

Random Transmit Power Control for DSRC and its Application to Cooperative Safety

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Abstract—Cooperative safety applications require Dedicated Short-Range Communications (DSRC) to provide position-awareness of neighboring vehicles at a specific level of reliability, i.e. awareness-quality, up to a given distance, i.e. awareness-range. However, heavy communication loads negatively impact such awareness requirements due to communication impairments, ranging from strict capacity limitations of DSRC channels to correlated packet collisions due to periodic communication patterns. Transmission control strategies may adapt power or rate to control such impairments but risk missing the requirements of cooperative safety applications. In this paper, we design a new awareness control strategy by implementing a spatial awareness framework. Specifically, we adapt the distribution of the awareness-quality as a function of the awareness-range. Therefore, we first propose 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. As RTPC is able to reduce the channel load, we secondly propose to combine RTPC with Transmit Rate Control (TRC) and to benefit from the gained channel resources by subsequently increasing the update-rate and by implication, the quality of position-awareness. The spatial awareness control capability of RTPC+TRC has been evaluated through simulations. We discuss the influence of RTPC+TRC on cooperative safety applications exemplarily for the Forward Collision Warning (FCW) application.

Index Terms—DSRC, Safety-critical Vehicular Communications, Awareness Control, Congestion Control, Random Transmit Power Control.

1 INTRODUCTION

DEDICATED Short Range Communications (DSRC) is 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 via so called Cooperative Awareness Messages (CAM)¹ [1].

In particular, safety-related applications like Forward Collision Warning (FCW) require a high up-to-dateness of the cooperative awareness, which is of higher quality the more regular CAMs are received. Hence, the performance of such applications heavily depends on the reliability of DSRC itself. Various standardization bodies, e.g. the Institute of Electrical and Electronic Engineers (IEEE), the European Telecommunication Standards Institute (ETSI), the International Standard Organization (ISO), have selected the well

known Wireless Local Area Network (WLAN) standard IEEE 802.11 [2] as the basic DSRC technology [3].

The major advantage of the WLAN standard and the reason for its success come from its flexibility and adaptability towards new environments. For instance, the challenging vehicular environment (strong fading, Doppler effect, dynamic topology) justified a new amendment initially referred to as IEEE 802.11p; in the meantime it has been included in the IEEE standard 802.11-2012 [2]. Although adapted, DSRC does not provide the strict Quality of Service (QoS) as in cellular networks, which raised growing concerns about the capability of DSRC to sustain vehicular safety. Indeed, *how can safety-critical information be transmitted over a potentially unreliable access technology?*

Such a remark is justified by the various challenges safety related applications bring to DSRC: First and foremost, the requirement of each vehicle to transmit safety-critical information regularly at the maximum range on a wireless communication channel with limited capacity possibly brings congestion on the channel, especially in dense traffic scenarios. Congesting a contention-based random access channel is known to increase the number of simultaneous transmissions, causing packet collisions, which significantly lower communication reliability [4], [5], [6]. Furthermore, CAM transmissions are broadcast and important packet collision avoidance mechanisms like the Request-To-Send/Clear-To-Send (RTS/CTS) handshake are disabled. As a result, DSRC suffers from severe hidden terminal conditions, which further boosts packet collisions.

Various transmission control strategies have been proposed, e.g. [7], [8], [9], [10], either to limit the load on the wireless channel (*congestion control*) or to fulfill the

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1. Equivalent to the Basic Safety Message (BSM) in the US.

application's requirements (*awareness control*) [11]. However, a property, all of them have in common, is to converge to harmonized constant transmit powers, as they aim at finding an optimal trade-off between transmit power and rate, which is able to cover the required awareness range with the necessary quality, without causing channel congestion. Hence, two issues remain open by this property: First, due to the periodic nature of cooperative safety messages, vehicles, moving with slow relative speeds, e.g. platoons on a highway, and transmitting with harmonized constant powers, typically cause *correlated packet collisions*, which can result in an outdated awareness of other vehicles in the surrounding. Second, current approaches can only adapt a single transmit power/rate pair at a time. This might be not an issue if the awareness requirements of a single application are addressed. However, cooperative awareness is the basis for many cooperative applications, which can have different awareness requirements in quality (rate) and range (power). This *transmit power/rate trade-off dilemma* is a very challenging transmission control issue.

In this paper, we present a new *awareness control strategy*, which is based on two independent components: First, we introduce *Random Transmit Power Control (RTPC)*, an enhancement of the basic idea provided in [12]. With RTPC, we are able to provide different levels of awareness quality at different awareness ranges, and adapt it to the requirements of cooperative safety applications. RTPC also randomizes collisions in space, and thus, increases reliability by mitigating correlated packet collisions. The second component is based on an appropriate Transmit Rate Control (TRC) strategy. As RTPC is able to reduce channel congestion and to improve transmission efficiency over space, channel resources are freed. TRC, then, can reuse the gained channel resources to further increase the rate, and by implication, the communication performance along the entire range. Together, RTPC and TRC implement a concept called *spatial awareness*, that is they adapt the distribution of the awareness quality as a function of the awareness range. Especially in the context of vehicular safety, reliable safety-critical information (high awareness quality) is much more important at close range than at high ranges. Hence, with our spatial awareness framework we provide a better spatial reuse of the wireless channel resources by improving the awareness at close ranges and accepting a soft degradation with increasing distance.

The performance of our RTPC-based awareness control strategy is evaluated for a dense multi-lane highway scenario: We first prove the communication benefits of RTPC and show that our concept is able to improve the transmission efficiency in space by mitigating significantly correlated packet collisions. We then show the improved communications performance at close ranges by the joint RTPC+TRC concept for the exemplary cooperative safety application FCW.

The rest of this paper is structured as follows: Sec. 2 provides an overview of the related work, followed by an introduction to the fundamentals of DSRC-based cooperative safety systems in Sec. 3. Open issues of current congestion or awareness control strategies are discussed in Sec. 4. Sec. 5 explains the RTPC design framework and its application to awareness control, followed by its evaluation in Sec. 6.

Finally, the paper is concluded by Sec. 7.

2 RELATED WORK

2.1 Congestion/Awareness Control

Initially, CAMs have been expected to be broadcast 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 vehicle's status (position, speed, heading) has changed since the last CAM transmission. Accordingly, ETSI has specified in [1] that a CAM transmission should be triggered with a fixed rate of 1 Hz *and* if additional mobility triggers are met, e.g. change in position by more than 4 m. To limit the maximum TX rate to 10 Hz, the mobility triggers are only checked every 100 ms.

Although limited, the default CAM generation policy may risk congesting the wireless DSRC channel in dense traffic scenarios like multi-lane highways. Therefore, various transmission control strategies have been published to avoid channel congestion and to support cooperative safety applications, e.g. [7], [8], [9], [10], [13], [14], [15], [16], [17]. While *congestion control* approaches regulate transmit power or rate to limit the load on the wireless channel, *awareness control* mechanisms aim at fulfilling the application's requirements by adapting power or rate accordingly [11]. A detailed survey on current approaches is given, for example, in [11].

