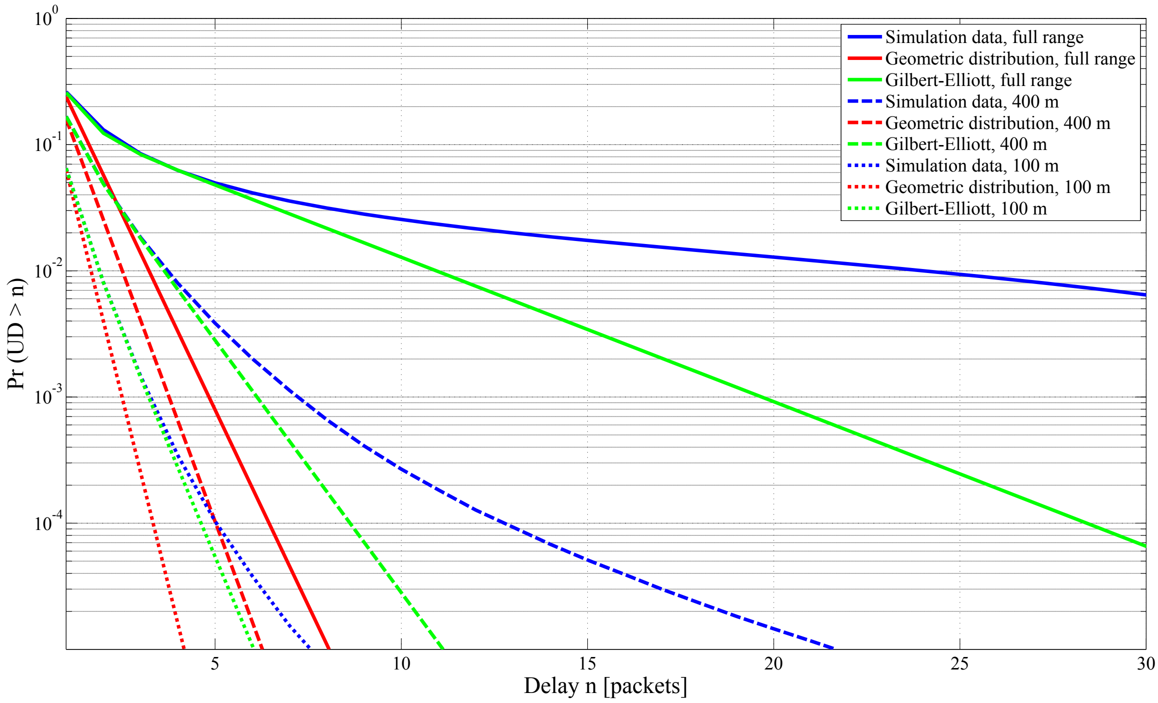


Figure 3.11: The Gilbert-Elliott model fitted to the simulation data, measured for three different ranges.

0.1 ($p_k = 0.9$, $p_h = 0.1$), shows a certain curvature behavior quite similar to the simulation data, at least for low update delay values. However, a reset of p_G and p_B to 0.5, fully compensates the curvature behavior, as the correlated state transitions have been fully decorrelated again.

A better fit of the Gilbert-Elliott model to the simulation data, may be obtained by curve fitting. A quite popular method, to solve generic curve fitting problems, is the Levenberg-Marquardt algorithm [82, 87]. A free implementation is provided by GNU Octave [1], which requires the corresponding model function, as well as its partial derivatives. In this case, the model function basically corresponds to equation 3.12, and the partial derivatives have been obtained numerically by calculating the central differences. The results of the Levenberg-Marquardt curve fitting are presented in Figure 3.11. It compares the packet-based update delay obtained by simulations with the fitted Gilbert-Elliott model as well as the fitted geometric distribution model. In addition, each of the three update delay CCDF curves is shown for three different ranges. The figure reveals immediately that the Gilbert-Elliott model matches the simulation data significantly better than the geometric distribution model. Obviously, VANETs indeed cause correlated packet collisions on the

MAC layer. In order to confirm this hypothesis, lets have a closer look on the parameter setup of the Gilbert-Elliott model, obtained by the converged Levenberg-Marquardt algorithm:

$$\begin{bmatrix} p_G \\ p_k \\ p_B \\ p_h \end{bmatrix}_{\text{entire range}} = \begin{bmatrix} 0.083 \\ 0.843 \\ 0.053 \\ 0.164 \end{bmatrix}, \quad \begin{bmatrix} p_G \\ p_k \\ p_B \\ p_h \end{bmatrix}_{\text{400 m}} = \begin{bmatrix} 0.207 \\ 0.914 \\ 0.077 \\ 0.501 \end{bmatrix}, \quad \begin{bmatrix} p_G \\ p_k \\ p_B \\ p_h \end{bmatrix}_{\text{100 m}} = \begin{bmatrix} 0.555 \\ 0.960 \\ 0.044 \\ 0.562 \end{bmatrix}$$

With focus on the entire range scenario, the transition probabilities p_G and p_B reveal a highly persistent behavior of the states G and B. This observation indeed confirms a high correlation of consecutive packet receptions/errors. As most of the PHY layer effects have been intentionally omitted, the correlated packet errors are solely caused by packet collisions on the MAC layer. If shorter ranges are considered, p_G is further increased, with the consequence being of receiving more often in the "good" state. Moreover, the reception probability p_k in state G is increased as well.

3.2.3 Discussion

Although the application of the Gilbert-Elliott model as described above has shown to be suited to confirm the hypothesis of correlated packet collisions caused by the MAC, it also shows some imperfection with respect to modeling correlated packet collisions with sufficient accuracy.

Considering Figure 3.11 again, the fitted Gilbert-Elliot model seems to provide a very good match for shorter update delays, but starts to show a diverging behavior for longer ones. Apparently, this effect is getting less significant with decreasing range. Due to the logarithmic-scaled y-axis, this observation is not that obvious from Figure 3.11. In Figure 3.12, however, this effect is clearly observable, as it plots the more common CDF representation, including a linear-scaled y-axis. Hence, the figure shows the probability (y-axis) that the update delay is less or equal a certain delay n (x-axis). The linear scale of the y-axis allows a better comparison of the fitting solutions for the three different ranges, as there is no logarithmic distortion by the y-axis anymore.

Indeed, the fitted Gilbert-Elliott models seem to provide higher accuracy the shorter the range. A possible explanation for this observation might be the accumulating behavior of the update delay measures. Whereas the short-range update delay measures only include

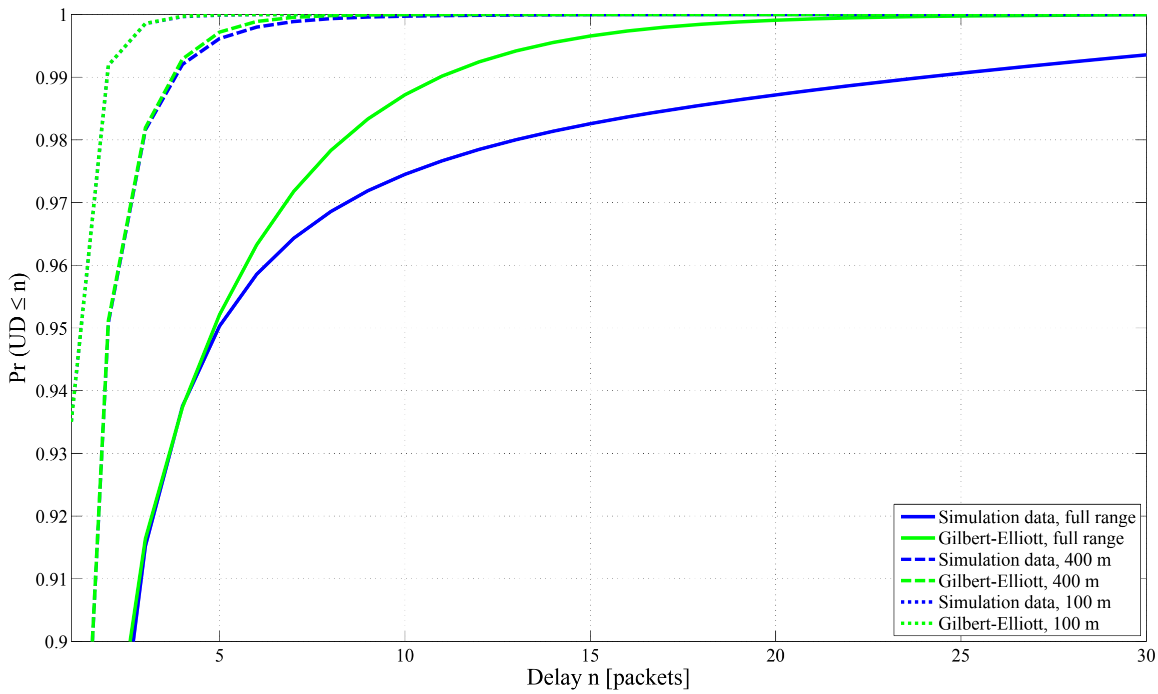


Figure 3.12: Measured and fitted update delays for different ranges, plotted as CDF.

the short ranges, the medium-range update delay measures include all ranges up to the medium range, that means, the short ranges as well. Likewise, the full-range update delay measures include all ranges.

With focus on PHY layer packet collisions, Shivaldova *et al.* [118] have shown that the correlation behavior is dependent in space. Therefore, they proposed a range-dependent modified Gilbert-Elliott model, in order to better describe the PHY-related correlated packet collisions. If the same is valid for correlated packet collisions on MAC layer, the observation from Figure 3.12 obviously makes sense. Consider the correlation behavior varies in space, but is quite constant within sections of Δ meters. Then, the Gilbert-Elliott model fitted to the update delay measures within Δ, would result in a quite accurate solution. However, the update delay measure within multiples of Δ, would include several sections, each with different correlation behavior. A Gilbert-Elliott model fitted to that measures, may only result in an accurate fit on average, but not for the entire distribution.

Altogether, the Gilbert-Elliott model presented above clearly shows a better suitability to model the update delay compared with the still widely used geometric distribution model (e.g. in [127]). However, the results have shown that the Gilbert-Elliott model indeed provides high accuracy for short distances, but is getting less accurate if longer ranges are considered, as it does not take the distance-dependent impact on packet receptions into account. Probably this issue could be fixed by introducing a spatial-dependent adaptation of the model (see [118]), but this is beyond the scope of this thesis. Furthermore, the Gilbert-Elliott model is not the only way to describe correlated packet errors. A variety of models for packet errors with memory are described in [67]. Maybe there are other ones, which are better suited to model correlated packet losses caused by the correlated behavior of packet collisions on the MAC layer.

3.3 Spanning the Solution Space

The objective of this thesis is to find possible solutions to the research question, stated at the beginning of this chapter. The entire solution space to address this problem may range from new PHY layer adaptation techniques to the introduction of new higher layer protocols, which is not possible to extensively discuss here. Whereas PHY layer adaptation concepts may require alternative or even new transceiver technologies, an increasing communications reliability by higher layer protocols would come at the cost of additional communications overhead.

Hence, this thesis will mainly focus on new collision mitigation concepts on MAC layer, which are able to remain compatibility with current ITS-G5 technology, as selected by the standardization bodies for Day one ITS communication in (European) VANETs. Moreover, this work will exclusively focus on CAM-based[1] cooperative safety. The reason is that CAMs comprise most of the generated data traffic on the primary channel (control channel) [31], and they are much more sensitive regarding their validity period.

Based on the observations above, three new broadcast collision mitigation strategies will be introduced, and investigated from two different perspectives. Whereas the MAC perspective highlights their direct impact on packet collisions in space as well as in time, the application's perspective demonstrates their ability to support basic requirements of cooperative safety applications.

One starting point are the results from Section 3.1.2, showing that a significant amount of MAC-related packet collisions at close ranges are caused by vehicles, which have chosen the same backoff counter. Hence, the first proposal is to generate the backoff counter dependent on the vehicles current position, in order to reduce the *same backoff* collisions

[1]Please note that the introduced concepts can be also applied to other messages with similar characteristics, i.e. periodic broadcast transmissions.

in the close vicinity, which is much more critical with respect to traffic safety.

Particularly correlated packet collisions have a negative impact on the awareness and its quality. From a MAC perspective, these collisions are caused by the quasi-periodic CAM transmissions, in combination with a quasi-static relative mobility between vehicles (cf. Section 2.5.1). Hence, possible countermeasures may either rely on making CAM transmissions less periodic, or making the vehicles relative mobility more dynamic. Each of them is the objective of two further transmission adaptation concepts. Whereas the random transmit jitter concept randomizes the periodic safety-broadcasts around the nominal transmission interval to make them less periodic in time, the concept of using random transmit powers is able to simulate random path losses for each transmission and vehicle, which corresponds to a random relative mobility between vehicles, transmitting at constant powers only.

From an application's perspective, especially in the context of cooperative safety, close ranges are much more critical than farther ones. Consequently, the idea is to reflect the spatial critical behavior by an appropriate awareness behavior in space. Whereas the geo-based backoff generation concept passively supports this spatial awareness behavior by reducing the amount of collisions at close ranges, the random transmit power concept even allows to actively adapt the awareness behavior in space. This is possible, as alternating transmit powers result in alternating transmission ranges, with the consequence being that nearby vehicles are provided more frequently with CAM updates than farther ones. Hence, random transmit powers provide the basis for a new awareness control strategy called fish-eye awareness, which is able to adapt the awareness quality in space.

Chapter 4

Broadcast Collision Mitigation Strategies

In this chapter, three new packet collision mitigation strategies will be introduced and evaluated from a MAC perspective. Whereas *geo-backoff* focuses on *same backoff* collisions during contention, the *random transmit jitter* and *random transmit power* concepts address the problem of correlated packet collisions, as well as their impact on the MAC-related communications performance.

4.1 Geo-Backoff

To mitigate *same backoff* packet collisions as discussed in Section 3.1.2, a new IEEE 802.11 MAC adaptation concept is introduced, called *geo-backoff* [73]. It is based on two steps: First, the probability of simultaneous transmissions is reduced in general, by increasing the Contention Window (CW). Second, to achieve a further reduction of the probability of simultaneous transmissions in the immediate (critical) vicinity, the backoff counter is generated by exploiting the vehicle's current position. The resulting desired collision behavior in space is illustrated in Figure 4.1.

4.1.1 Step 1: Contention Window Adaptation

The main objective in this section is to improve the communications performance in the context of vehicular safety, specifically in close-up range, where reliable communications is safety-critical, and packet collisions are undesirable. Regarding the results from Section

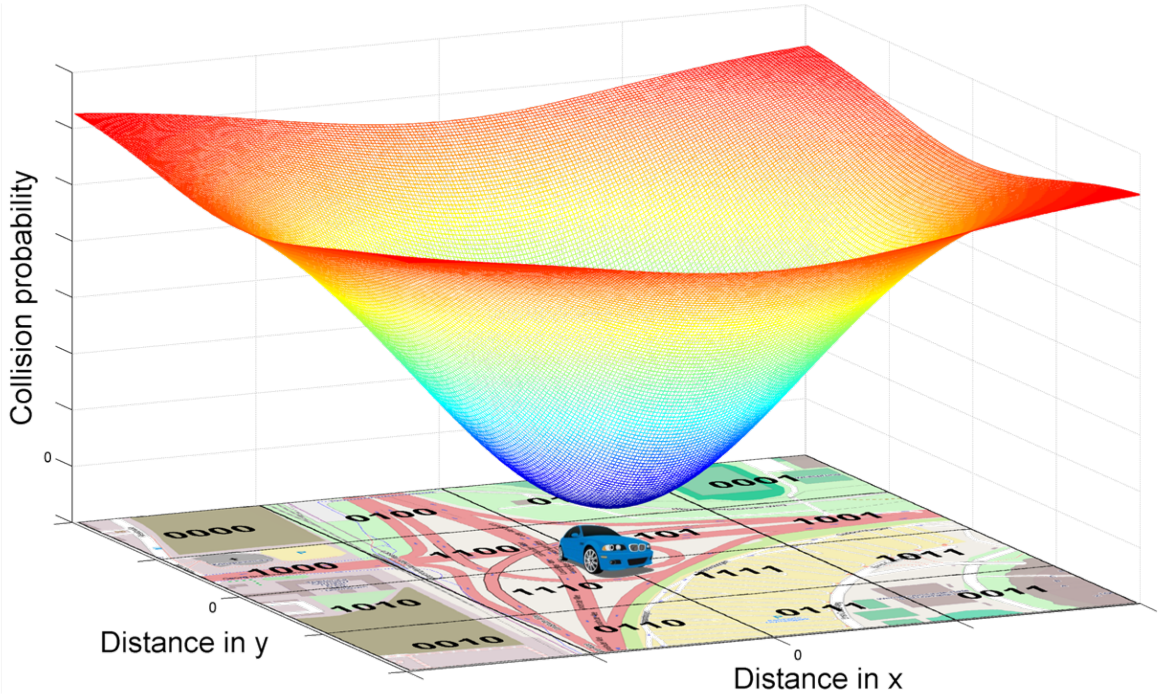


Figure 4.1: The desired behavior of packet collisions in space: Further mitigation of nearby collisions, as this is the critical area regarding vehicular safety.

3.1.2, about 45 % of the total amount of packet collisions are caused by vehicles, which have chosen the same backoff counter. Due to the lack of (negative) acknowledgments for broadcast transmissions, the original IEEE 802.11's collision avoidance mechanism of exponentially increasing the CW does not work for CAMs. Hence, the minimum CW size of only 8 slots will remain the same, even in highly dense traffic scenarios. Therefore, a reasonable starting point is to simply increase the CW size that reduces probability of choosing the same backoff counter in general. The CW adaptation studies, summarized in Section 2.4.3, indeed have already shown that it makes sense to increase the CW, and by implication, to improve the communications performance (e.g. [25, 22, 99, 124]). Hence, this work lays the focus on the position-based backoff generation, as discussed in the next subsection.

4.1.2 Step 2: Geo-based Backoff Generation

Regardless of whether the CW size is increased or not, the current ITS-G5 backoff generation is based on a uniformly distributed random process, and thus, it is not able to distinguish between near and far. After having reduced the *same backoff* collisions in

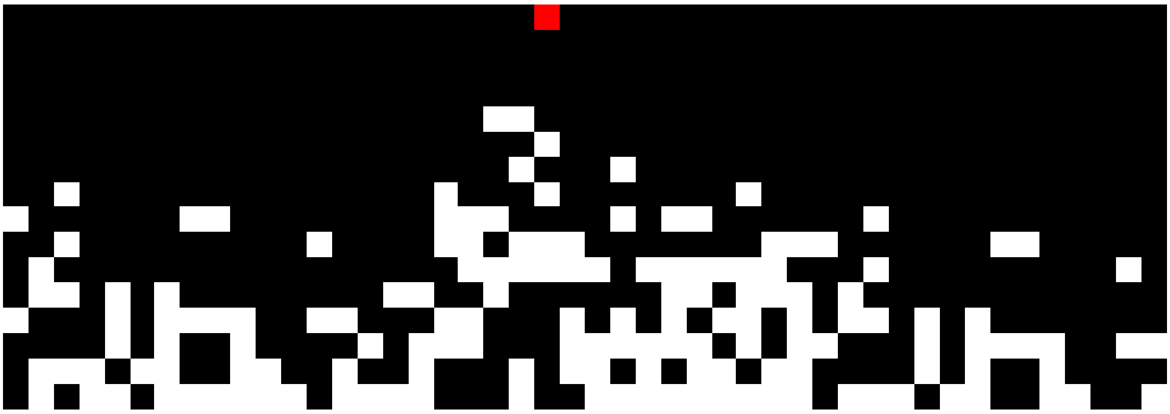


Figure 4.2: Avalanche effect of the SHA-1 hash function (Source: Wikimedia Commons)

general by step 1, the objective in this step is to redistribute the remaining *same backoff* collisions in space, specifically, to shift them from near to far, where it is less critical with respect to vehicular safety (see Figure 4.1).

To achieve this behavior, the main objective is to generate different backoff counters for nearby vehicles during channel contention, by simply exploiting their current position. Therefore, two approaches are investigated and described hereafter.

Crypto-based Geo-Backoff

The first idea to further reduce nearby collisions is to make use of cryptographic hash functions. These special functions have a relevant property:

> *A slight change in the original message (e.g. a bit-flip) results in a significant change of the hash value.*

This property is known as the *avalanche effect*. The term was first introduced by Feistel [51] in 1973, but the concept is actually based on *diffusion*, already introduced by Shannon [117] in 1949. An example for the avalanche effect is depicted in Figure 4.2. It shows the avalanche progress of the Secure Hash Algorithm (SHA), specifically SHA-1 [15], for the first 46 bits, round by round, if only one bit (red) of the input vector is flipped.

An other important property in combination with the avalanche effect is *completeness*, introduced by Kam and Davida [66]. In the context of hash functions, it means that each output bit must depend on all input bits.

By transferring cryptographic hash functions to the backoff generation in ITS-G5, the objective is to have a geo-backoff function, which provides the following property:

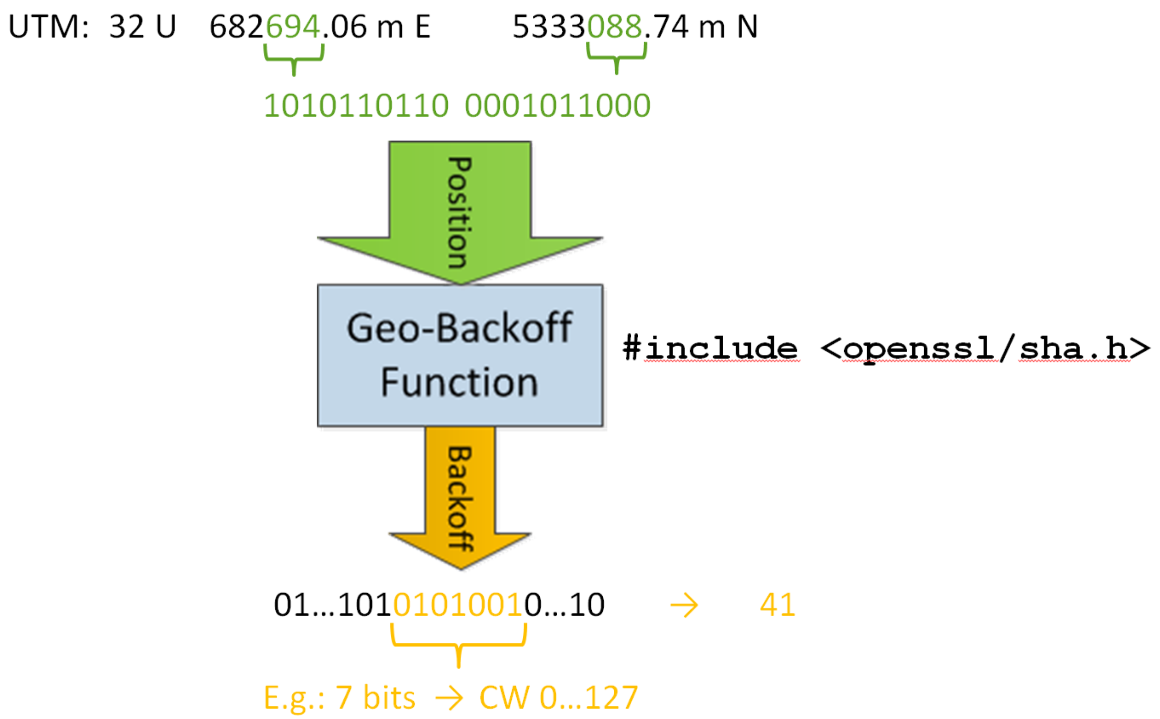


Figure 4.3: Prototype implementation of the proposed crypto-based geo-backoff function.

> *A slight change in position (e.g. difference by just a few meters) results in a significant change of the generated backoff counter.*

Hence, the intuitive idea is to use a cryptographic hash function to calculate the backoff counter, with the current position as input. As nearby vehicles only show a minor change in position, the crypto-based geo-backoff function is expected to generate a significant different hash value, from which the backoff counter is extracted.

Another interesting property of that approach is that it is working on absolute positions only. There is no need to transmit the current position of other vehicles in advance to determine the current distance. Consequently, no additional overhead is introduced by using the crypto-based geo-backoff. To avoid that two nearby vehicles will generate the same crypto-based backoff value, a certain position precision is required, that means, nearby vehicles must provide different position measures.

The implementation approach for the crypto-based geo-backoff function is illustrated in Figure 4.3, and takes the current position of the backoff generating vehicle as input. To get a high variety of the position inputs, only the relevant digits are extracted. In this work, distances up to 999 m are considered, in order to cover the maximum communication range ($\approx$ 970 m) with a resolution of 1 m. Please note that the geo-backoff function is not only limited to Universal Transverse Mercator (UTM) coordinates. Other coordinate systems can be used as well.

Once, the relevant digits have been extracted from the position coordinates, they are passed to the geo-backoff function. Here, the geo-backoff function is represented by SHA-256 [14], a cryptographic hash function from the second series of the SHA. Therefor, the simulation framework has been extended by including the cryptographic library OpenSSL [4]. As a consequence, the SHA-256 geo-backoff function delivers a 256 bit hash value from the corresponding position input. As the entire hash value is too long to represent an appropriate backoff counter, only a certain amount of bits is extracted from the hash value to generate the backoff counter (e.g. 8 bit for a backoff counter between 0 and 255). For well designed cryptographic hash functions it does not matter which bits are extracted, as each output bit depends on all input bits (completeness property [66]).

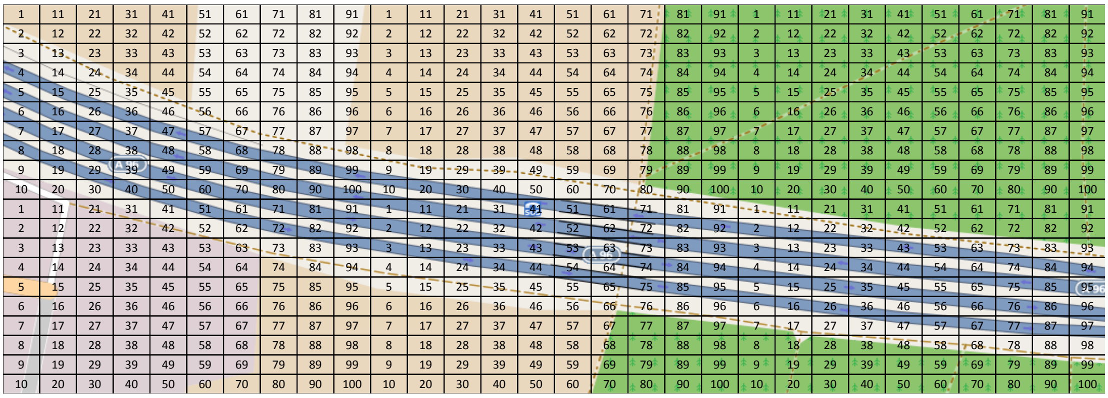
It should be noted that the presence of cryptographic hash functions in VANETs is indeed given, as they are required to secure vehicular safety communications (cf. security plane in Figure 2.1).

Grid-based Geo-Backoff

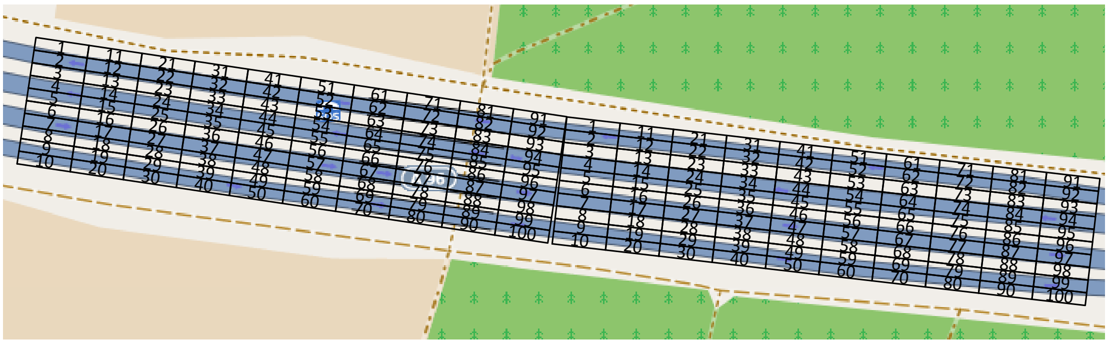
The second geo-backoff approach, investigated in this thesis, is based on a grid, which is mapped onto the road, as illustrated in Figure 4.4. Then, the backoff counter is generated depending on the cell, in which the vehicle is currently located. The big advantage of the grid-based geo-backoff concept is that, dependent on the grid design/mapping, it can be guaranteed that vehicles in different cells will generate different backoff counter values for sure.

In order to satisfy the latency requirements for safety-critical messages, the size of the CW cannot be arbitrarily large. Hence, grid cells may recur at a certain distance, and therefore, the backoff counter values as well. To avoid same backoff collisions within a certain grid section, equal backoff counter values should be mapped to cells, which are displaced as far as possible. Another layout criterion is the cell size. If designed too small, backoff counter values are recurring at shorter distances. If chosen too large, the probability that at least two vehicles are located within the same cell (they would choose the same backoff counter) is too high.

Whereas a non-aligned grid layout (see Figure 4.4a) may implicitly decrease the effective CW, as a lot of cells may be mapped to regions, where a vehicle is quite unlikely to be (e.g. forest areas), the proposal here is to align the grid along the road shape, as illustrated



(a) A non-aligned grid-layout may result in many wasted cells, mapped to locations a vehicle is very unlikely to appear, which results in a decrease of the effective CW.



(b) An aligned grid-layout, however, may significantly increase the effective CW, as cells are only mapped to locations, a vehicle is likely to be (i.e. the road).

Figure 4.4: Illustration of possible grid layouts for an example multi-lane highway scenario in Munich (Source: OpenStreetMap).

in Figure 4.4b. Then, each cell covers at least one part of the road, that means, only locations a vehicle is likely to appear. Therefor, information obtained from maps may be used, to determine the longitudinal location along a certain road. In lateral direction, each cell may be mapped to one lane, again by means of map information. In principal, the grid-based approach uses a hash function, too, which takes the current position along the road, and the current lane number as input, and calculates the corresponding backoff counter. Assuming that map information, including road topology and more, is available, and assuming that GNSSs, like Galileo, in combination with additional sensors are able to provide lane level position precision, it should be feasible for vehicles to map themselves into the corresponding cells with sufficient reliability.

Traffic scenario	10-km highway with 6 lanes in each direction
Evaluation section	5 km (from 2.5 – 7.5 km)
Vehicle generation process	Erlang distributed ($\mu = 2.25$ s)
Speed profile	From 20 to 40 m/s (4 m/s increase from outer to inner lane)
Access technology	ITS-G5 on control channel
Radio propagation model	Log distance (exponent 2.35)
Transmit power profile	constant at 33 dBm
CAM generation policy	1 Hz + trigger conditions
CW sizes	8 (default), 16, 32, 128, 256, 512, 1024
Geo-backoff approaches	cryptohash-based (CW = 256), grid-based (CW = 252)
Metrics	latency, update delay, normalized packet collision rate, packet collision ratio

Table 4.1: Simulation parameters for the geo-backoff investigations.

4.1.3 Evaluation by Simulations

The geo-backoff concept, presented above, has been evaluated by means of simulations. The basic environment and metrics are described in Appendix A. However, it has been extended by the crypto- and the grid-based geo-backoff implementations, as described in the previous subsection, including a variety of increased CW sizes. A summary of the most important simulation parameters is given by Table 4.1.

Latency

The common justification for keeping a small CW (currently 8 slots) may be based on the traditional end-to-end perspective, that means, to strictly limit the end-to-end delay (latency) of CAMs to a maximum of 100 ms, as postulated in [43]. Sure, increasing the CW will increase the latency as well. But the question is: *Does increasing the CW violate the latency requirements?*

Therefore, the latency behavior is analyzed first with respect to increasing the CW, as proposed by step 1 of the presented geo-backoff concept. Figure 4.5 shows the latency distribution within the close vicinity (up to 100 m) for various CW sizes (powers of 2). Even for the latency, the CCDF representation is used, because of the advantages summarized in Appendix A. Hence, the graph simply provides the probability (y-axis) of exceeding a

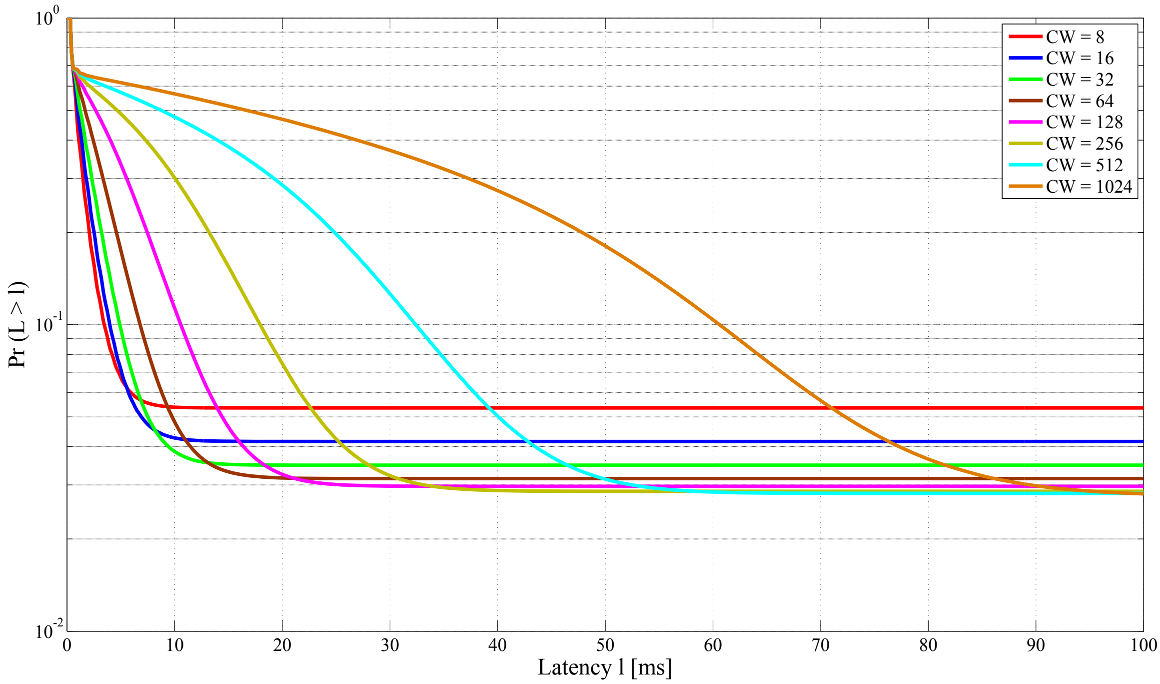


Figure 4.5: Latency CCDF for different CW sizes, measured only within the close vicinity (up to 100 m).

given latency value (x-axis). As expected, the figure clearly shows the increasing latency with increased CW size. However, it also reveals that the different curves are converging towards a certain probability value. Because failed CAM receptions are considered to have an infinite latency within the simulation, this value corresponds to the probability of not receiving a CAM at all (1 − reception probability). Obviously, increasing the CW size lowers the complementary reception probability, and thus, increases the reception probability. However, the improvement of the reception probability is getting less significant with increased CW size. The reason is that the larger the CW, the more idle slots are required, in order to decrement the backoff counter. More idle times on the wireless channel lower the effective throughput. For CWs of 256 and more, for instance, the complementary reception probabilities have almost converged to the same value. Although the latency by using a CW size of 1024 is still below the requirement of 100 ms (cf. [43]), this could be an indication for selecting an "optimal" CW size, regarding latency and reception probability.

The latency has been also measured within the entire transmission range. However, the CCDF behavior is similar to the close range case, except that the complementary reception probabilities have been increased. Because the curves do not provide any new findings, they are not shown here.

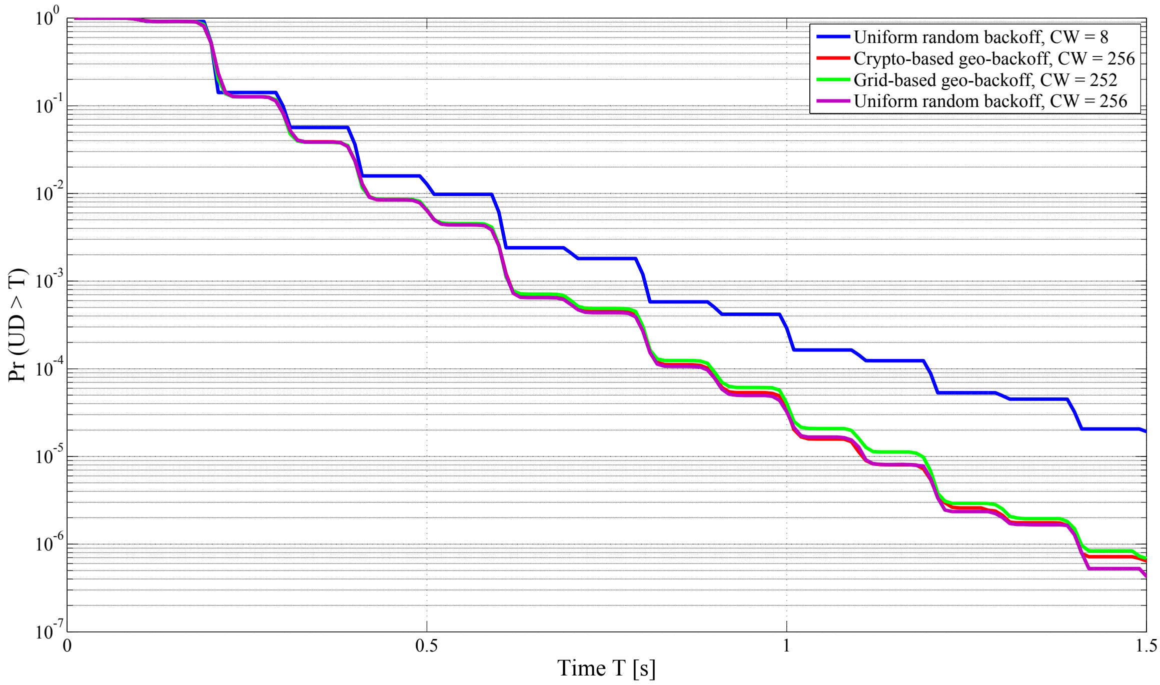


Figure 4.6: Comparison of the time-based update delay performance within the close vicinity only (up to 100 m).

Assuming the CW size is only increased within certain limits, then, the answer to the previous question is: *Increasing the CW size is fully in line with the latency requirements for CAM-based safety applications!*

Update Delay

As the focus of this thesis is on the CAM dissemination performance, the update delay (RX-centric perspective) in units of time is of much more interest as explained in Section 2.2. Figure 4.6 compares the time-based update delay performance of the default backoff mechanism (CW = 8) with the proposed geo-backoff implementations, within a range of 100 m. In order to differentiate the improvements coming from the CW increase (step 1) and the improvements coming from the position-based backoff generation (step 2), the default backoff mechanism (uniform random) with similar CW size used for the geo-backoff approaches is shown as well. Because the size of the CW for the grid-based approach depends on the grid-layout, and by association on the street-layout, the next possible CW size, starting from 256 downwards, is applied, resulting in 252.