The currently most relevant approach for Day one ITS applications is ETSI's Decentralized Congestion Control (DCC) [7]. 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. 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 this approach has been shown to lead to severe instability and unfairness between vehicles [18], [19] on the other hand.

Regardless of using ETSI's simple three-state DCC or one of the more sophisticated congestion/awareness control approaches above, all of them tend to converge to a reduced (harmonized) constant transmit power. Thus, the issue of correlated packet collisions and the transmit power/rate trade-off dilemma still remain.

Focusing on application requirements, Gozalvez *et al.* [20] introduced an interesting application-driven awareness control technique, which addresses the TX power/rate trade-off dilemma by adapting the current TX power/rate based on the distance-dependent application requirement. However, it implements a range to power mapping scheme and leads to a gradual adaption of the power/rate, thus, still preserving the issue of correlated packet collisions.

2.2 Correlated Packet Collisions

Already in 1991, Gudmondson [21] observed a correlated behavior of shadow fading in mobile radio systems. Sepulcre *et al.* have applied this knowledge to analyze the impact of radio propagation modeling on wireless vehicular communication systems by means of simulations. The existence

of correlated packet losses in real world DSRC networks has been demonstrated by Martelli *et al.* [22]. Performing a measurement-based analysis with two IEEE 802.11 p devices, the authors observed temporal correlated blackouts, due to persistent channel/link conditions.

While all the publications just mentioned were focusing on correlation effects on the PHYSical (PHY) layer, this paper is focusing on correlated packet collisions caused by the Medium Access Control (MAC) protocol, due to the quasi-periodic CAM transmission policy in combination with the quasi-static relative mobility between the vehicles.

A potential approach to mitigate MAC-related correlated packet collisions may be found in the class of random repetition-based MAC protocols, e.g. [23]. 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 [24], MS-Aloha [25], STDMA [26]), 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 has been studied and proven to be practicable for more than a decade, STDMA and MS-Aloha require a redesign of the transceiver chipset, which is currently not accepted by the standardization bodies and industry.

2.3 Random Transmit Powers

Using random signal levels for channel access has been proposed earlier by Lee [27]. 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.* [28] concentrated on Poisson distributed arrival processes and additionally discussed design issues, such as number of levels and selection schemes. La Maire *et al.* [29] determined an optimal choice of power levels and probability distributions to optimize the throughput. In [30], the authors 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 [31] and with frequency-domain equalization [32]. Behzad *et al.* [33] introduced the Fair Randomized Power Control (FRPC) algorithm to increase throughput while providing fairness for different mobile users in the system. In [34] the authors 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. In [12], we adopted the basic concept of random transmit powers to DSRC networks. Although we could show an improvement of the communication performance in general, we still missed to proof the claimed communication benefits on the MAC layer as well as the beneficial impact on cooperative safety applications, based on the new spatial awareness framework.

3 COOPERATIVE SAFETY BY AWARENESS

CAM [1] and Decentralized Environmental Notification Messages (DENM) [35] are the most relevant message types in Europe² to support novel cooperative safety applications. While CAMs are regularly broadcast by each vehicle to provide information about their current status, e.g. position, speed, heading, to other vehicles in the vicinity, DENMs are only transmitted for certain events, e.g. road works. Hence, CAMs are expected to generate most of the load on the wireless control channel [36]. This paper, therefore, exclusively focuses on the challenges of broadcasting CAMs in order to support cooperative safety in vehicular networks.

The purpose of broadcasting CAMs is to provide and promote *awareness* [37], [38]. In the context of vehicular safety communication, awareness can be defined as follows:

Definition (Awareness). *It is the ability of an application to know the status, e.g. position, speed, heading, of neighboring vehicles. Awareness is qualified by its range, i.e. distance at which the application at most becomes aware of vehicles, and its quality, i.e. accuracy/up-to-dateness of the status information.*

The most important transmission parameters impacting the awareness are power and rate. Whereas the transmit power adjusts the coverage of CAM broadcasts and by implication, the awareness range, the transmit rate controls how often neighboring vehicles are updated with fresh status information and thus, directly impacts the quality of the awareness.

CAM-based applications fully rely on the awareness of other vehicles in their surrounding. To work with sufficient reliability, each application has its individual requirements on the awareness of neighboring vehicles. Here, it is not possible to provide an exhaustive list of these requirements. Our aim instead is to focus on vehicular safety and provide two generic requirements, based on the awareness definition above to assess cooperative safety applications.

The first requirement corresponds to the *T-window reliability* in [39] and [16], which addresses the quality (up-to-dateness) aspect of the awareness as defined above:

Requirement 1. *A safety-related application detects, i.e. receives at least one message, from a vehicle with a certain probability P from a range X within a time frame T .*

Please note that X and T are application-dependent, whereas T also depends on the speed of the vehicle to be detected.

² Similarly, Basic Safety Messages (BSMs) are the corresponding message types in the US.

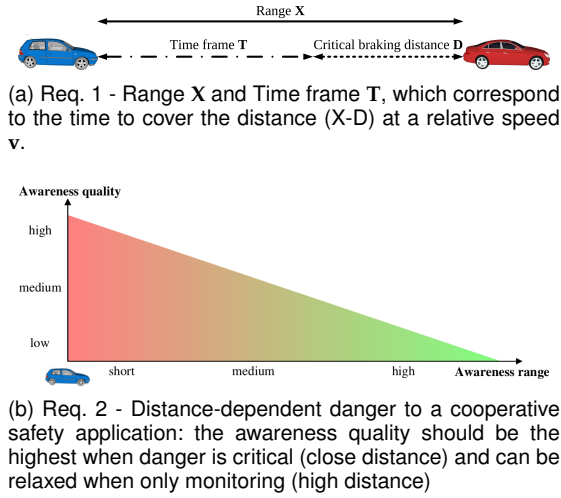


Fig. 1. Illustration of the two generic requirements for cooperative safety applications.

The second requirement addresses the range qualifier of the awareness:

Requirement 2. *The quality of the status information, e.g. position, speed, heading, of each neighboring vehicle is proportional to the potential relevance, e.g. danger, to the safety-related application.*

Both requirements are illustrated in Fig. 1. Whereas Fig. 1a depicts the relaxation of the range requirement by receiving at least one message within a given time frame, allowing multiple reception attempts, Fig. 1b shows the spatial relaxation of the quality requirement. Particularly in the context of traffic safety, closer vehicles are much more relevant than farther away ones. This allows more freedom in the control strategies of transmit power and rate.

Please note that the safety communication requirements just mentioned have to be fulfilled at the receiver side. The controllability, however, is on the transmitter side. Therefore, the classical control loop is not feasible as CAMs are transmitted in broadcast mode, that is without expecting any feedback. Thus, transmit policies have been developed, based on the transmitter's own status (position, speed, heading) and the congestion situation (channel load).

4 CHALLENGES OF COOPERATIVE SAFETY

In vehicular safety communication broadcast delivery is life critical, which brings DSRC to a major conundrum: *How can safety-critical information be transmitted with sufficient reliability with a potentially unreliable access technology?*

A potential answer to this question is therefore to define efficient control strategies for the transmission of CAMs at a target channel load that ensures not to operate beyond the channel capacity. This is certainly the right approach, but current mechanisms still suffer from safety-relevant issues as described hereafter.

4.1 Correlated Collisions on the Wireless Channel

Although the additional trigger conditions do not imply *periodic* CAM transmissions anymore, it may still be observed

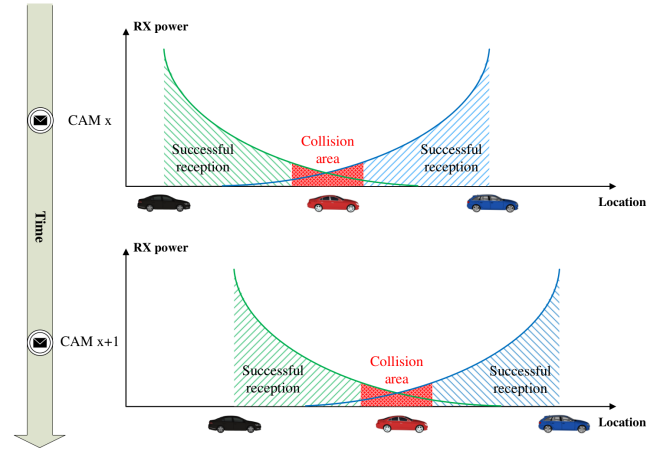


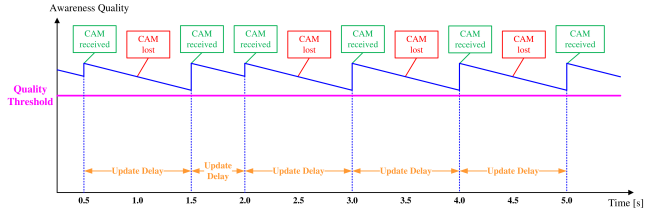
Fig. 2. A packet collision, likely to recur at the same receiver due to the periodic nature of safety broadcasts in combination with slow relative speeds.

that certain mobility conditions do 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' 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.

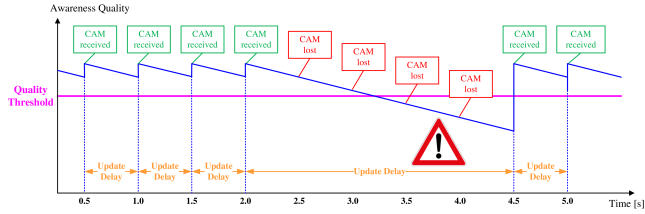
The resulting effect of quasi-periodic CAM transmissions at common transmit powers in combination with quasi-static relative mobility is illustrated in Fig. 2. Let us assume three vehicles forming a platoon, and two of them approximately transmit simultaneous. Then, a possible receiver in between experiences a packet collision, resulting in the loss of both CAMs. Due to the quasi-periodic nature of CAM transmissions in combination with quasi-static relative mobility, especially in case of platooning, the collision can recur for several subsequent transmissions at the same receiver, resulting in *correlated packet collisions*.

Indeed, packet collisions in general have a negative impact on the communications performance. 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. Cooperative safety applications require regular status updates from other vehicles within a certain range through CAMs. Whereas they can support the loss of individual messages, the loss of several subsequent CAMs quickly leads to outdated status information about the corresponding vehicle, which significantly lowers the application's reliability.

Fig. 3 illustrates the impact of lost CAMs on the awareness. If CAMs are lost individually, the awareness quality remains sufficiently high, as it is still updated in a regular manner (see Fig. 3a). However, if CAMs are lost in bursts, the awareness quality decreases significantly, falling below an allowed threshold value, which is required by the application to work with sufficient reliability (see Fig. 3b).



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



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

Fig. 3. Whereas cooperative safety applications can support the loss of individual CAMs, the awareness gets too much outdated, if CAMs are lost in bursts.

The highlighted fact has an important consequence on the significance of current communication performance studies, which have only focused on the reception probability or Packet Delivery Rate (PDR). In both cases, the PDR 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 correlated packet collisions/losses (see Fig. 3).

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 sensing. Furthermore, no acknowledgments are provided, which would indicate a possible collision at the receiver, and would allow to adapt the transmit policy thus that the next collision could be avoided.

4.2 The Trade-Off Dilemma: TX Power vs. Rate

Ideally, one would provide maximum awareness quality within the maximum awareness range, by simply transmitting at maximum rate and maximum power. However, in reality the channel capacity is limited and has to be shared among many cooperating vehicles. Hence, transmitting at maximum power and rate works only for isolated vehicles. Yet, it far exceeds the capacity of current DSRC channels in real-world vehicular networks, e.g. multi-lane highways and urban intersections.

As indicated in [16], the control parameters transmit power and rate are inversely correlated at constant target load on the wireless channel: Reducing the transmit power

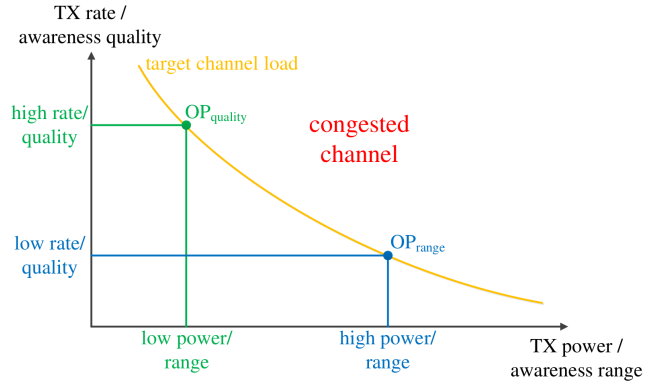


Fig. 4. The trade-off dilemma by using constant transmit powers: Whereas the operating point OP_{quality} provides a high rate (quality) but a short awareness range, the OP_{range} provides a high awareness range but at a low rate (quality).

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, this can result in the *transmit power/rate trade-off dilemma* as illustrated in Fig. 4: To fulfill the awareness range requirement (OP_{range}) by increasing the power, the rate has to be reduced, failing to achieve the required quality. On the other hand, to fulfill the quality requirement (OP_{quality}) by increasing the rate, the power has to be reduced, failing to achieve the required awareness range.