Similar to the latency plot, the various update delay CCDF curves provide the probabil-

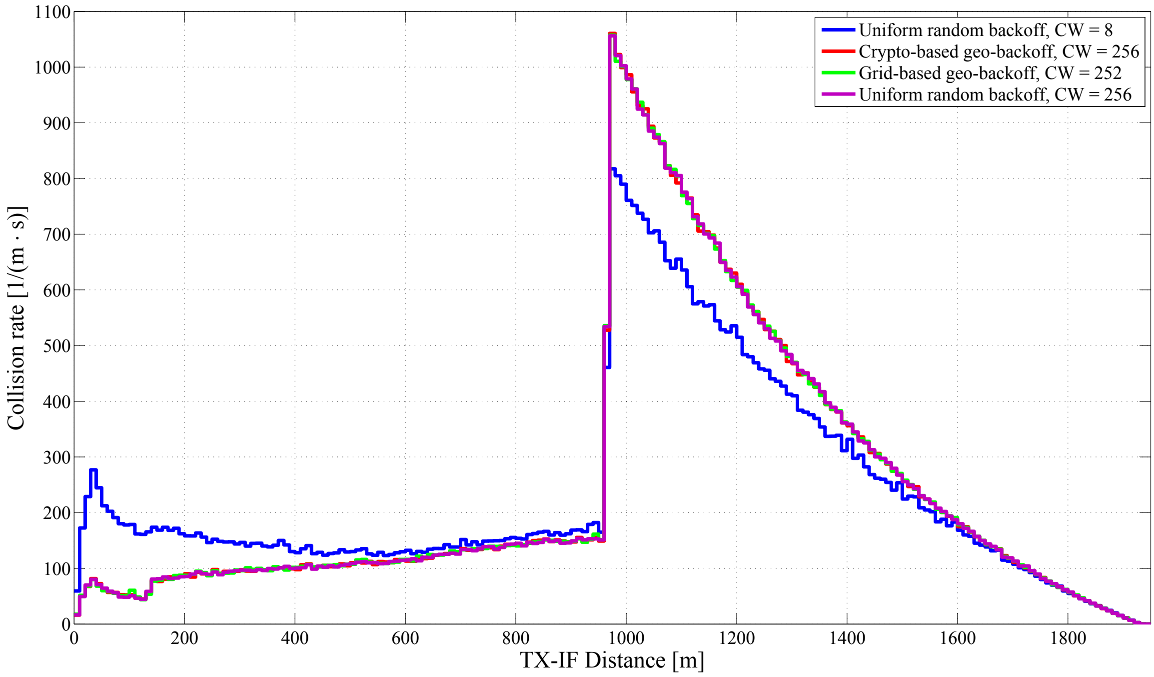


Figure 4.7: Total normalized collision rate for all considered approaches, plotted against the TX-IF distance.

ity (y-axis) of exceeding a given time frame T (x-axis). To provide a better understanding of how to interpret the update delay CCDF figures, a cooperative safety application is assumed, which requires to receive the next CAM update from other vehicles within the critical range after 1 s latest, with a probability of 0.9999. That means, the probability of exceeding an update delay of 1 s should be less than 10^{-4}. This can be easily checked by evaluating the corresponding update delay CCDF curve. Considering Figure 4.6, it can be observed that all approaches with increased CW size are able to fulfill this example requirement, except the default mechanism. But even more interesting is the fact that the default mechanism with increased CW performs just as well as the geo-backoff approaches. This observation suggests that the improvement is not a result of the geo-based backoff generation, but of the increased CW. Hence, a closer look on the collisions may provide a better understanding.

Packet Collisions

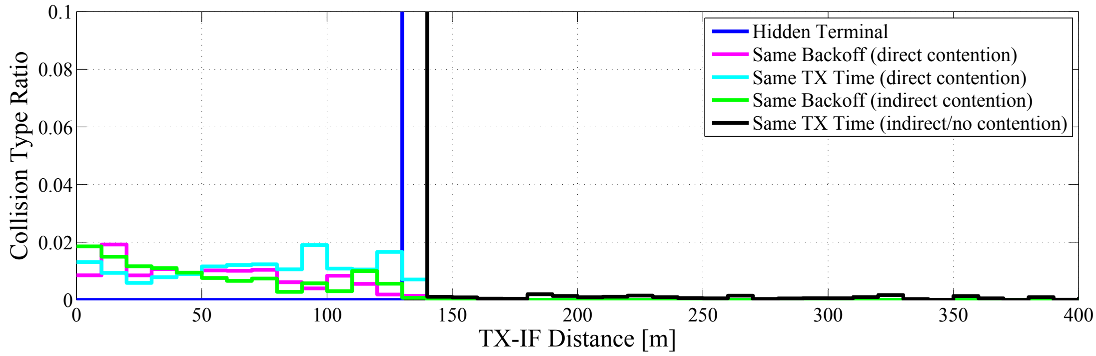
Figure 4.7 compares the total collision rate, as a function of the distance between the actual transmitter (TX) and the interferer (IF), for the different approaches with each other. The first observation from that figure is that compared to the default mechanism all approaches with increased CW show a significant reduction of the number of collisions within the transmission range. Especially at very close distance (≈ 40 m), the collision rate has been reduced by approximately 71 %. This may explain the improved update delay performance within close vicinity (cf. Figure 4.6).

The second observation is that beyond the transmission range (≈ 970 m) the behavior is the other way around. Thus, the approaches with increased CW now show a slightly higher number of packet collisions than the default one. In principle, this behavior corresponds to the desired behavior illustrated in Figure 4.1, that means, shifting packet collisions from near to far.

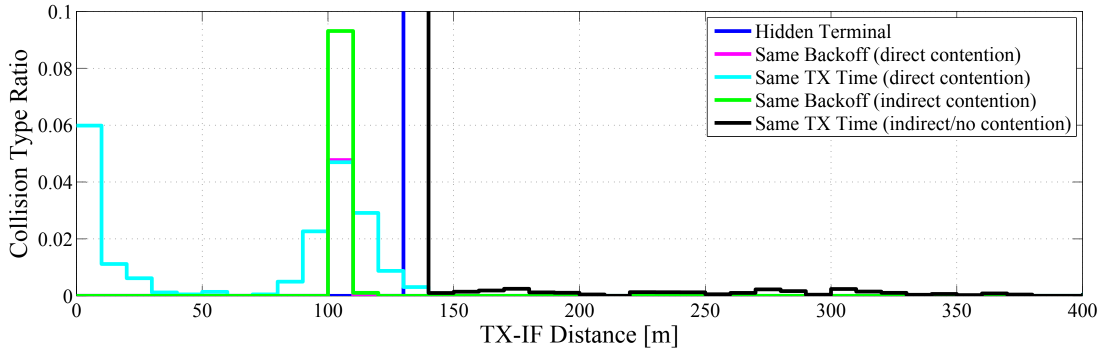
But again, the most interesting observation is that the crypto- and the grid-based geo-backoff approaches do not show any improvement compared to the default backoff mechanism with similar CW size.

A more detailed view is given by Figure 4.8, showing the collision type ratio, as a function of the distance between TX and IF for the crypto-based geo-backoff, the grid-based geo-backoff, and the default mechanism with increased CW. Whereas the crypto-based geo-backoff mechanism was able to reduce the *same backoff* collisions in the close vicinity from approximately 45 % (cf. Figure 3.3) to approximately 3-4 % (see Figure 4.8a), the grid-based geo-backoff approach was able to reduce them completely, up to a range of approximately 100 m (see Figure 4.8b). The peak afterwards demonstrates the recurrence behavior of grid cells, due to a limited CW size. Then, vehicles at a certain distance (approx. 100 m in that case) will choose the same backoff counter for sure, if both are in contention with each other. Considering the default uniform random mechanism with increased CW it can be observed that it is able to reduce the *same backoff* collisions just as well as the crypto-based geo-backoff approach. Apparently, the implemented version of the crypto-based geo-backoff function is not able to provide the desired backoff counter distribution, regarding the near-far behavior.

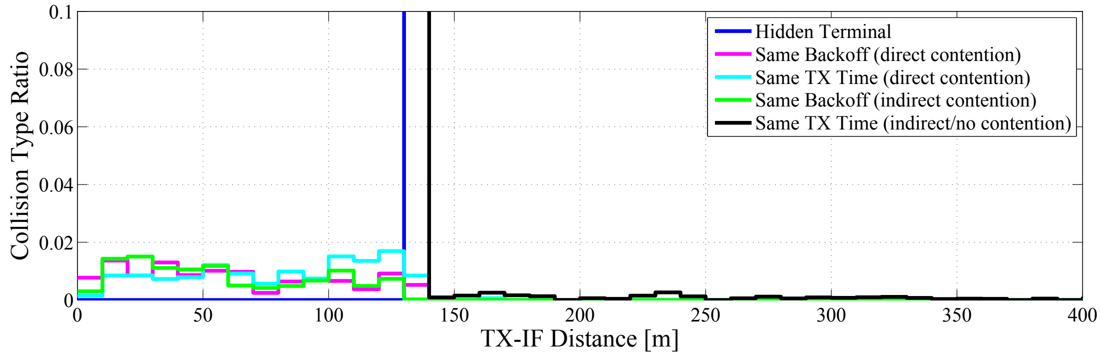
This observation explains the similar behavior with respect to the update delay performance and amount of collisions. Taking also the grid-based geo-backoff approach into account, obviously a further reduction of the remaining 3-4 % of *same backoff* collisions is not significant enough, to show up in an additional improvement of the update delay performance (cf. Figure 4.6).



(a) Crypto-based geo-backoff based on a CW size of 256.



(b) Grid-based geo-backoff based on a CW size of 252.



(c) Uniform random backoff generation (default) based on a CW size of 256.

Figure 4.8: Comparison of the collision type ratio between the different backoff generation approaches, plotted against the TX-IF distance.

4.1.4 Discussion

The broadcast policy for CAM transmissions implicitly deactivates the collision avoidance mechanism of exponentially increasing the CW. Hence, the initial CW will never increase. The initial CW for CAM transmissions, however, only consists of 8 slots. Considering a highly dense traffic scenario on a multi-lane highway, vehicles are expected to contend with more than 7 neighbors for channel access, which is a recipe for packet collisions, especially at close ranges (contention area).

Addressing exactly this issue is the objective of the geo-backoff concept. It aims at improving the backoff counter selection in case of contention by exploiting the vehicle's position information. This idea, however, implicitly requires to increase the CW as well, because packet collisions cannot be effectively mitigated as long as the number of available backoff counters is too small compared with the number of contending vehicles, even if the geographic information is used to select the backoff counter.

Increasing the CW obviously increases the latency of CAMs. If the latency is too long, the information contained in CAMs might be already outdated, albeit the CAM has just been received. This latency impact is not sufficiently considered by the update delay, and even less by the PDR. Thus, the latency behavior with an increasing CW has been analyzed first. The simulation results have shown that if the CW is increased properly, latency is not an issue according to the requirements claimed in [43]. Further results have indeed shown that the update delay performance could be improved by using geo-backoff. However, considering the results of the crypto-based geo-backoff, apparently the proposed implementation is not able to transfer the property of cryptographic hash-functions to the backoff generation. It rather shows a similar behavior as the default approach with the same CW size. But even if the grid-based approach is taken into account, obviously it is not worth trying to further mitigate the remaining *same backoff* collisions by exploiting geographic information. This conclusion may be drawn, as all the results indicate that the improvements are solely dominated by the first step only, that means, by just increasing the CW. These findings are not necessarily disappointing. Simply increasing the CW might be the most attractive solution here, as it is simple and fully compliant with the current ITS-G5 technology (no hardware or software modifications necessary).

Although the concept of adapting the CW in VANETs is state-of-the-art, this section provides an evaluation from an RX-centric perspective by analyzing the update delay as well, which is more suitable to investigate the performance of CAM dissemination, while most of the related publications (e.g. [22, 99, 124]) have only focused on traditional network metrics like reception probability or throughput. Reinders *et al.* [101] have also analyzed the inter-reception time (update delay), but in contrast to the results presented here, and in contradiction to the conclusions of other related publications [22, 99, 124], their outcome was that increasing the CW does not improve the beaconing performance in vehicular networks. The reason for that might be their use of a too simplified communications scenario (e.g. no path loss, closed network, short transmission range).

4.2 Random Transmit Jitter

Correlated packet collisions may significantly increase the update delay, and by implication degrade the quality of the (position) awareness. Whereas current solutions to that problem either increase the load on the channel, e.g. [140], or require significant modifications of current VANET transceivers, e.g. [112, 29], in this thesis a new transmit policy at higher layers is presented [71]. Specifically, the proposal is to add a random transmit jitter to the periodic CAM broadcast interval for each transmission (not only at boot up), in order to make correlated collisions more uncorrelated in time. As the jitter is added at higher layers, full compatibility with current VANET communications technology is maintained.

4.2.1 Concept

The basic principle is illustrated in Figure 4.9, by means of a space-time schematic. Assuming the same spatial situation as in Figure 2.5, vehicle TX and IF, now, add a controlled random transmit jitter to their periodic broadcast interval, resulting in randomized CAM transmissions over time (see subsequent bell-shaped curves). Please note that the Gaussian PDF in Figure 4.9 is just for illustrating the randomness of the added transmit jitter. In principle, any PDF can be used, which complies with the corresponding requirements (e.g. maximum update delay). However, for the implementation here a uniform PDF is preferred. The reason for that is twofold: First, the uniform PDF is clearly limited by its interval bounds, which in turn clearly limit the delay spread around the nominal broadcast interval. Second, the uniform PDF provides the maximum randomness (entropy) among all distributions, which support the same interval [33].

The purpose of adding a random transmit jitter is to avoid recurring simultaneous transmissions, and by implication, temporal correlated packet collisions. Without loss of generality, the random jitter is modeled by the random variable J with zero mean, and its PDF is denoted as $f_J(j)$, uniformly distributed. Furthermore, the nominal transmit

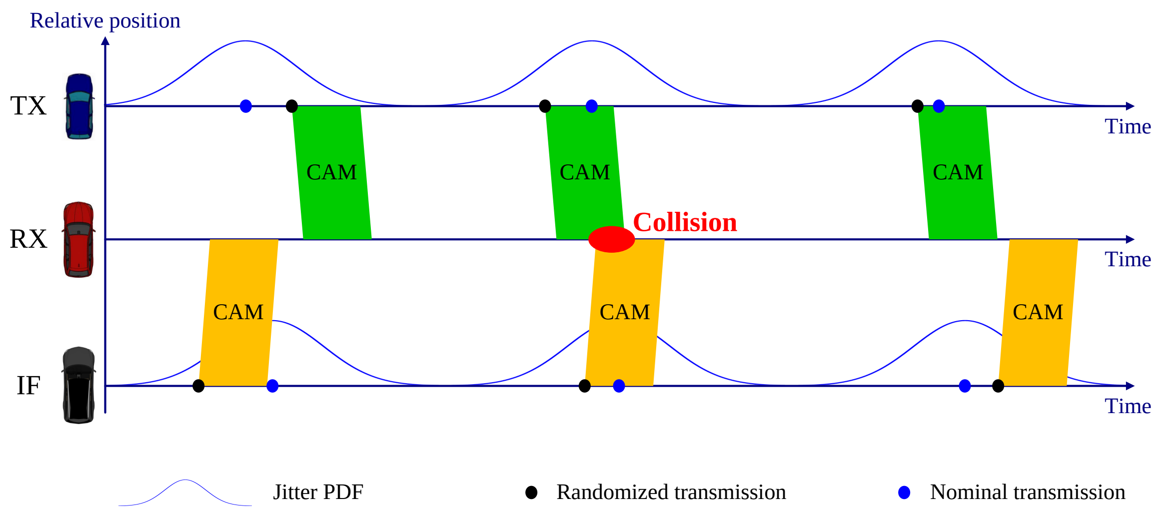


Figure 4.9: Space-time schematic of three vehicles TX, RX and IF: A random transmit jitter is indeed not able to avoid simultaneous transmissions completely, but it mitigates recurring ones at the same receiver RX.

times for the next CAM transmission of vehicle TX and vehicle IF are denoted as t_{TX} and t_{IF}, respectively. Then, the randomized transmissions for the next CAM of vehicle TX and vehicle IF can be modeled by the random variables $X = J + t_{\mathrm{TX}}$ and $Y = J + t_{\mathrm{IF}}$, respectively, and the corresponding PDFs are shifted versions of $f_J(j)$:

$$\begin{aligned} f_X(x) &= f_J(x - t_{\mathrm{TX}}) \\ f_Y(y) &= f_J(y - t_{\mathrm{IF}}) \end{aligned} \tag{4.1}$$

The probability of having a simultaneous transmission (i.e. at least partially overlapping packets), is the probability that vehicle TX transmits at time X and vehicle IF transmits at time Y, with $Y \in [X - l; X + l]$, and l denoting the packet duration:

$$\begin{aligned} &\mathbf{Pr}(\text{packet overlap}) = \mathbf{Pr}(X - l < Y < X + l) \\ &= \int_{-\infty}^{\infty} \int_{x-l}^{x+l} f_{X,Y}(x, y)\,\mathrm{d}y\,\mathrm{d}x \\ &\overset{(*)}{=} \int_{-\infty}^{\infty} \int_{x-l}^{x+l} f_X(x) \cdot f_Y(y)\,\mathrm{d}y\,\mathrm{d}x \end{aligned}$$

$$\stackrel{(4.1)}{=} \int_{-\infty}^{\infty} f_J(x - t_{\text{TX}}) \cdot \int_{x-l}^{x+l} f_J(y - t_{\text{IF}}) \, \mathrm{d}y \, \mathrm{d}x \tag{4.2}$$

The multiplication at $(*)$ is valid, as both vehicles choose their random jitter independently from each other.

It should be noted that the size of the random interval for the artificial jitter plays an important role. Assuming $t_{\text{TX}} = t_{\text{IF}}$ and the interval size is smaller than the packet duration itself, then the transmitted packets will always overlap, at least partially. Thus, it is necessary to choose a sufficiently large interval size, e.g. multiples of the packet duration, in order to significantly reduce the probability of overlapping packet transmissions.

Please note as well that the natural jitter of the clocks in vehicular communications systems is not sufficient to mitigate an overlap of subsequent CAM transmissions, as it is far below the packet duration (e.g.: $l \approx 0.5$ ms for 300 Byte CAM payload transmitted at 6 Mbps), especially if synchronized with GPS or Galileo. Although the larger the interval size, the lower the probability of recurring packet collisions, the interval size should be strictly limited in practice. On the one hand, the delay between consecutive packet transmissions should be limited, as it directly affects the update delay. On the other hand, an overlap of consecutive broadcast intervals should be avoided.

How the probability of a recurring packet overlap depends on the random jitter interval, is illustrated in Figure 4.10. Based on the assumption that $t_{\text{TX}} = t_{\text{IF}}$, it shows the $\mathbf{Pr}$(packet overlap) plotted against t_i, which defines the entire random jitter interval $[-t_i, +t_i]$. Two different random jitter distributions are considered. Whereas the interval of the uniform distribution is clearly defined, the normal distribution has no strict bounds. Therefore, the interval for the normal distribution has been approximated by $[-3\sigma \text{ ms}, +3\sigma \text{ ms}]$, which represents the 99.7 % confidence interval. As expected, the uniform distribution provides a lower probability of a recurring packet overlap. However, with an increasing interval size, the difference is getting less significant.

A similar plot is presented in Figure 4.11. Instead of the interval size, the probability of a packet overlap $\mathbf{Pr}$(packet overlap) is plotted against the packet duration l. Therefor, the random jitter interval has been fixed to $[-50 \text{ ms}, +50 \text{ ms}]$. The interval size of the normal distribution has been approximated just as previously described. Here again, the uniform distribution provides lower probabilities of a recurring packet overlap. However, the behavior is different now, as the difference between both distributions is increasing with increasing l. This is not surprising, as an increasing packet duration lowers the remaining

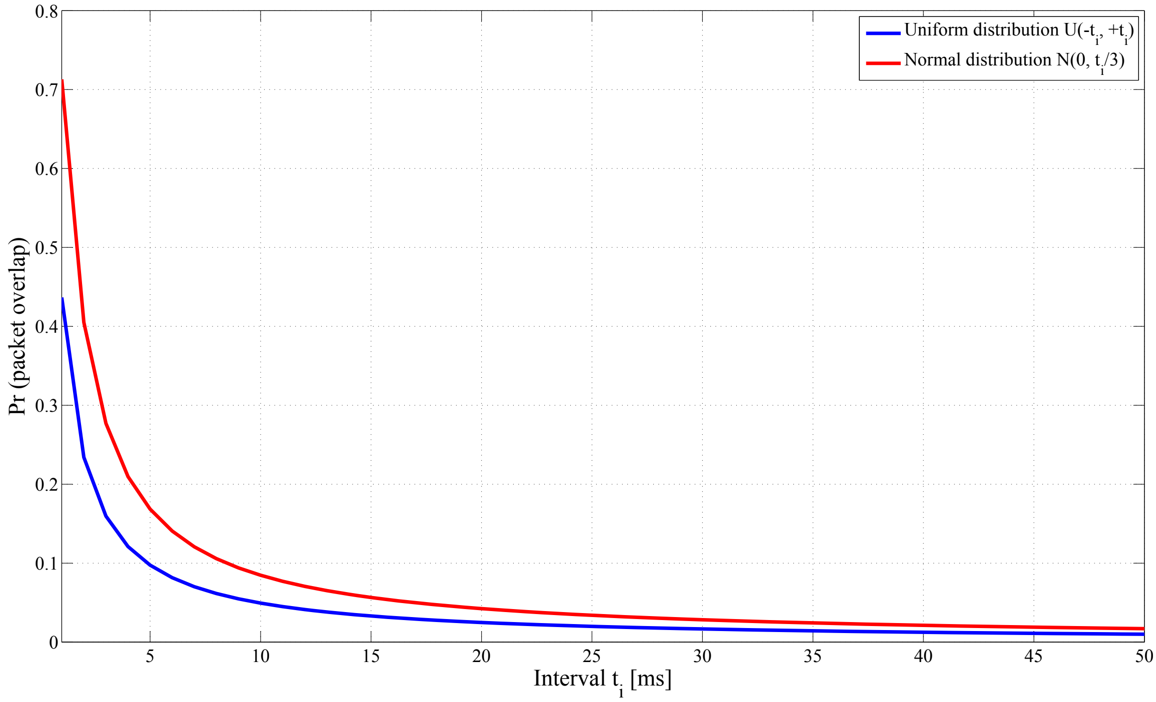


Figure 4.10: Probability of a recurring packet overlap, dependent on the random jitter interval $[-t_i, +t_i]$: Uniform random jitter vs. normal random jitter.

time interval for a second non-overlapping transmission within the common entire interval.

It should be noted that the last two figures just present the recurring packet overlap probability for a simplified scenario with only two transmitters. The objective was to demonstrate the pure impact on the recurring packet overlap probability of two important parameters, the interval size and the packet duration. The impact of a random transmit jitter with respect to a more realistic scenario is discussed in the next subsection.

An important benefit of the random transmit jitter concept is that it is fully compatible with the current ITS-G5 access technology. As the random transmit jitter is added at higher layers, no modification of the access layer is required, neither hardware nor software. Furthermore, the presented concept can be integrated with most of the existing congestion and awareness control strategies, like ETSI's DCC.

Another important property of the random transmit jitter approach is that it is able to keep fairness with respect to the current transmit rate between neighboring vehicles. As long as the added jitter is based on random variables with the same mean, the transmissions are scheduled on average with the original broadcast interval.

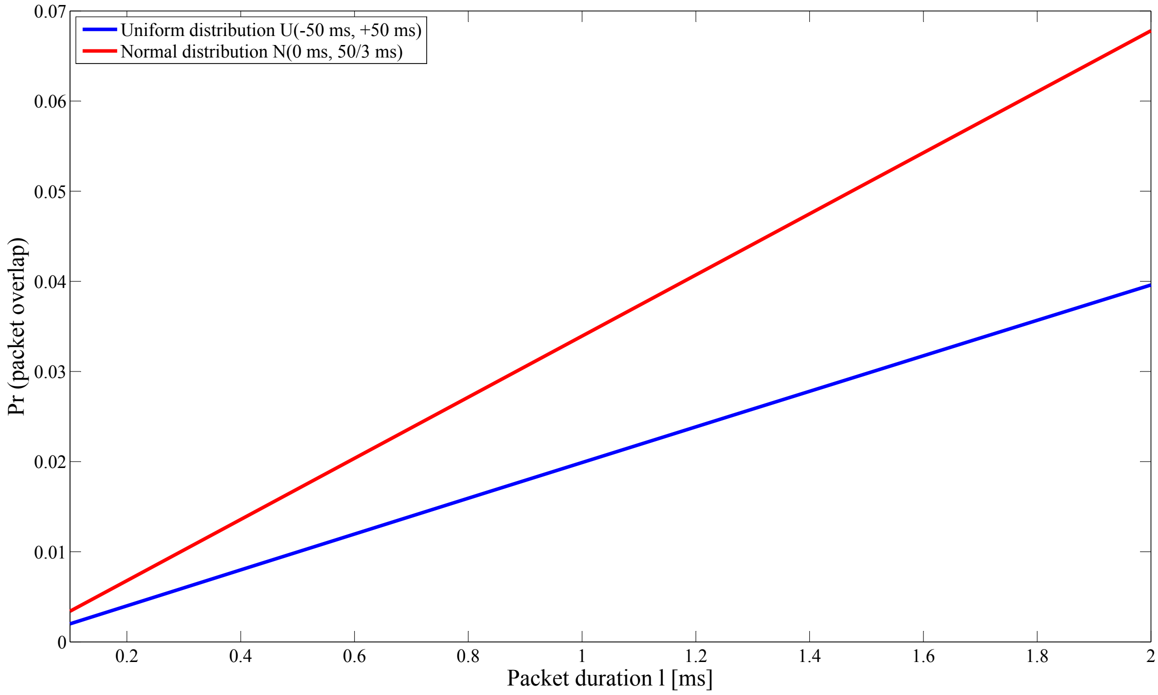


Figure 4.11: Probability of a recurring packet overlap, dependent on the packet duration: Uniform random jitter vs. normal random jitter.

4.2.2 Evaluation by Simulation

The random transmit jitter concept has been evaluated by simulations, based on the framework described in Appendix A. In addition, low, medium, and high channel load conditions are simulated as well. To keep the CAM generation policy fixed, the number of lanes on the highway has been varied between 2, 4, and 6, resulting in 29 %, 50 % and 66 % of channel load (CBT ratio), respectively. The most important simulation parameters are summarized in Table 4.2.

Due to the additional CAM trigger conditions [11], the basic concept introduced above has to be slightly modified. If the jitter is added to the basic broadcast interval only, it will be useless, in case a change in position, speed or heading would trigger the CAM before the nominal broadcast interval has expired. Thus, the implementation within this work adds the random jitter to the interval, which periodically checks the corresponding conditions. As this checking interval is set to 100 ms (to limit the maximum transmit rate to 10 Hz), the jitter has been specified to be uniformly distributed between $[-50\text{ ms};\ +50\text{ ms}]$, in order to minimize the probability of recurring simultaneous transmissions, while an overlap of subsequent transmission intervals is avoided.

Traffic scenario	10-km highway
Lanes per direction Resulting CBT ratio	2, 4 and 6 29 %, 50 % and 66 %, respectively
Evaluation section	5 km (from 2.5 – 7.5 km)
Vehicle generation process	Erlang distributed ($\mu = 2.25$ s)
Speed profile	From 20 to 40 m/s (4 m/s increase from outer to inner lane)
Access technology	ITS-G5 on Control Channel
Radio propagation model	Log-distance (exponent 2.35)
TX power profile	constant at 33 dBm
CAM generation policy	1 Hz + trigger conditions
CAM packet duration	≈ 0.5 ms
Random transmit jitter	$\mathcal{U}(-50 \text{ ms}, +50 \text{ ms})$
Metrics	normalized collision rate, packet collision ratio, update delay

Table 4.2: Simulation parameters for the random transmit jitter investigations.

Correlated Packet Collisions

The recurrence behavior of packet collisions, without and with adding a random transmit jitter, is presented in Figure 4.12. The six curves represent the recurring packet collision rate (normalized in time and space) for three different traffic/channel load scenarios, each with and without the corresponding random transmit jitter. Due to the huge difference of the value ranges for the low and the high channel load scenario (approx. factor 30), the y-axis is log scaled. The most significant reduction of correlated packet collisions can be observed for the low channel load scenario with 29 % CBT ratio. By adding an artificial random jitter, the total number of recurring packet collisions at short distances (up to 100 m) can be reduced by more than a factor of 10. But if the channel load is increased, obviously the improvement is getting less significant. In the high channel load scenario with 66 % CBT ratio, for instance, only up to a distance of 500 m a reduction of the amount of recurring collisions is observable.

An explanation for this behavior is based on the MAC technology of ITS-G5: As the contention (backoff) procedures tend to serialize simultaneous transmission attempts in a decentralized way, a previously added random transmit jitter at higher layer might be absorbed again on the MAC layer, as well as its beneficial impact. As long as the load on the channel is low, the contention on the MAC layer is low, too. Consequently, most

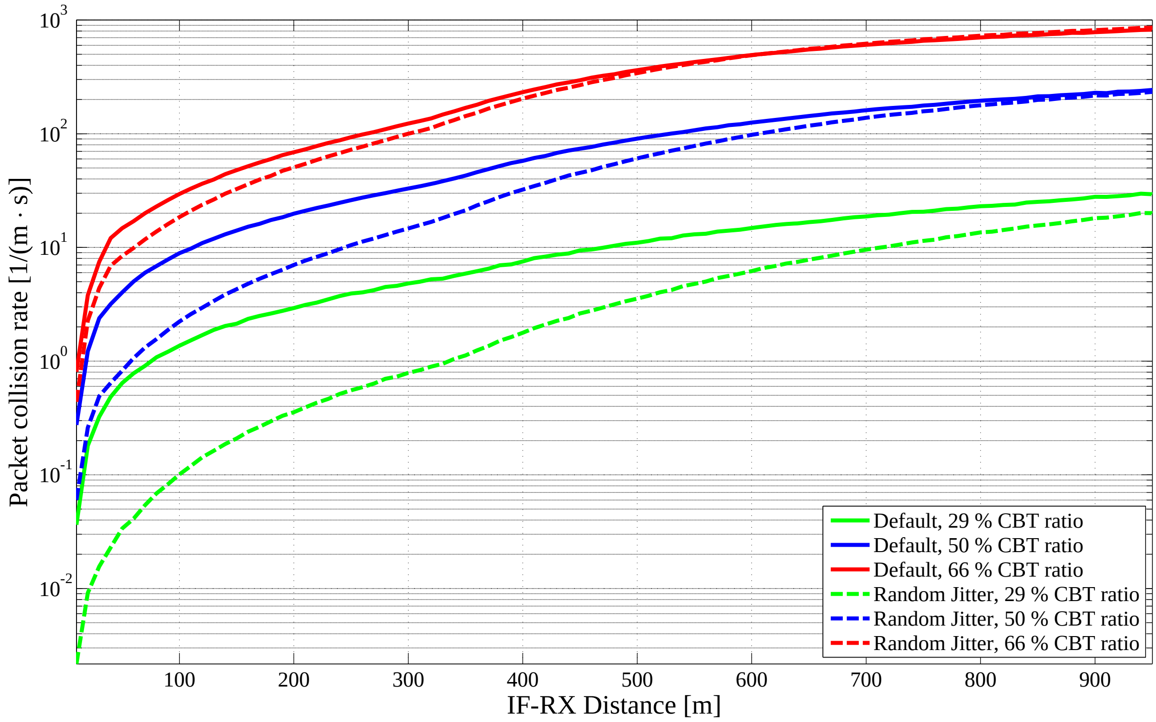


Figure 4.12: Comparison of the recurring packet collision rate (normalized in time and space) for low (29 % CBT ratio), medium (50 % CBT ratio), and high (66 % CBT ratio) channel load conditions.

of the added random jitter remain up to the time of physical transmission. But if the channel load is increased, a growing number of previously added random jitters are going to be absorbed by the increasing queuing and serialization procedures caused by MAC contention.

More details on the bursty behavior of correlated packet collisions are presented in Figure 4.13. It compares the update delay CCDFs, measured in units of packets, between the default approach, and the random transmit jitter within the entire transmission range (≈ 970 m). Furthermore, the corresponding geometric distribution is plotted as well, just to get an indication of how a perfectly decorrelated packet collision behavior might look like[1]. All the curves just described, are shown for the three different channel load conditions. Like previous CCDF plots, the current one provides the probability (y-axis) of exceeding a certain delay n in packets (x-axis). Considering the preceding figures, it is not surprising that the decorrelation effect by adding a random transmit jitter is most

[1]Please note that the geometric distribution assumes perfect independence between consecutive packet receptions.

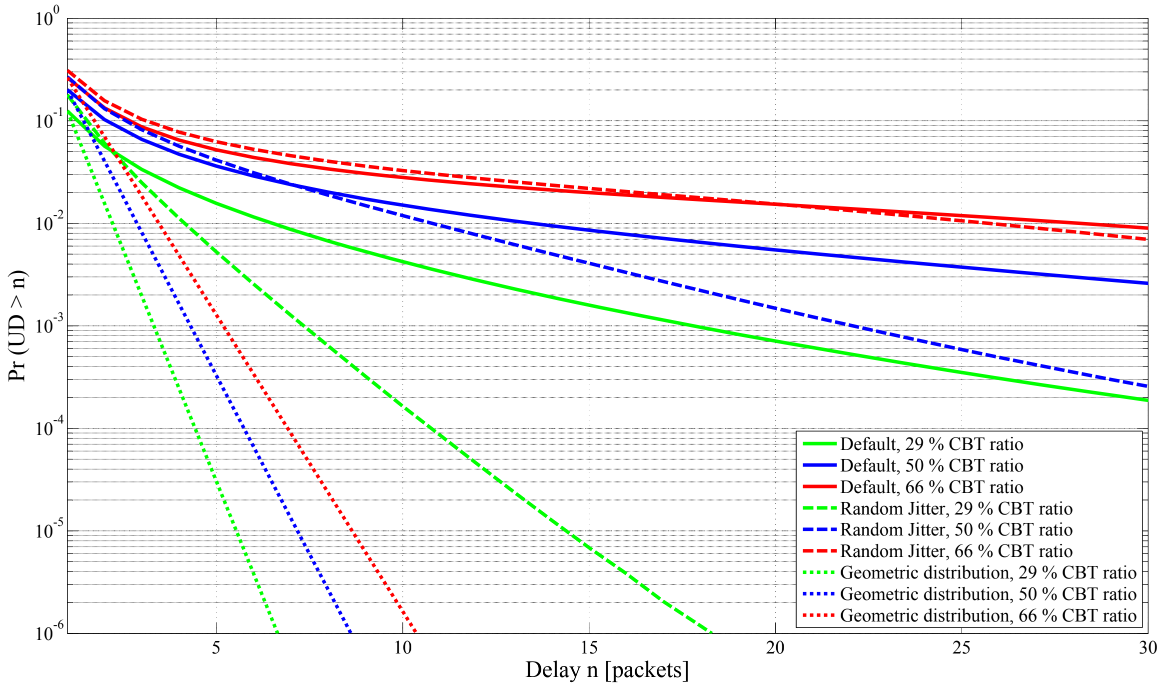


Figure 4.13: Comparison of the packet-based update delay, measured within the entire transmission range, for low, medium and high channel load conditions: Default approach, i.e. periodic + trigger conditions vs. random transmit jitter vs. geometric distribution (lower bound according to correlation behavior).

significant for the lowest channel load scenario. Another interesting observation is that for small n the random jitter approach always seems to be a bit worse than the default one, but shows a better performance with increasing n. Basically, this behavior confirms the capability of the random transmit jitter concept to make correlated packet collisions more uncorrelated in time, which is reflected by the update delay statistics: While the total amount of packet collisions approximately remained the same, the amount of longer update delay measures (high temporal correlation) has been reduced, and the amount of low update delay measures (low temporal correlation) has been increased.

Figure 4.14 shows the same update delay CCDF representations, but for close ranges only (up to 100 m). An interesting observation here is that the random jitter approach is able to get quite close to the geometric distribution. Apparently, the random jitter is able to decorrelate packet collisions within close ranges quite well.

It should be noted that the packet-based update delay representation is only used to get an insight into the correlation behavior of consecutive packet collisions. It is not suitable to analyze the communications performance, as it heavily depends on the CAM generation

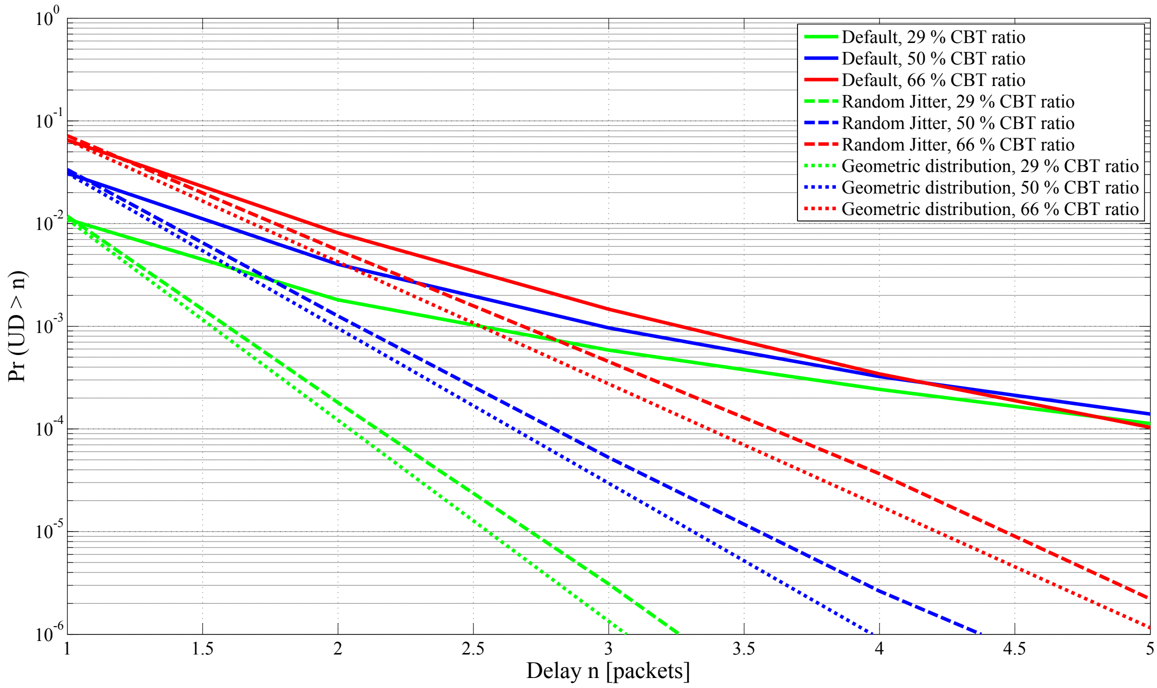


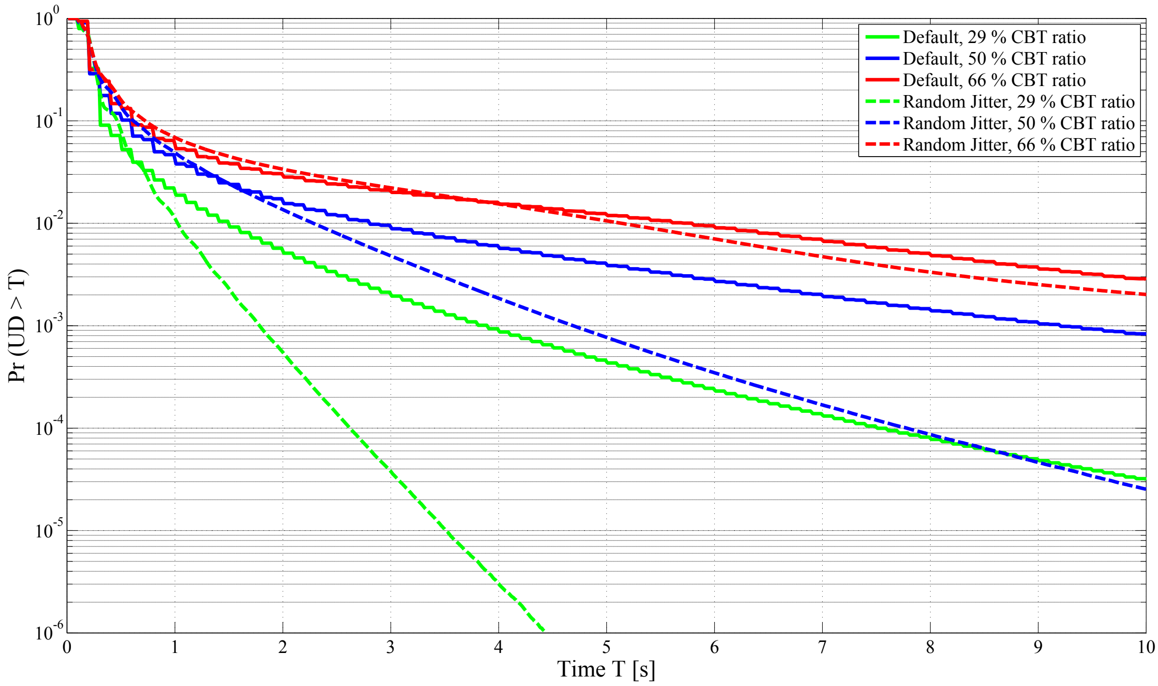
Figure 4.14: Comparison of the update delay, measured within close range only (up to 100 m), for low, medium and high channel load conditions: Default approach (i.e. periodic + trigger conditions) vs. random transmit jitter vs. geometric distribution (lower bound according to correlation behavior).

policy, which may vary between vehicles due to the additional trigger conditions.

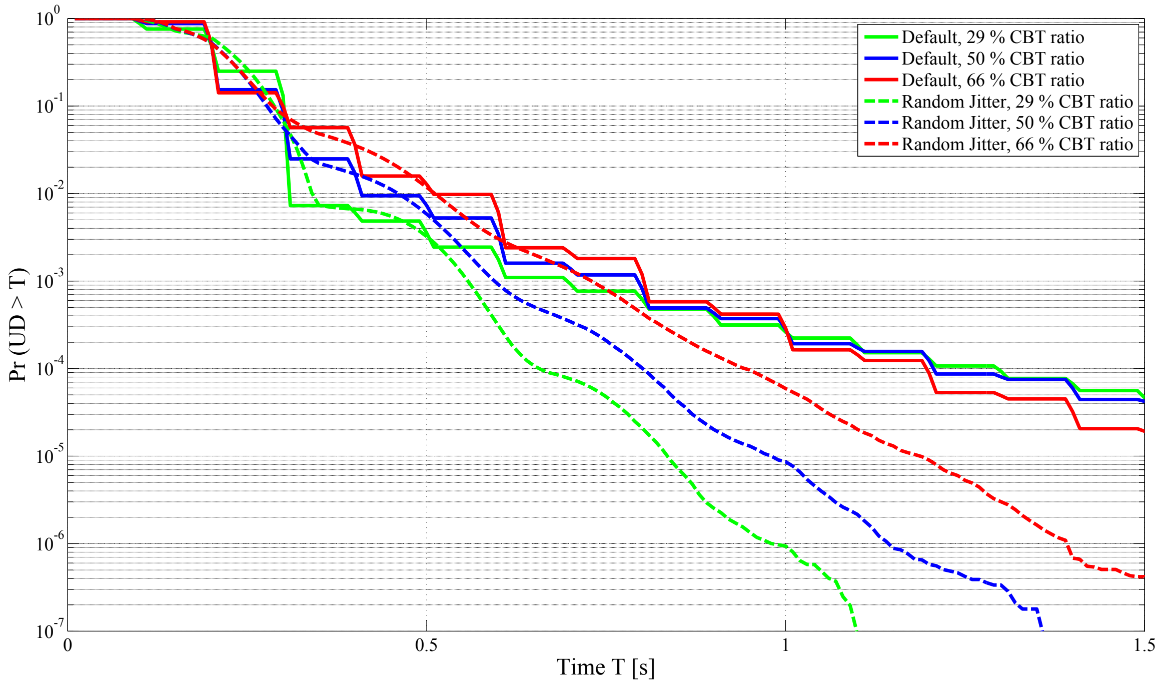
Communications Performance

To analyze the CAM communications performance with respect to the awareness quality, a better approach is to measure the update delay in units of seconds. Therefore, Figure 4.15 compares the different time-based update delay CCDFs between the default scheme and the random transmit jitter approach. The interpretation is similar to the previous ones. In this case, the update delay CCDF plot provides the probability (y-axis) of exceeding a given time frame T (x-axis).

In Figure 4.15a, the update delay has been measured within the entire transmission range. If applied to a concrete example, the CCDF plot provides a probability of $9 \cdot 10^{-4}$ that a vehicle remains undetected within a time frame of $T = 4$ s (corresponds to a traveled distance of 320 m at a maximum relative speed of 80 m/s), in case of the low channel load scenario (29 % CBT ratio) and without random jitter. By adding a random transmit jitter this probability is reduced to approximately $3 \cdot 10^{-6}$, which corresponds to an improvement



(a) Update delay within the entire transmission range.



(b) Update delay within 100 m only.

Figure 4.15: Comparison of the time-based update delay performance, between the default approach and the random transmit jitter concept.

by approximately a factor of 300. For the medium channel load conditions (50 % CBT ratio) the improvement has been reduced significantly, but still provides approximately a factor of 3. For the high channel load scenario (66 % CBT ratio), there is no improvement regarding an update delay value of 4 s. The reason for the reduced improvement with increasing load has been already explained during the discussion of the packet-based update delay. For very small T the default approach provides a slightly better performance than the random jitter concept. However, if increased, the random jitter outperforms the default one. With increasing channel load, the breakpoint is shifted to higher T, as the benefit of decorrelation is reduced. Referring to the high channel load scenario again, the breakpoint is approximately at $T = 4$ s, with the consequence being that the random jitter concept is not able to show a better performance than the default one according to the 4 s requirement.

Especially in the context of vehicular safety, closer ranges (e.g. up to 100 m), and less time delays (up to 1 s) are much more relevant, as only nearby vehicles may pose an imminent danger, regarding physical collisions between vehicles. Thus, Figure 4.15b compares the different update delay CCDFs within a range of 100 m only. Now, one might be interested in the probability that a nearby vehicle remains without any CAM update within a time frame of 1 s. Then, the value of 1 s on the x-axis delivers the corresponding probability value on the y-axis. Similar to the previous case, the lower the channel load, the more significant is the improvement. For the low channel load scenario (29 % CBT ratio), for instance, the default approach provides a probability of approximately $3 \cdot 10^{-4}$ compared to less than 10^{-6} by adding an artificial random jitter. This corresponds to an improvement by more than a factor of 300. Also considering the higher channel load scenarios, the random jitter approach still provides an improvement by approximately a factor of 30 in the case of 50 % CBT ratio, and by a factor of 5 in the case of 66 % CBT ratio.

Please note that the aforementioned update delay evaluation is just an example, in order to make the comparison between the two approaches less abstract. Although a maximum allowed time frame of 1 s has been assumed here, its specification may vary from application to application. The evaluation of a more concrete cooperative safety application example is discussed in Chapter 5.

4.2.3 Discussion

Temporal correlated packet collisions significantly lower the reliability of ITS-G5-based cooperative safety applications. Whereas previous studies [88] have focused on correlated packet collisions on the PHY layer, caused by persistent channel link conditions, in this work, the MAC-related correlated packet collisions have been investigated. They are caused by the *quasi-periodic transmission policy* in combination with *quasi-static relative mobility* between neighboring vehicles. While randomized time-related repetition schemes, e.g. [140], address correlated packet collisions at the cost of an increased channel load, non IEEE 802.11 alternatives, e.g. [29], usually require modified or even new transceiver technologies.

In this section, a new concept has been introduced that is fully compliant with the current ITS-G5 access technology and does not come at the cost of an increased channel load. Instead, the basic objective is to directly address the quasi-periodic transmission pattern, which is one of the two reasons for MAC-related correlated packet collisions. Whereas parts of the research community aim at adapting the communications technology to the periodic communication pattern (e.g. STDMA), the proposed random transmit jitter concept does the reverse, that means, it adapts the communication pattern to the communications technology. Specifically, it aims at making periodic CAM transmissions less periodic in time. For that purpose a controlled random transmit jitter is added to the nominal broadcast interval, which results in randomized transmission times within a certain period, without any negative impact on the performance of safety applications. On the contrary, due to a less periodic distribution of CAM transmissions in time, the temporal correlated packet collisions even have been mitigated significantly, which in turn has improved the update delay performance, especially in low and medium channel load conditions.

One might think that the concept of adding a random transmit jitter is useless in practice, as real-world effects like different drifts of the clocks are not considered within the simulation. Simulators, instead, are usually based on a single time base, which provides the same accuracy to all entities within the simulation. Two aspects should be discussed here: First, in the presented simulation study an absolute synchronization between the vehicles is avoided, because for each vehicle a random initial start time for the first CAM transmission is introduced. Thus, the observed temporal packet correlations are expected to be caused by the by the quasi-periodic transmission policy in combination with quasi-static relative mobility between neighboring vehicles, and not by simulation artifacts. Second, although different clock drifts between different vehicles are not considered in the simulation, such effects are expected to have a minor impact on the temporal correlation of packet collisions in reality. The reason for this is that not only position information, but also a highly accurate time plays an essential role in vehicular networks, as safety-related messages also have to be labeled with a highly accurate time stamp in order to determine the up-to-dateness of received status information correctly. For that purpose the local clocks are usually synchronized with the time base of the GNSS, which may result in a highly accurate synchronization between real-world vehicles. As the provided time accuracy by GNSS is very much below the packet duration of a CAM (nanoseconds vs. milliseconds), the random transmit jitter concept is expected to become also highly relevant under real-world conditions. As the proof by appropriate real-world measurements is out of the scope of this thesis, it has to be left for future work.

The proposed random transmit jitter concept may also have a positive impact on the privacy issue in VANETs. Although vehicles are compelled to change their pseudonyms after a certain amount of time, two subsequent used pseudonyms might be linked with each other, if the vehicle's periodic transmission times are analyzed. Adding a random jitter, instead, obfuscates the nominal broadcast interval as the transmissions are not pure periodic anymore.

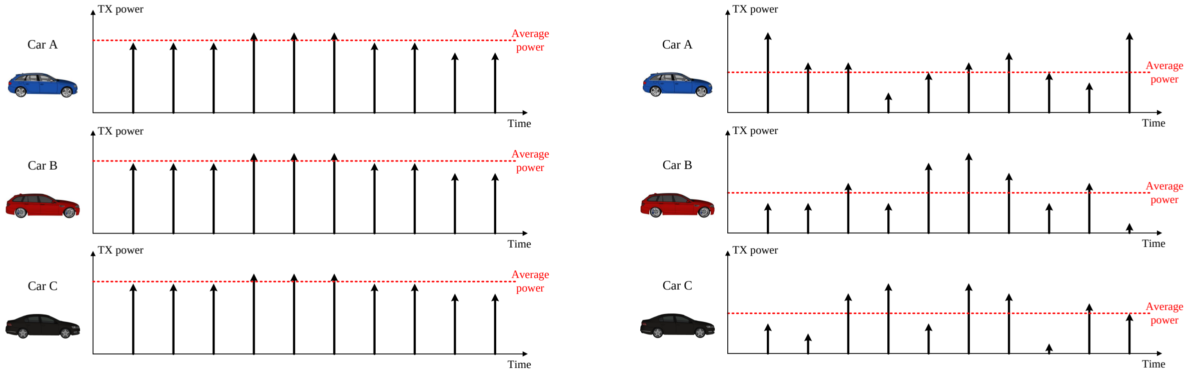
4.3 Random Transmit Power

A complementary proposal to mitigate the problem of correlated packet collisions is the concept of random transmit powers [72]. Like the random transmit jitter concept, this approach maintains full compatibility with current VANET communications technology as well, but instead of decorrelation in time, it decorrelates packet collisions in space.

4.3.1 Concept

The basic principle is illustrated in Figure 4.16, in comparison with current transmission control principles. As explained in Section 2.5, current transmit power control solutions tend to converge to reduced, harmonized, and quasi-constant transmit powers (cf. Figure 4.16a). With the concept of random transmit powers, instead, each vehicle transmits each CAM with a randomly chosen transmit power level (see Figure 4.16b).

Its impact on correlated packet collisions is illustrated in Figure 4.17. It assumes the same platooning scenario as illustrated in Figure 2.5, but instead of time, the focus here is on the location. Whereas with quasi-constant transmit powers the collision and interference areas may remain quasi-constant for consecutive (simultaneous) transmissions (see Figure 4.17a), the application of random transmit powers arrange for shifted collision and interference areas, and by implication make correlated collisions more uncorrelated



(a) Current transmission control mechanisms tend to converge to harmonized quasi-constant transmit powers.

(b) Randomly selected transmit powers for each CAM transmission and vehicle.

Figure 4.16: Current transmit power control strategies in comparison with the concept of random transmit powers.

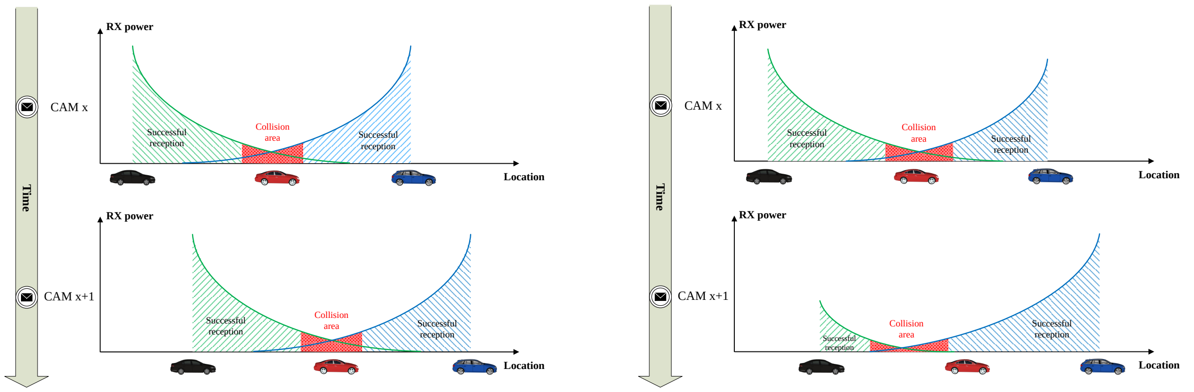
in space (see Figure 4.17b). It should be noted that simultaneous transmissions do not necessarily lead to packet losses within the entire overlapping area. Instead, it usually depends on the local Signal to Interference and Noise Ratio (SINR), which is required to be above a certain threshold, in order to still decode the corresponding packet successfully.

Besides the mitigation of correlated packet collisions, the concept of using random transmit powers reveals other important beneficial effects, too. They include:

- **Congestion reduction:** By using random transmit powers, congestion on the communication channel can be reduced, because vehicles may transmit with less power on average (cf. Figure 4.16b), while keeping the same awareness range. Transmissions with constant full power $P_{\max}$, for instance, are able to achieve the maximum intended communication range with each transmission[2]. A random transmit power profile, based on the set of random transmit powers $\{P_{\min}, ..., P_{\max}\}$, instead, transmits with less power on average, while the maximum communication distance can still be covered, however, with a certain (reduced) probability.

- **Higher transmission efficiency:** By using random transmit powers the number of transmissions to farther vehicles is reduced, where the reception probability drops down due to increasing packet collisions with distance (cf. Figure 3.4). Hence,

[2]That is only valid in theory, i.e. under perfect conditions, because the communication range heavily depends on the current radio propagation conditions.



(a) A packet collision, likely to recur at the same receiver for quasi-constant transmit powers due to the periodic nature of safety broadcasts in combination with slow relative speeds.

(b) Decorrelated collisions in space, due to the variation of the randomly selected TX power for both simultaneously transmitting vehicles.

Figure 4.17: Comparison of (spatial) correlated packet collisions between constant and random transmit power strategies.

the efficiency of CAM transmissions is increased with growing distance, and the contribution to congestion is reduced, where the performance is bad anyway.

- **Spatial transmit rate adaptation:** Dependent on the applied probability distribution, random transmit powers introduce alternating transmission ranges: While high power transmissions are able to cover the nearby and the farther vehicles, low power transmissions can only reach the nearby vehicles. Consequently, random transmit powers implicitly perform a spatial prioritization of vehicles. This effect is illustrated in Figure 4.18, as nearby vehicles are provided with much more CAM updates than farther ones, during the same time interval.

- **Local fairness:** A popular justification in harmonizing transmit powers for all vehicles in the same local vicinity is to guarantee fairness [130], as vehicles transmitting continuously with high power adversely affect vehicles transmitting with less power. Instead of "constant" fairness by using harmonized transmit powers, random transmit powers provide "statistical" fairness, as long as all vehicles apply the same probability distribution, and thus, the same effective transmit power on average. Hence, local fairness may still remain.

- **Controllability:** As long as the random transmit powers are based on a well-defined probability distribution, the randomness can be controlled accordingly. For instance, it can be adapted to the current situation and needs. In addition, future vehicles

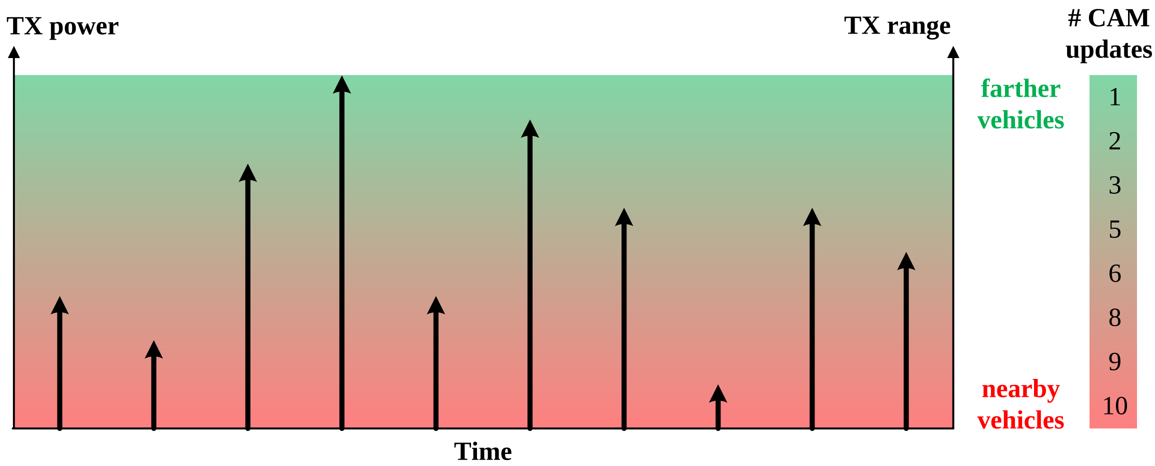


Figure 4.18: Whereas nearby vehicles are covered by low, medium and high transmit powers, farther vehicles are only reached with high powers. Hence, nearby vehicles are provided with much more CAM updates than farther ones, during the same time interval.

will not only run one cooperative safety application, but several in parallel. Each application may specify its own probability distribution, well adapted to meet the corresponding requirements. An appropriate combination (e.g. joint distribution) could control the random transmit power selection for CAM transmissions to meet the requirements of all applications.

- **Compatibility:** By using well-defined probability distributions for the randomization of transmit powers, the concept can be simply integrated with current TPC algorithms, for instance, by adapting the mean or variance of the probability distribution, instead of the current transmit power value. Hence, state-of-the-art TPC is able to make use of all the communications benefits just described.

4.3.2 Mitigating Communication Range Degradation

Temporal correlated packet collisions, caused by quasi-constant power transmissions, as indicated in Figure 4.17a, may lead to a significant degradation of the actual intended communication range. Whereas without interferer a successful reception is possible up to the maximum intended communication range, with interferer a successful reception typically requires a certain Signal to Interference Ratio (SIR), which only may be given at significantly shorter distances to the transmitter (see reduced successful reception area in Figure 4.17a). If the latter situation holds for several subsequent transmissions, the maximum

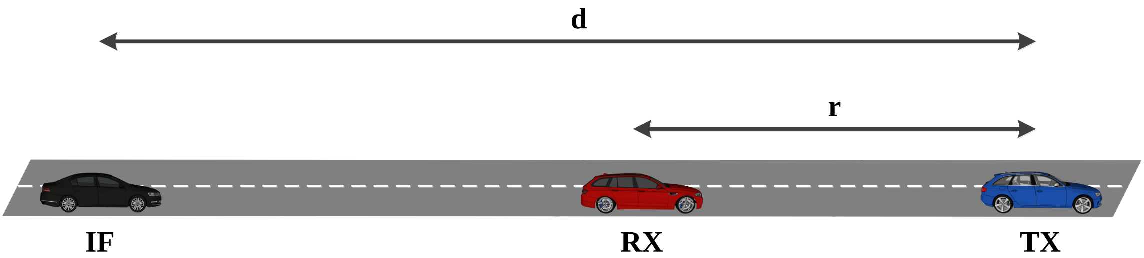


Figure 4.19: Simplified platooning scenario: transmitter TX, receiver RX, and interferer IF.

intended communication range reduces to the effective communication range, where the SIR criterion is fulfilled for successful receptions. This behavior has been demonstrated by Schmidt *et al.* [111], first, by means of simulations, and later, by real-world experiments [110]. Although their scenario was focused on an emergency vehicle approaching a receiver, and a farther located interferer, it may be also applied for a platooning scenario, as illustrated in Figure 4.17. As random transmit powers are shifting the collision and interference areas in space, the current SIR-based communication range is changed as well with each transmission, which may lead to a higher effective communication range on average.

For a better understanding, a simple platooning scenario, illustrated in Figure 4.19, is considered. Furthermore, it is assumed that the transmitter TX and the interferer IF are hidden from each other, i.e. $d >$ max. communication range, and they are accidentally transmitting at approximately the same time, causing a packet collision. Due to the quasi-periodic CAM transmission policy in combination with quasi-static relative mobility, the collision is likely to recur for several subsequent transmissions almost surely. Without loss of generality, all power values are assumed to be in the dB domain. For simplicity, the path loss at distance r is calculated by using the log-distance path loss model of the form

$$L(r) = L(r_0) + 10 \cdot \gamma \cdot \log_{10}\left(\frac{r}{r_0}\right) \tag{4.3}$$

with $L(r_0)$ specifying the reference loss at reference distance r_0, and γ defining the path loss exponent.

To determine a successful reception at the receiver RX, a simple SIR model is applied.

Specifically, for a successful reception from TX, the following condition has to be met:

$$SIR_{\mathrm{dB}} = X - Y > \Delta \tag{4.4}$$

where X and Y correspond to the received signal power from TX and IF, respectively, and Δ specifies the required power difference for a successful decoding of the corresponding signal.

Assuming that TX and IF are transmitting with constant powers all the time, the received powers X and Y, and by implication, the corresponding SIR, remain the same, and will not change for a certain RX location. However, if TX and IF are transmitting independently with random transmit powers, modeled by the random variables U and V, respectively, the corresponding received powers X and Y are obtained by transforming U and V as follows:

$$\begin{aligned} X &= g(U) = U - L(r) \\ Y &= g(V) = V - L(d-r) \end{aligned} \tag{4.5}$$

Their PDFs correspond to

$$\begin{aligned} f_X(x) &= f_U\left(x + L(r)\right) \\ f_Y(y) &= f_V\left(y + L(d-r)\right) \end{aligned} \tag{4.6}$$

where $f_U(x)$ and $f_V(y)$ denote the PDF of U and V, respectively. Then, the probability of a successful reception from TX can be calculated by

$$\begin{aligned} &\mathbf{Pr}(\text{successful reception}) = \mathbf{Pr}(Y < X - \Delta) \\ &= \int_{-\infty}^{\infty} \int_{-\infty}^{x-\Delta} f_{X,Y}(x,y)\, \mathrm{d}y\, \mathrm{d}x \\ &\overset{(*)}{=} \int_{-\infty}^{\infty} \int_{-\infty}^{x-\Delta} f_X(x) \cdot f_Y(y)\, \mathrm{d}y\, \mathrm{d}x \\ &\overset{(4.6)}{=} \int_{-\infty}^{\infty} f_U\left(x + L(r)\right) \int_{-\infty}^{x-\Delta} f_V\left(y + L(d-r)\right)\, \mathrm{d}y\, \mathrm{d}x \end{aligned} \tag{4.7}$$

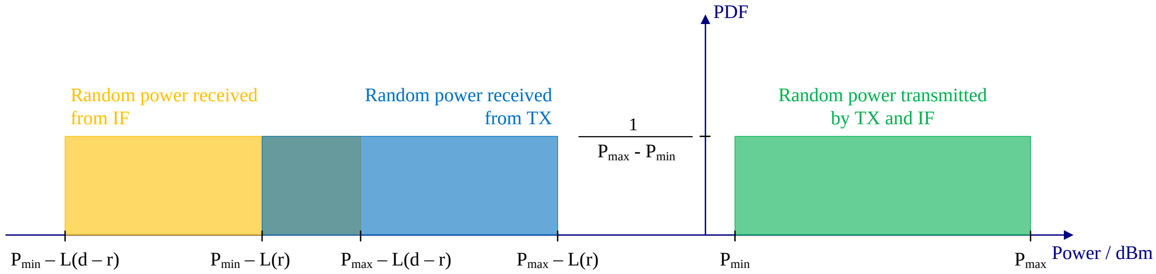


Figure 4.20: In the dB domain the received powers from TX and IF are just shifted versions of the corresponding random transmit powers U and V.

where $(*)$ follows, as U and V are independent, so X and Y are independent as well.

The derivation just described is graphically sketched in Figure 4.20. Without loss of generality, $U \sim V \sim \mathcal{U}(P_{\min}, P_{\max})$ is assumed. As the powers and path loss are considered in the dB domain, the random received powers X and Y are just shifted versions of U and V, respectively.

To evaluate the behavior of the effective communication range, the basic scenario as illustrated in Figure 4.19, has been analyzed analytically, as well as by simulations. Therefor, the log-distance model from Equation (4.3) has been applied, with the path loss exponent $\gamma = 2.35$, and the reference loss L_0, which is obtained by Friis' equation at reference distance $r_0 = 1$ m for $f = 5.9$ GHz, according to ITS-G5 (control channel). This configuration results in a maximum communication range of $CR_{\max} = 966$ m, if a maximum transmit power of 33 dBm is assumed (similar to the setup description in Appendix A). To calculate the reception probability, the distance between TX and IF has been fixed to $d = 1.25 \cdot CR_{\max} \approx 1206$ m, in order to get a hidden terminal situation. The distance r between TX and RX has been varied from 10 m to 1200 m with an increment of 10 m.

Figure 4.21 compares the two transmit power approaches. While the constant power approach is set to the maximum allowed transmit power of 33 dBm, the random power concept is based on the uniform distribution $\mathcal{U}(13 \text{ dBm}, 33 \text{ dBm})$. The figure shows the PDR of both approaches over r, obtained analytically from Equation (4.7) on the one hand, and obtained by Monte-Carlo simulations (100 independent runs, with a simulation time of 30 min = 1800 s each) on the other hand. Whereas the constant power policy clearly shows a significant degradation of the effective communication range, the random transmit power concept is able to cover higher ranges as well, albeit with decreasing reception probability. However, the increased effective communication range comes not for free. While the constant power policy is able to cover its entire effective communication range

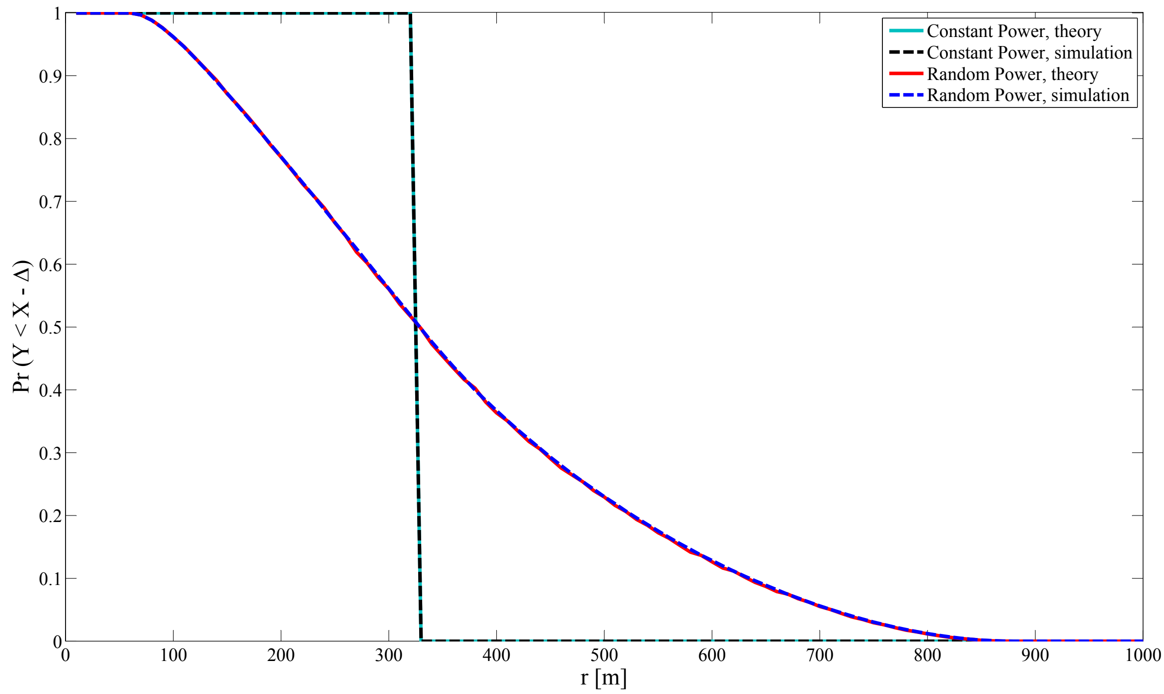


Figure 4.21: Comparison of the constant power approach with the random transmit power concept, with respect to the communication range degradation.

with a probability of 1, the random power approach decreases the PDR already at shorter ranges. Nevertheless, this is not an issue due to the following two reasons: First, the random transmit power interval can be adapted accordingly. If it is required to provide a PDR of 100 % also at higher ranges, the lower bound of the random power interval could be adapted accordingly. Then, all possible receivers within the range covered by $P_{\min}$ are reached with each transmission as well. Second, as discussed in Section 2.5.1, the reception probability itself does not reflect the communications performance properly. A reception probability of 50 % might be sufficient, as long as the CAMs are not lost in bursts. As the random transmit power concept itself aims at making correlated packet collisions more uncorrelated in space, thus, the reception probability behavior shown in Figure 4.21 might be sufficient with respect to the update delay performance.

4.3.3 Evaluation by Simulation

The concept of using random transmit powers in the context of a more realistic scenario has been evaluated by means of simulations, using the framework described in Appendix A. In order to provide a fair comparison with the (harmonized) quasi-constant transmit power policy, the following two perspectives are considered:

- *Coverage:* In that context, a fair comparison is based on the requirement that both approaches have to provide the same coverage range. That means, the random transmit power approach will be compared with the constant power approach, configured to apply the maximum power value from the random power interval. The coverage perspective is particularly important, if spatial application requirements have to be fulfilled.

- *Energy:* In this case, a fair comparison might be based on the same amount of energy, put into the wireless channel. Hence, the random transmit power approach will be compared with the constant power scheme, configured to apply the power, which corresponds to the mean of the random power interval.

Another perspective could be also based on the same load generated on the wireless channel. However, this perspective is discussed in more detail in Chapter 5, and is not further elaborated here.

Based on the two comparison perspectives, the following three transmit power profiles are considered:

- **Constant Full transmit Power (CFP):** To achieve maximum awareness range, all vehicles transmit each CAM with the maximum transmit power limit on the control channel (33 dBm).

- **Random Transmit Power (RTP):** All vehicles randomly choose the current transmit power based on a discrete random variable, which is uniformly distributed on the interval [3 dBm; 33 dBm], with a 0.5 dB step size (μ = 18 dBm). To perform a comparison with respect to the same coverage, the upper bound of the random transmit power interval corresponds to the maximum power limit applied within CFP. The lower bound is based on exemplified requirement specifications for an example cooperative safety application, which is discussed in more detail in Chapter 5.

- **Constant Mean transmit Power (CMP):** To perform a comparison regarding the same energy, all vehicles transmit each CAM with the mean power value of the applied RTP profile above (18 dBm).

A summary of the most important simulation parameters is given in Table 4.3.

Traffic scenario	10-km highway with 6 lanes in each direction
Evaluation section	5 km (from 2.5 – 7.5 km)
Vehicle generation process	Erlang distributed ($\mu = 2.25$ s)
Speed profile	From 20 to 40 m/s (4 m/s increase from outer to inner lane)
Access technology	ITS-G5 on Control Channel
Radio propagation model	Log-distance (exponent 2.35)
Transmit power profiles	constant at 33 dBm, $\mathcal{U}[3, 33]$ dBm ($\mu = 18$ dBm), constant at 18 dBm
CAM generation policy	1 Hz + trigger conditions
Metrics	CBT, packet collision rate, packet collision ratio, update delay

Table 4.3: Simulation parameters for the random transmit power investigations.

Channel Load

The capability of reducing the load on the wireless channel is an essential requirement for congestion control. RTP's ability to reduce congestion is presented in Figure 4.22, in comparison with CFP and CMP. The figure shows the average CBT ratio along the highway, for all three transmit power profiles. Whereas CFP causes a CBT ratio of approximately 66 %, RTP is able to decrease the load to approximately 27 %, that corresponds to a reduction by a factor of 2.5. Although RTP and CMP are transmitting with the same power on average, the latter causes a still lower CBT ratio of only 20 %. This effect may be explained by the non-linear mapping between transmit power and transmission range, assuming a log-distance path loss model. Whereas the mean transmit power is the same for RTP and CMP, the average transmission range is not.

Packet Collisions

Figure 4.23 compares the total as well as the recurring normalized packet collision rate for CFP, RTP, and CMP, plotted against the IF-RX distance. The figure clearly highlights the improved transmission efficiency by using RTP. Compared with CFP and CMP, RTP is not only able to reduce the number of collisions in general, it also shows a more efficient behavior in space. As the number of transmissions to farther vehicles, where the collision probability is high anyway, has been reduced, the amount of collisions has been significantly decreased with increasing distance.

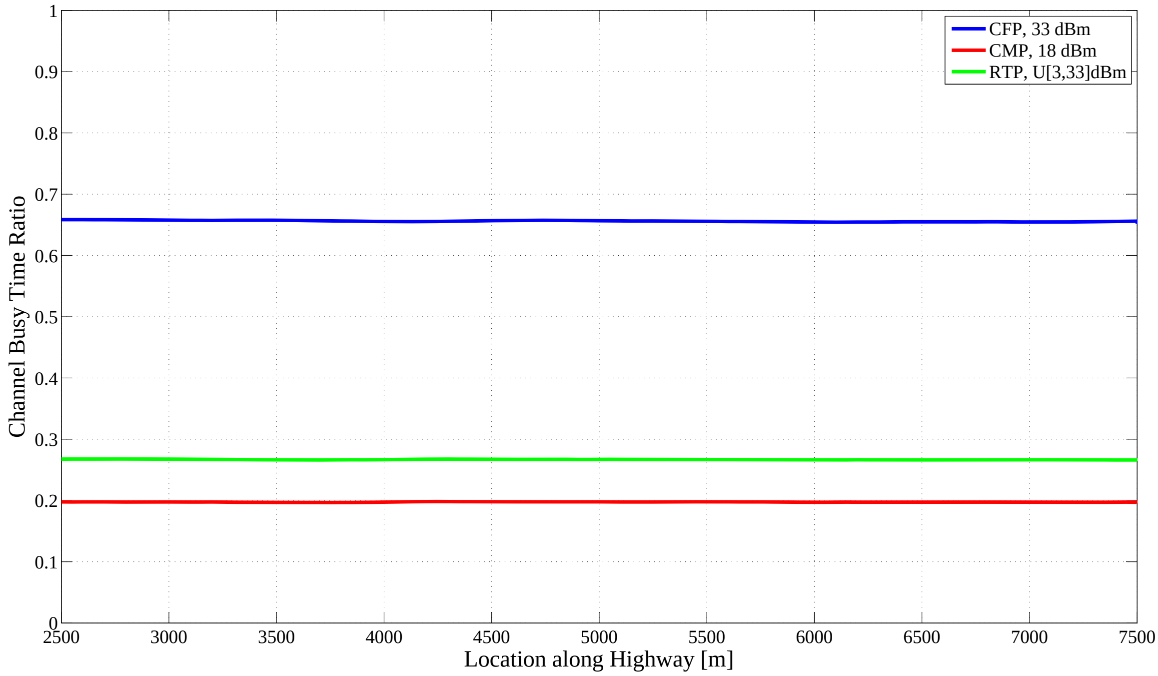


Figure 4.22: The average CBT ratio along the evaluation section of the highway scenario by using CFP, RTP, and CMP.