In order to find an appropriate OP, Tielert *et al.* [40] 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, they are probably quite unreliable in more general conditions, due to the unpredictable wireless radio propagation, 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, let us assume one application requires high range (power) but a low rate (quality), and another application requires a short range (low power) but a high rate (quality). The channel, however, does not always provide both, especially in highly dense scenarios. So, which requirements should be satisfied?

5 RANDOM TX POWER CONTROL FOR DSRC

In previous work, we have introduced the basic concept of random transmit powers applied to DSRC networks [12]. In this paper, we provide a new spatial awareness control strategy. Therefore, we enhance the initial idea to *Random Transmit Power Control (RTPC)* and combine it with Transmit Rate Control (TRC). Thus, we are able to provide a better spatial reuse of the wireless resources in the context of cooperative safety applications.

5.1 Design Framework

Our spatial awareness control concept is based on the following design approach:

5.1.1 Spatial Awareness

The starting point is Req. 2 from Sec. 3, that is the awareness quality does not have to be homogeneous in space. An intuitive implementation is to introduce alternating transmit powers and by implication, alternating awareness ranges. Specifically, this means that each vehicle transmits each CAM with different powers within a certain time. Then, low power transmissions can only reach the close-by vehicles while high power transmissions are able to cover the far-away ones as well. Compared with transmitting periodically with constant power, it provides the same update rate to close-by vehicles and less updates to far-away ones, resulting in an implicit update rate adaptation in space. Depending on the selection process on the set of different power values, we are able to shape the awareness behavior in space at this stage. Specifically, we are able to provide different levels of awareness quality at different ranges, while keeping the same awareness range as with constant power.

5.1.2 Randomization against Correlated Collisions

To mitigate the problem of correlated packet collisions while keeping the spatial awareness capability, we propose to select the current transmit power randomly for each CAM transmission and vehicle from the set of alternating transmit powers [12]. As we are not able to vary the distribution of the vehicles, which are under the influence of a hidden terminal situation (cf. conclusion from Sec. 4.1), this approach simulates a varying distribution of the vehicles, by simply transmitting at random powers.

With the introduction of random transmit powers, we are able to make correlated packet collisions more uncorrelated in space. As the current transmit powers are changed randomly with each transmission, the radio propagation conditions are also changed randomly with each transmission, as well as the collision and interference areas. This effect is illustrated in Fig. 5, where a collision does not recur at the same receiver (centered vehicle), due to the variation of the randomly selected TX power of both transmitting vehicles. This and other important communication benefits provided by randomized transmit powers are summarized in Table 1.

Although the concept of random transmit powers is indeed able to provide spatial awareness and to mitigate correlated packet collisions, it does not automatically fulfill the safety communication requirements, which can even

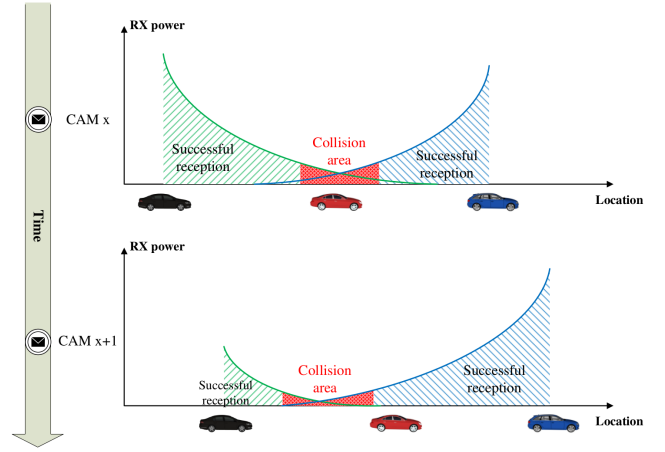


Fig. 5. Decorrelated collisions in space, due to the variation of the randomly selected TX power for both simultaneously transmitting vehicles.

differ from application to application. Therefore, what is still missing is the ability to adapt to the awareness requirements in terms of range as well as of quality.

5.1.3 Controlling Spatial Awareness

To provide spatial awareness adapted to the cooperative safety requirements, while keeping the communication benefits provided by random transmit powers, we finally enhance our approach to *Random Transmit Power Control (RTPC)*. Only by the introduction of controllability, we are able to adapt the spatial awareness concept to the requirements of cooperative safety applications.

With RTPC, we aim to control the shaping of awareness in space by adapting randomization, that is the probability distribution and its parameters, e.g. shape, mean, variance. By selecting the shape, for instance, we are able to control the weighting on the set of available power values and their corresponding ranges, and by implication, the spatial awareness behavior. The variance controls the spreading between high and low transmit powers, and by association, the degree of randomizing collisions in space. With the mean, we finally control the transmit fairness (equal power

TABLE 1

Communication benefits provided by random transmit powers [12].

Congestion reduction	On average, the vehicles are transmitting with the reduced mean power value of the used probability distribution.
Higher transmission efficiency	Broadcast transmissions are reduced for longer ranges as well as their contribution to congestion there. The longer the distance, the more they are wasted due to the increasing amount of collisions.
Update rate adaptation in space	Low power transmissions can only reach the close-by vehicles while high power transmissions are able to cover the far-away ones as well. Thus, close-by vehicles experience a higher update rate than far-away ones.
Randomized collisions in space	Random transmit powers randomize the collision and interference areas.
Local fairness	'Statistical' fairness is provided as long as all vehicles use the same probability distribution and thus, the same TX power on average.

between nodes on average) as well as the congestion on the DSRC channel.

Referring to Fig. 4, with RTPC we are able now to operate along a pathway instead of a single OP only. However, this does not mean that the pathway represents already an ‘optimum’. To provide the full potential of RTPC, we aim to bring the operating pathway closer to a certain target channel load. Therefore, we apply a Transmit Rate Control (TRC) strategy in addition. With RTPC only, we are able to shape the awareness behavior in space. An appropriate TRC strategy in addition can reuse freed channel resources by further increasing the transmit rate until a certain target channel load has been reached. Thus, the awareness quality along the entire awareness range can be increased subsequently.

By integrating RTPC with TRC, we also relax the trade-off dilemma (cf. Fig. 4). Instead of trading awareness range for awareness quality, we simply perform a reallocation of the awareness quality in space. Consequently, we shift some awareness quality from far-away to close-by, where it is much more relevant with respect to vehicular safety, while keeping the maximum required awareness range. Thus, we are able to provide a better spatial reuse of the wireless resources in the context of cooperative safety.

5.2 RTPC Featuring Spatial Awareness Control

Fig. 6 illustrates our proposal for implementing the above spatial awareness control framework, which is based on the following two independent control modules:

- **RTPC:** This block adapts the current random transmit power distribution to control the “shape” of the awareness 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 can be based on a look-up table, which provides for each application the desired probability

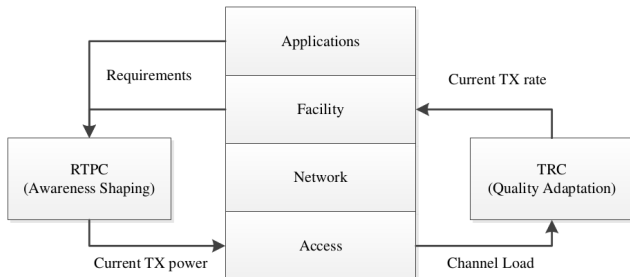


Fig. 6. Proposed awareness control strategy based on two independent modules: RTPC and TRC.