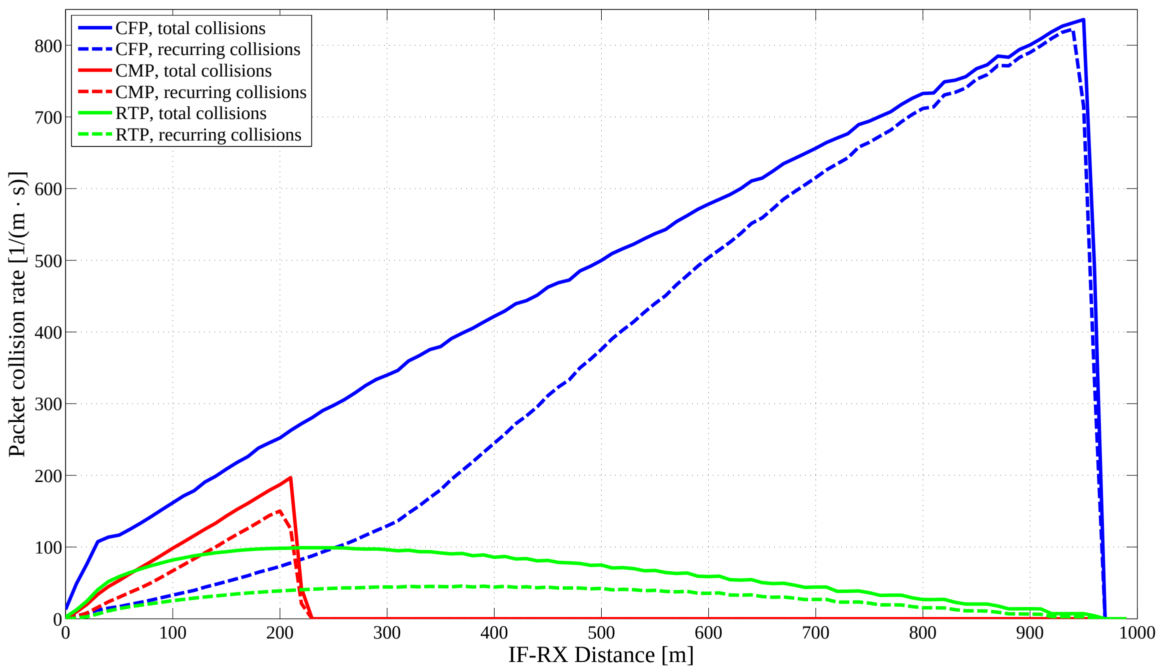
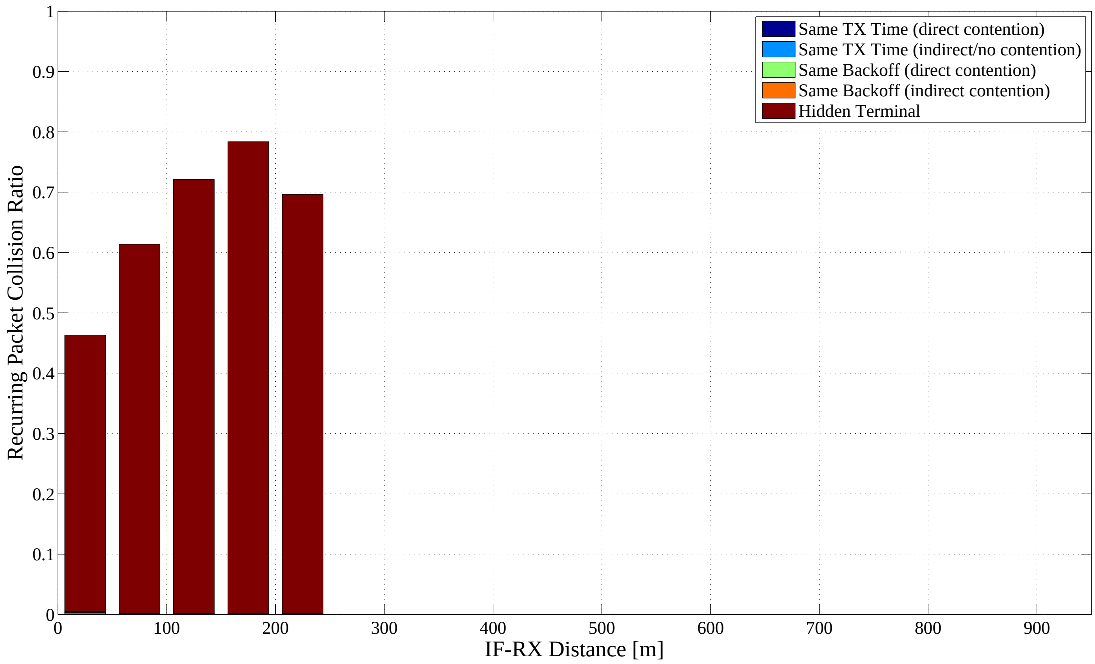
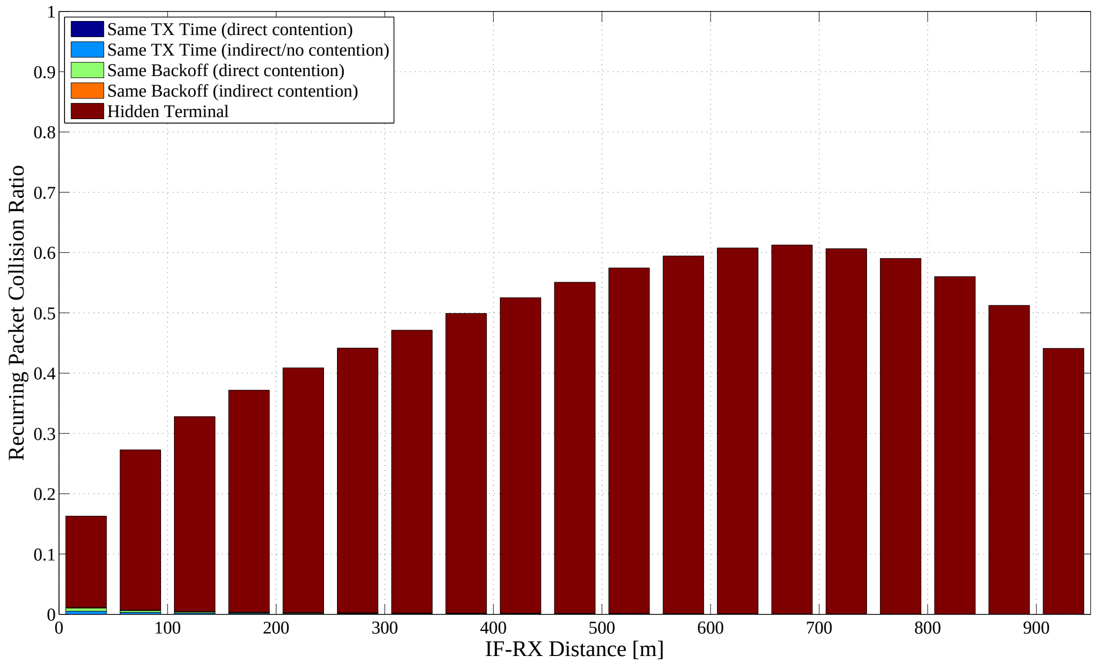


Figure 4.23: Total and recurring number of packet collisions (normalized in time and space), plotted against the IF-RX distance: Comparison among CFP, CMP, and RTP.



(a) Recurring collision ratio for CMP.



(b) Recurring collision ratio for RTP.

Figure 4.24: Comparison of recurring packet collision ratios.

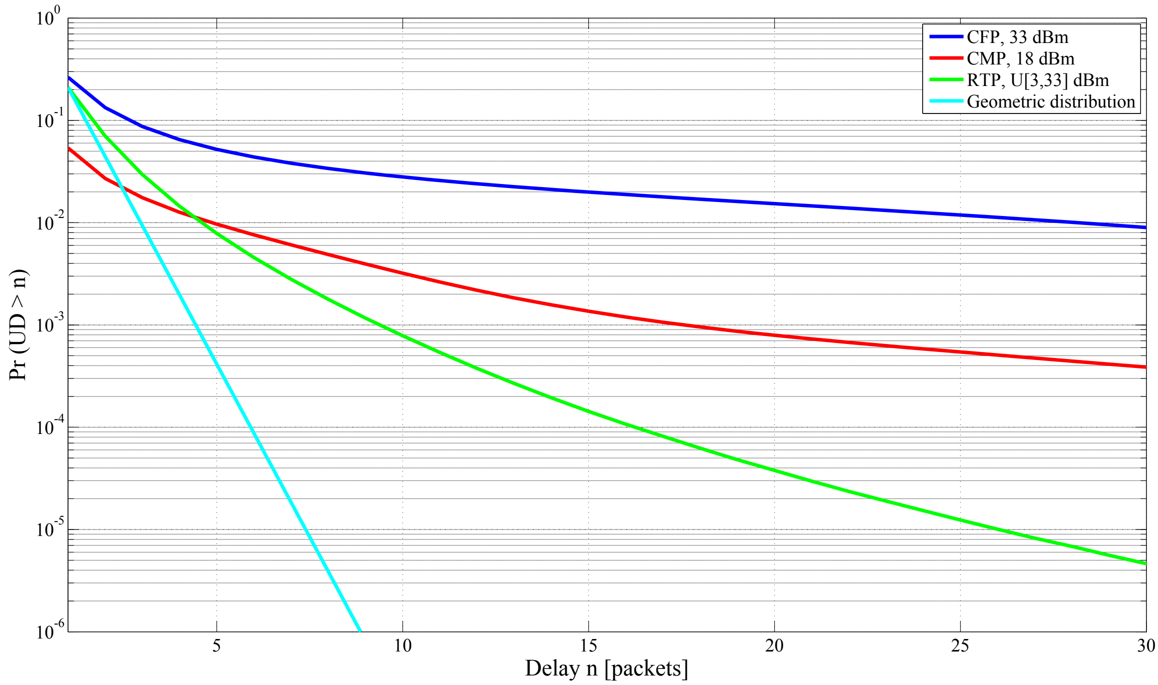


Figure 4.25: Comparison of the packet-based update delay, measured within the entire transmission range, plotted for CFP, CMP, RTP, and the geometric distribution (lower bound according to correlation behavior).

Please note that this statement is not valid for CMP, despite showing no packet collisions for higher ranges. The reason is that CMP only provides a maximum communication range of approximately 230 m, compared to about 970 m for CFP and RTP. The strong increase of CFP at the first 40 m is again due to a side effect given by the highway scenario (see Section 3.1.2).

For a better comparison regarding recurring packet collisions, Figure 4.24 shows the recurring packet collision ratio for CMP and RTP. The same plot for CFP, has been already presented in Figure 3.6 in Section 3.1.2. Compared with CFP and CMP, RTP provides a significantly lower amount of recurring collisions, especially with increasing distance. Whereas CFP reveals a maximum recurring collision ratio of 98 %, and CMP a maximum recurring collision ratio of 78 %, the maximum ratio with RTP has been reduced to 62 %. As the amount of recurring collisions for CMP does not show any improvement compared with CFP, obviously the reason for the enhancement by using RTP is not the channel-load reduction, but the randomization of the collision and interference areas in space.

Figure 4.25 provides a better insight into the correlation behavior of packet collisions. It shows the packet-based update delay, measured within the entire transmission range, for

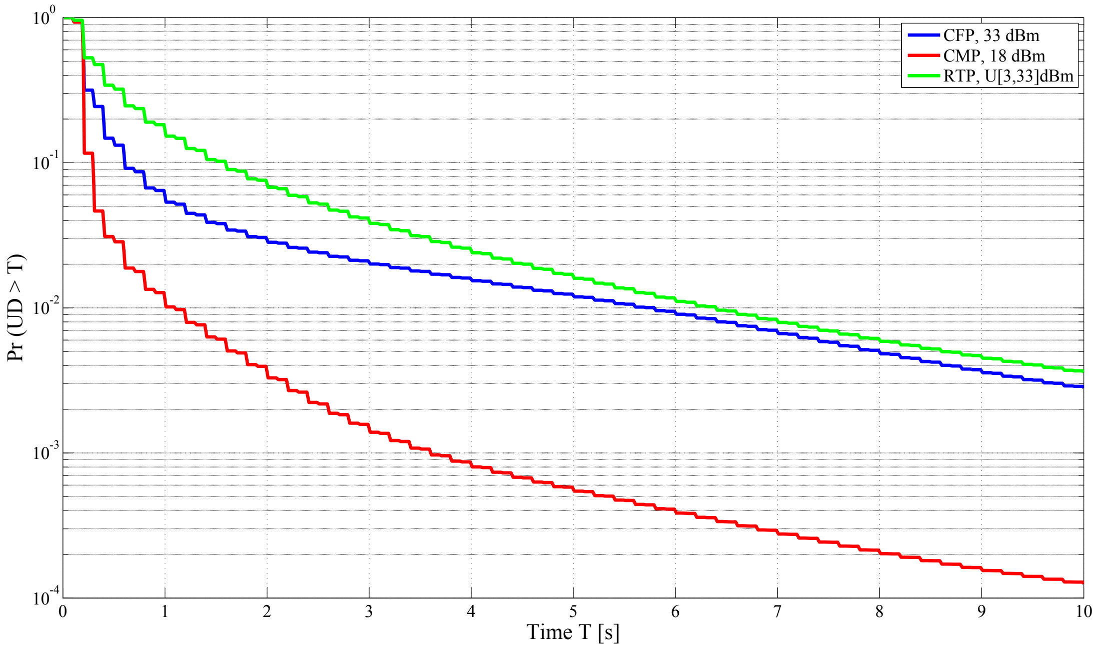
CFP, CMP, and RTP. Compared to CFP, RTP clearly shows an improved decorrelation behavior (much lower probability of exceeding higher update delay values). However, compared to the geometric distribution, which presents a perfect decorrelation, there is still room for further improvements. Although CMP shows the best behavior for small n, RTP is able to outperform CMP already for $n > 4$. This again shows the improved decorrelation behavior of RTP, as correlated packet collisions with a burst length $n > 4$ are more unlikely, compared to CMP. To provide a better insight into the communications performance, the time-based update delay is discussed next.

Communications Performance

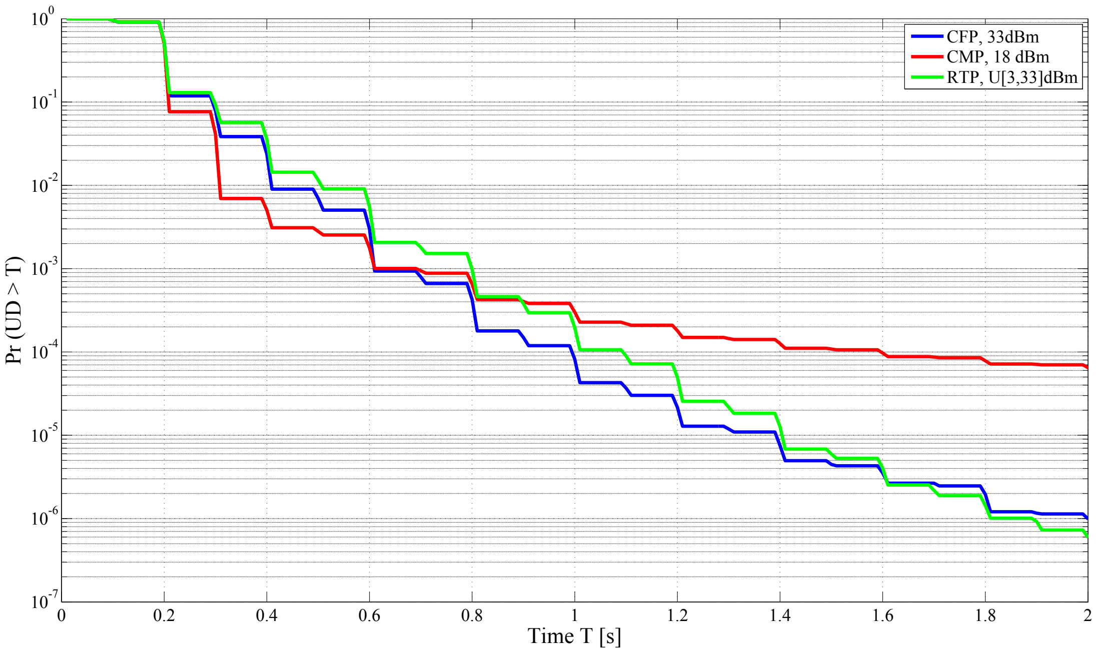
A comparison between the three different transmit profiles, regarding the CAM-related communications performance, is presented in Figure 4.26. It shows the time-based update delay for CFP, CMP, and RTP, each represented as CCDF, measured within the entire transmission range on the one hand, and within close range (up to distances of 50 m) on the other hand. Like in previous update delay figures, the CCDF plot provides on the y-axis the probability $Pr(\text{UD} > T)$ of the Update Delay (UD) exceeding a certain time frame T on the x-axis. Please note that within this chapter, the main focus is on the relative performance comparison only. An interpretation in the context of a concrete cooperative safety application example will be discussed in the next chapter.

In Figure 4.26a, CMP shows the best performance. However, it should be noted that the entire transmission range for CMP is only approximately 230 m, compared with approximately 970 m in case of CFP and RTP. Thus, a comparison with CMP might be fair from an energy perspective, but is unfair regarding coverage. Although RTP has shown a better performance than CFP with respect to the packet-based update delay (see Figure 4.25), in case of the time-based update delay it is worse. The reason is that RTP provides less transmissions (CAMs per time interval) with increasing range. While the packet-based update delay takes this not into account, the time-based update delay does. However, this fact is not necessarily a problem, and will be discussed in Chapter 5.

A similar behavior is shown in Figure 4.26b. Although the 50 m range is covered by CFP and RTP with the same frequency, CFP still shows a slightly better performance than RTP. The reason is that the low power transmissions within RTP are more sensitive to high power transmissions of other vehicles, which also impacts the SINR. However, due to the better decorrelation capability regarding packet collisions, RTP is even starting to outperform CFP for $T > 1.6$ s. In the short range case, CMP shows the best performance



(a) Update delay performance within the entire transmission range. Please note that the maximum communication range of CMP is only approx. 230 m, compared to approx. 970 m for CFP and RTP.



(b) Update delay performance within 50 m.

Figure 4.26: Comparison of the time-based update delay performance between CFP, CMP, and RTP.

for small T again, but starts quickly to get worse with longer time frames T, due to a relative high correlation of packet collisions (see Figure 4.24a).

4.3.4 Related Work

Using random signal levels for channel access has been proposed earlier by Lee [80]. He applied this scheme to the slotted Aloha access mechanism, and significantly increased the throughput performance, compared with the conventional slotted Aloha system, by making use of the capture effect. Many of the subsequent publications have focused on the same problem, that is, to further increase throughput for time-slotted shared radio channel systems, by exploiting the capture effect. Cidon *et al.* [32] concentrated on Poisson distributed arrival processes, and additionally discussed design issues, such as number of levels and selection schemes. La Maire *et al.* [78] determined an optimal choice of power levels and probability distributions to optimize the throughput. In [142], Wang *et al.* applied random transmit power control to DS-CDMA packet mobile radios to obtain the capture effect and increase the link capacity. They enhanced their random TPC approach by combining it with inter-path interference cancellation [76], and with frequency-domain equalization [64]. Behzad *et al.* [24] introduced the Fair Randomized Power Control (FRPC) algorithm to increase throughput, while providing fairness for different mobile users in the system. In [70], Tae-Suk and Seong-Lyun presented a stochastic analysis of randomized transmit power compared with fixed power control in a single-frequency CDMA network. They found that the performance of both approaches depends on the network density. Whereas random transmit power performs better in high-density networks, fixed power control is more favorable for low-density situations. Instead of focusing on throughput performance, Pereira et al. [97] improved the energy consumption in wireless sensor networks until reaching a consensus. They proposed a heuristic scheme of randomized transmission power to balance the energy consumed by the network among the nodes, and to reduce the convergence time.

4.3.5 Discussion

In this section, a new concept has been introduced that addresses the second reason for correlated packet collisions caused by the MAC. Specifically, the basic objective is to make the quasi-static relative mobility between neighboring vehicles more dynamic or even random. Moving vehicles randomly in space is probably not possible in practice. Fortunately, this is not necessary. The concept of random transmit powers results in random transmission ranges, and thus, it is able to simulate a random relative mobility between neighboring vehicles transmitting at constant powers without moving them physically. As a result, correlated packet collisions are mitigated, because they are randomized in space without much efforts. At the same time, channel congestion is even reduced, due to an improved transmission efficiency over range. The latter is achieved by an implicit reduction of transmissions, where the chance of correct reception is low anyway.

Automotive safety systems engineers in particular might be afraid of cooperative safety applications running on top of a randomized transmission scheme. However, it should be noted that randomization is controllable, and then the randomization can be limited to a certain region only. Lets consider again an arbitrary random power interval limited by a minimum and a maximum transmit power. Dependent on the current radio propagation conditions, transmissions with the minimum power are able to cover a certain range. As there are no transmissions with less power, this range is always covered by each transmission (apart from fading effects). Hence, vehicles within that minimum range experience the same number and frequency of CAM updates as with constant power transmissions applying the same rate. Only vehicles beyond the minimum range are influenced by the randomization of the transmit powers. On average, they experience a decreasing number and frequency of CAM updates with increasing range.

Please note as well that the minimum range can be increased by simply increasing the minimum transmit power. If the lower bound (minimum power) of the transmit power interval is approaching the upper bound (maximum power), the random transmit power concept is converging towards a constant transmit power approach. This behavior is an important feature: first, in very sparse traffic scenarios the channel load is low anyways and there is no need to reduce the channel load by transmitting with less power on average. Second, in sparse traffic scenarios low power transmissions are wasted if there are no nearby vehicles most of the time. Finally, it remains backward compatibility.

Some might wonder, if shadow fading is able to provide the same randomization feature. Although an exact answer cannot be given here, as more detailed investigations on that issue are out of the scope of this thesis, there are a few aspects, which may provide an indication: First, there are many publications, e.g. [60, 85, 92, 94, 88], showing that shadow fading is not independent, but rather shows correlated behavior. Hence, the received signal powers from a certain transmitter may not vary significantly enough for subsequent packets, which would result in only minor shifts of the corresponding collision and interference areas. In principle, random transmit powers may even help to make correlated shadowing more uncorrelated again, in order to address the problem of correlated packet collisions on the PHY layer. Furthermore, shadow fading is not controllable at all. It depends completely on the current environment, and thus, it cannot be adapted to application requirements or to current contexts.

Chapter 5

Fish-eye Awareness Control

Current transmission control schemes cannot have a cake and eat it too. Specifically, they cannot provide a high awareness range *and* quality at the same time (transmit power/rate trade-off dilemma). This issue is relevant in particular, if either the traffic density is high, or multiple cooperative applications, which may be based on different awareness requirements, are running in parallel.

In this chapter, a new concept is introduced called fish-eye awareness. It relaxes the transmit power/rate trade-off by providing a high awareness quality at close ranges, but reduces it at higher distances where it is less critical. Therefor, the random transmit power concept from the previous chapter is enhanced by Random Transmit Power Control (RTPC), that manages to adapt the awareness-quality as a function of range, while mitigating correlated packet collisions by randomizing them in space. Because RTPC is able to reduce the channel load, it is combined with TRC to benefit from the gained channel resources by subsequently increasing the update-rate, and by implication the awareness quality. The resulting Fish-eye Awareness Control (FAC) strategy is evaluated by simulations, considering cooperative driving applications, such as platooning.

5.1 Fish-eye View for Cooperative Awareness

As concluded in Section 2.4, current congestion control approaches tend to converge to harmonized quasi-constant transmit powers. Thus, they are facing problems like the transmit power/rate trade-off dilemma and correlated packet collisions (see Section 2.5). Even awareness control solutions are mainly focusing on TRC, while the transmit power is simply adapted to satisfy a single (maximum) awareness range required by the corresponding

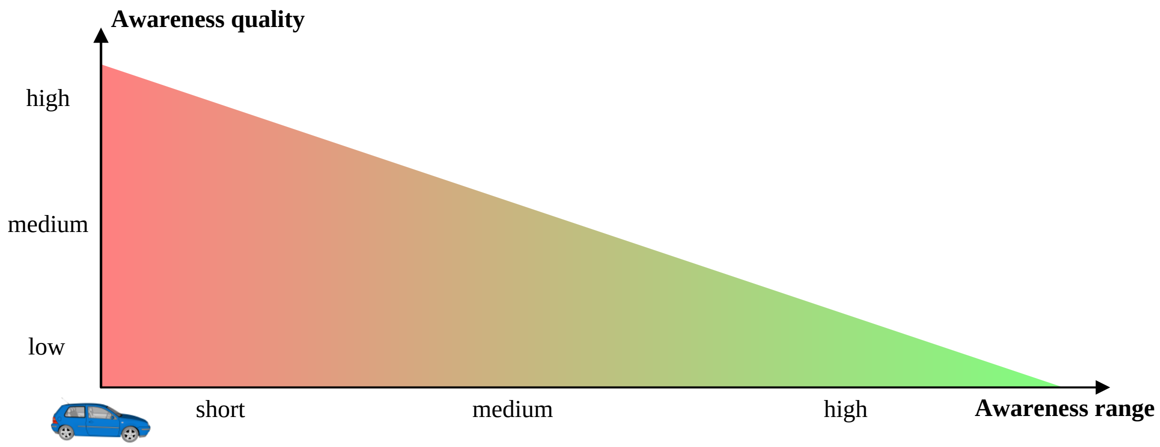


Figure 5.1: Distance-dependent danger to a cooperative safety application: the awareness quality should be the highest when danger is critical (close distance) and may be relaxed when only monitoring (high distance)

cooperative safety application, or the most demanding one in case of multiple applications [115]. As a result, vehicles try to reach all their neighbors located within the single (maximum) awareness range with the same CAM update rate (awareness quality).

5.1.1 The Concept

Especially with focus on traffic safety, it may be observed that the behavior of the awareness quality does not have to be homogeneous in space. Quite the contrary, the relevance of neighboring vehicles should be the higher the closer they are, as only nearby vehicles might pose an immediate danger with respect to physical collisions between vehicles. This effect is illustrated in Figure 5.1. It shows the relevance, or rather the real required awareness quality, plotted against awareness range, with the distance-dependent danger indicated by the coloring, ranging from green (no danger) to red (very high danger). Obviously, current transmission control solutions may provide an over-dimensioned, or even wrong-dimensioned awareness in space. This may result in a waste of wireless resources, as they try to transmit with a high rate at high ranges, where the chance of successful reception is low anyway, and where it is not even necessary.

Based on these observations, the idea is to apply the so called fish-eye view [139] to VANETs, with focus on the cooperative awareness. The Advantages are illustrated in Figure 5.2. Lets assume the quality of the awareness is indicated by the local focus (sharpness) of the picture, the maximum communication range is represented by the size

(a) High awareness range, but at low quality only.

(b) High awareness quality, but at short range only.

(c) High awareness quality at short range, and low awareness quality at high range.

Figure 5.2: Transmit power/rate trade-off dilemma vs. fish-eye concept.

of the circle, and the white vehicle in the center corresponds to the ego vehicle that is aware of others in the surrounding. Due to the trade-off dilemma, as explained in Section 2.5.2, current transmission control approaches suffer in either covering high ranges, but at low quality (see Figure 5.2a), or providing a high quality, but at short ranges only (see Figure 5.2b). The fish-eye view, instead, is able to provide high quality for the close vicinity, with a soft degradation (increasing blur) for increasing ranges (see Figure 5.2c). This behavior fully supports the distance-dependent relevance of neighboring vehicles according to Figure 5.1.

5.1.2 Related Work

Applying the fish-eye concept to wireless networks is not new. In 2000, Pei *et al.* [95] introduced a new routing protocol for wireless ad-hoc networks, called Fish-eye State Routing (FSR). The authors applied the fish-eye view regarding the knowledge of the best route towards a certain destination. For that purpose the authors provide a higher quality of the routing information, the closer a packet has got towards its final destination. They showed that FSR provides a more desirable scalability for large mobile networks. In principle, the authors address the same overall problem in ad-hoc wireless networks, i.e.

the scalability issue. However, the main difference between FSR and the proposed fish-eye concept above is that both address completely different challenges. Whereas Pei *et al.* address the route selection issue for wireless networking via multiple hops, this work is focusing on the distance-dependent quality of safety-related information within single-hop transmissions.

In the context of road traffic, Wischof *et al.* [138] proposed a Self-Organizing Traffic Information System (SOTIS). Instead of providing traffic and travel information (e.g. congested streets or dangerous road conditions) based on the conventional centralized analysis at the traffic information center and dissemination via radio broadcast stations or cellular base stations, they equip some vehicles with SOTIS technology, and thus, are able to disseminate traffic and travel information in a completely decentralized manner. In their work, they also identified the distance-dependent relevance of traffic information and proposed to gracefully degrade the information resolution with increasing distance. This behavior has been implemented via multi-hop packet propagation by discarding non-relevant information before rebroadcasting, dependent on the distance. However, the main difference between SOTIS and the fish-eye concept introduced above is that this work applies such distance-dependent information dissemination to cooperative awareness in VANETs, and by association is implemented for single-hop transmissions.

5.2 Fish-eye Awareness - A Design Framework

In this thesis, a new practical design framework is introduced, called *fish-eye awareness*. It enables to adapt the distribution of the awareness quality as a function of the awareness range within a single-hop transmission. Therefore, the following two steps are proposed:

5.2.1 Awareness Shaping with RTPC

The basic idea is to introduce alternating transmit powers, which would result in alternating transmission (awareness) ranges. Specifically, each vehicle transmits each CAM with different power levels within a certain time. Then, low power transmissions can only reach the nearby vehicles, while high power transmissions are able to cover the farther ones as well. As a result, closer vehicles experience a higher update rate than farther ones, and by association different levels of awareness quality are provided at different ranges.

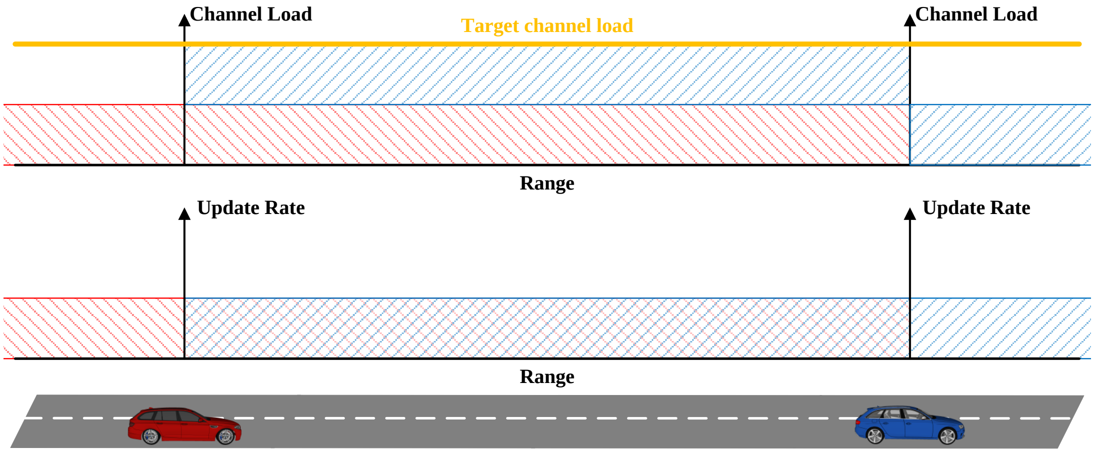
Figure 5.3 compares alternating and quasi-constant transmit powers with respect to their impact on the update rate in space and on the local channel load for the example of two vehicles. Due to fairness, both approaches are assumed to transmit at the same rate and to aim at the same maximum awareness range. Figure 5.3a illustrates the local update rate and channel load behavior for quasi-constant transmit powers. As both vehicles aim to provide the same update rate along the entire range, their superimposed generated channel load may quickly reach the capacity limit of the wireless channel. With alternating transmit powers, however, a similar update rate is only provided at close ranges (see Figure 5.3b). As the update rate is reduced with increasing distance, the corresponding contribution to the local channel load is reduced as well.

Please note that the property just mentioned is already provided by the concept of random transmit powers (see Section 4.3). Even more, it is able to mitigate the issue of correlated packet collisions in addition. Hence, the concept of random transmit powers will provide the basis for the proposed fish-eye awareness framework.

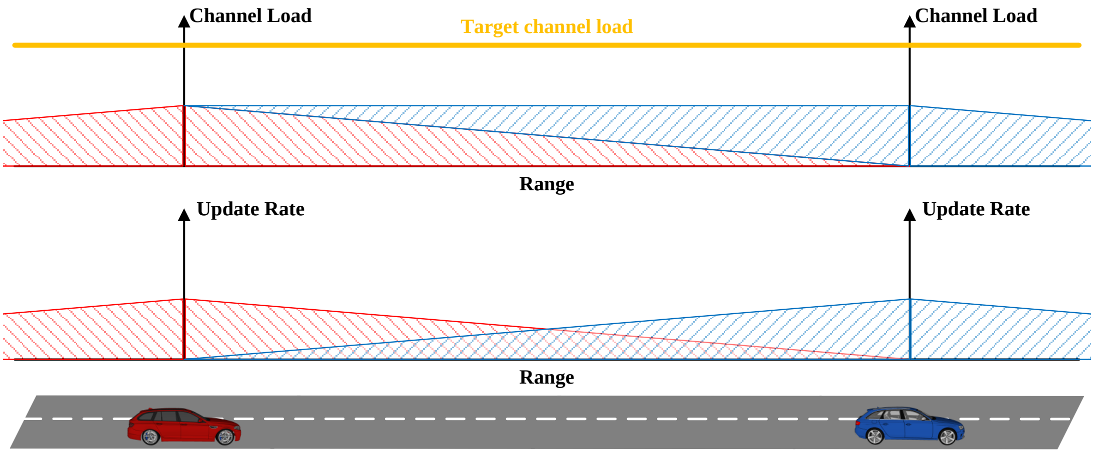
Although the concept of random transmit powers is indeed able to provide different levels of quality at different ranges, it does not automatically fulfill the required awareness quality behavior in space, which may even differ from application to application. Depending on the probability distribution defined on the set of random power levels, the spatial behavior of the awareness quality may result in different shapes. However, only a certain probability distribution may be able to provide the required shape. Hence, the basic concept of random transmit powers is enhanced by *Random Transmit Power Control (RTPC)*, which adds controllability in order to adapt the awareness shaping accordingly, and by implication makes it applicable to cooperative safety applications. Therefore, RTPC aims at controlling the probability distribution and its parameters, e.g. shape, mean, and variance. By selecting the shape, for instance, the weighting on the set of available power levels and their corresponding ranges is controlled as well as the spatial awareness behavior. The variance may control the spreading between high and low transmit powers, and by association, the degree of randomizing collisions in space. With the mean, the transmit fairness (equal power between nodes on average), as well as the congestion on the wireless channel may be adapted.

RTPC is also able to relax the transmit-range-to-power-mapping problem, as it may introduce fuzziness into the mapping procedure. Instead of focusing on a single required (maximum) awareness range, and by implication on a fixed quasi-constant transmit power, the applied probability distribution may also consider some tolerance around the corresponding awareness range without increasing the contribution to the channel load.

Finally, RTPC even overcomes the transmit power/rate trade-off dilemma (see Figure



(a) As quasi-constant power transmissions aim at providing the same update rate within a single (maximum) awareness range, the generated channel load of both vehicles may superimpose within their common transmission range.



(b) Although alternating transmit powers provide the same update rate to nearby vehicles, they reduce it with increasing distance, which results in a reduced load on the shared wireless channel.

Figure 5.3: Comparison of quasi-constant transmit powers and alternating powers, based on the same transmit rate and awareness range requirements: Impact on the update rate in space, as well as the channel load.

2.6). Whereas current approaches are mainly operating in a single OP, RTPC enables to operate along a pathway, as it implicitly provides different rates (quality levels) at different ranges. However, this does not mean that the pathway represents already an "optimium".

5.2.2 Quality Adaptation with TRC

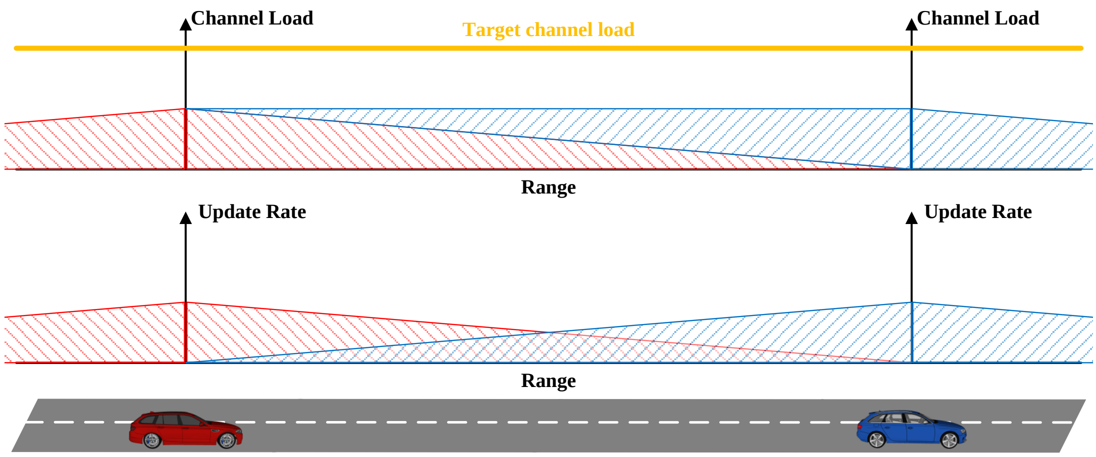
To provide the full potential of RTPC, the objective of this second step is to bring the operating pathway closer to a certain target channel load. As RTPC is able to reduced the load on the wireless channel (see Figure 5.3b), the gained wireless resources (channel load) may be used to further improve the awareness quality subsequently. Therefor, Transmit Rate Control (TRC) is applied in addition to further increase the transmit rate until a certain target load has been reached again. The corresponding impact on the update rate in space and the local channel load is illustrated in Figure 5.4.

Efficient TRC mechanisms, which are based on adapting the current rate dependent on the observed channel load, are described, for instance, in [127, 23]. Hence, this issue will not be further elaborated within this thesis.

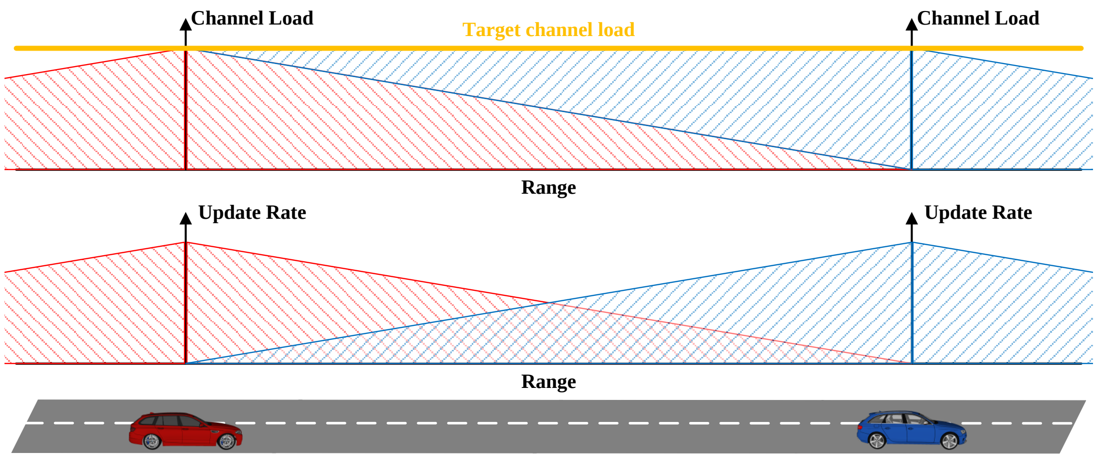
5.2.3 Traffic Safety Assessment

With the introduction of the fish-eye concept in Section 5.1, a continuous behavior of the awareness quality in space is assumed (see Figure 5.1). Because requirement specifications on a continuous behavior are too complex and probably not suitable in practice, the proposal here is to introduce discrete zones, which basically correspond to a quantization of the desired continuous behavior. An example with three different zones is shown in Figure 5.5, with each zone specifying its own requirement on the awareness quality: In the first zone, the awareness range is short, but the quality is high as it represents the most critical area with respect to traffic safety. Its size may be composed of a final detection distance (represented by a maximum allowed update delay), plus the braking distance required to avoid a crash situation. In the second zone, the quality of the awareness is reduced as the increased range mitigates the potential danger. Finally, in the third zone the awareness quality is low, but as the range is high a precise knowledge of the current status, e.g. position, speed, of each vehicle is not required yet.