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 [17], [40]. If channel load resources are gained by RTPC, TRC will subsequently increase the current transmit rate until the target load is reached.

The spatial awareness control strategy we describe here is quite similar to the joint TX power/rate congestion control strategy suggested in [40], yet relying on randomized transmit powers to provide a heterogeneous awareness quality in space and to relax the strict transmit range to power mapping. Instead of finding the optimal, but still constant TX power, we propose to find an optimal TX power distribution that in turn represents an optimal behavior of the awareness quality in space. Thanks to the modularity of our control strategy, a practical implementation can be to simply replace the TPC component with RTPC, while the TRC module is maintained.

5.3 Safety Assessment

With the introduction of general safety communication requirements in Sec. 3, we started by assuming a continuous behavior of the awareness quality in space (see Fig. 1b). Because requirement specifications on a continuous behavior are too complex and probably not suitable in practice, we propose to introduce discrete zones, which basically correspond to a quantization of the desired continuous behavior. An example with three different zones is shown in Fig. 7, 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. Its size is typically composed of a maximum allowed communication delay (represented as distance) plus the braking distance required to finally 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.

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

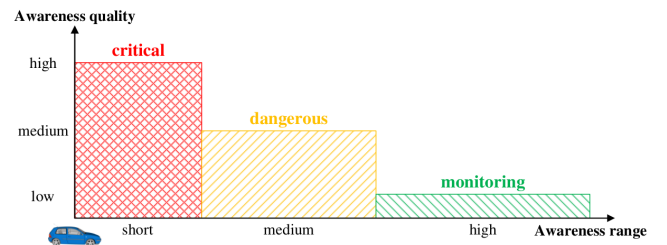


Fig. 7. Simplification of the spatial awareness, where three discrete zones exemplarily provide various awareness quality/range mappings.

To avoid misinterpretation, please note that cooperative safety applications typically require all zones all the time. Especially multiple applications can require different quality levels at different ranges. With focus on traffic safety, the proposed framework 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).

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 powers can be configured such that the critical zone is covered with each transmission³. 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 Sec. 3, the applied transmit policy is indifferent to the application, as long as the required awareness quality is provided. This makes the modification of transmission parameters, like power or rate, completely transparent to the application.

6 PERFORMANCE EVALUATION

Realistic scenarios are too complex in general to be analyzed theoretically with sufficient validity. For that reason, we have decided to follow a simulative approach here. We start this section by describing the simulation scenarios first. Then, we analyze the communication benefits of RTPC and finally discuss a spatial awareness control example by means of the FCW application.

6.1 Simulation Scenarios

Our simulations have been conducted by using the well known network simulator ns-3 [41] that implements the following environment and metrics.

6.1.1 Evaluation Environment

To get a challenging communication setup, a 10-km highway has been simulated, with 6 lanes in each direction. Vehicles have been generated for each lane following an Erlang distribution to control the timely separation between consecutive vehicles. Their mean has been set to a value of 2 seconds to comply with the recommended time-ahead distance between consecutive vehicles in Germany. Finally, the Erlang distributions have been shifted by 0.25 seconds, to avoid time-ahead distances shorter than the length of a

vehicle. To remove the border effect, only vehicles within the evaluation section between 2500 m and 7500 m are considered.

The implementation of DSRC is based on the European Profile Standard ITS-G5 [3], with the possibility of setting the TX power on a per packet basis. The following TX power strategies are considered:

- **Constant Full TX Power (CFP):** All vehicles transmit each CAM with the maximum allowed TX power on the control channel (33 dBm).
- **Random TX Power Control (RTPC):** All vehicles randomly choose the current TX 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 ($\mu = 18$ dBm). The reason for this setting is described in Sec. 6.3.
- **Constant Mean TX Power (CMP):** All vehicles transmit each CAM with the mean power value of the applied RTPC mechanism (18 dBm).

The implemented CAM transmission policy complies with the trigger-based policy as described in [1].

On radio propagation level, the default log-distance model from ns-3 has been used and configured to get a maximum communication distance of almost 1 km. It has been demonstrated, for instance, by Gallagher *et al.* [42] as well as Schmidt *et al.* [43] that a maximum communication range of about 1 km is not unrealistic.

To measure the channel load distribution in space, the simulation environment was 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. These stations 'measure' the so-called Channel Busy Time (CBT) ratio, which is defined in the next subsection.

6.1.2 Evaluation Metrics

The following metrics are used to analyze the communication benefits of RTPC and to assess the applications reliability from a communications perspective:

- *Packet collision rate:* The number of packet collisions, normalized in time and space.
- *Channel Busy Time (CBT) ratio:* The amount of time, the channel is sensed to be busy, with respect to a certain time interval.
- *Update Delay (UD):* The elapsed time between two consecutive CAMs successfully received from the same transmitter (RX-centric).

We use the *update delay* to assess the awareness as defined in Sec. 3 in a simple manner from a communications perspective. As the accuracy of the received status information, e.g. position, speed, heading, is communication independent, we assume accurate status information for the awareness quality here and focus on its up-to-dateness only⁴. The update delay measures the age of received status

3. In contrast to the transmit range to power mapping problem, the key difference here is that transmissions do not only apply the lower bound power level. Instead, considerably more higher power levels are used as well, which are able to cover the critical zone almost surely.

4. Note that the accuracy of the status information depends in reality on the environment and varies over time. However, as we are focusing on communication aspects here, the accuracy of status information is out of the scope of this paper

TABLE 2
Most important simulation parameters.

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 (2.25 s mean)
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)
RTPC distribution	Uniform (discrete interval from 3 to 33 dBm with 0.5 dB step size)
Constant TX power values	33 dBm (full), 18 dBm (mean)
CAM TX rate	1 Hz + triggers, 17 Hz (TRC)
Zones	50 m, 150 m, 800 m

updates per definition. Hence, it is able to represent the up-to-dateness and by implication, the quality of the awareness from a communications perspective. To qualify the awareness by range, we evaluate the update delay for various zones, that is only for vehicles located within a considered zone/range.

In other publications, e.g. [9], [15], [44], the update delay metric is better known as ‘Packet Inter-Arrival Time’ or ‘Inter-Reception Time’. However, the main difference is that we use a special representation called *Complementary Cumulative Distribution Function (CCDF)*. The advantages are twofold: First, the distribution keeps all the measured information which is not the case by focusing on average values or confidence intervals. Second, as we are focusing on the reliability of DSRC-based cooperative safety applications, we are interested in probability values very close to 1. Although using a log-scaled probability axis, the CDF does not provide the necessary resolution around 1. By using the $CCDF = 1 - CDF$, we can get (theoretically) an infinite resolution around the value we are interested in.

Table 2 summarizes the most important parameters used for our simulations.

6.2 Communication Benefits of RTPC

We start to proof the most important communication benefits from Table 1, which plays a decisive role in our awareness

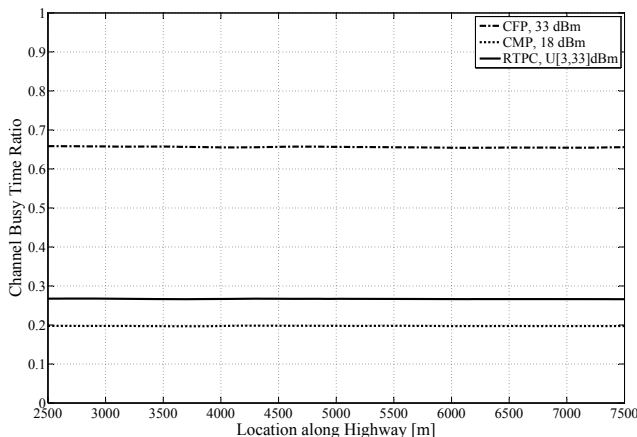


Fig. 8. The average CBT ratio along the evaluation section of the highway scenario by using CFP, RTPC, and CMP.

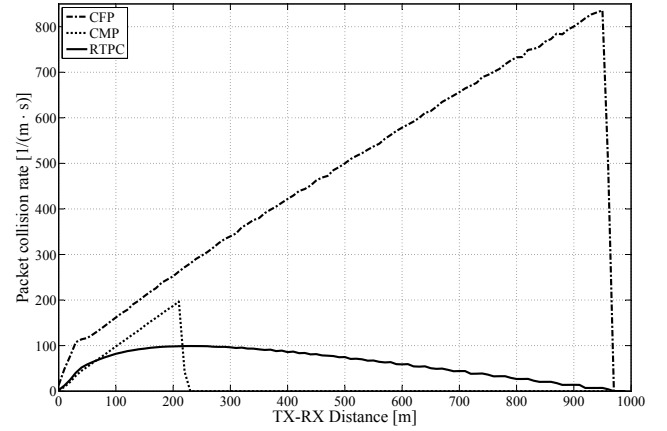


Fig. 9. Total number of packet collisions (normalized in time and space) plotted against the distance between the collision-inducing transmitter and the receiver: Comparison among CFP, CMP, and RTPC.

control strategy and its application to cooperative safety. The ability to reduce congestion is presented in Fig. 8. It shows the average CBT ratio along the highway, for all three approaches (CFP, RTPC, and CMP). Whereas CFP causes a CBT ratio of approximately 66 %, RTPC is able to decrease the load to approximately 27 %, that is a reduction by approximately a factor of 2.5. Although RTPC and CMP are transmitting with the same power on average, the latter still causes a reduced CBT ratio of only 20 %. This is because of the non-linear mapping between TX power and TX range assuming a log-distance path loss model, that is RTPC and CMP provide the same mean with respect to transmit power but not the same mean regarding transmit range.

Fig. 9 compares the rate of total collisions, normalized in time and space, for CFP, CMP, and RTPC, respectively. The collision rate is shown along the distance between the collision-inducing transmitter and the collision-observing receiver. To make it comparable between the different scenarios, it has been normalized in time and distance (number of collisions per second and meter). Fig. 9 clearly highlights the improved transmission efficiency by using RTPC. Compared with CFP and CMP, RTPC 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 far-away vehicles, where the collision probability is high anyway, has been reduced, the amount of collisions has been significantly decreased with increasing distance. The strong increase of CFP at the first 50 m is a side effect given by the scenario. Because the highway has a width of approximately 40 to 50 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 increasing number of collisions. To avoid misinterpretation, please note that the CMP approach has only a maximum communication range of approximately 230 m. This is the reason that no packet collisions are observed beyond that range.

The correlation behavior of packet collisions for CFP, CMP, and RTPC, is shown in Fig. 10. For this purpose, we make use of the update delay CCDF. Due to the additional CAM trigger conditions, however, vehicles may broadcast

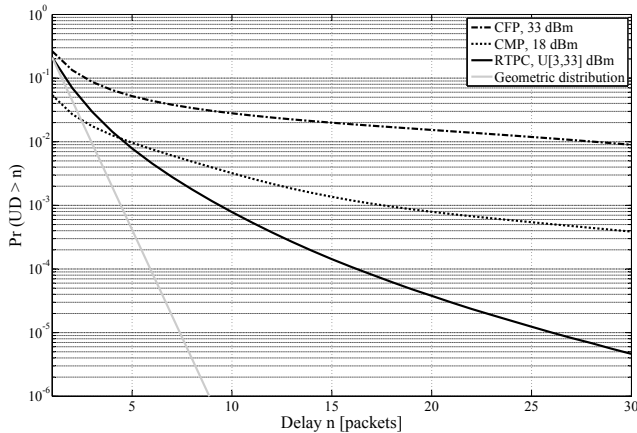


Fig. 10. Correlation behavior of packet collisions represented by the update delay CCDF normalized to packets.

at different rates. Thus, for the evaluation in this subsection we normalize the update delay to the amount of packets between two consecutive successful receptions. Consequently, the plot provides the probability $\Pr(UD > n)$ of exceeding a certain amount of n consecutive packets, which corresponds to the probability of having n or more packets lost in a row from the same transmitter. The figure also shows a fourth curve, labeled with "geometric distribution". The geometric distribution is often used to model the reception process of subsequent packets, that allows to derive the update delay or inter-reception time from a single parameter, that is the reception probability (see [40]). However, the geometric distribution assumes perfect independence between two consecutive reception events by definition, and thus, it describes a perfect decorrelation behavior for a given reception probability. Consequently, we use it here as a benchmark regarding correlated packet losses.

Compared with CFP, RTPC indeed shows a better decorrelation behavior, as the occurrence of n or more packet losses in a row is much less likely. Also taking the geometric distribution into account, RTPC is able to bring the update delay curve significantly closer to the desired benchmark curve. Although CMP shows the best behavior for small n , RTPC is able to outperform CMP already for $n > 4$. This again shows the improved decorrelation behavior of RTPC, as correlated packet losses of burst length $n > 4$ are more unlikely, compared to CMP.

Please note that we do not explicitly evaluate TRC, as this mechanism is already state of the art. There are several publications, e.g. [9] or [17], which introduce and evaluate potential TRC candidates.

6.3 Spatial Awareness Control with RTPC and TRC

To demonstrate the spatial awareness capability of RTPC, the time-based update delay performance will be evaluated for three different zones, and discussed in the context of an example cooperative safety application.