To avoid misinterpretation, please note that cooperative safety applications typically require all zones all the time. Especially multiple applications may require different quality levels at different ranges. With focus on traffic safety, the fish-eye awareness framework



(a) With RTPC only, the provided update rate is further reduced with increasing range, resulting in saved resources on the wireless channel.



(b) An additional TRC strategy is able to exploit the gained channel resources by subsequently increasing the transmit rate, and by association, the update rate along the entire awareness range.

Figure 5.4: Awareness quality adaptation with TRC: Impact on the local update rate and channel load.

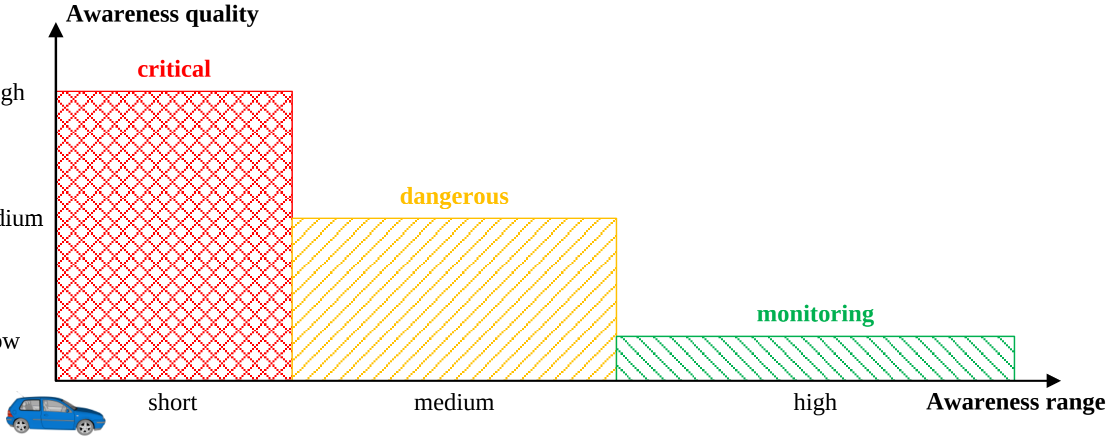


Figure 5.5: Simplification of the fish-eye awareness, where three discrete zones exemplary provide various awareness quality/range mappings.

aims at providing a high awareness quality in the immediate vicinity (critical zone), and accept a soft degradation with increasing distance (from dangerous zone to monitoring zone).

Such a simplified representation is much more practical in defining zones including range and quality requirements, and in assessing them for different transmission control policies.

Although some might link "safety" with "deterministic" instead of random approaches, the following aspects should be taken into account: First, even deterministic transmit powers will never result in deterministic awareness ranges. This follows from the transmit-range-to-power-mapping problem, caused by the unpredictability of the radio propagation in real world environments. Second, the proposed randomness can be controlled completely by the corresponding distribution and its parameters, e.g. shape, mean, variance. Finally, the lower bound of the random power interval may be configured such that the critical zone is covered with each transmission[1]. Then, RTPC provides the same number of updates within the critical zone as the constant power approach, in case of both applying the same transmit rate. But as RTPC manages to reduce the channel load, the transmit rate can be increased additionally, which further increases the awareness quality.

Thanks to the awareness concept, described in Section 2.2, the applied transmit policy is indifferent to the application, as long as the required awareness quality is provided.

[1]This might remind of the transmit-range-to-power-mapping problem. The key difference here is that transmissions do not constantly apply the lower bound power level only. Instead, considerably more higher power levels are used as well, which are able to cover the critical zone almost surely.

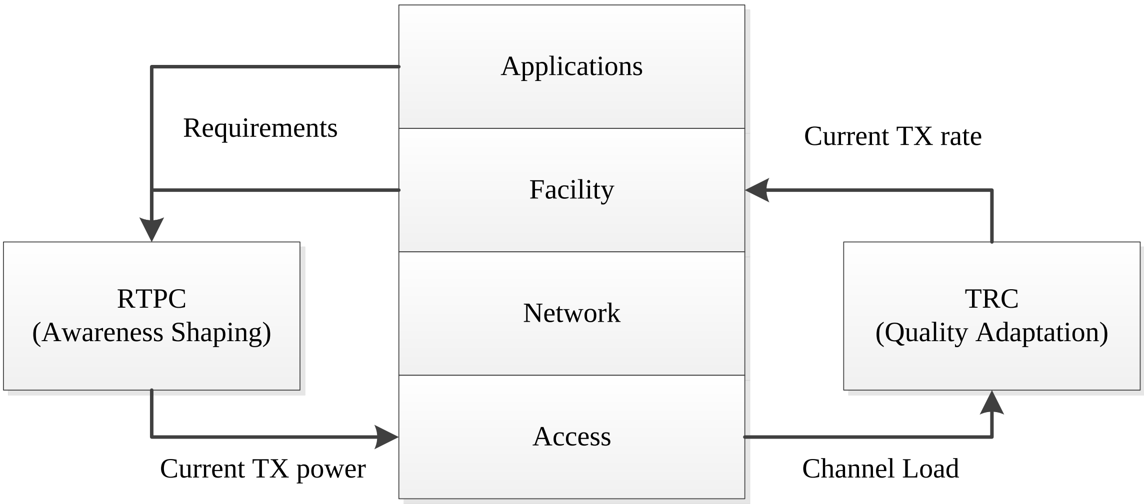


Figure 5.6: Proposed awareness control implementation based on two independent modules: RTPC and TRC.

This makes the modification of transmission parameters, like power or rate, completely transparent to the application.

5.3 Implementing Fish-eye Awareness Control

The basic architecture to implement Fish-eye Awareness Control (FAC) is presented in Figure 5.6. It is based on the following two independent control modules:

- **RTPC:** This block adapts the current transmit power profile according to Section 5.2.1. It controls the "shape" of the fish-eye awareness, that is the distribution of the awareness quality in space. The basic input parameters are the requirements on the awareness behavior in space of the corresponding safety application. To further optimize the shaping process, these parameters can be complemented by other ones, e.g. position, speed, or direction indicator. Then, even more information about the current situation, like the geographic situation (highway vs. intersection), or maneuver situation (vehicle going straight vs. vehicle turning left), could be provided. These input parameters are mapped to an appropriate probability distribution, e.g. defined by its shape, mean, and variance, on the set of allowed transmit power levels. A first practical solution may be based on a look-up table, which provides for each application the desired probability distribution. Finally, the output of this block is a random power value for each CAM transmission, which corresponds to the adapted probability distribution.

- **TRC:** This block aims at adapting the channel load to obtain an optimal target load, e.g. as proposed in [127, 23]. If channel load resources are gained by RTPC, TRC will subsequently increase the current transmit rate until the target load is reached.

Thanks to the modularity of the proposed FAC strategy, other awareness control solutions may also benefit from the introduced fish-eye awareness feature. Therefor, the corresponding TPC component may be simply replaced by the proposed RTPC block.

5.4 FAC Supporting Cooperative Safety Applications

To demonstrate how FAC supports cooperative safety in VANETs, it will be evaluated in the context of cooperative driving applications, such as platooning.

5.4.1 Assumptions and Methodology

One of the most common cooperative driving application is platooning [98], where vehicles automatically follow each other in a safe and efficient manner. Therefor, all vehicles in the platoon may implement Cooperative Adaptive Cruise Control (CACC), that is Adaptive Cruise Control (ACC) enhanced by communications. An example for a concrete CACC controller design is given in [98].

Please note that the evaluation of the entire platooning system is out of the scope of this thesis. As the focus here is on communications, the most relevant information is about the communications requirements. Whereas the latency is clearly required to be smaller than 200 ms [98], no clear statements on the required update delay or inter-reception time can be found. Instead, the authors state a requirement on the transmit rate of 10 Hz minimum. If mapped to the time domain, this would correspond to a maximum update delay of 100 ms. Achieving that requirement would mean that no packets may get lost. In their paper this was not an issue, because in their experimental setup the scalability problem does not appear. However, in more dense traffic scenarios, simultaneous transmissions are very likely, causing packet collisions, and resulting in a significant degradation of the communications performance.

Assuming the CACC controller requires to get an update every 100 ms minimum, this is not a problem, if an information fusion filter is used to process the received position information. The information fusion filter is able to provide position information to the CACC controller every 100 ms, even if the update delay on the communications side is longer. This is because the position is predicted as long as no new update is received (see Section 2.2).

For that reason, the proposed evaluation methodology in this section is based on analyzing the impact of the update delay on the position error by using an information fusion filter. As the focus of this thesis is on the communications impact, the measurement accuracy is neglected, and the position information, contained in CAMs, is assumed to be highly accurate. Furthermore, lets suppose the current position of a neighboring vehicle is predicted based on constant velocity kinematics. That means, as long as no new CAM update is received, the ego vehicle assumes the target continues traveling with the last received velocity update v_{last}. For simplicity, the platooning application is assumed to only perform longitudinal control. In that case, the distance estimate determines the quality of the position awareness. Then, the predicted traveled distance d_{pred} during time frame T can be simply calculated by

$$d_{\text{pred}} = v_{\text{last}} \cdot T \tag{5.1}$$

In the worst case, the target vehicle has just transmitted a CAM, which is assumed to have been successfully received by the ego vehicle. But immediately after transmission, the target vehicle has to perform a hard breaking with deceleration $-a$. In that case, the true traveled distance d_{real} during time frame T is computed as follows:

$$d_{\text{real}} = v_{\text{last}} \cdot T + \frac{1}{2} \cdot a \cdot T^2 \tag{5.2}$$

The difference between d_{pred} and d_{real} corresponds to the accumulated distance error of the prediction during time frame T. Making use of Equation (5.1) and (5.2), the accumulated distance error d_{err}, can be expressed by

$$d_{\text{err}} = \left| \frac{1}{2} \cdot a \cdot T^2 \right| \tag{5.3}$$

If Equation (5.1) and (5.2) are simply subtracted, the distance error would be either positive or negative, depending on whether the target vehicle has accelerated or decelerated. To simply obtain the deviation from the true distance, the absolute value of the difference is computed.

If T is interpreted as the update delay, Equation (5.3) finally provides the accumulated distance error, while no new CAM update has been received. Furthermore, a concrete mapping between update delay and accumulated distance error is available now. As a consequence, update delay CCDFs can be converted to distance error CCDFs. Then, the resulting curves provide the probability $\mathbf{Pr}(D > d)$ that the distance error measures D exceed a certain distance value d.

In order to account for the fish-eye effect, the distance error CCDF is evaluated for different ranges. Therefore, the more practical zone approach from Section 5.2.3 is applied. In this case, the three-zone approach in Figure 5.5 serves as a template. Please note that there is no clear method yet for the platooning application in order to define the different sizes of the zones. Within this thesis, the following zones have been chosen, but are not limited to the proposed values, as they can be adapted accordingly:

- **Zone 1 (critical) up to 50 m:** In case of a dangerous event, platooning vehicles are very likely to collide with their predecessor or successor, and thus, the awareness of those vehicles shall be of very high quality. Hence, these vehicles shall define the most critical distance within the platoon. As platooning aims at efficient driving by reducing the gap between consecutive vehicles to several meters only, 50 m seems to be too large. However, those gaps may increase significantly, if platoon forming procedures, like merging or leaving, are considered as well.

- **Zone 2 (dangerous) up to 150 m:** Although radar sensors are able to cover distances up to about 150 m [136], their effective coverage is limited by the preceding vehicle. This is because radar sensors unconditionally require Line Of Sight (LOS). With communications, however, vehicles are able to be aware not only of the predecessor, but of several vehicles in front and from behind. This can significantly speed up the reaction time along the platoon, because a dangerous event is not propagated from one neighboring vehicle to another. In this example, the maximum range of automotive radar sensors ($\approx$ 150 m) serves as a guideline to define zone 2, which is still classified as dangerous range.

- **Zone 3 (monitoring) up to 800 m:** Vehicles beyond zone 2 are not declared as immediately dangerous any more. However, it might be still of interest to be able to detect approaching vehicles already at far distances, and monitor them at least, but with more relaxed requirements on the awareness quality.

Several studies on CACC have demonstrated a well-performing platooning application by only communicating the corresponding information from the preceding vehicle (e.g. one-vehicle look-ahead strategy in [98]). So, one might wonder whether the first zone only might be already sufficient. However, it should be noted that platooning is not the only cooperative application. Instead, it will be merged with other ones like the lane change assist. But different applications running in parallel may require different zones. Hence, the consideration of different zones is important. As long as CACC is based on CAMs, its transmission policy cannot be adapted to satisfy CACC only.

5.4.2 Evaluation

Based on the evaluation methodology previously described, first, the corresponding update delay performance is determined by simulations. Therefore, the simulation framework described in Appendix A has been enhanced by a proof-of-concept implementation for FAC. The two blocks (RTPC and TRC) are implemented as follows:

- **RTPC:** Whereas the search of the optimal transmit power distribution is beyond the scope of this thesis and might be a topic for future work, the focus here is on demonstrating RTPC's fish-eye awareness capabilities. Basically the RTPC implementation corresponds to the Random Transmit Power (RTP) implementation from Section 4.3. This configuration is justified by the following reasons: To comply with the current standard according to the transmit power control settings as specified in [8, 46], the RTPC implementation is based on discrete equidistant transmit power levels in dB, ranging from the smallest possible power level of 0 dBm to the transmit power limit of 33 dBm (control channel), with a power level increment of 0.5 dB. To be able to cover zone 1 with *each* transmission, the lower bound of the applied probability distribution is set to 3 dBm, which was obtained by evaluation of the corresponding radio propagation model. The upper bound is set to the maximum allowed transmit power of 33 dBm, to relax the transmit-range-to-power-mapping problem, by including some tolerance according to the coverage of zone 3.

- **TRC:** The proposed target channel load for this block is 0.66. This value corresponds to the channel load caused by the reference constant transmit power profile, which will be compared with the present FAC strategy. In order to provide a fair comparison with respect to channel usage, the TRC block will only reuse the amount of channel load saved by RTPC. The proposed target channel load of 0.66 is also in line with the recommendation in [49], where the authors have shown that their information

Traffic scenario	10-km highway with 6 lanes in each direction
Evaluation section	5 km (from 2.5 – 7.5 km)
Vehicle generation process	Erlang distributed ($\mu = 2.25$ s)
Speed profile	From 20 to 40 m/s (4 m/s increase from outer to inner lane)
Access technology	ITS-G5 on Control Channel
Radio propagation model	Log-distance (exponent 2.35)
Transmission control profiles	CFP, i.e. 33 dBm @ 1 Hz + triggers FAC, i.e. $\mathcal{U}[3;33]$ dBm @ 17 Hz
Awareness ranges (= zones)	50 m, 150 m, 800 m
Target channel load	66 % CBT ratio
Metric	update delay mapped to distance errors ($a = 10$ m/s^2)

Table 5.1: Simulation parameters for the FAC demonstration.

dissemination rate metric is maximized for loads between approximately 0.65 and 0.7.

Finally, the resulting update delay CCDFs are mapped to the corresponding distance error CCDFs by using Equation (5.3). Therefore, a maximum deceleration of $-a = -10$ m/s^2 is assumed. The most important parameters are summarized in Table 5.1.

To demonstrate the FAC capability, it is compared with a reference constant transmit power profile, as a general representative for most of the current transmission control policies. To provide a fair comparison from an application's perspective, the reference constant power profile is configured to achieve the same maximum awareness range as with the FAC setup. Hence, the reference constant power profile corresponds to the Constant Full transmit Power (CFP) implementation from Section 4.3.

Figure 5.7 shows the mapped distance error CCDF curves within the critical zone 1 for CFP and FAC. Once again, the CCDF plots provide on the y-axis the probability $\mathbf{Pr}(D > d)$ that the obtained distance measures D exceed a certain distance threshold d on the x-axis.

Lets assume the considered platooning application would support position errors up to 1 m for vehicles within close vicinity (zone 1). Then, CFP is able to provide that accuracy with a probability of approximately $1 - 9 \cdot 10^{-3} = 99.1$ %. FAC, instead, is able to provide about $1 - 8 \cdot 10^{-4} = 99.92$ %. That corresponds to an improvement by more than a factor of 10. Nevertheless, the question still remains, if 99.92 % is already sufficient?

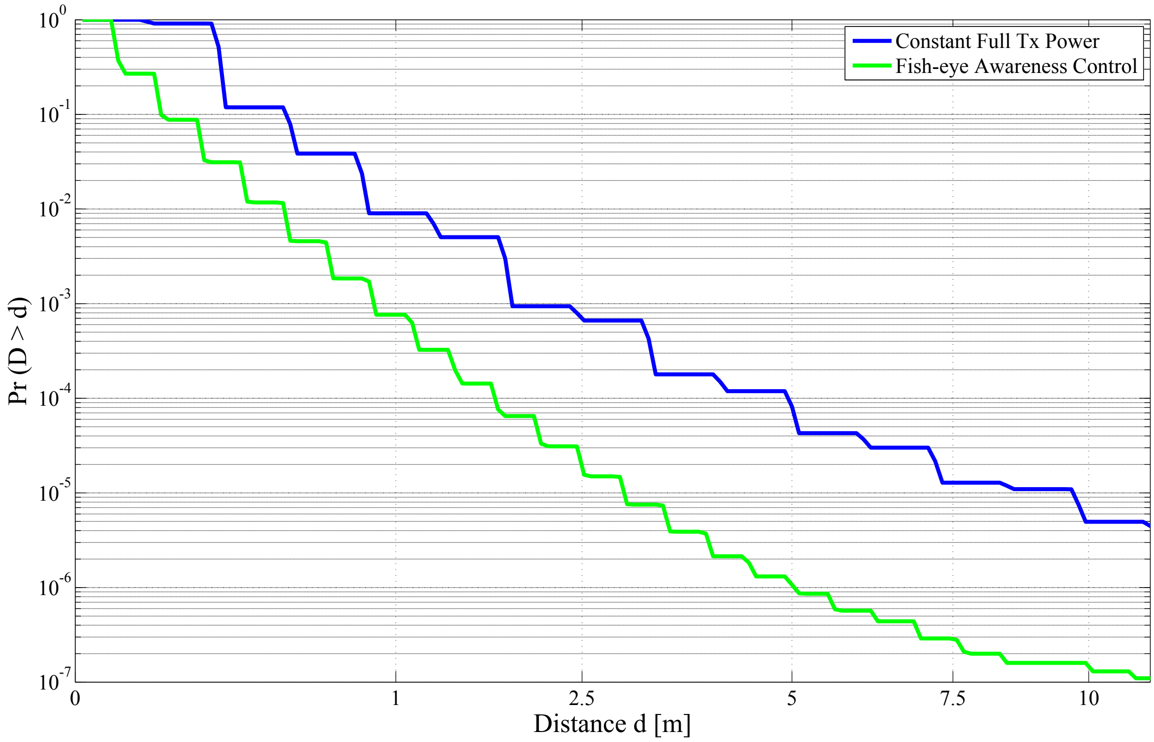


Figure 5.7: Accumulated (longitudinal) position errors for CFP and FAC within zone 1, represented as CCDF.

The answer to that question heavily depends on the design of the safety system. Using additional sensors, for instance, to determine the current position awareness by sensor data fusion could certainly increase the probability of providing the aforementioned accuracy. Another option could be to account for longer safety gaps between consecutive vehicles, in order to relax the required position accuracy. Assuming the inter-vehicle distances are increased such that the platooning application would support a maximum distance error of 5 m within zone 1. Then, CFP is able to provide that accuracy with a probability of approximately $1-7\cdot 10^{-5} = 99.993$ %, while FAC can provide about $1-10^{-6} = 99.9999$ %. That is an improvement by approximately factor 70.

Regardless of providing 99.92 % or 99.9999 %, the answer on whether one or the other is sufficient has to be left to the automotive safety systems engineers. The objective of this thesis is not to design an automotive safety system, including its requirements. The focus is exclusively on the communications part, and the demonstration of how VANET communications can be improved in the context of cooperative safety applications.

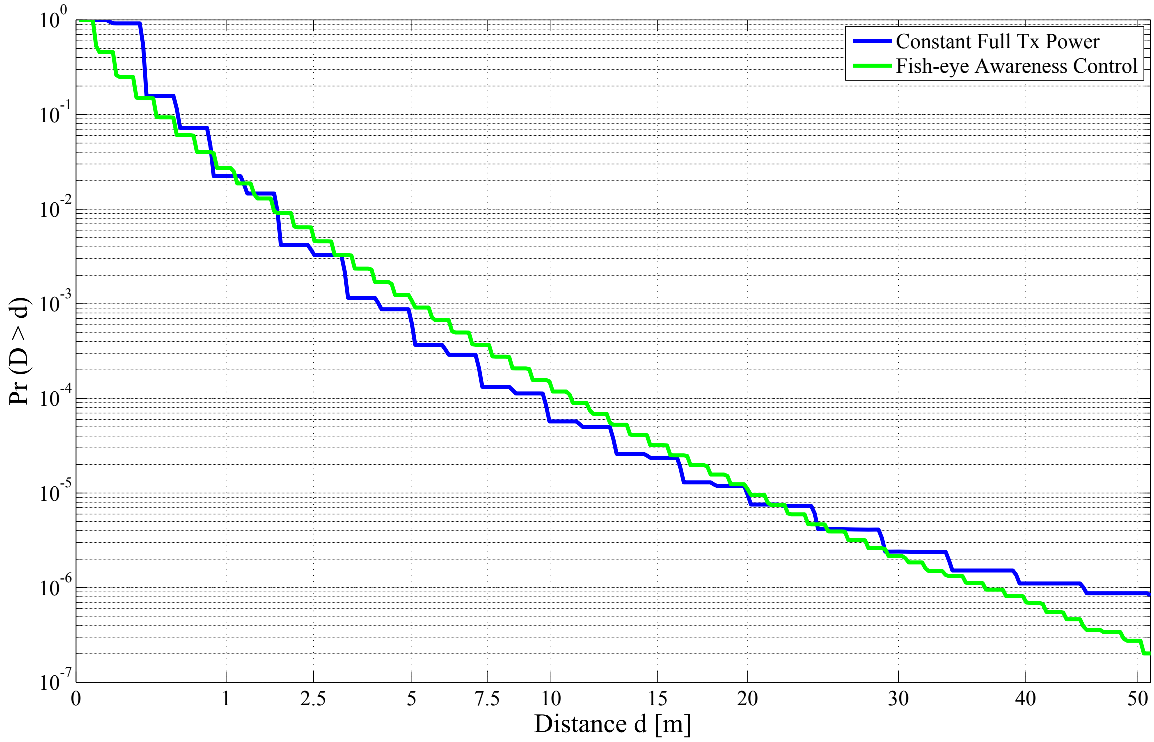


Figure 5.8: Accumulated (longitudinal) position errors for CFP and FAC within zone 2, represented as CCDF.

Figure 5.8 shows the mapped distance error CCDFs for CFP and FAC within zone 2. In that case, both schemes seem to provide similar performance.

Finally, Figure 5.9 compares CFP and FAC for zone 3. Contrary to Figure 5.7 and 5.8, it shows the CCDFs for the time-based update delay instead of the distance error. The reason is that for the large zone 3 the distance error assumptions introduced above might be not that suitable anymore. However, large zones may help, for instance, to detect new vehicles, entering the transmission range, with sufficient lead time. Then, the update delay CCDF may provide the probability that a vehicle remains undetected for a certain time frame T. Here as well, the question what time frame T is required may heavily depend on the corresponding safety application, and therefore, is up to the cooperative safety systems engineer. However, if CFP and FAC are compared with each other, the figure shows that within zone 3 FAC now performs worse than CFP. Please note that this behavior is not that bad, because it corresponds to the desired fish-eye concept introduced above. As the ranges have been increased, a soft degradation of the (position) awareness is accepted.

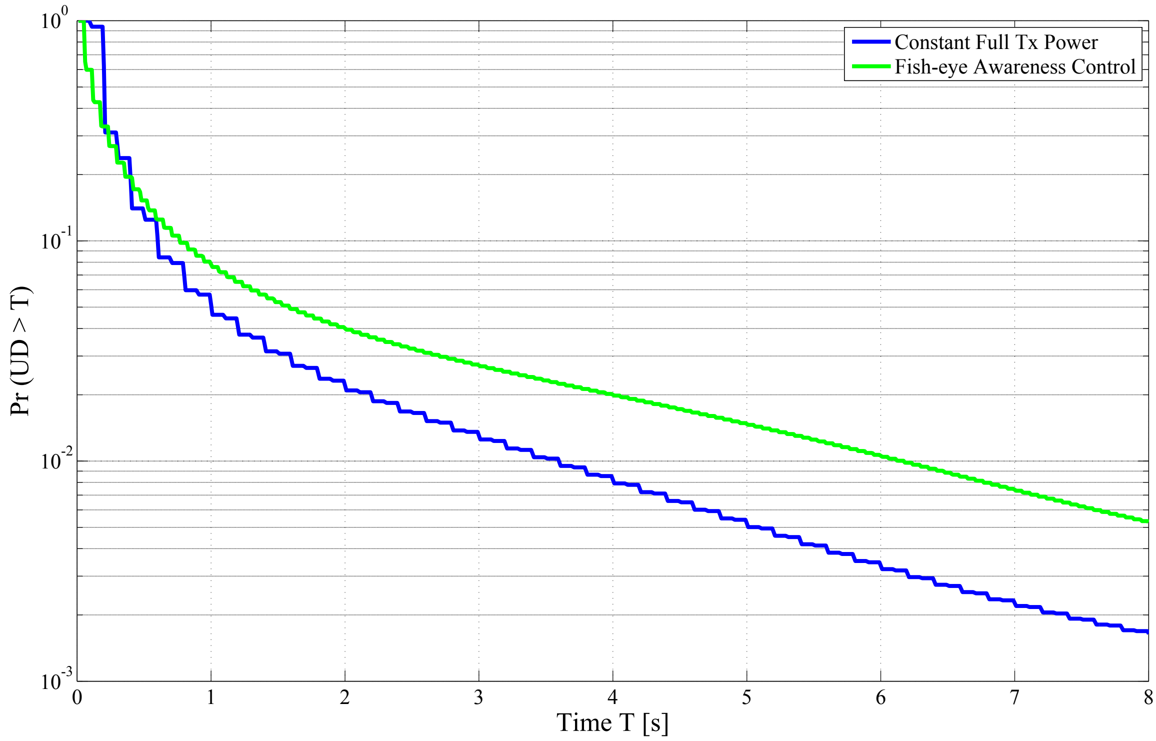


Figure 5.9: Update delay CCDFs for CFP and FAC within zone 3.

Altogether, the proposed FAC strategy is not the "jack of all trades". Instead, it provides the ability to adapt/relocate the awareness quality in space. Thus, the gain at close ranges (cf. Figure 5.7) is not for free, but comes at the cost of some loss at farther distances (cf. Figure 5.9). But especially in the context of traffic safety, where nearby vehicles are much more critical than farther ones, the proposed awareness control strategy deals much better with the wireless resources in VANETs, as their usage may be adapted to the spatial requirements of cooperative safety applications.

5.4.3 Joining Forces - Integration with Random Jitter and Increased CW

After demonstrating the spatial awareness control capabilities of FAC, and by association the significant performance improvement within the close vicinity, the last step within this thesis is to eventually investigate further possible improvements by joining FAC with the random transmit jitter and an increased CW. Therefore, the previously introduced FAC implementation is integrated with the random transmit jitter implementation from Section

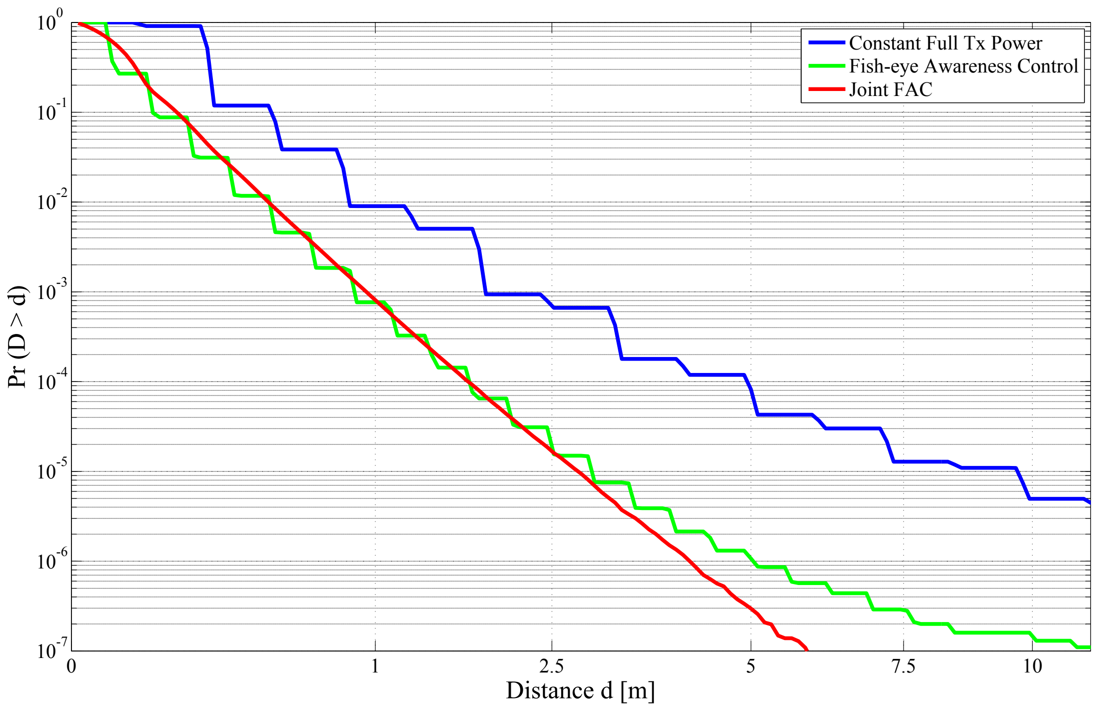


Figure 5.10: Position error performance of joint FAC within zone 1.

4.2, and an increased CW of 256 as discussed in Section 4.1. Please note that due to the outcome of the geo-backoff investigation, only the first step of the geo-backoff concept is considered here, i.e. just increasing the CW.

The corresponding results are presented in Figure 5.10, 5.11, and 5.12. They compare pure FAC with joint FAC, i.e. FAC + random transmit jitter + increased CW, for the three different zones, respectively. For the sake of completeness, CFP is shown as well. Similar to the previous discussion, the first two zones are considered with respect to the distance error, and the last zone focuses on the time-based update delay.

Within zone 1 (see Figure 5.10), joint FAC does not show any performance improvement up to distance error requirements of $d \approx 2.5$ m, compared with pure FAC. However, for distance error requirements above, joint FAC starts to outperform pure FAC. Considering $d = 5$ m, for instance, joint FAC is able to further reduce $\mathbf{Pr}(D > d)$ approximately by factor 3. But if only a maximum position error of 1 m is allowed, there is no improvement by joint FAC.

A similar behavior is shown for zone 2 (see Figure 5.11). For small position errors there is no improvement by joint FAC. But for approximately $d > 7.5$ m, joint FAC starts to outperform pure FAC. Considering zone 3, finally, there is no improvement at all by joint

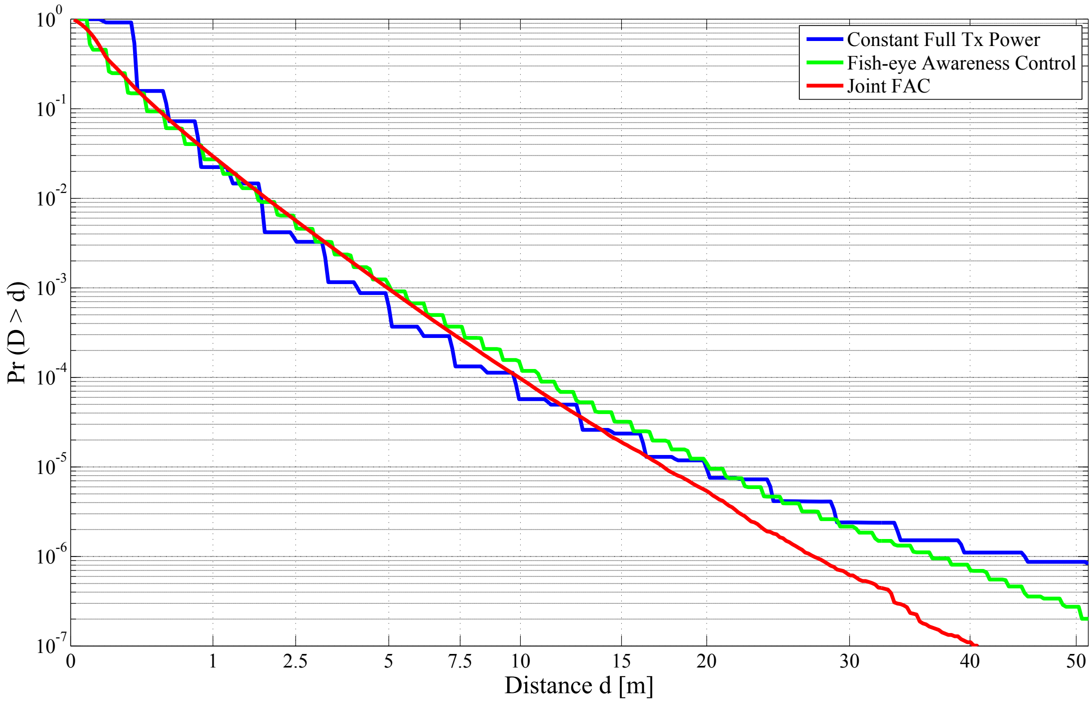


Figure 5.11: Position error performance of joint FAC within zone 2.

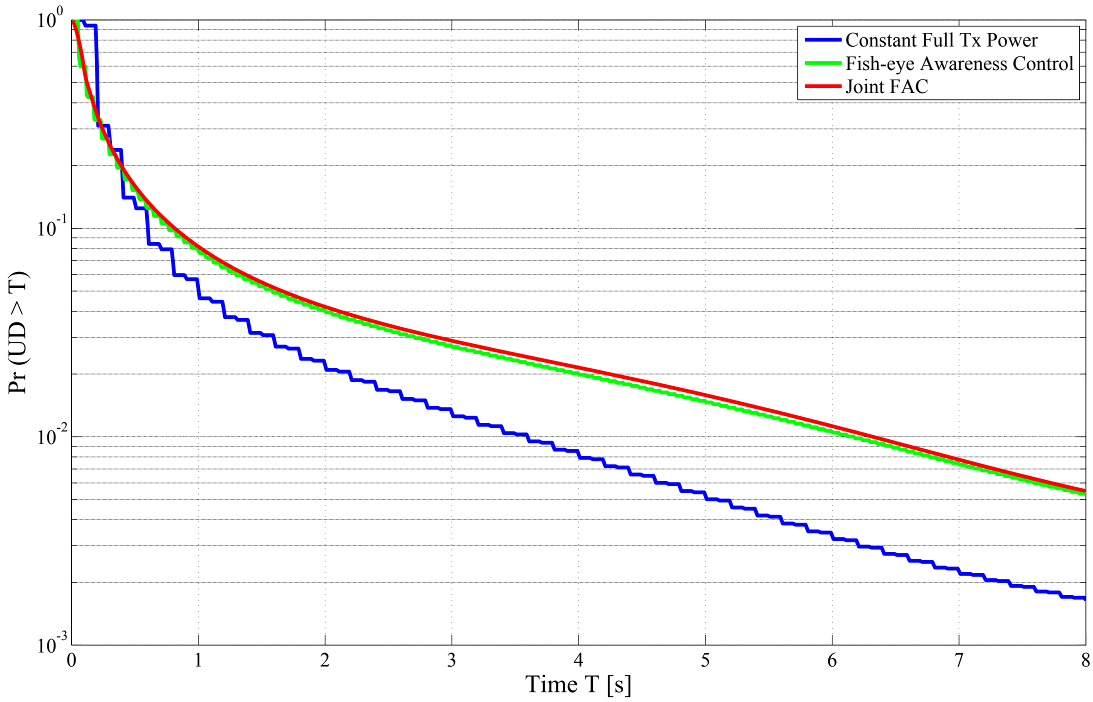


Figure 5.12: Update delay performance of joint FAC within zone 3.

FAC (see Figure 5.12).

Altogether, the results just presented should not imply that joint FAC is valueless. The reason is that requirement specifications may vary from application to application. Whereas an application that requires 1 m position accuracy within zone 1 would not benefit from joint FAC, another application that supports position errors up to 5 m certainly would, in fact by a factor of 3. Once again, whether a requirement might be based on a position accuracy of 1 m, 5 m, or something else, is not the focus of this thesis. That is more an issue for the corresponding application developer. The basic objective here was to demonstrate the capabilities of the introduced transmission adaptation concepts, as well as their combination.

5.5 Discussion

Current CAM-based safety applications require safety-critical information to be disseminated by using an undependable access technology. The resulting reliability issues are primarily addressed by transmission control strategies. However, due to the limited channel capacity, trade-offs must be found. As most of the current transmission control strategies aim at finding a single harmonized awareness operating point regarding range (power) and quality (rate), they might provide an optimal awareness on average, but may risk in being over-designed at high ranges and under-designed at close ranges.

In this thesis, a trade-off has been found by exploiting the distance-dependent criticality/relevance in the context of traffic safety. If RTPC is adapted to cover the critical zone with each transmission, it provides the same amount of updates there as a constant power approach operating at the same rate. However, as RTPC is able to reduce the load on the wireless channel, an additional TRC mechanism can reuse the gained resources by further increasing the rate. Then, much more updates are provided within the critical zone compared with a constant power approach operating at the same target channel load. Both together, RTPC and TRC, implement a new awareness control scheme called Fish-eye Awareness Control (FAC). It is able to adapt the awareness quality as a function of the awareness range. Whereas current transmission control policies are limited to define a single Operating Point (OP) regarding power and rate, FAC allows to define an operating pathway. This feature is illustrated by Figure 5.13. While RTPC only, first, shapes the pathway on the transmit power/rate plane, TRC in addition, finally, improves the quality along the entire range by further increasing the rate.