6.3.1 Assumptions and Methodology

A well-known cooperative safety application is FCW as described in [45]. It warns the driver in case of an impending

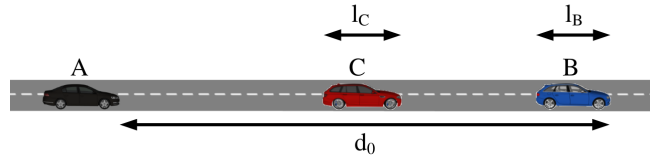


Fig. 11. Example scenario for the FCW application, where a possible braking maneuver of vehicle B is not visible for vehicle A, because vehicle C is blocking its view.

rear-end collision with the vehicle in front. This functionality is particularly relevant, if the braking vehicle B is not visible because another vehicle C in between is blocking the view of vehicle A, as depicted in Fig. 11. Therefore, vehicle A has to constantly track the preceding vehicles B and C by receiving CAMs at high frequency. As explained in [45], a rear-end collision would be avoided, if the update delay is kept below a certain threshold. The other way around, a collision would occur if vehicle A does not receive any new CAM update from vehicle B for a certain amount of time, while B is braking.

Assuming the considered vehicles are driving with the same initial speed v_0 , the maximum allowed update delay UD_{\max} is described by the following inequality [45]:

$$UD_{\max} < \frac{d_0 - l_C - l_B}{v_0} - T_r \quad (1)$$

where d_0 is the initial distance between vehicle A and B, l_B and l_C correspond to the length of vehicle B and C, respectively, and T_r represents the driver's reaction time.

Figure 12 shows the maximum allowed update delay dependent on the initial speed v_0 according to Eqn. (1). The plots are obtained for three different initial distances d_0 , assuming a vehicle length of $l_B = l_C = 4$ m, as well as a reaction time of $T_r = 1$ s.

Please note that the update delay represented as CCDF provides the probability $\Pr(UD > T)$ of exceeding a certain time value T . Hence, it automatically provides the probability of exceeding a certain maximum allowed update delay threshold $T = UD_{\max}$, which corresponds to the probability of FCW application failure.

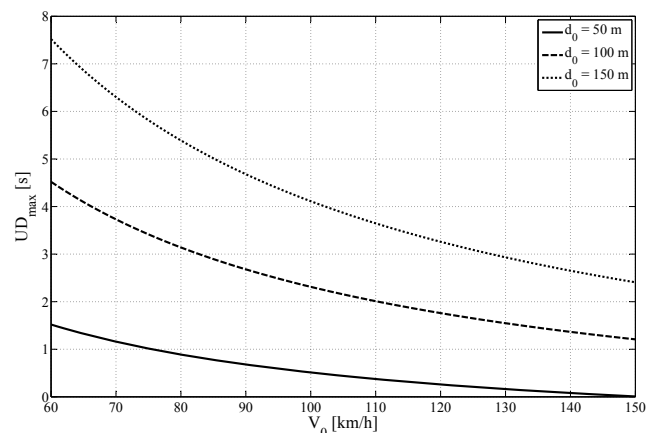


Fig. 12. Maximum allowed update delay UD_{\max} according to Eqn. (1) plotted against v_0 (according to [45]).

The main objective here is to demonstrate the spatial awareness capability of RTPC in combination with TRC. Therefore, the more practical zone approach from Sec. 5.3 is applied. In this case, the three-zone approach in Fig. 7 serves as a template. Please note that there is no clear method yet for the FCW application in order to define the different sizes of the zones. Further, FCW is not the only cooperative (safety) 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 transmission policy of CAMs cannot be adapted to satisfy FCW only. In this paper, the following zones have been chosen exemplarily, but are not limited to the proposed values, as they can be adapted accordingly:

- **Zone 1 (critical) up to 50 m:** From Eqn. (1) we know that the closer the braking vehicle is, the more challenging is the requirement on the maximum allowed update delay. In order to define the critical Zone 1, the idea is to cover the really close vehicles, including the preceding one, because in case of an impending rear-end collision, vehicles most likely collide with their predecessor. Thus, we define all vehicles within 50 m as really close, and they should be tracked with very high quality.
- **Zone 2 (dangerous) up to 150 m:** Although conventional radar sensors are able to cover distances up to about 150 m [46], their effective coverage is limited by the preceding vehicle. This is because radar sensors unconditionally require line-of-sight. 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 considerably enhance the perception of the current environment by local sensors and can significantly relax the required lead time for FCW. In this example, the maximum range of automotive radar sensors (≈ 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.

6.3.2 Implementation

A proof-of-concept implementation of the spatial awareness control strategy from Sec. 5.2 is implemented as follows:

- **RTPC:** Whereas the search of the optimal transmit power distribution is beyond the scope of this paper and might be a topic for future work, the focus here is on demonstrating RTPC's spatial awareness control capabilities. Basically the RTPC implementation corresponds to the one described in Sec. 6.1.1. This configuration is justified by the following reasons: To comply with the current standard according to the transmit power control settings, as specified in [3], [7], the RTPC implementation is based on discrete equidistant transmit power levels in dB, ranging from the smallest possible power level of 0 dBm to

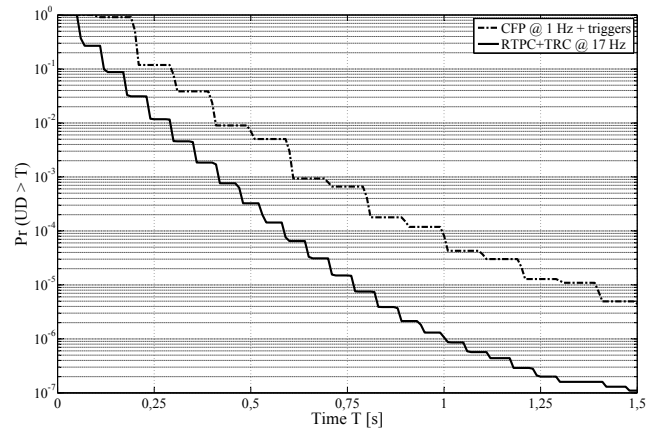


Fig. 13. Update delay CCDF for CFP and RTPC+TRC within Zone 1, represented as CCDF.

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 spatial awareness control 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 [15], where the authors have shown that their information dissemination rate metric is maximized for loads between approximately 0.65 and 0.7. With respect to our simulation scenario and the previously described RTPC configuration, the TRC block is able to further increase the transmission rate up to 17 Hz.

6.3.3 Evaluation

To demonstrate the spatial awareness control capability of RTPC+TRC, the proposed framework has been 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 spatial awareness control implementation previously described. Hence, the reference constant power profile corresponds to the CFP implementation from Sec. 6.1.1.