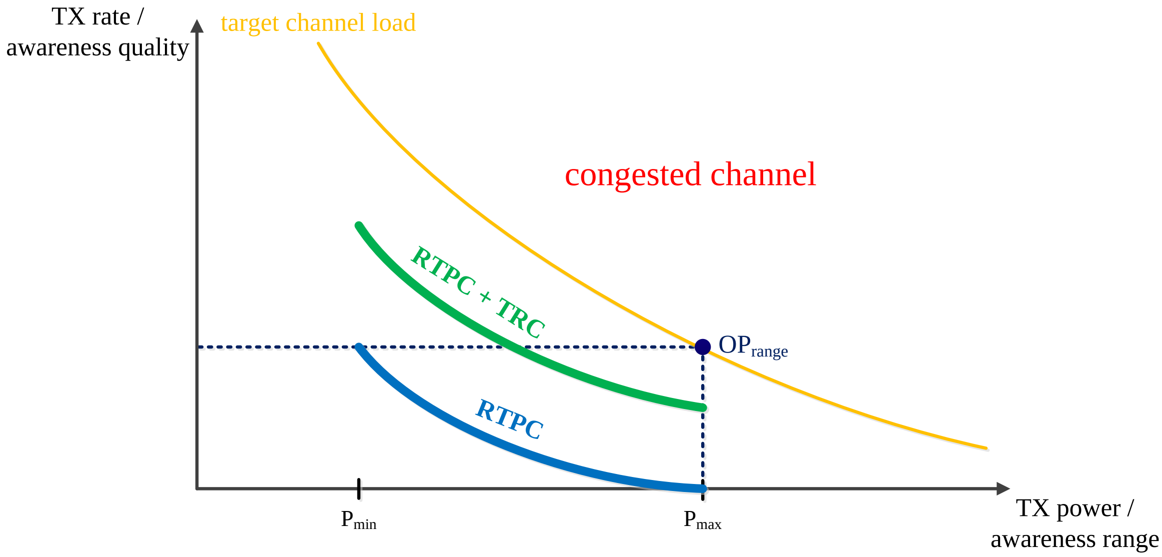


Figure 5.13: FAC overcomes the trade-off dilemma by operating along a pathway on the transmit power/rate plane.

However, the introduced FAC strategy is not the 'jack of all trades', but has limitations as well. It is not able to establish more resources for free. If the awareness quality is improved at close ranges, it will be reduced at farther distances at the same time. Metaphorically speaking, FAC relocates awareness quality from higher ranges to closer ones, while keeping the maximum required awareness range. Especially in the context of traffic safety, this behavior is absolutely acceptable as closer vehicles are much more critical (relevant) than farther ones.

Thanks to the awareness concept, the applied transmission control policy is completely transparent to the application. Regardless of using randomized or deterministic powers, and regardless of adding a random jitter or not, it does not matter, as long as the required awareness is fulfilled.

Chapter 6

Conclusion and Future Work

To conclude this thesis, the main contributions are summarized, and some directions for future work are provided.

6.1 Summary

This work has focused on new broadcast collision mitigation strategies, as well as their impact on cooperative safety applications, introduced by Vehicular Adhoc NETworks (VANETs) in the near future. The communications technology used in VANETs is referred to as ITS-G5, which is based on IEEE 802.11 (WLAN). Although parts of IEEE 802.11 have been slightly adapted to support vehicular environments, it never has been designed to support cooperative safety applications, which differ significantly in terms of communication policies and requirements. Especially the transmission of safety-related information in broadcast mode implicitly disables IEEE 802.11's collision avoidance mechanisms, and aggravates the problem of simultaneous transmissions caused by hidden terminals. As a result, current VANETs are known to suffer from a severe degradation of the communications performance, if the communication load is high, which is nothing unusual, considering multi-lane highways or urban intersections. Thus, using IEEE 802.11 as the basis for ITS-G5, in order to support cooperative safety in VANETs seems to be a paradox. This leads to the research question addressed within this thesis: *How to transmit safety-related information with sufficient reliability by using a potentially undependable communications technology?*

Whereas some related research studies propose alternative communications technologies, one important objective within this thesis is to maintain compatibility with the current ITS-G5 profile standard. With that objective in mind, the most common approach to the research question above is to reduce packet collisions in general by the use of appropriate transmission control policies. They aim at regulating the current transmit power or rate to control the generated load on the wireless channel. However, as almost all of them tend to converge to harmonized quasi-constant transmit powers, they still suffer from VANET-specific issues, like the transmit power/rate trade-off dilemma, or correlated packet collisions on the MAC layer, caused by the quasi-periodic broadcast pattern in combination with quasi-periodic relative mobility between vehicles.

The main contribution of this thesis is as follows: In order to take appropriate countermeasures, first, the problem of MAC-related packet collisions has been analyzed in detail. On the one hand, the results have shown that a significant amount of nearby collisions are caused by IEEE 802.11's contention procedure. About 45 %, for instance, are caused by vehicles, which have chosen the same backoff counter. On the other hand, consecutive packet collisions on the MAC layer rather show a correlated behavior. Especially in the context of regular safety-related broadcast transmissions, correlated packet collisions have a significant negative impact on the reliability of cooperative safety applications. These observations have been also confirmed by analytical studies. Therefor, the proposal was to model correlated packet collisions not by the traditional geometric distribution model, but rather following the Gilbert-Elliott model, which is widely used to consider correlated or burst errors. Whereas the geometric distribution model assumes perfect independence between consecutive packet losses, the Gilbert-Elliott model shows a better fit to the simulation data, which confirms the correlated behavior of MAC-related packet collisions.

Based on this observation, second, three new packet collision mitigation strategies have been proposed. They are designed to address the following issues:

- The objective of the *geo-backoff concept* is to reduce the nearby packet collisions by increasing the CW size on the one hand, and by exploiting geographic information for the backoff counter generation on the other hand. The results have shown that the nearby collisions can be reduced significantly, resulting in an improvement of the update delay performance by a factor of 10. However, they have shown as well that the performance improvement is dominated by the CW increase, while the contribution from the geographic-based backoff generation is negligible. Although increasing the CW implies an increasing latency, the results have also shown that a certain increase of the CW is absolutely tolerated by cooperative safety applications.

- The *random transmit jitter concept* addresses the problem of correlated packet collisions, by adding a controlled random jitter to the nominal broadcast interval. The results have shown significant improvements up to a factor of 300 for close ranges. However, if the load is increased, the random jitter, added at higher layers, is absorbed by MAC-based contention procedures, which introduce more synchronization again.

- Whereas the random transmit jitter concept mitigates correlated packet collisions in the time domain, the *concept of random transmit powers* addresses them in the space domain. If each vehicle selects the current transmit power randomly for each transmission, the collision and interference regions are shifted randomly in space. As a result, a possible receiver may not be located in the same collision or interference area for subsequent transmissions. Besides a significant reduction of recurring packet collisions, the random transmit power concept was able reduce the load on the wireless channel by a factor of about 2.5. Only the time-based update delay has not yet improved. The main reason is that much less transmissions are provided with increasing range.

In the final part, the previously introduced broadcast collision mitigation strategies have been reconsidered, but with focus on application-specific requirements. Particularly the transmit power/rate trade-off dilemma of current transmission control policies may result in an inefficient use of the wireless resources, as they aim at providing the same communications performance up to a certain range. However, especially in the context of traffic safety, the nearby vehicles may pose a higher danger, and thus, are much more relevant, than farther ones. Based on this behavior, a new awareness control strategy has been introduced, which implements a framework called *fish-eye awareness*. It allows to adapt the communications performance in space, even within single-hop transmissions. The first block is implemented by Random Transmit Power Control (RTPC), which manages to provide different levels of awareness quality at different ranges, while mitigating correlated packet collisions by randomizing them in space. Because RTPC is able to reduce the channel load, the second block is implemented by Transmit Rate Control (TRC), in order to benefit from the gained channel resources, by subsequently increasing the transmit rate, and by implication the awareness quality along the entire range. The proposed Fish-eye Awareness Control (FAC) strategy is evaluated by simulations, discussing cooperative driving applications like platooning. The results have shown that the FAC strategy is indeed able to adapt the awareness quality in space. Whereas the awareness quality has been improved by a factor of 10 to 70 in the nearby area, it has been reduced for ranges beyond 150 m. Consequently, the proposed awareness control strategy is not able to improve awareness along the entire range, but it provides a better spatial utilization of the wireless resources in the context of cooperative safety. To benefit from the first two collision mitigation concepts in addition, the geo-backoff and random transmit jitter has been integrated as well. However, whether an application may still benefit from that final integration typically depends on its specified requirements.

6.2 Outlook

During this work, a lot of new additional issues have been faced, which create many opportunities for future investigations:

In Section 3.2, the Gilbert-Elliott model has been used in order to confirm the hypothesis of correlated packet collisions on the MAC layer. However, it has been observed that the model's fitting quality decreases with increasing range. A possible explanation is that the correlation behavior is distance-dependent. Shivaldova *et al.* [118], therefore, proposed a range-dependent modified Gilbert-Elliott model. While they focused on correlated errors on PHY layer, similar investigations on correlated packet collisions on the MAC layer are still up to future work. Moreover, the proposed Gilbert-Elliott model has been used to derive the packet-based update delay. However, a derivation of the time-based update delay could be of much more interest, as it is more suitable to evaluate the communications performance. Finally, there are much more models, which describe packet errors with memory [67]. Investigating them could probably provide more accuracy, but may also increase complexity.

While this thesis has mainly focused on the MAC, future investigations should also integrate PHY layer effects like fading. More sophisticated receiver technologies also implement a PHY-related feature called frame capture, which is able to suppress the weaker signal of two packets, in case of a collision due to simultaneous transmissions. As described in [133], the frame capture performance heavily depends on the order and the difference of the arrival times, and finally on the SINR of both colliding packets. Hence, analyzing the impact of frame capture and fading on correlated packet collisions and the update delay performance seems to be an important next step, as the random transit jitter and the random transmit power concept randomly change the arrival times and the SINR, respectively.

One of the main objectives of this thesis was to demonstrate the fish-eye awareness capability of FAC for CAM-based safety applications like platooning. However, no approved requirement specifications regarding RX-centric metrics, like the update delay or inter-reception time, have been found in standards or literature. Hence, a mandatory objective for future activities must be on defining realistic requirement specifications for CAM-based CACC, but also for other cooperative applications, by exploiting RX-centric metrics, such as the update delay or inter-reception time.

The fish-eye awareness control strategy presented within this thesis is based on a simplified prototypical implementation of the two blocks, RTPC and TRC. Thus, there are still a lot of opportunities for more sophisticated enhancements. The RTPC implementation, for instance, has only considered a uniform distribution. Although carefully selected with respect to cooperative safety, it does not mean that the uniform distribution represents the "optimum". This leads to the next question: What is actually the "optimum"? Moreover, there are many other cooperative (safety) applications, which may have different spatial requirements. Those applications may also run in parallel at the same time. Then, an "optimal" random distribution has to be found, which is able to meet the spatial requirements of all of them. Currently, the random distribution of RTPC is defined by the application requirements. However, it might be worth to consider the current context as well (context awareness). Although the application remains the same, there might be a difference in driving on a multi-lane highway, or an ordinary highway. Such situation could be detected, for instance, by using position information in combination with maps. Also speed or turn signal information could be used to determine the current maneuver, which might be used to further improve the adaptation of RTPC. Finally, the simplified TRC implementation can be enhanced as well, for example, by applying more sophisticated solutions as presented in Section 2.4.

Although the proposed broadcast collision mitigation strategies have been only investigated in the context of ITS-G5 equipped vehicles, they could become even more relevant if pedestrians are considered for safety communications as well. Then, ITS-G5 might be integrated in mobile phones, in order to periodically broadcast pedestrian-related CAMs. However, a mobile phone that transmits periodically with high powers might be considered much more skeptically regarding health effects by electromagnetic radiation. As random transmit powers are able to reduce the transmission power on average, while keeping the awareness range, the concept could indeed arouse much more interest for future pedestrian ITS-G5.

Appendix A

Simulation Framework

Realistic VANET scenarios are too complex in general to be analyzed theoretically with sufficient validity. For that reason, a simulative approach is followed within this thesis.

There are different types of simulation frameworks used within the ITS research community. While frameworks like iTETRIS [2] or Veins [5] integrate both, a traffic simulator and a network simulator, in this thesis an isolated approach with the well-known network simulator ns-3 [3] has been selected. The reason for that is manifold: As this thesis is about broadcast collision mitigation on the MAC, the focus here is on the communications and not modeling or altering traffic. A MAC challenging scenario typically requires a high number of communicating vehicles, which in turn increases computational complexity, and by association the computation time. To keep them manageable, first, the computational overhead for the integration between traffic and network simulator is avoided, and second, the complexity of traffic modeling is reduced by implementing a simplified mobility in ns-3.

Ns-3 is an open-source discrete-event network simulator, developed for educational and research purposes. It provides a C++ library including a set of simulation models for different type of communications technologies and layers. More details on the ns-3 architecture and models are provided by the documentation on the ns-3 website [3].

The rest of this chapter starts by describing the traffic mobility modeling, followed by the communications implementation. Then, the transceiver model is explained, including the evaluation techniques based on that model. The last section, finally, describes the applied metrics within this simulation framework.

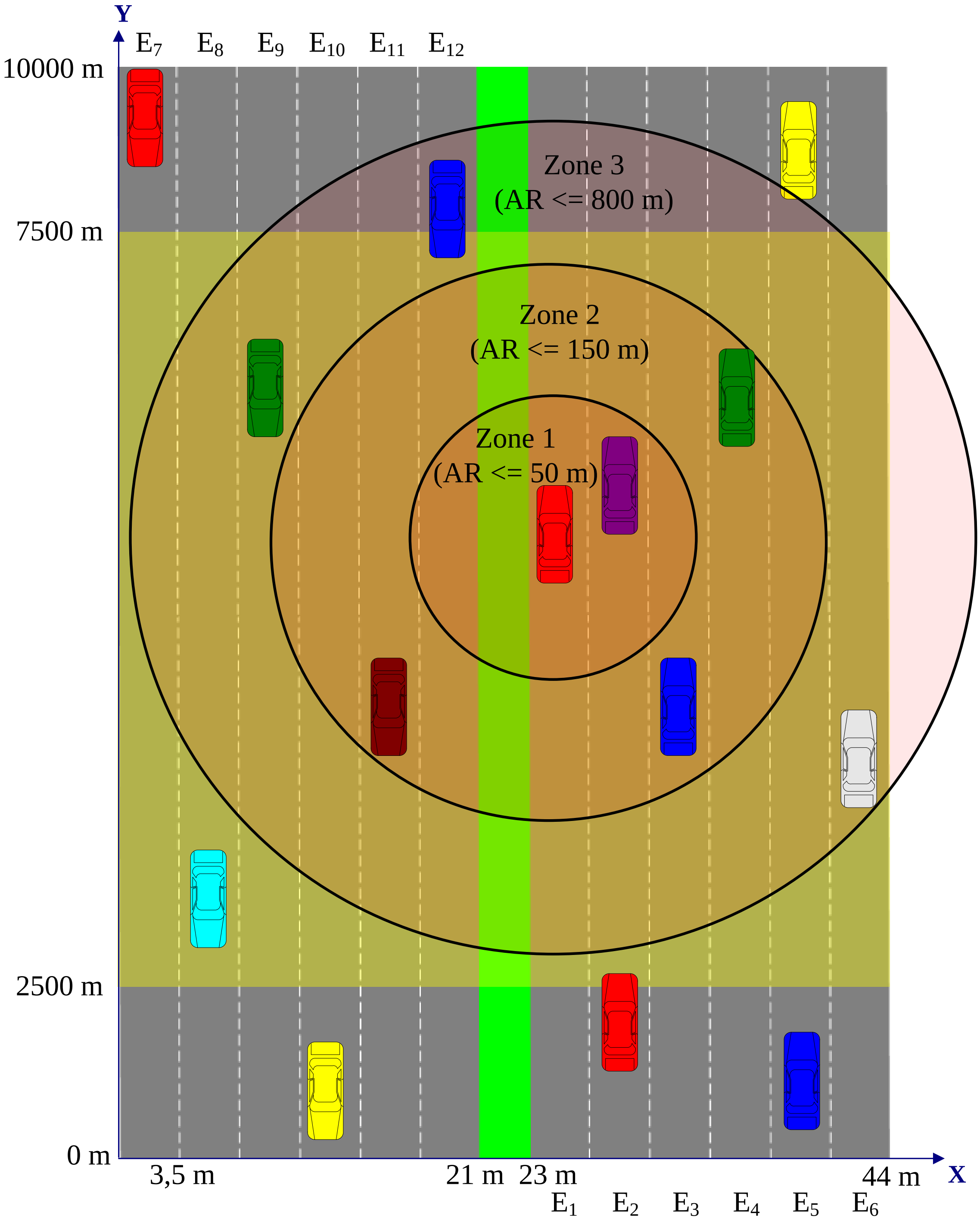


Figure A.1: The simulation scenario: a 10-km highway with six lanes in each direction. The vehicles are generated at the edges following an Erlang distribution. To remove the border effect, only vehicles within the evaluation section (from 2500 m to 7500 m) are evaluated.

Traffic scenario	10-km highway with 6 lanes in each direction
Evaluation section	5 km (from 2.5 – 7.5 km)
Vehicle generation process	Erlang distributed ($\mu = 2.25$ s)
Speed profile	From 20 to 40 m/s (4 m/s increase from outer to inner lane)

Table A.1: Basic traffic scenario and configuration.

A.1 Traffic Mobility Modeling

The basic traffic scenario is illustrated in Figure A.1. To obtain a MAC challenging communications setup, a 10-km multi-lane highway has been implemented. Vehicles are generated for each lane following an Erlang distribution (E_x) to control the timely separation between consecutive vehicles. The mean of these Erlang distributions has been set to a value of 2 seconds, which corresponds to the recommended time-ahead distance between consecutive vehicles in Germany, plus a minimum safety gap between vehicles of 0.25 s. As the focus of this thesis is on communications, the mobility of the vehicles is simplified, that means, no lane change maneuvers and no varying driving behaviors are considered. Moreover, all vehicles are driving at a constant speed, which is increased from the outer (20 m/s) to the inner lane (40 m/s) by an equidistant increment. Such mobility behavior can be seen as a worst case scenario with respect to the problem of correlated packet collisions on the MAC layer. To remove the border effect, only vehicles within the evaluation section between 2500 m and 7500 m are considered.

The basic traffic scenario and configuration are summarized in Table A.1.

A.2 Communications Modeling

In order to reduce the computational complexity as much as possible even within an isolated ns-3, only the relevant layers are considered and enhanced for the simulations.

Facilities layer

Starting from the top, a CAM application is implemented within ns-3 as a simplified representative for the facilities layer. On the one hand, it implements the default CAM generation policy based on the basic rate of 1 Hz and the additional mobility triggers as described in section 2.2. On the other hand, it also implements the proposed transmission

AC	**CW_min**	**CW_max**	**AIFS**
AC_VO	3	7	58 μs
AC_VI	7	15	71 μs
AC_BE	15	1023	110 μs
AC_BK	15	1023	149 μs

Table A.2: EDCA specific parameters for ITS-G5 (Source: Annex B in [10]).

policies for broadcast collision mitigation, like the random transmit jitter as well as the random transmit power concept. For the CAM payload, a size of 300 Bytes (including security) is selected. As the focus of this thesis is on MAC communications, CAMs are represented by dummy packets, i.e. the payload does not contain any valuable information. The packet tags from ns-3 are used to assign user priorities to packets, which are extracted on the MAC and mapped onto the corresponding AC according to EDCA, At the time the simulations have been performed, CAMs were foreseen to be transmitted on the AC_VI queue. Thus, the user priorities are configured accordingly. The packet tag class is also used to specify the current transmit power for each individual CAM, which is in particular relevant for the random transmit power concept.

As CAMs are still disseminated via single-hop broadcast, geo-networking has been neglected here.

Access layer

To provide an access layer that is compliant with the European Profile Standard ITS-G5 [8, 10], the ad hoc Wi-Fi implementation of ns-3 has been enhanced accordingly. That includes the correct setup of EDCA parameters like the AIFS and the minimum and maximum CW sizes for the different ACs, as well as OFDM PHY specific parameters. The applied configuration of both, the EDCA and the OFDM PHY, are summarized in Table A.2 and Table A.3, respectively.

Although specified at higher layers, the current transmit power is set here on a per

Parameter	**Value**
aSlotTime	13 μs
aSIFSTime	32 μs
aCWmin	15
aCWmax	1023

Table A.3: OFDM PHY specific parameters for ITS-G5 (Source: Annex B in [10]).

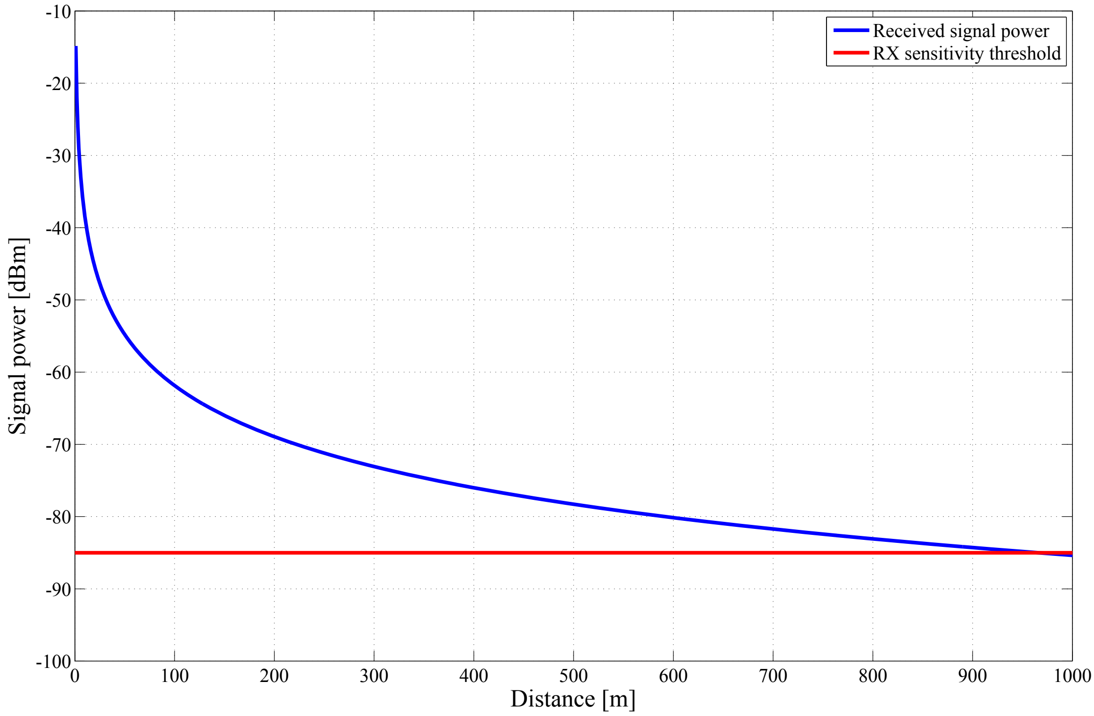


Figure A.2: Received signal power for the log-distance path loss model plotted against distance. In this case, a transmission power of 33 dBm is assumed.

packet basis, taking into account the transmit power control settings in [8, 46]. This includes possible transmit power levels from 0 dBm up to a maximum of 33 dBm on the control channel, with a power level increment of 0.5 dB. The default transmit power profile is composed by a simple constant transmit power approach as a general representative of current transmission control policies, which predominantly tend to converge to harmonized quasi-constant powers (see Section 2.6). To cover the worst case regarding channel load and packet collisions, vehicles will mainly broadcast at the transmit power limit of 33 dBm on the control channel [10].

Regarding the communication mode in ITS-G5, the default Wi-Fi implementation has been changed to OCB broadcast transmissions. As the backoff generation is part of the MAC protocol, the corresponding method in ns-3 has been enhanced by the two geo-backoff approaches described in Section 4.1.

For implementing the communications channel, a control channel is introduced with a bandwidth of 10 MHz. Its center frequency is configured to 5.900 GHz. The default data rate on the control channel is 6 Mbit/s, which is also applied for the simulations. Considering the aforementioned CAMs payload size of 300 Bytes, the transmission time of a CAM is approximately 0.5 ms.

As this thesis is mainly focusing on communication performance issues caused by the MAC layer, the objective is to remove PHY layer effects like fading or frame capture, in order to mitigate their impact on the corresponding performance metrics as much as possible. As a consequence, a simple log-distance model is used. It is described by the following equation:

$$L(r) = L_0 + 10 \cdot \gamma \cdot \log_{10}\left(\frac{r}{r_0}\right) \tag{A.1}$$

L_0 specifies the reference loss at reference distance r_0. In this simulation framework, L_0 has been set to 47.854475448 dB, which has been obtained by using Friis transmission formula in [53] for 5.9 GHz at $r_0 = 1$ m. The path loss exponent γ has been set to 2.35. Figure A.2 shows the resulting received signal power depending on the distance, assuming a transmission power of 33 dBm. Together with an applied receiver sensitivity threshold of −85 dBm, a maximum communication distance of almost 1 km (more precisely, 966 m) is achieved. That a maximum communication range of about 1 km is not unrealistic, has been demonstrated, for instance, by Gallagher *et al.* [55] as well as Schmidt *et al.* [110]. The CCA threshold is set to −65 dBm, which corresponds to the default of 20 dB above the receiver sensitivity threshold.

The used frame error model is SINR based. An example with three interfering packets is illustrated in Figure A.3. Based on the applied radio propagation model, the signal power is calculated for the corresponding packet. As the PHY layer is simplified, this signal power is assumed to be constant for the entire packet duration. Therefore, a piecewise linear SINR function for the duration of the currently receiving packet is determined. From that function, first, the Bit Error Rate (BER) and finally the Packet Error Rate (PER) is derived, dependent on the applied modulation and coding scheme. More details about the frame error model are given in the documentation of the ns-3 model library [3] and in [96].

The basic communications scenario and settings are summarized in Table A.4.

A.3 Transceiver Modeling and Evaluation Techniques

The transceiver model implemented in ns-3 is based on a state machine with the following states:

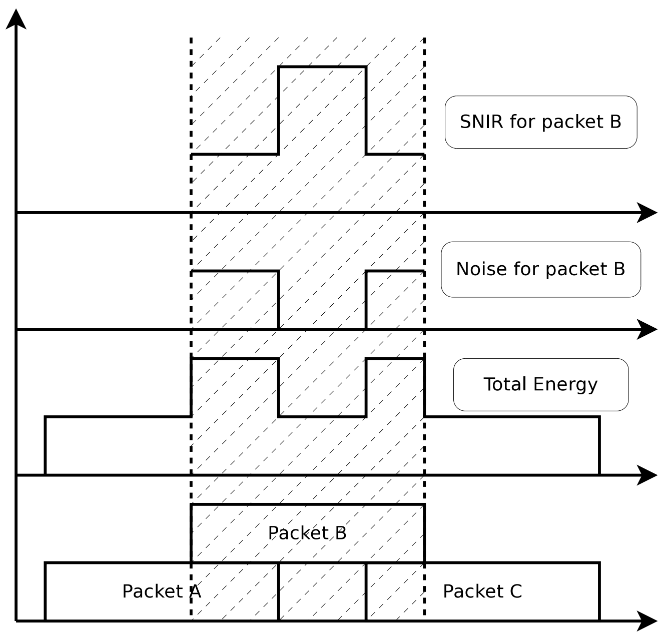


Figure A.3: SINR-based frame error model: Signal levels from packet A and packet C are treated as accumulative noise for packet B. Based on that a piecewise linear SINR function for packet B is determined. (Source: [3])

Default CAM generation policy	1 Hz + trigger conditions
CAM payload size	300 Byte
Access technology	ITS-G5 (based on IEEE 802.11 EDCA) on control channel (10 MHz bandwidth, located at 5.9 GHz)
Access Category (AC) for CAMs	AC_VI
Default data rate	6 Mbit/s
Transmit power setting	per packet from 0 dBm to 33 dBm (power level increment: 0.5 dB)
Receiver sensitivity threshold	−85 dBm
CCA threshold	−65dBm
Radio propagation model	Log distance ($L_0 = 47.854475448$ dB, $\gamma = 2.35$)
Maximum communication range	966 m @ 33 dBm

Table A.4: Basic communications scenario and configuration.

- IDLE: Channel is declared as idle.
- SWITCHING: The transceiver is switching to another channel (e.g. service channel).
- RX: The transceiver is receiving an incoming packet.
- TX: The transceiver is transmitting an own packet.
- CCA_BUSY: In case the transceiver could not sync on a packet (e.g. because the preamble was missed), it is not able to decode the rest. However, there is a certain remaining signal level on the channel for the duration of that packet. If this signal level is above the CCA threshold, the channel is declared as busy.

This model is the basis to detect packet collisions and to determine the channel load.

It should be noted that the SWITCHING state is not relevant within this framework, as the focus is exclusively on CAMs, which are considered to be transmitted on the control channel only.

A.3.1 Packet Collision Detection

In this simulation framework, *packet collisions* on the MAC layer are detected by the potential receiver (receiver-based), as illustrated in Figure A.4. It shows a simplified flow chart for a new incoming packet. Based on that, a packet collision is identified, if a new incoming packet is arriving, while the node is already processing an ongoing reception (RX-state) or an ongoing transmission (TX-state). In both cases, a packet collision is notified and the incoming packet is dropped. Although the packet has been dropped internally, a certain signal level will remain on the channel for the packet duration. Hence, after processing the current ongoing reception/transmission, it is checked if the remaining signal is above the CCA threshold and the channel has to be declared as busy (CCA_BUSY) accordingly. In case there is no ongoing reception/transmission, the node switches to the RX state and processes the new incoming packet accordingly.

In order to identify the different reasons for packet collisions, packet tags from ns-3 have been used to provide transmitter-related information at the receiver side. This information includes the chosen backoff counter, the position (in order to determine the distance between transmitter and receiver regarding hidden terminal situations), the previous channel state (IDLE or CCA_BUSY), and the transmission time on the PHY.

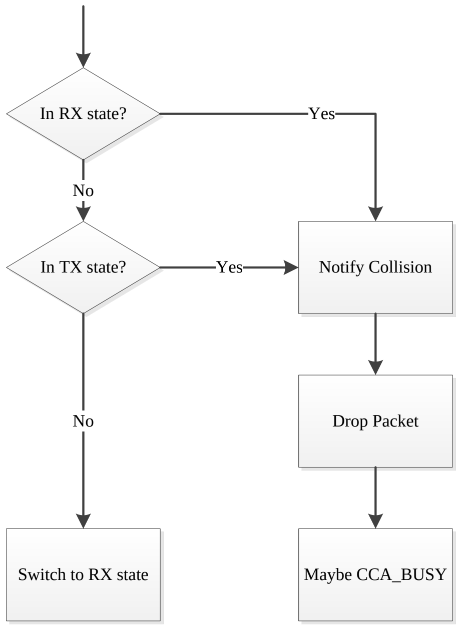


Figure A.4: Receiver-based detection of a packet collision in case of a new incoming packet.

A.3.2 Channel Load Measuring

There is no widely adopted standard yet in order to measure the channel load. Hence, in this framework the transceiver model introduced above is used to determine the channel load. For that purpose the amount of time, the channel is declared as busy, is measured. The channel is declared as busy, if the node is either in RX-state, in TX-state, or in CCA_BUSY-state. These busy periods are accumulated for 1 s, and then, the ratio is computed with respect to the 1 s reference interval. It should be noted, however, that the proposed approach might not be fully compliant with current practical mechanisms, as it is not based on regular channel probing at the PHY.

In order to provide the channel load distribution in space, the simulation environment has been enhanced by virtual static measurement stations, placed on the central dividing strip along the evaluation section of the highway with a spacing of 50 m next to each other.

A.4 Metrics

As the focus of this thesis is on the MAC performance, the entire evaluation is done on the MAC layer. For that purpose, the following metrics are considered:

- *Packet collision rate:* The number of packet collisions, normalized in time and space.

As the focus in this thesis is on the MAC layer, a packet collision here is defined by two overlapping packets at a certain receiver. It is detected by the simulation framework, if a new incoming packet arrives, while the receiver is already receiving another packet or is transmitting an own packet.

- *Packet collision ratio:* The ratio of a certain type of packet collisions divided by the total amount of packet collisions.
- *Channel Busy Time (CBT) ratio:* The amount of time, the channel is declared as busy, with respect to a certain time interval. Hence, the CBT ratio corresponds to the channel load.
- *Latency:* The delay, starting when the packet is delivered to the MAC on the transmitter side and stopping when the packet is received at the receiver side. This conventional end-to-end is applied in case of relevance.
- *Time-based Update Delay (UD):* As explained in Section 2.2, the update delay is used to assess the awareness in a simple manner from a communications perspective. It is defined as the time interval between two consecutive successfully received CAMs from the same transmitter (receiver-centric). As the accuracy of the received status information, e.g. position, speed, heading, is communications independent, accurate status information for the awareness quality is assumed here and the focus is only on its up-to-dateness[1]. The update delay measures the age of received CAM-updates per definition. Hence, it is able to represent the up-to-dateness and by implication, the quality of the awareness. To qualify the awareness at different ranges, the update delay is evaluated for various Awareness Ranges (ARs) or zones (see Figure A.1), that is, only for vehicles located within a considered AR.
- *Packet-based Update Delay (UD):* In this thesis, the update delay is also used to analyze correlated packet collisions. But instead of time, the packet-based update delay is defined by the gap between two consecutive successfully received CAMs from the same transmitter, in units of packets, which corresponds to the amount of consecutive lost packets plus the finally received one. The reason is that the time-based update delay does not distinguish between different transmission rates. Hence, it cannot be used to analyze consecutive packet losses, if the transmission rate is not

[1] This assumption does not fully comply with reality. However, as communications performance is the focus here, the accuracy behavior of status information is out of the scope of this thesis.

clearly defined. The packet-based update delay, instead, directly accumulates the number of subsequent lost packets up to and including the next successful reception from the same transmitter.

In other publications, e.g. [41, 49, 126], the update delay metric is better known as packet inter-arrival time or inter-reception time. However, the main difference is that a special representation called *Complementary Cumulative Distribution Function (CCDF)* is used. The advantages are manifold: First, the distribution keeps all the measured information, which is not the case by focusing on average values and/or confidence intervals. Second,the CCDF provides the complement of the T-window reliability, another application-related metric introduced in [20]. Third, as the focus is on the reliability of ITS-G5-based cooperative safety applications, the range of interest for the probability values is very close to 1. Although using a log-scaled probability axis, the CDF does not provide the necessary resolution around 1. By using the CCDF $= 1 - \text{CDF}$, a (theoretically) infinite resolution around the value of interest can be obtained. Because of the latter point, the CCDF representation is also used to evaluate the latency.

Appendix B

Résumé détaillé

B.1 Introduction

L'une des plus importantes visions en ce qui concerne les systèmes de transport intelligents (ITS: Intelligent Transport System) est de mettre en place un transport plus efficace, plus propre et plus sûr à l'avenir. Particulièrement en ce qui concerne la sécurité routière, une contribution significative est observée dans les réseaux ad hoc de véhicules (VANET: Vehicular Ad hoc NETwork) [61], où les véhicules et même les sites infrastructures sont équipés d'une technologie de communications dédiée, appelée ITS-G5 [8]. Le schéma de communication est basé sur la norme IEEE 802.11 [9], qui est utilisé dans les réseaux actuels sans fil (WLAN), avec de légères modifications pour prendre en charge les communications ad-hoc immédiates entre les entités VANET. La capacité d'échanger des informations pertinentes (par exemple: position, vitesse, direction) rapidement les uns avec les autres, va bien au-delà des capacités des radars embarqués et des capteurs basés sur la vision actuels. Par conséquent, les véhicules sont obligés de diffuser régulièrement des informations sur leur état actuel aux autres qui sont à proximité. En recevant ces informations, les véhicules sont capables de générer une vision plus nette de l'environnement actuel appelé "conscience" coopérative [91, 108, 17, 38, 93], qui fournit la base pour de nombreuses nouvelles applications véhiculaires coopératives [43].

Un exemple de nouvelle application coopérative est la mise en peloton. Une approche de mise en œuvre typique est basée sur la régulation adaptative de la vitesse (CACC: Cooperative Adaptive Cruise Control) [43], la version améliorée de la régulation adaptative de vitesse (ACC: Adaptive Cruise Control). Alors que l'ACC basé sur le radar n'est en mesure de suivre que le véhicule qui précède, ce qui peut même ne pas fonctionner en présence de virages serrés ou de ralentisseurs, le CACC est capable de suivre tous les véhicules coopératifs, au sein du peloton, qui sont à portée de communication. Ceci permet d'accélérer considérablement le temps de réaction en cas d'événements dangereux se produisant dans le peloton, ainsi qu'une meilleure adaptation de la boucle de contrôle pour atténuer l'effet d'onde de choc en cas de freinage brusque [107, 81].

Pour que le CACC soit en mesure de suivre les véhicules correspondants avec une fiabilité et une précision suffisantes, une technologie de communication extrêmement fiable est nécessaire, en particulier dans le contexte de la sécurité des véhicules. Comme tous les véhicules coopératifs doivent partager un canal radio commun (support), l'utilisation de stratégies de contrôle d'accès au support efficaces et évolutives (MAC: Medium Access Control) des stratégies joue par conséquent un rôle décisif. Au lieu d'une technologie de communication dédiée, qui serait en mesure de répondre exactement aux défis posés par les communications de sécurité de véhicule, divers organismes de normalisation (par exemple: ASTM, IEEE, ETSI, ISO) ont choisi la norme WLAN bien connue IEEE 802.11 [9] en tant que technologie des communications de base. Dans le contexte de VANET, il est généralement dénommé ITS-G5 en Europe, ou communications dédiées à courte portée (DSRC: Dedicated Short Range Communications) dans d'autres pays.

Le principal avantage de la norme WLAN, et la raison de son succès, vient de sa souplesse et de son adaptabilité. Par exemple, l'environnement difficile des véhicules (avec des connexions hautement transitoires) justifie un nouvel amendement de la référence IEEE 802.11: un nouveau mode de fonctionnement appelé 'hors du contexte d'un ensemble de services de base' (OCB: Outside the Context of a Basic service set)[1]. Ce mode active de véritables communications ad-hoc décentralisées entre les véhicules, sans aucune procédure d'association et d'authentification vers un point d'accès de type WLAN. Par conséquent, le mode OCB rend la connectivité VANET assez souple et sécuritaire.

B.2 Défis

Des applications coopératives de sécurité fiables nécessitent que la "conscience" de chaque véhicule soit très à jour. Cela nécessite alors que des diffusions générales d'un seul bond à des fins de sécurité soient régulièrement reçues avec une grande fiabilité. Même adaptée, la norme IEEE 802.11 n'est pas en mesure de fournir des communications fiables, c'est une source de préoccupations croissantes en ce qui concerne la capacité de l'ITS-G5 à

[1] Anciennement dénommé IEEE 802.11 p.

maintenir des applications de sécurité routière. L'une des principales raisons pour cela est le protocole MAC appliqué dans la norme IEEE 802.11.

La couche MAC coordonne l'accès au canal sans fil partagé entre plusieurs participants de la communication. Le schéma d'accès au canal de base dans IEEE 802.11 est mis en œuvre par le protocole d'accès multiple par détection de porteuse avec évitement de collision (CSMA/CA: Carrier Sense Multiple Access with Collision Avoidance) [9]. Il fonctionne de manière totalement décentralisée, ce qui rend le réseau très flexible et robuste. Cependant, le CSMA/CA est un protocole MAC basé sur la contention et l'aléatoire, un principe n'est pas en mesure de garantir un accès déterministe au canal sans fil. En outre, il peut même provoquer le risque d'accorder l'accès au canal sans fil à plusieurs nœuds en même temps, ce qui est habituellement connu comme étant une collision de paquets. Cette imperfection du MAC IEEE 802.11 se présente en particulier quand le nombre de nœuds de transmission augmente [77]. Le canal CSMA/CA est alors sur le point d'être congestionné, ce qui augmente la probabilité de causer des collisions de paquets. La performance de communication (fréquence) se dégrade en conséquence de manière significative [25]. Outre la question de la congestion de canal, le CSMA/CA souffre également du fameux problème du terminal caché [77]. Envisageons une transmission active entre deux nœuds. Un terminal caché est un troisième nœud qui est à portée du récepteur, mais hors de portée de l'émetteur correspondant. Le terminal caché n'étant, par conséquent, pas capable de détecter une transmission en cours de l'émetteur correspondant, peut aussi commencer à transmettre, et provoquer une collision de paquets au niveau du récepteur. Pour éviter de telles situations, un protocole d'établissement de liaison appelé RTS/CTS (Request To Send/Clear To Send [Demande d'émission/Prêt à émettre]) [9] a été introduit. En principe, l'émetteur, indique d'abord une réservation du canal sans fil (RTS) pour un paquet de données, ce qui est confirmé par le récepteur correspondant (CTS). Malheureusement, l'établissement de liaison RTS/CTS ne peut s'appliquer qu'à une communication en monodiffusion. Le problème du terminal caché demeure donc pour des diffusions générales.

Examinons maintenant les VANET basés sur IEEE 802.11 et leurs propriétés. En particulier dans des scénarios de trafic dense, il existe un grand nombre de véhicules en train de transmettre, par exemple, dans un scénario d'autoroute à plusieurs voies comme représenté à la Figure B.1. L'exigence que chaque véhicule doit transmettre régulièrement des informations relatives à la sécurité à la portée maximale sur un canal CSMA/CA à capacité limitée, le congestionnera sans doute. En outre, la plupart des transmissions relatives à la sécurité sont diffusées. En conséquence, l'ITS-G5 souffre en plus de

Figure B.1: Particulièrement dans des scénarios de trafic très dense, chaque véhicule transmet régulièrement des informations relatives à la sécurité à la portée maximale engorge généralement le canal sans fil (Source: Wikimedia Commons).

sévères conditions de terminal caché, ce qui complique de façon significative le problème de collisions de paquets [49]. Dans l'ensemble, il a particulièrement été démontré que les VANET souffrent d'une dégradation importante des performances de communications [75, 40, 84, 28, 35, 27, 113, 122, 74, 132, 37]. En effet, la distribution de diffusion dans les VANET est cruciale, ce qui fait que l'ITS-G5 se retrouve confronté à un dilemme majeur: *Comment transmettre des informations relatives à la sécurité avec une fiabilité suffisante en utilisant une technologie MAC potentiellement peu fiable?*

L'approche la plus commune pour limiter les collisions de paquets pendant l'accès au canal est d'éviter un canal encombré. Cela a fait l'objet de nombreuses études, par exemple [54, 131, 18, 90, 21, 123, 99, 46, 49]. Elles régulent les paramètres de transmission, comme l'énergie ou le la fréquence, pour limiter la charge sur le canal sans fil. Ceci est communément dénommé contrôle de congestion. Au lieu de contrôler la charge du canal, les autres adaptent les mêmes paramètres de transmission en mettant l'accent sur le respect des exigences de l'application, ce qui est généralement appelé contrôle de la "conscience", par exemple [102, 57, 63, 114, 108, 120, 115, 126].

Indépendamment de l'encombrement ou du contrôle de la "conscience", presque tous les implémentations gardent une puissance d'émission constante ou font en sorte que tous les noeuds proches convergent vers une puissance ou fréquence d'émission harmonisé quasi-constant. Toutefois, en raison de cette caractéristique, les problèmes suivants spécifiques aux VANET demeurent: Alors que les approches de contrôle de congestion actuels visent en général, à atténuer les collisions de paquets relatives au MAC en faisant fonctionner le canal dans un état non encombré, ils ne prennent en considération ni leurs causes ni leur comportement spatial et temporel. Cependant, les modes de communication principalement périodiques, combinés à une mobilité relative lente entre les véhicules, par exemple, la présence d'un peloton sur une autoroute, peut entraîner des collisions de paquets récurrents chez le même récepteur. De telles collisions de paquets corrélées peuvent rapidement causer une connaissance obsolète des autres véhicules à proximité, étant donné qu'aucune nouvelle mise à jour d'état n'est reçue sur une période plus longue.

Les schémas de répétition aléatoires, par exemple [140], sont une solution pour régler ce problème. Cependant, comme ils répètent de façon aléatoire la transmission du même message à plusieurs reprises, ils augmentent implicitement encore la charge sur le canal sans fil, ce qui est plutôt une approche contre-productive, si le canal est déjà dans un état congestionné.

Une autre partie de la communauté de recherche pense, toutefois, que des technologies alternatives, comme l'accès multiple par répartition dans le temps autogéré (STDMA: Self-organized Time Division Multiple Access) [29], l'Aloha mobile à tranches (MS-Aloha: Mobile Slotted Aloha) [112], ou même des solutions cellulaires [86], peuvent mieux répondre aux politiques de transmission pour les communications de sécurité des véhicules. Comme WLAN, STDMA et MS-Aloha sont des approches entièrement décentralisées. Comme les deux sont basées sur les créneaux horaires réservés, elles conviennent mieux en effet à la configuration de communication périodique des diffusions générales relatives à la sécurité. Cependant, contrairement au WLAN, elles nécessitent une synchronisation temporelle bien précise entre les nœuds, ce qui est encore plus difficile dans les réseaux décentralisés. Tandis que le WLAN est une technologie mature dans le contexte des réseaux mobiles ad-hoc, qui ont été étudiés et ont montré leur praticabilité pendant plus d'une décennie, STDMA et MS-Aloha sont relativement de nouvelles approches. Par conséquent, leurs partisans ont eu des difficultés à convaincre les organismes de normalisation de leur aptitude pratique dans un proche avenir. Le désavantage des approches cellulaires actuels, comme le système universel de télécommunication mobile (UMTS: Unviversial Mobile Telecommunications System) ou la technologie d'évolution à long terme (LTE: Long Term Evolution), est leur structure de réseau centralisée. Les informations pertinentes, destinées aux véhicules proches, doivent d'abord être transmises par la station de base au réseau cellulaire fédérateur, avant d'arriver à la destination finale, qui pourrait éventuellement être situé à seulement quelques mètres devant ou derrière. Cela peut augmenter la latence des informations relatives à la sécurité de manière significative [137]. Un autre problème des réseaux cellulaires centralisés est la couverture requise par les stations de base, ce qui n'est pas toujours obtenu, en particulier dans les zones rurales. Cependant, les activités de recherche dans les réseaux cellulaires progressent de manière significative, également en ce qui concerne les capacités ad hoc comme les communications dispositif à dispositif (D2D: Device-to-Device) dans le LTE avancé [83].

Réduire les collisions de paquets sur la couche MAC en réduisant la charge du canal est absolument raisonnable. Le défi est, cependant, d'effectuer un contrôle de congestion sans violer la portée de la "conscience" et les exigences de qualité des applications coopératives de sécurité. Par conséquent, un compromis optimal entre la puissance et la fréquence de transmission doit être trouvé, parce que les deux ont un impact proportionnel sur la "conscience" et la charge du canal. Bien qu'augmenter la puissance d'émission puisse améliorer la couverture, et par voie de conséquence, la portée de la "conscience", il augmente également la charge du canal dans l'espace, puisque les transmissions peuvent occuper le canal partagé jusqu'aux plages les plus élevées. De même, augmenter la fréquence de transmission peut améliorer la qualité de la "conscience" en fournissant des mises à jour de l'état du véhicule plus souvent, mais cela augmente la charge de canal au fil du temps, puisque davantage de messages sont transmis. Ce comportement peut conduire au dilemme suivant en matière de compromis: Afin de réduire la charge de canal, il est possible de réduire la puissance d'émission, mais au risque de ne plus satisfaire la portée de connaissance requise, ou il est possible de réduire la fréquence d'émission, mais au risque de ne pas satisfaire la qualité de connaissance nécessaire.

Une approche intéressante pour trouver un tel compromis entre puissance et fréquence d'émission est proposée, par exemple, par Tielert *et al.* [127]. Les auteurs proposent, d'abord, de cartographier la distance souhaitée de la cible pour obtenir la puissance d'émission correspondante, puis d'adapter la vitesse de transmission pour maintenir une certaine charge de canal cible. Bien qu'une telle cartographie de la puissance de transmission en fonction de la distance de la cible puisse être possible dans des conditions spécifiques, elle est relativement peu fiable dans des conditions plus générales, en raison de l'imprévisibilité de la propagation des ondes radio sans fil, particulièrement dans des environnements contenant des véhicules. En outre, fixer la puissance de transmission afin de couvrir une certaine distance cible contient encore le problème des collisions de paquets corrélées comme décrit dans le paragraphe précédent. En outre, les futurs véhicules n'exécuteront pas qu'une seule application de sécurité coopérative, mais plusieurs en même temps. Trouver, alors, une seule paire puissance/fréquence en mesure de remplir les exigences de la portée et de la qualité de la "conscience" de toutes les applications, devient encore plus difficile.

B.3 Objectifs et méthodologie

Indépendamment du fait que les technologies alternatives puissent faire preuve d'une meilleure aptitude quant aux communications de sécurité des véhicules, les organismes de normalisation se sont prononcés en faveur d'IEEE 802.11 que la technologie de première génération des ITS-G5. Ainsi, ce travail adresse la compatibilité subsistant avec l'ITS-G5 actuel et aborde les grands défis que présente la couche MAC à prendre en charge la sécurité coopérative à l'aide de diffusions générales sans relais. Sur cette base, les objectifs de ce travail sont comme suit :

- *Comprendre les collisions de paquets:* Alors que les schémas de contrôle de congestion actuels réduisent simplement la charge du canal sans fil afin d'atténuer les collisions de paquets sur la couche MAC, cette thèse vise à étudier leurs différentes raisons, ainsi que leur apparition dans l'espace et dans le temps.

- *Atténuation des collisions de paquets de la proximité:* Comme les véhicules proches sont beaucoup plus critiques que ceux qui sont plus éloignés, un autre objectif est d'atténuer en particulier les collisions de paquets de la proximité.

- *Décorrélation des collisions de paquets corrélées:* Ce sont surtout les collisions de paquets corrélés qui dégradent considérablement la qualité de la "conscience". Pour cette raison, cette thèse vise à décorréler les collisions de paquets corrélées.

- *L'assouplissement du dilemme quant au compromis puissance/fréquence d'émission:* Atténuer les collisions de paquets sans violer les exigences de portée et de qualité de l'application est très difficile. Par conséquent, l'objectif final de ce travail est d'assouplir le dilemme quant au compromis puissance/fréquence d'émission.

Afin d'atteindre ces objectifs, la méthodologie suivante est proposée:

Étude des collisions de paquets

Les collisions de paquets relatives au MAC sont probablement les facteurs de performance les plus limitants d'ITS-G5 dans les scénarios de trafic dense. La majorité des approches de contrôle des transmissions en cours vise à réduire la probabilité générale de collisions de paquets à l'aide d'une simple réduction de la charge du canal de communication sans fil. Cependant, ils n'abordent pas expressément la source des collisions de paquets causées par le MAC.

En particulier, la mobilité des véhicules des VANET et leur politique de transmission peuvent avoir un impact significatif sur la performance du MAC. Par conséquent, la première étape consiste à analyser les collisions de paquets en prenant en compte leurs causes, ainsi que leur comportement en termes d'apparition spatiale et temporelle. Comme l'objectif de ce travail est sur la couche MAC, la plupart des effets de la couche physique (PHY), comme l'affaiblissement ou la capture, sont intentionnellement négligés, afin de limiter l'impact de la couche PHY sur la performance du protocole MAC.

L'espoir est d'obtenir une compréhension suffisante des collisions de paquets relatives au MAC. Ce n'est que si le problème des collisions de paquets est bien compris que des contre-mesures appropriées peuvent être prises pour les atténuer en conséquence.

Identification des concepts d'atténuation de collision

En fonction des résultats de l'analyse des collisions de paquets, des concepts possibles d'atténuation de collisions sont identifiés lors de cette étape. Il convient de noter que l'espace des solutions est limitée puisque ce travail adresse la compatibilité subsistant avec la norme actuelle. Par conséquent, les approches alternatives se basant sur le TDMA ne sont pas considérées comme des solutions possibles dans cette thèse. Le maintien de la compatibilité avec la norme actuelle comprend aussi le fait que la "conscience" coopérative est toujours fournie par des diffusions générales relatives à la sécurité sans relais. Cela signifie que le problème des collisions causé par les terminaux cachés demeure. Ce travail met donc l'accent sur les aspects temporels et spatiaux des collisions de paquets dans le contexte de la sécurité routière. Dans ce contexte, par exemple, les véhicules proches sont beaucoup plus pertinents que ceux qui sont plus éloignés. La raison en est que seuls les véhicules proches peuvent présenter un danger imminent en ce qui concerne une collision physique entre véhicules. Un des objectifs est donc de réduire les collisions de paquets dans la région à proximité. Une quantité importante des collisions de paquets de proximité est causée par les véhicules ayant choisi le même compteur de temporisation. Un même compteur de temporisation signifie le même temps d'attente jusqu'à l'accès au canal, ce qui se traduit généralement par une collision de paquets. Ce travail étudie donc le potentiel du compteur de temporisation et sa procédure de génération afin d'atténuer les collisions de paquets entre véhicules proches.

En particulier, les collisions de paquets corrélés dégradent considérablement la "conscience" des autres véhicules à proximité. Elles sont causées par le mode de transmission essentiellement périodique des diffusions relatives à la sécurité, combinées avec la mobilité relative lente existant entre les véhicules voisins, par exemple en présence d'un peloton sur une autoroute. Des contre-mesures possibles peuvent s'appuyer soit sur le fait de rendre les diffusions relatives à la sécurité moins périodiques, soit sur le faite de rendre la mobilité relative entre véhicules plus dynamique voire même aléatoire. Bien qu'une "conscience" coopérative à jour nécessite de recevoir des diffusions relatives à la sécurité d'une manière régulière, il n'est pas nécessaire de les recevoir exactement à une certaine fréquence périodique fixe. Il peut être suffisant de recevoir des diffusions relatives à la sécurité à une certaine fréquence moyenne, et en acceptant une certaine variation autour de l'intervalle de diffusion nominal afin de rompre la périodicité stricte permettant d'atténuer les collisions de paquets corrélées dans le temps. Alors que rendre aléatoire la mobilité des véhicules n'est guère possible dans la pratique, une adaptation de la puissance de transmission semble être beaucoup plus prometteuse. Bien qu'une augmentation de la puissance d'émission puisse être l'équivalent d'un émetteur se rapprochant, une réduction peut être équivalente à un émetteur s'éloignant. Par conséquent, une randomisation des puissances de transmission pourrait simuler la mobilité aléatoire souhaitée entre véhicules voisins.

Impact sur le MAC

La procédure de génération de la temporisation est une partie essentielle du mécanisme MAC, et a donc un impact direct sur l'apparition de collisions de paquets. L'adaptation la plus probablement intuitive de la procédure de génération de la temporisation est d'augmenter le nombre de valeurs disponibles dans le compteur de temporisation comme proposé par exemple dans [124]. Bien que cela réduise la probabilité de choisir le même compteur de temporisation de manière générale, elle ne prend pas en compte la situation spatiale entre véhicules comme proche ou éloigné. Par conséquent, ce travail vise à générer un compteur de temporisation actuel dépendant de la distribution spatiale des véhicules. Alors qu'avec l'approche actuelle, la probabilité de choisir le même compteur de temporisation est le même pour tous les véhicules en lice, l'objectif principal ici est de réduire cette probabilité plus les véhicules sont proches les uns des autres.

Alors que la procédure de génération de la temporisation est une composante directe du MAC, la politique de transmission, s'appuyant sur l'intervalle ou la puissance, ne l'est pas. Cependant, la politique de transmission a toujours un impact significatif sur la performance MAC. Une adaptation de la puissance de transmission se traduit par une adaptation de la plage de transmission, ce qui peut alors adapter la situation de collision actuelle dans l'espace. Une collision de paquets observée à un certain endroit, par exemple, peut ne pas se reproduire à nouveau au même endroit, puisque les plages de transmission des deux émetteurs peuvent avoir changé. Veuillez noter qu'une adaptation de la puissance d'émission ne signifie pas nécessairement que les collisions de paquets sont réduites de manière générale. Si une collision de paquets ne se reproduit pas à un certain endroit, elle a peut-être été simplement déplacée ailleurs. Toutefois, le point important ici est que les collisions de paquets corrélées deviennent plus décorrélées dans l'espace. Au lieu de l'espace, une adaptation de l'intervalle de transmission peut affecter l'apparition de collisions de paquets dans le temps. Une collision de paquets entre deux émetteurs peut ne pas se reproduire lors de la prochaine transmission, puisque les deux pourraient transmettre leur prochain paquet à des moments différents. Cependant, la même conclusion que ci-dessus s'applique ici aussi. Si une collision de paquets entre deux émetteurs ne se reproduit pas à nouveau, cela ne signifie pas nécessairement que les collisions de paquets sont réduites en général, puisque de nouvelles collisions avec d'autres terminaux (cachés) peuvent être induites. Cependant, dans le contexte de la "conscience" coopérative, l'objectif principal ici est de rendre les collisions de paquets corrélées plus décorrélées dans le temps.

Impact sur les applications

Alors que dans la partie précédente, les concepts d'atténuation de collisions identifiés sont étudiés en tenant compte des collisions de paquets causées par le protocole MAC, dans la dernière partie, leur impact sur les applications est analysé. Finalement, c'est l'application de sécurité qui doit fonctionner avec une fiabilité suffisante. Dans le contexte de la sécurité coopérative, la fiabilité d'une application s'appuie généralement sur la

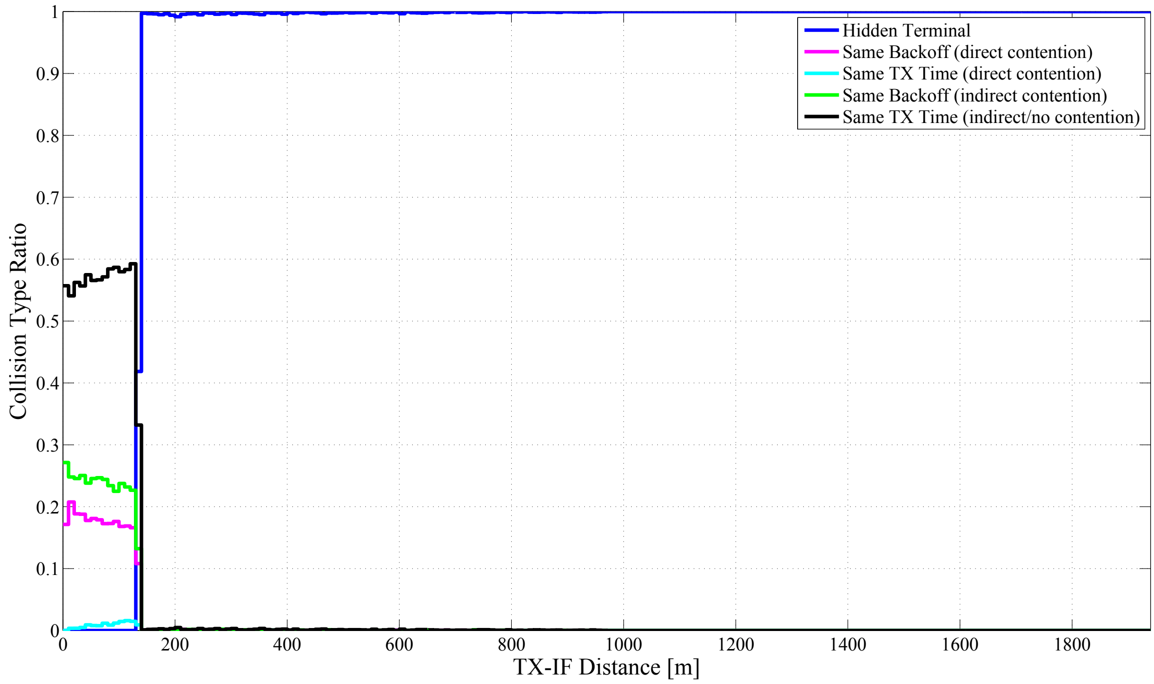


Figure B.2: Quantité relative de collisions de paquets, divisée par les différents types de collisions, tracée en fonction de la distance entre les deux émetteurs induisant la collision (TX et IF).

"conscience" coopérative. En particulier, l'intervalle et la puissance de transmission ont respectivement un impact significatif sur la qualité et la portée de la "conscience". Alors que la puissance d'émission définit la portée jusqu'à laquelle l'information relative à la sécurité est transmise, l'intervalle de transmission indique quand la prochaine mise à jour relative à la sécurité est fournie aux autres véhicules à proximité. En raison de cette observation, l'adaptation de la puissance ou de l'intervalle de transmission peut fournir la clé permettant d'adapter la "conscience" coopérative en fonction des besoins de l'application.

B.4 Contribution

Suivre la méthodologie proposée ci-dessus expose la contribution principale de cette thèse:

B.4.1 Analyse des collisions de paquets

Afin de prendre les contre-mesures appropriées, le problème des collisions de paquets relatives au MAC a d'abord été analysé en détail au moyen de nombreuses simulations. Prenez

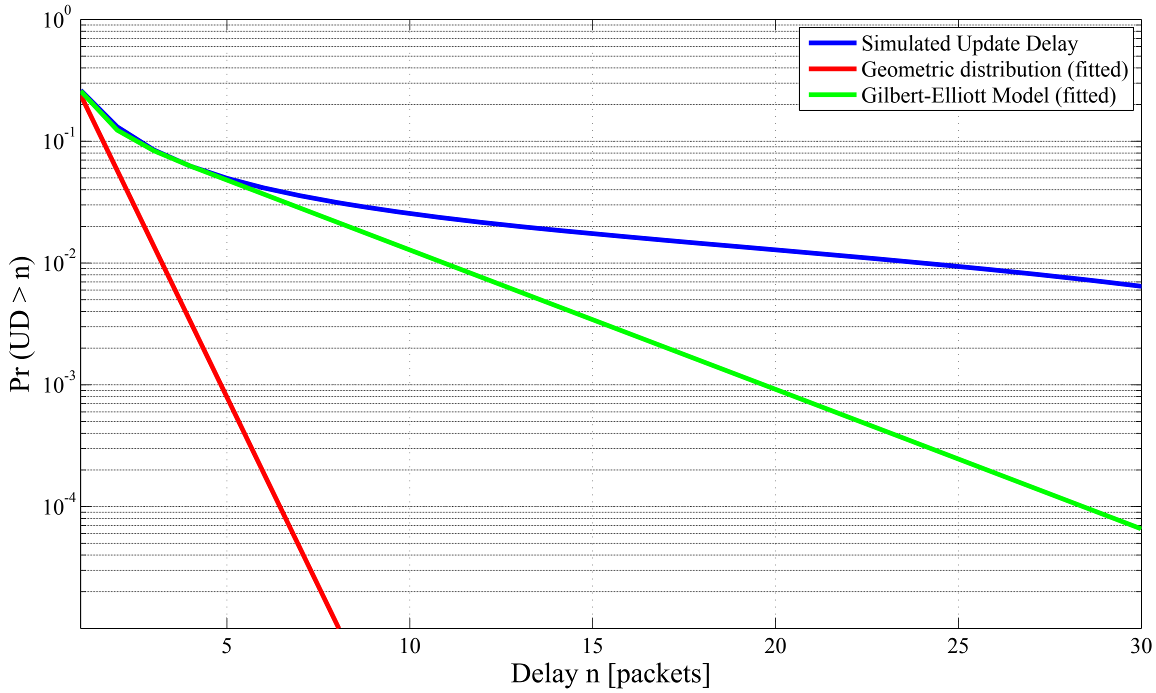


Figure B.3: Comparaison des résultats de simulation avec le modèle de distribution géométrique et le modèle Gilbert-Elliott.

la peine de noter que l'accent est mis ici sur le MAC et ses collisions de paquets causées par le protocole CSMA/CA. Par conséquent, dans ce travail, une collision de paquets est définie par deux transmissions simultanées (qui se chevauchent), détectées au niveau du récepteur correspondant, qui est situé à portée de communication des deux émetteurs. Les collisions de paquets ont été analysées en considérant leurs causes comme leur comportement spatial et temporel. D'une part, les résultats ont montré qu'une quantité importante de collisions de proximité est causée par la procédure de conflit d'IEEE 802.11. Comme indiqué à la Figure B.2, environ 45 % de la quantité totale des paquets provenant des collisions de paquets est causée par des véhicules qui ont choisi le même compteur de temporisation. Ce type de collisions de paquets a une contribution significative en particulier à courte distance.

D'un autre côté, lorsque la portée est plus grande, il existe une quantité importante de collisions de paquets causée par des terminaux cachés. En outre, les modes de communication périodiques combinés à la mobilité relative lente entre véhicules indiquent plutôt un comportement corrélé des collisions de paquets consécutives sur la couche MAC. Surtout dans le contexte des émissions générales régulières relatives à la sécurité, les collisions de paquets corrélés ont un impact négatif significatif sur la qualité de la ”conscience”, et par voie de conséquence, sur la fiabilité des applications de sécurité coopératives. L’existence de collisions de paquets corrélés sur le MAC est démontrée à la Figure B.3. Il montre le retard de mise à jour en unités de paquets, représentée en tant que fonction de distribution cumulée complémentaire (CCDF: Complementary Cumulative Distribution Function). La CCDF fournit la probabilité (axe des y) de dépassement d’un délai de mise à jour de n paquets (axe des x), ce qui équivaut à un dépassement de $n-1$ paquets perdus consécutifs d’affilée. Afin de valider la corrélation temporelle des collisions de paquets sur le MAC, les résultats de la simulation ont été également comparé à deux modèles théoriques. La Figure B.3 compare les résultats de simulation obtenus avec le modèle de distribution géométrique, qui est encore couramment utilisé pour modéliser le retard de mise à jour (délai d’interréception) dans les VANET (voir par exemple [127]). Cependant, les résultats montrent que les données de simulation ne correspondent pas au modèle de distribution géométrique. La raison en est que le modèle de distribution géométrique suppose une parfaite indépendance entre les pertes de paquets consécutifs, et, par implication, ne prend pas en compte les collisions de paquets corrélées sur la couche MAC. Toutefois, si les données de simulation obtenues sont comparées avec le modèle Gilbert-Elliott, qui est largement utilisé pour modéliser les corrélations ou les salves d’erreurs, les deux courbes, celle des données de simulation et celle du modèle Gilbert-Elliott, présentent une bien meilleure concordance. Cette observation confirme l’hypothèse d’un comportement corrélé des collisions de paquets sur la couche MAC.

B.4.2 Stratégies d’atténuation des collisions - Impact sur le MAC

Basées sur les résultats de la précédente analyse des collisions de paquets, trois nouvelles stratégies d’atténuation de collisions de paquets sont proposées. Elles sont conçues pour répondre aux questions suivantes:

Géotemporisation (Temporisation en fonction de la distance)

Comme il a déjà été mentionné, les résultats ci-dessus ont montré qu’une quantité importante des collisions de paquets de proximité est causée par les véhicules ayant choisi le même compteur de temporisation. Mitiger ce type de collisions de paquets est l’objectif du concept de géotemporisation. Il met en œuvre une approche en deux étapes: tout d’abord, la fenêtre de conflit (CW: Contention Window) est augmentée, ce qui réduit la probabilité

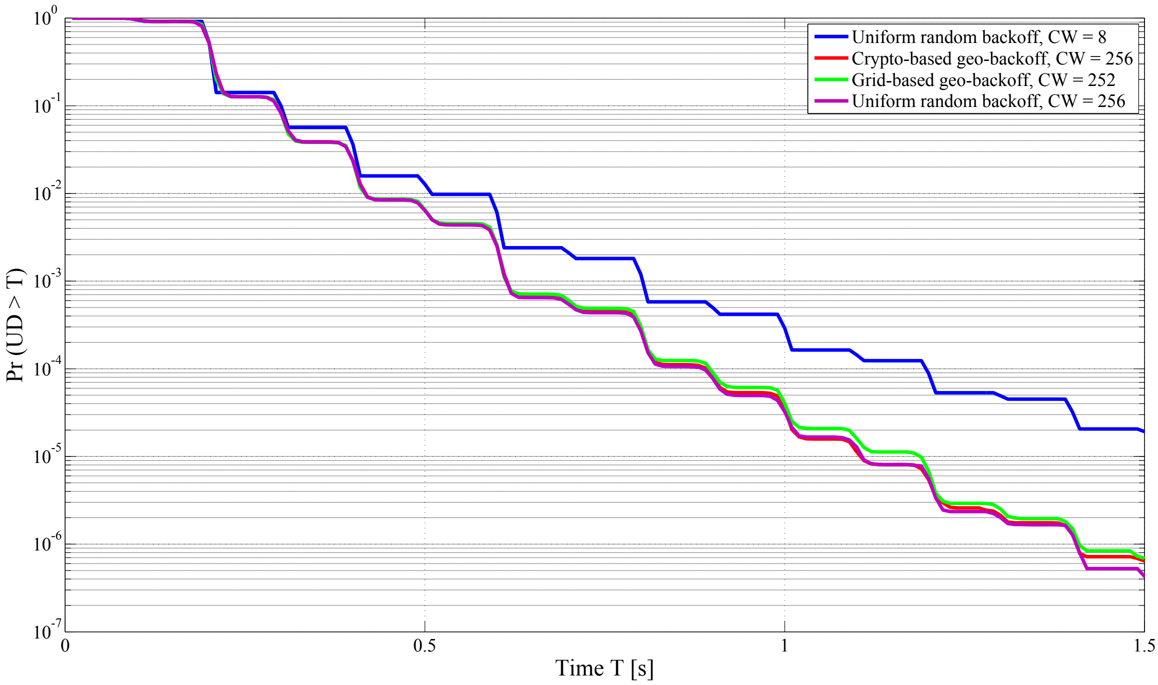
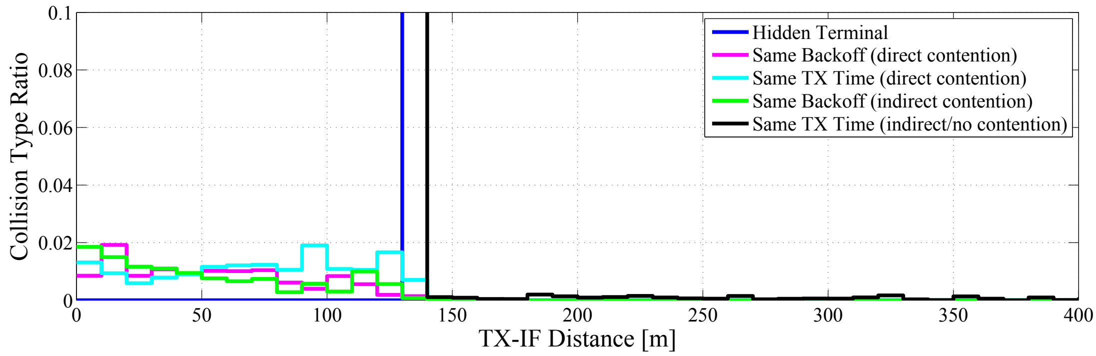


Figure B.4: Comparaison de la performance du retard de mise à jour dans le voisinage proche (jusqu'à 100 m).

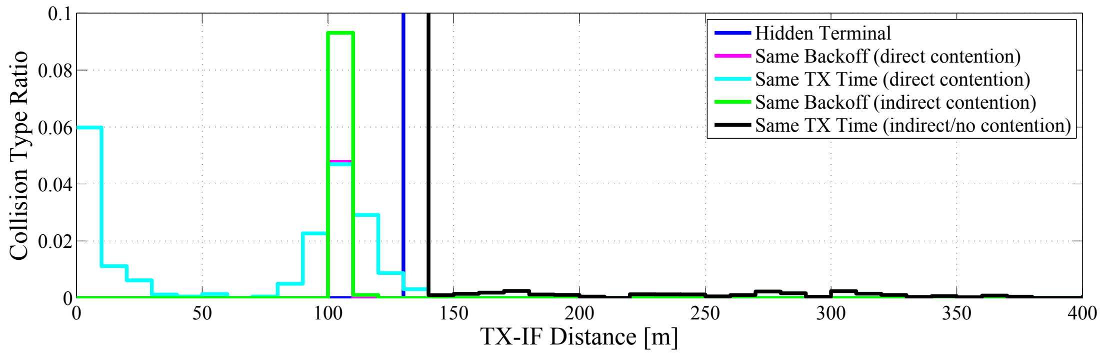
de choisir le même compteur de temporisation de manière générale. Deuxièmement, il vise à déplacer les mêmes collisions dues à la temporisation vers les véhicules, qui sont situés géographiquement aussi loin que possible, en utilisant la position actuelle du véhicule. Alors que la première étape est conforme à l'état de l'art, ce travail se concentre principalement sur la seconde. Deux approches de mise en œuvre de la génération de compteur de temporisation basée sur la géographie ont été étudiées: alors que l'approche basée sur le chiffrement fait usage de la propriété des fonctions de hachage cryptographiques, l'approche basée sur les grilles nécessite le tracé d'une grille le long de la route pour pouvoir déterminer le compteur de temporisation correspondant.

La Figure B.4 compare la performance du retard de mise à jour basée sur le temps du mécanisme de temporisation par défaut (CW = 8) aux deux implémentations proposées de géotemporisation, sur une plage de 100 m. Afin de différencier les améliorations venant de l'augmentation de la CW des améliorations venant de la génération de temporisation basée sur la position, le mécanisme de temporisation par défaut (aléatoirement uniforme) de taille CW similaire, comme celui utilisé pour les approches de géotemporisation, est aussi présenté. Les différentes courbes CCDF de retard de mise à jour fournissent la probabilité (axe des y) de dépassement d'un laps de temps donné T (axe des x). Pour permettre une meilleure compréhension de la façon d'interpréter les chiffres CCDF de retard de mise à jour, une application de sécurité coopérative est supposée, ce qui nécessite de recevoir la prochaine mise à jour de message de "conscience" coopératif (CAM: Cooperative Awareness Message) des autres véhicules dans la plage critique au bout d'une seconde au plus tard, avec une probabilité de 0.9999. Cela signifie que la probabilité de dépassement d'un retard de mise à jour d'une seconde doit être inférieure à 10^{-4}. Ceci peut être facilement vérifié en évaluant le retard de mise à jour correspondant de la courbe CCDF. En considérant la Figure B.4, on peut observer que toutes les approches ayant augmenté la taille de la CW sont en mesure de satisfaire cet exemple d'exigence, à l'exception du mécanisme par défaut. Mais encore plus intéressant est le fait que le mécanisme par défaut dont la CW augmente se comporte aussi bien que les approches de géo-temporisation. Cette observation suggère que l'amélioration n'est pas un résultat de la génération de temporisation basée sur la géographie, mais de l'augmentation de la CW. Par conséquent, regarder de plus près les collisions de paquets pourrait fournir une meilleure compréhension.

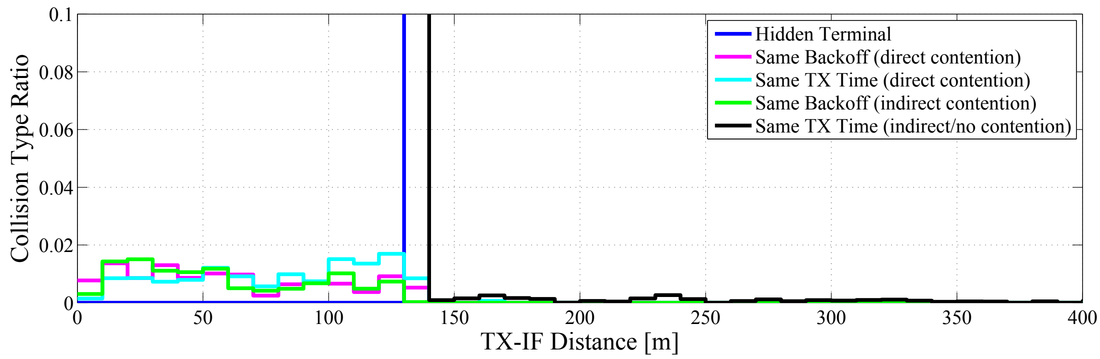
La Figure B.5 montre la proportion des types de collision en fonction de la distance entre TX et IF pour la géotemporisation basée sur le chiffrement, la géotemporisation basée sur la grille, et le mécanisme par défaut avec une CW augmentée. Alors que le mécanisme de géotemporisation basé sur le chiffrement a pu réduire les mêmes collisions de temporisation dans le proche voisinage d'environ 45 % (voir la Figure B.2) à environ 3-4 % (voir la Figure B.5a), l'approche de géotemporisation basée sur une grille a été en mesure de les réduire complètement, jusqu'à une distance d'environ 100 m (voir la Figure B.5b). Le pic qui suit montre le comportement de récurrence des cellules de la grille, en raison de la taille limitée de la CW. Puis, les véhicules à une certaine distance (env. 100 m dans ce cas) choisiront de façon certaine le même compteur de temporisation, s'il y en a deux en lice. Compte tenu du mécanisme aléatoire uniforme par défaut avec une CW augmentée, il peut toutefois être observé qu'il est capable de réduire les mêmes collisions de temporisation tout aussi bien que l'approche de géotemporisation basée sur le chiffrement. Apparemment, la version mise en œuvre de la fonction de géotemporisation basée sur le chiffrement n'est pas en mesure de fournir la distribution de compteurs de temporisation souhaitée, en ce qui concerne le comportement proche-lointain. Cette observation explique le comportement similaire à l'égard de la performance du retard de mise à jour de retard et du nombre de collisions. En tenant compte également de l'approche de géotemporisation basée sur une grille, il est évident qu'une réduction supplémentaire des 3 à 4 % restants des mêmes collisions de temporisation n'est pas suffisamment important pour montrer une



(a) Géotemporisation basée sur le chiffrement avec une CW de taille 256.



(b) Géotemporisation basée sur la grille avec une CW de taille 252.