Fig. 13 shows the update delay CCDF curves within the critical Zone 1 for CFP and RTPC+TRC. Hence, the curves provide the probability $\Pr(UD > T)$ (y-axis) that the update delay measures UD obtained from the simulations exceed a certain time interval T (x-axis).

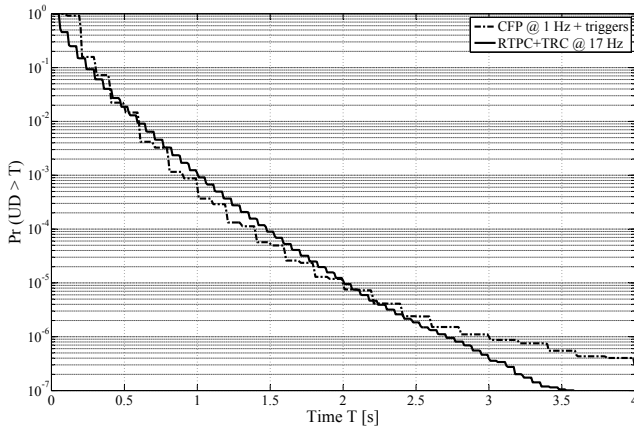


Fig. 14. Update delay CCDF for CFP and RTPC+TRC within Zone 2.

Let us consider an FCW scenario as indicated in Fig. 11. Assuming an initial speed of $v_0 = 120$ km/h, Fig. 12 provides for $d_0 = 50$ m a maximum allowed update delay value of $UD_{\max} = 0.26$ s. From Fig. 13, we can obtain now the probability of exceeding this maximum allowed update delay value, which in turn represents the probability that the FCW application fails. In case of the conventional CFP approach, the plot reveals a probability of approximately 0.119 for exceeding an update delay threshold of 0.26 s. If RTPC+TRC is considered, a significantly lower probability of approximately 0.0117 is obtained. That corresponds to an improvement by more than a factor of 10. Please remember that the transmit rate of 17 Hz is caused by the TRC block, as it exploits the gain channel load from RTPC by further increasing the transmit rate.

If an initial speed of $v_0 = 100$ km/h is assumed instead, the update delay threshold is almost doubled, specifically $UD_{\max} = 0.51$ s (see Fig. 12). As the update delay requirements are more relaxed, lower exceedance probabilities can be achieved. In that case, CFP provides a probability of $5.04 \cdot 10^{-3}$, while RTPC+TRC is even able to achieve $3.25 \cdot 10^{-4}$.

Assuming an initial speed of $v_0 = 120$ km/h again, Fig. 12 provides a maximum allowed update delay value of $UD_{\max} = 1.76$ s for $d_0 = 100$ m, and $UD_{\max} = 3.26$ s for $d_0 = 150$ m. In order to obtain the corresponding exceedance probabilities, Fig. 14 is used now, which shows the update delay CCDF curves within the dangerous Zone 2 for CFP and RTPC+TRC. While for $UD_{\max} = 1.76$ s CFP and RTPC+TRC show a similar probability of about $2.36 \cdot 10^{-5}$ and $3.16 \cdot 10^{-5}$, respectively, for $UD_{\max} = 3.26$ s RTPC+TRC again outperforms CFP by more than a factor of 4.

Finally, Fig. 15 compares the update delay performance of CFP and RTPC+TRC for Zone 3. As for this range FCW is probably not that critical anymore, we dispense with a concrete example and focus on a relative comparison to discuss the spatial awareness behavior introduced above. The figure clearly shows that RTPC+TRC now performs worse than CFP. However, please note that this behavior corresponds to our desired spatial awareness behavior in the context of traffic safety. Taking also Fig. 13 and Fig. 14 into account, RTPC+TRC is indeed able to improve the communications performance at close ranges, by accepting

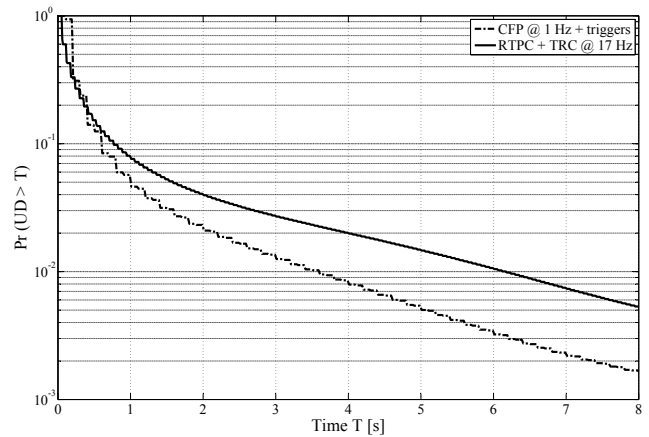


Fig. 15. Update delay CCDF for CFP and RTPC+TRC within Zone 3.

a soft degradation with increasing distance.

Altogether, the proposed spatial awareness 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. Fig. 13) is not for free, but comes at the cost of some loss at farther distances (cf. Fig. 15). 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 DSRC networks.

7 CONCLUSION

In current DSRC, safety applications require safety-critical information to be disseminated using an unreliable access technology. The resulting reliability issues are primarily addressed by congestion or awareness control strategies. However, it shall be clear: *safety-critical applications cannot have their cake and eat it, too*. Trade-offs must be found, which can even vary in space, as close-by vehicles are much more relevant to cooperative safety applications than farther away ones. Because most of the current congestion and awareness control strategies aim at finding a single harmonized awareness operating point regarding range (power) and quality (rate), they can provide an optimal awareness on average, but risk in being over-designed at high ranges and under-designed at close ranges. Furthermore, correlated packet collisions represent a major challenge to safety applications, as they are a root cause of unreliable vehicular communications, that DSRC alone cannot mitigate. While randomized time-related repetition schemes address correlated collisions at the cost of an increased channel congestion, we first propose in this paper RTPC, which introduces a controlled randomization on the transmit powers. Thus, RTPC is able to decorrelate packet collisions by randomizing them in space at the same time as reducing channel congestion, due to an improved transmission efficiency over range. The latter enables to combine RTPC with an additional TRC strategy, that allows to further increase the transmit rate and by implication, the awareness quality along the entire awareness range. Together, RTPC and TRC introduce a new framework called *spatial awareness control*, which provides different levels of awareness at different ranges.

The performance of our spatial awareness control framework has been demonstrated by evaluating the update delay metric for three different zones within a dense multi-lane highway scenario and for the cooperative safety application FCW. The results show that our approach of integrating RTPC with TRC is able to improve the communication performance in the immediate vicinity by more than a factor or 10, albeit traded for a reduced performance at higher ranges. Especially in the context of vehicular safety, this corresponds to a more efficient use of wireless resources, as close-by vehicles are much more critical than farther away ones. Thanks to the awareness concept, the used TX policy is completely transparent to the application. Hence, applying random or deterministic powers is all the same, as long as the application requirements are fulfilled.

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