(c) Génération de temporisation aléatoire uniforme (par défaut) basée sur une CW de taille 256.

Figure B.5: Comparaison de la proportion du type de collision entre les différentes approches de génération de temporisation, tracée en fonction de la distance entre deux émetteurs inducteurs de collision (TX et IF).

amélioration supplémentaire de la performance du retard de mise à jour (voir Figure B.4). Ces résultats ne sont pas nécessairement décevants. Juste augmenter la CW pourrait être la solution la plus attrayante ici, car elle est simple et entièrement compatible avec la technologie ITS-G5 actuelle (aucune modification matérielle ou logicielle requise).

Bien que le concept de l'adaptation de la CW dans les VANET est conforme aux règles de l'art, cette thèse fournit une évaluation du point de vue centré sur le RX en analysant aussi le retard de mise à jour, ce qui est plus approprié pour étudier la performance de diffusion des CAM, tandis que la plupart des publications connexes (par exemple [22, 99, 124]) n'ont mis l'accent que sur les métriques de réseau traditionnelles comme la probabilité de réception ou la fréquence. Reinders *et al.* [101] ont également analysé le temps d'interréception (retard de mise à jour), mais à la différence des résultats présentés ici, et en contradiction avec les conclusions d'autres publications connexes [22, 99, 124], leur conclusion fut que l'augmentation de la CW n'améliorait pas les performances de balisage dans les réseaux de véhicules. La raison est peut-être l'utilisation d'un scénario de communications trop simplifié (par exemple, pas de perte de chemin, réseau fermé, courte portée de communication).

Fluctuation de la transmission aléatoire

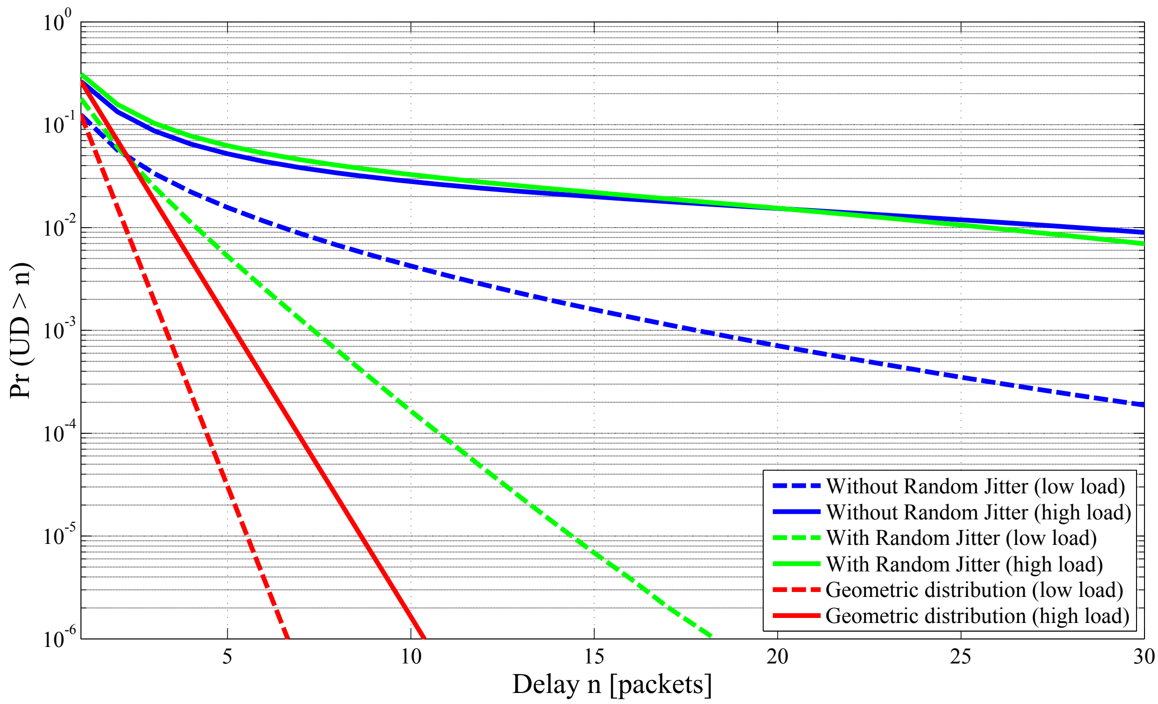
Le concept de fluctuation de transmission aléatoire se concentre sur le problème de collisions de paquets corrélées. Une des sources de collisions de paquets corrélées sur le MAC est le mode de transmission périodique strict des transmissions relatives à la sécurité. Par conséquent, le concept de fluctuation de transmission aléatoire a pour but de rendre les diffusions générales relatives à la sécurité moins périodiques en ajoutant simplement une fluctuation aléatoire artificielle à l'intervalle d'émission nominal. En conséquence, des transmissions se chevauchant à un moment donné (c.-à-d. des collisions de paquets) sont moins susceptibles de se chevaucher à nouveau lors de la transmission suivante, puisque les deux émetteurs sont susceptibles de choisir des moments de transmission différents. Le comportement de corrélation des collisions de paquets est présenté à la Figure B.6a. Il compare les CCDF de retard de mise à jour, mesurés en unités de paquets, entre deux approches, à l'intérieur de toute la portée de la communication ($\approx$ 970 m). Les deux approches transmettent avec la même puissance constante, une avec et l'autre sans fluctuation de transmission aléatoire supplémentaire. En outre, la distribution géométrique correspondante est aussi tracée, ce qui représente une limite en ce qui concerne une décorrélation parfaite[2]. Toutes les courbes venant d'être décrites sont indiquées pour des conditions de charge faible et élevée de données/trafic. Comme les tracés de CCDF précédents, celui-ci présente la probabilité (axe des y) de dépasser un certain retard n de paquets (axe des x).

Lorsqu'on considère le scénario de faible charge de trafic/données, la politique de transmission avec fluctuation aléatoire montre clairement un comportement de décorrélation amélioré (significatif d'une faible probabilité de dépassement des valeurs de retard de mise à jour les plus élevées) comparée à celle sans fluctuation aléatoire. Le comportement de décorrélation amélioré est plus évident, si la distribution géométrique est aussi considérée, puisqu'elle représente le comportement souhaité. Cependant, si la charge de trafic/données est augmentée, la fluctuation aléatoire, ajoutée au niveau des couches supérieures, est absorbée par les procédures de conflit basées sur le MAC, ce qui introduit de nouveau plus de sérialisation et de synchronisation des transmissions.

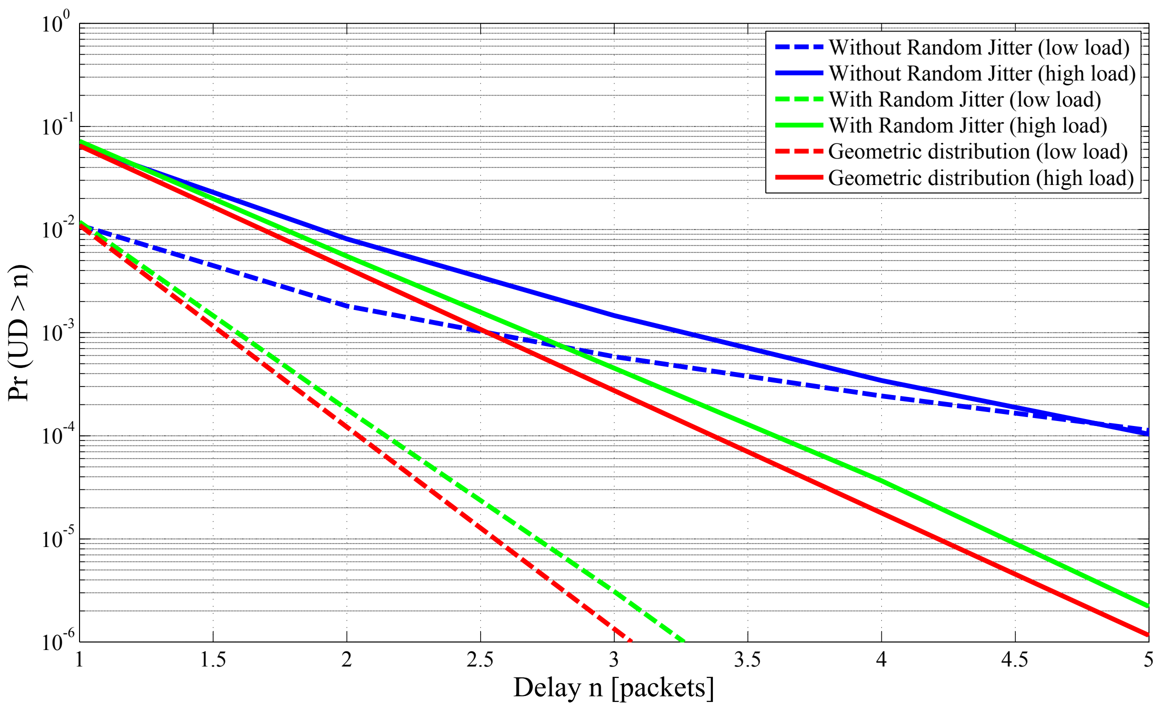
Une autre observation intéressante est que pour les petits n l'approche avec fluctuation aléatoire semble toujours un peu plus mauvaise que celle par défaut, mais montre une meilleure performance lorsque n'augmente. Ce comportement confirme fondamentalement la capacité du concept de fluctuation de transmission aléatoire de rendre les collisions de paquets corrélées plus décorrélées dans le temps, ce qui se traduit par les statistiques du retard de la mise à jour: bien que le nombre total de collisions de paquets est resté le même à peu près, le nombre de mesures de retards de mise à jour plus longs (forte corrélation temporelle) a été réduit, et le nombre de mesures de faibles retards de mise à jour (faible corrélation temporelle) a augmenté.

La Figure B.6b montre les mêmes représentations de retard de mise à jour CCDF, mais uniquement pour les courtes distances (jusqu'à 100 m). Maintenant, la fluctuation de transmission aléatoire fournit même un comportement de décorrélation amélioré de collisions de paquets pour le scénario avec une charge de trafic/données élevée. Une observation intéressante ici est que l'approche de la fluctuation aléatoire est en mesure de beaucoup se rapprocher de la limite (distribution géométrique). Apparemment, la gigue aléatoire est capable de bien décorréler les collisions de paquets sur de courtes distances.

[2]Veuillez remarquer que la distribution géométrique suppose une indépendance parfaite entre les réceptions de paquets consécutifs.

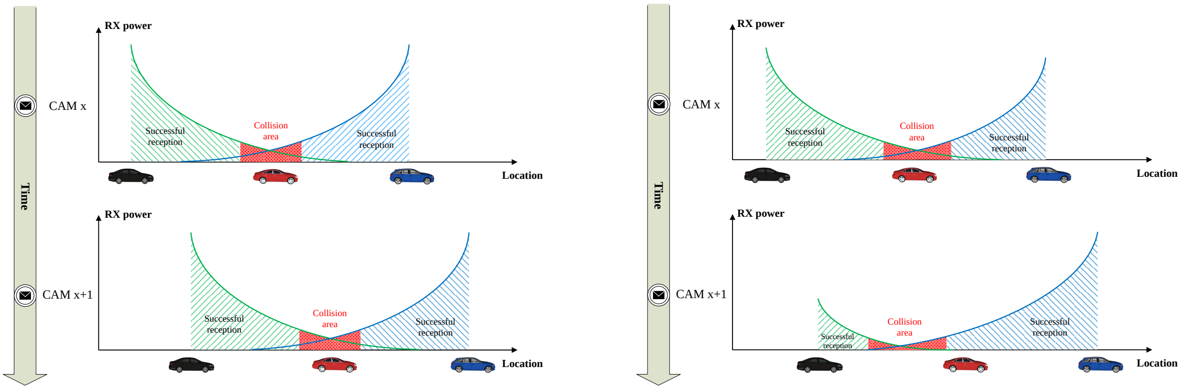


(a) Retard de mise à jour basé sur les paquets mesuré à l'intérieur de toute la portée de la communication.



(b) Retard de mise à jour basé sur les paquets mesuré sur les courtes distances (jusqu'à 100 m).

Figure B.6: Évaluation du retard de la mise à jour de l'approche avec fluctuation de transmission aléatoire.



(a) Une collision de paquets susceptible de se reproduire sur le même récepteur pour des puissances d'émission quasi constante en raison de la nature périodique des émissions de sécurité combinée aux vitesses relatives lentes.

(b) Collisions décorrélées dans l'espace, en raison de la variation de la puissance TX choisie au hasard pour les deux véhicules émettant simultanément.

Figure B.7: Comparaison des collisions de paquets corrélées (spatial) entre les stratégies transmission de puissance constantes et aléatoires.

Puissance de transmission aléatoire

La deuxième source de collisions de paquets corrélés sur le MAC est la mobilité relative quasi statique entre véhicules voisins. Toutefois, la randomisation de la mobilité des véhicules n'est guère possible dans la pratique. Heureusement, ce n'est pas nécessaire. Le concept de l'utilisation des puissances d'émission aléatoires est basé sur la sélection de la puissance de transmission actuelle de manière aléatoire pour chaque transmission et véhicule. Ceci provoque des portées de transmission aléatoires et présente le même effet qu'une mobilité relative aléatoire entre véhicules, qui transmettraient uniquement à puissances constantes. Utiliser des puissances d'émission aléatoires se traduit par une randomisation des zones de collision et d'interférence dans l'espace pour les transmissions consécutives, et décorrèle par conséquent les collisions de paquets corrélées dans l'espace. Ainsi, comme illustrée à la Figure B.7, une collision de paquets est peu susceptible de se reproduire à nouveau sur le même récepteur (distance) au cours des transmissions simultanées suivantes.

Ce comportement de décorrélation de collisions de paquets est représenté à la Figure B.8. Elle compare une approche de puissance de transmission constante avec une approche de puissance randomisée, les deux fournissant la même portée/puissance maximale. Pour aussi montrer le comportement de décorrélation maximal, la distribution géométrique est également tracée. La figure démontre clairement le comportement de décorrélation con-

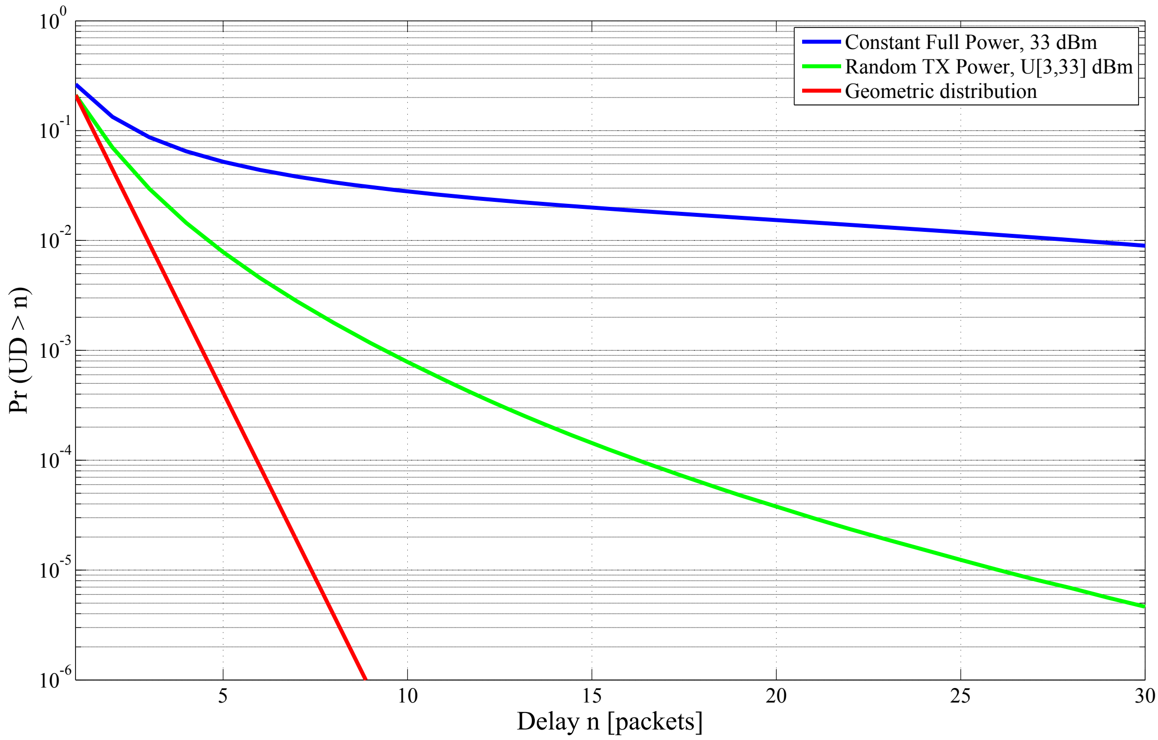


Figure B.8: Comparaison des retards de mise à jour basés sur les paquets, mesurés sur toute la portée de la communication, tracée pour CFP, CMP, RTP, et la distribution géométrique (limite inférieure selon le comportement de corrélation).

sidérablement amélioré des collisions de paquets en utilisant une puissance de transmission aléatoire. Outre l'effet de décorrélation positif des collisions de paquets, le concept de puissance d'émission aléatoire est même capable de réduire la charge sur le canal sans fil par un facteur d'environ 2.5, puisque les véhicules transmettent avec moins de puissance en moyenne.

B.4.3 Contrôle de la "conscience panoramique" - Impact sur les applications

Dans le paragraphe précédent, de nouvelles stratégies d'atténuation des collisions de paquets ont été présentées. Elles montrent en effet un impact bénéfique sur le MAC, cependant, la question qui reste à poser est de savoir si ce résultat est encore valable pour les applications, car au bout du compte, c'est l'application qui doit fonctionner avec une fiabilité suffisante. En particulier, le concept de randomisation peut paraître assez contradictoire au premier abord, étant donné que les applications de sécurité s'exécutent

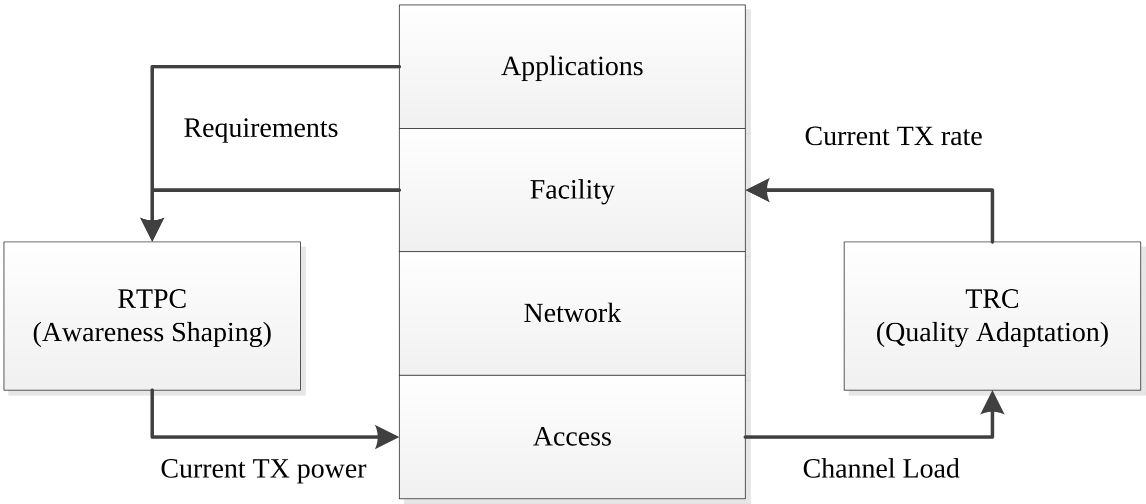


Figure B.9: Mise en oeuvre proposée du contrôle de la prise "conscience" sur la base de deux modules indépendants: RTPC et TRC.

au-dessus. Veuillez toutefois remarquer que le caractère aléatoire peut être entièrement contrôlé par sa distribution de probabilité (par exemple: la forme, la moyenne, la variance), ce qui renforce le concept de base du contrôle de puissance de transmission aléatoire (RTPC: Random Transmit Power Control). Comme les véhicules transmettent avec des puissances changeantes aléatoires, mais contrôlées, ils transmettent de manière implicite à des distances différentes. Alors que les transmissions de faible puissance transactions ne peuvent atteindre que les véhicules à proximité, les transmissions à puissance élevée sont aussi en mesure d'atteindre les plus lointaines. Par conséquent, les véhicules à proximité connaissent une fréquence de mise à jour plus élevée que ceux qui sont plus éloignés. Le résultat est une qualité de "conscience" dépendant de la distance, qui se dégrade lorsque la portée augmente. C'est un effet intéressant, particulièrement dans le contexte de la sécurité des véhicules, car les véhicules proches sont plus critiques en ce qui concerne les collisions physiques entre véhicules.

Bien qu'avec RTPC, la "conscience" est de meilleure qualité sur les distances plus courtes que celles éloignées, pour certaines applications (de sécurité) la qualité fournie à courte distance pourrait toujours ne pas être suffisante. Tout le potentiel est révélé, si RTPC est combiné avec une stratégie supplémentaire de contrôle des fréquences de transmission (TRC: Transmit Rate Control). Puisque le RTPC est en mesure de réduire la charge sur le canal sans fil, la fréquence de transmission peut être augmentée par la suite, ce qui à son tour augmente la qualité de la "conscience" sur toute la portée. Avec cette

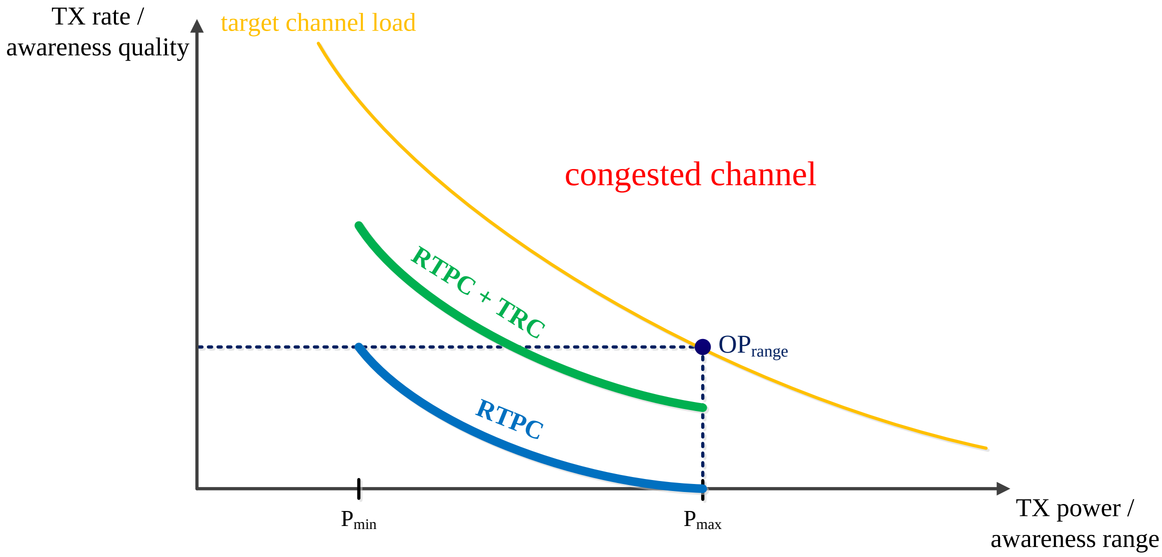


Figure B.10: Le FAC surmonte le dilemme du compromis en opérant le long d'un chemin sur le plan de transmission puissance/fréquence.

approche, un nouveau cadre appelé Contrôle de "conscience panoramique" (FAC: Fish-eye Awareness Control) est introduit. Il permet d'adapter la qualité de la "conscience" en fonction de la distance. La Figure B.9 présente l'architecture de contrôle proposée, qui est basée sur les deux modules indépendants, RTPC et TRC.

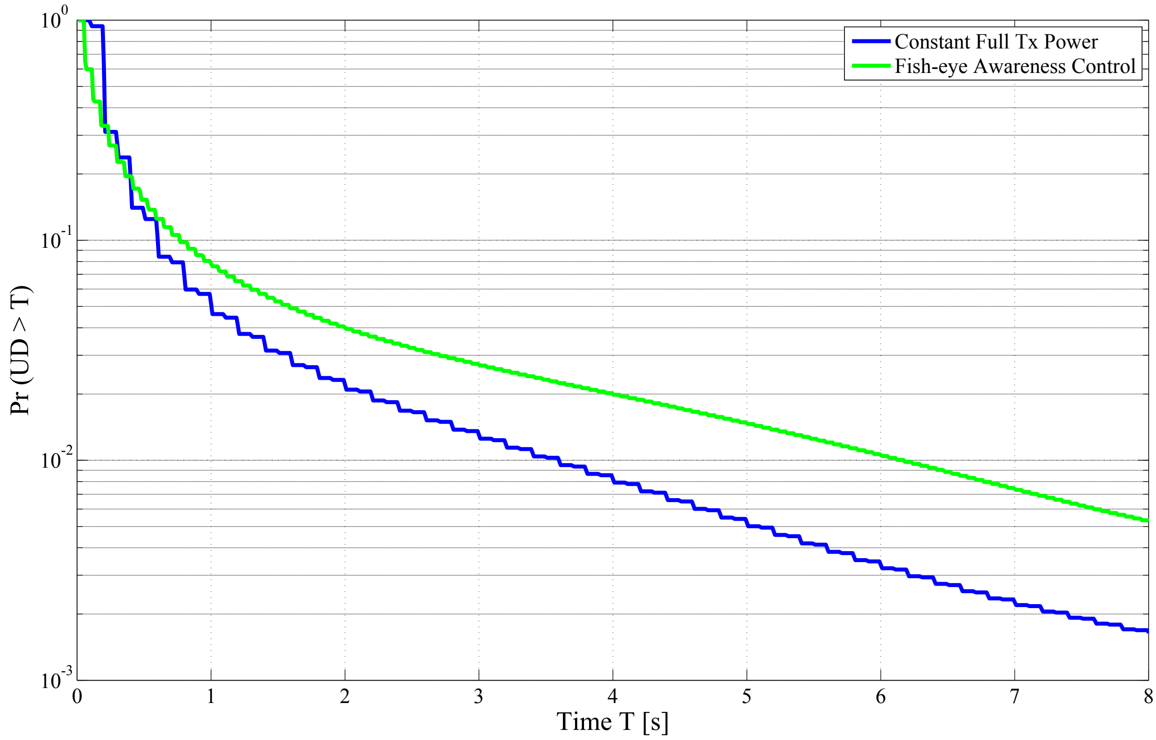
La stratégie de FAC proposée n'est pas en mesure d'améliorer la "conscience" sur toute la portée, mais elle fournit une meilleure utilisation spatiale des ressources sans fil dans le contexte de la sécurité coopérative. Comme la plupart des stratégies de contrôle de transmission actuelles visent à trouver un seul point de fonctionnement de "conscience" harmonisé en ce qui concerne la portée (puissance) et la qualité (fréquence), elles pourraient fournir en moyenne une "conscience" optimale, mais au risque d'être exagérées pour les distances élevées et insuffisantes pour les courtes distances. Avec le FAC, un compromis a été trouvé en utilisant la criticité/pertinence dépendante de la distance dans le contexte de la sécurité routière. Si RTPC est adapté pour couvrir la zone critique à chaque transmission, il y fournit la même quantité de mises à jour-là qu'une approche avec puissance constante fonctionnant à la même fréquence. Cependant, comme RTPC est en mesure de réduire la charge sur le canal sans fil, un mécanisme TRC supplémentaire peut réutiliser les ressources acquises en augmentant davantage la fréquence. Par conséquent, beaucoup plus de mises à jour sont fournies dans la zone critique en comparaison à une approche avec puissance constante fonctionnant à la même charge de canal cible. Alors que les politiques de contrôle de transmission actuelles sont limitées à la définition d'un seul point de fonctionnement (OP: Operating Point) en ce qui concerne la puissance et la fréquence, le FAC permet de définir un chemin de fonctionnement adaptable. Cette caractéristique est illustrée à la Figure B.10. Bien que le RTPC façonne en premier, le chemin sur le plan de la puissance/fréquence de transmission, le TRC améliore par ailleurs la qualité sur toute la portée en augmentant davantage la fréquence. Il en résulte une amélioration significative à courte distance, en échange de performances réduites pour les plus grandes distances, et par association, les distances beaucoup moins critiques.

Pour démontrer la capacité du FAC, une mise en œuvre de preuve de concept est comparée avec un profil de puissance de transmission constante de référence, en tant qu'échantillon représentatif de la plupart des politiques de contrôle de transmission actuelles. Pour fournir une comparaison équitable du point de vue d'une application, le profil de puissance constante de référence est configuré pour obtenir la même portée de "conscience" maximale que la configuration du FAC. La comparaison des deux approches a été effectuée à des distances différentes (zones). Commençons par la Figure B.11a, qui compare les performances de communication à des distances élevées (jusqu'à 800 m). Elle montre le retard de mise à jour en unités de secondes, de nouveau représenté en tant que CCDF. Par conséquent, les courbes de retard de mise à jour fournissent la probabilité (axe des y) de dépassement d'un laps de temps donné T (axe des x). La figure révèle que le FAC réduit en effet la qualité de la "conscience" à des distances élevées. Cependant, ce n'est pas un problème, car les distances élevées sont moins critiques dans le cadre de la sécurité routière.

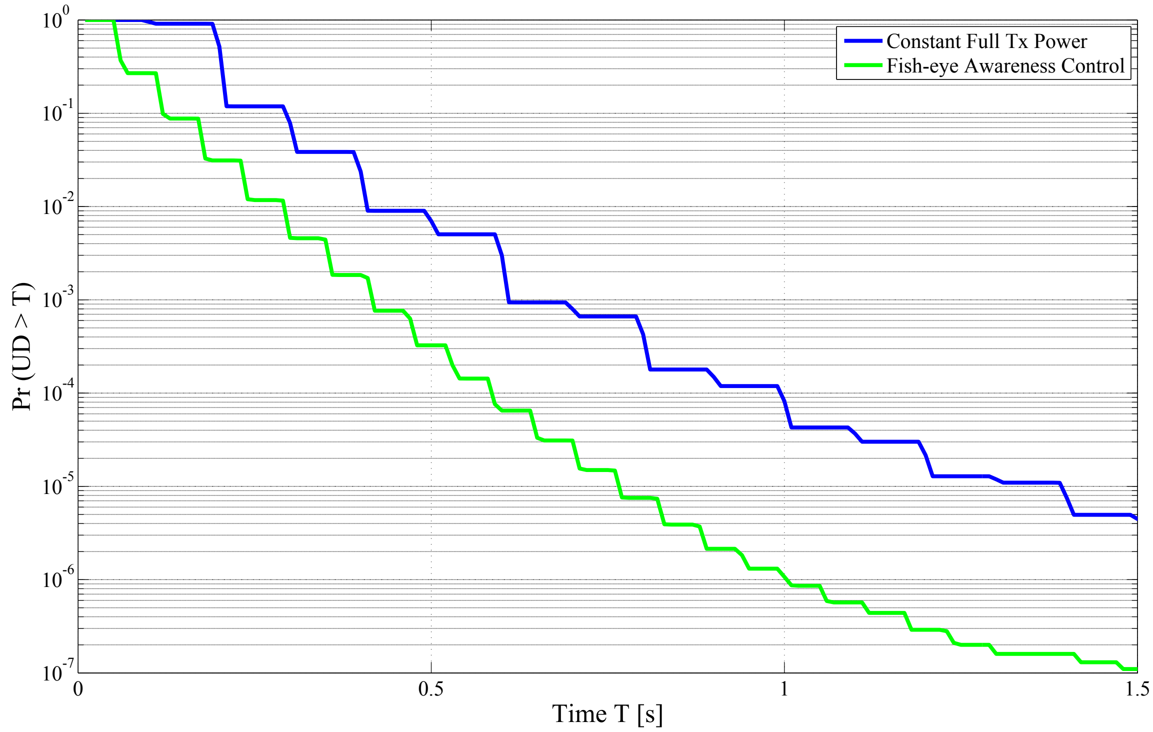
Maintenant, examinons à la place la Figure B.11b. Elle montre la performance du retard de mise à jour à courte distance (jusqu'à 50 m). Comme prévu, dans ce cas, le FAC est en mesure d'améliorer la performance du retard de mise à jour de manière significative.

Pour bénéficier des deux premiers concepts d'atténuation de collision, la géotemporisation et la fluctuation de transmission aléatoire ont par ailleurs été aussi intégrées. La Figure B.12 montre la performance du retard de mise à jour correspondante à courte distance (jusqu'à 50 m). L'intégration fournit plus améliorations importantes en particulier pour les retards de mise à jour les plus longs. Toutefois, qu'une application puisse encore bénéficier de cette dernière intégration dépend généralement de ses exigences spécifiées.

De manière générale, la stratégie FAC présentée n'est pas la "solution universelle", car elle a aussi ses limites. Il n'est pas en mesure d'établir plus de ressources gratuitement. Si la



(a) Performance du retard des mises à jour mesurée à moins de 800 m.



(b) Performance du retard des mises à jour mesurée à moins de 50 m.

Figure B.11: Comparaison des CCDF du retard de mise à jour entre l'approche avec puissance constante et le FAC.

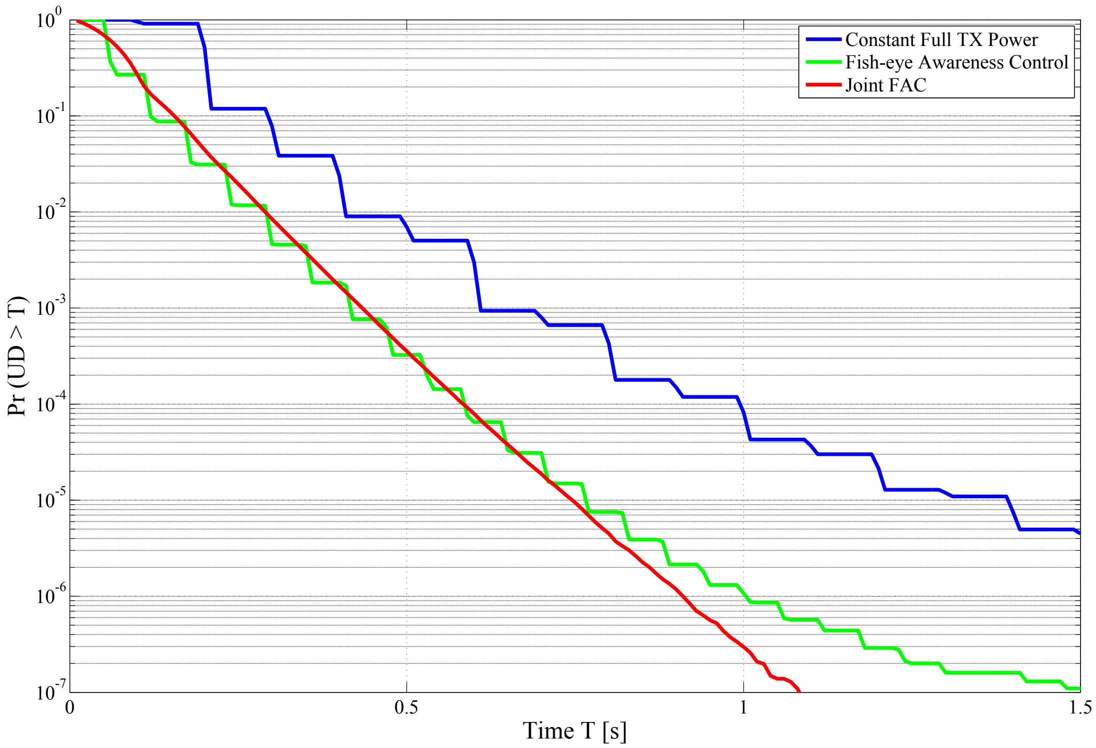


Figure B.12: CCDF du retard de mise à jour des FAC commun à moins de 50 m.

qualité de la "conscience" est améliorée à courte distance, elle sera en même temps réduite sur les plus grandes distances. Métaphoriquement parlant, le FAC déplace la qualité de la conscience des distances éloignées aux distances proches, tout en gardant la portée de "conscience" maximale requise. Ce comportement est tout à fait acceptable, surtout dans le contexte de la sécurité routière, puisque les véhicules les plus proches sont beaucoup plus critiques (pertinents) que les plus lointains.

Grâce au concept de "conscience", la politique de contrôle de transmission appliquée est complètement transparente pour l'application. Indépendamment de l'utilisation de puissances randomisées ou déterministes, et indépendamment de l'ajout d'une fluctuation aléatoire ou non, cela importe peu, tant que la qualité de "conscience" requise est observée.

Appendix C

List of Publications

C.1 Related Publications

1) B. Kloiber, J. Härri, T. Strang and C. Rico García: *Random Transmit Power Control for DSRC and its Application to Cooperative Safety*, IEEE Transactions on Dependable and Secure Computing (TDSC), *Major Revision Decision.*

2) B. Kloiber, J. Härri, T. Strang and S. Sand: *Bigger is Better - Combining Contention Window Adaptation with Geo-based Backoff Generation in DSRC Networks*, International Conference on Connected Vehicles and Expo, November 2014, Vienna, Austria.

3) B. Kloiber, J. Härri, F. de Ponte Müller and S. Sand: *Random Transmit Jitter Against Correlated Packet Collisions in Vehicular Safety Communication*, International Symposium on Wireless Vehicular Communications, September 2014, Vancouver, Canada.

4) B. Kloiber, J. Härri and T. Strang: *Tweaking Vehicular Safety Communications*, Smart Mobility 2020, July 2013, Frauenchiemsee, Germany.

5) B. Kloiber, J. Härri and T. Strang: *Dice the TX Power - Improving Awareness Quality in VANETs by Random Transmit Power Selection*, IEEE Vehicular Networking Conference 2012, November 2012, Seoul, Republic of Korea.

6) B. Kloiber, C. Rico-García, J. Härri and T. Strang: *Update Delay: A new Information-Centric Metric for a Combined Communication and Application Level Reliability*

Evaluation of CAM based Safety Applications, ITS World Congress, October 2012, Austria.

C.2 Other Publications

1) F. De Ponte Müller, E. Munoz Diaz, Estefania, B. Kloiber and T. Strang: *Bayesian Cooperative Relative Vehicle Positioning using Pseudorange Differences*, IEEE/ION Position Location and Navigation Symposium, Mai 2014, Monterey, USA.

2) T. Strang, B. Kloiber, A. Lehner, C. Rico-García and O. Heirich: *What throughput can't tell you: Performance Analysis in V2V networks using the Update Delay metric*, Seminar, March 2013, Nihon University, Tokyo, Japan.

3) T. Strang, B. Kloiber, A. Lehner, C. Rico-Garcia and O. Heirich: *V2V Communications: Performance Analysis using the Update Delay*, NICTA NRG Seminar, November 2012, Sydney, Australia.

4) H. Spijker, B. Kloiber, T. Strang and G. Heijenk: *Improving Information Dissemination in Sparse Vehicular Networks by Adding Satellite Communication*, IEEE Intelligent Vehicles Symposium, June 2012, Alcalá de Henares, Spain.

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