Multi-Channel Operations, Coexistence and Spectrum Sharing for Vehicular Communications

Jérôme Härri and John Kenney

Abstract Dedicated Short Range Communication (DSRC) has been allocated (3 in EU, 7 in US) dedicated channels at 5.9GHz for vehicular communications. Although resource allocations on the common control channel (CCH) reserved for safety-related applications have been well investigated, efficient usage of the other Service Channels (SCHs) is less developed. With new Intelligent Transportation System (ITS) safety-related applications appearing, such as autonomous driving or truck platooning, as well as the expected coexistence between ITS and non-ITS technologies for smart mobility applications, operating on multiple channels and efficiently sharing the ITS spectrum become critical. First, multi-channel operations aim at mitigating the communication load on specific channels by offloading part of traffic to alternate channels. Second, multi-channel operations aim at providing mechanisms to dynamically change channels and fit to the service requirements as function of external interferences or to varying traffic conditions. In this chapter, we describe the regulations and mechanisms for ITS multi-channel operation and coexistence in the US and in the EU. We first provide an overview of the frequency allocations and access restrictions for ITS, and then describe the protocols available in standards and R&D for multi-channel operations.

Jérôme Härri
Mobile Communications EURECOM, Sophia Antipolis, France, e-mail: haerri@eurecom.fr

John Kenney
Toyota InfoTechnology Center, USA, e-mail: jkenney@us.toyota-itc.com

1 Introduction

Since the pioneer developments of DSRC technologies for Cooperative Intelligent Transportation Systems (C-ITS), road safety applications had the favors of car industry as a major factor of industrial growth and revolutionary driving experience. At that time, all traffic safety applications involved the transmission of safety-related messages - Cooperative Awareness Messages (CAMs) / Decentralized Environmental Notification Messages (DENMs) in the EU or Basic Safety Messages (BSMs) in the US - on a single common well known safety channel to detect and anticipate road hazard ((See Chap. 5 for a detailed description of these messages). Considering the limited capacity of this channel, most of the scientific, standardization and industrial Research & Development (R&D) aimed at developing smart cooperative communication and network strategies to mitigate congestion on this channel.

Yet, more than one channel are available for C-ITS applications. In 1999, the Federal Communication Commission (FCC) in the US allocated seven 10MHz channels for C-ITS in the 5.9GHz band, while in 2008 the Electronic Communication Committee (ECC) in the EU allocated three 10 MHz channels, including four extra 10MHz channels to be allocated in the future. And despite their early availability and the potential innovations from C-ITS applications, the available C-ITS spectrum have not been well used.

C-ITS applications considered for *Day One* deployments, such as *Road Hazard Warning* or *Intersection Collision Warning* have been specified to only use a single of these channels, the channel called *Control Channel (CCH)* in the EU, and Channel 172 in the US. Yet, with the appearance of C-ITS applications considered for *Day Two* deployments, such as *autonomous driving* or *platooning*, as well as the future coexistence of DSRC with non-ITS technologies, such as WiFi-Giga or LTE-Direct, smart and dynamic multi-channel mechanisms for a fair and efficient usage of the overall C-ITS spectrum at 5.9 GHz are expected to become critical.

Multi-channel mechanisms have three objectives. First, they allow to efficiently use the resources of all available channels by off-loading some type of traffic to adjacent channels. Second, they specify mechanisms for Service Providers (SPs) to dynamically offer services on various channels and Service Consumers (SCs) to switch to the corresponding channel to consume the offered service. Finally, they provide the opportunity for various technologies to co-exist in same spectrum bands, by detecting potential harmful interferences and dynamically move to other channels.

Standards describing these mechanisms showed different maturity evolutions between the US and the EU, and although globally sharing same objectives, they differ in some aspects. The 70 MHz spectrum in the US motivated the early development of multi-channel switching mechanisms, including network-layer primitives. Accordingly, the IEEE 1609.4 [19] describing multi-channel switching mechanisms, and the IEEE 1609.3 [20] describing multi-channel service management primitives have been completed as early as 2010. In the EU, the smaller 30 MHz ITS spectrum instead motivated the development of smart traffic offloading or relaying mechanisms on alternate channels. Accordingly, the ETSI provided TS 102 636-4-2 [13] describing the DSRC network-level support for multi-channel operations, and the TS 103 165 [15] describing multi-channel congestion control mechanisms. However, these ETSI standards were still under development at the time of writing of this Chapter.

Using C-ITS channels depends on specific per-channel access restrictions, both in terms on radiation as well as applications. Channels may be a control channel, a channel open to any C-ITS services, or a channel restricted to only one type of C-ITS application. In Section 2, we survey the different channel allocation plans in the US and in the EU, emphasizing their differences and similarities, as well as describing the use of the different channels for C-ITS applications.

Not all DSRC devices are born equal. Different types exist, from those that are only static or mobile, to those that are capable of switching and those that are not, and those that include multiple transceivers and those that do not. In Section 3, we review the different ITS stations and capabilities in the US and in the UE. We will describe the differences between On-Board Units (OBUs) and Road Side Units (RSUs), as well as their capabilities to access different types of channels.

Efficiently using all available channels for DSRC devices supporting one of more transceivers require mechanisms to switch between channels either synchronously or asynchronously, monitor the load on various channels and offload traffic to available channels, and provide mechanisms for C-ITS SPs and SCs to *rendezvous* on common channels to consume services. In Section 4, we take a holistic view and describe the multi-channel mechanisms first in the US standards and in the EU standards, emphasizing the multi-channel switching mechanisms and their applications for multi-channel congestion control and multi-channel service management.

Finally, available spectra is usually very scarce in the telecommunication domain. When 70 MHz are reserved and not efficiently used, it attracts the attentions of other technologies. The DSRC technology is therefore expected to have to coexist, but the sensitivity of some C-ITS applications, and the resource greediness of non-ITS applications are expected to make such coexistence very challenging. In Section 5, we introduce the reasoning behind such co-existence, from the resource requirements of the new very high speed IEEE 802.11ac [24] standard, to potential strategies for efficient and fair coexistence between ITS and non ITS devices in the 5 GHz band.

We conclude this Chapter in Section 6, and emphasize future challenges in multi-channel operations and coexistence for DSRC and C-ITS applications.

2 Frequency Allocation

One of the foundations of the Cooperative ITS system architecture (also referred to in the US as DSRC) is the spectrum in which the vehicle-to-vehicle (V2V) and vehicle-to/from-infrastructure (V2I) communication takes place. In both the US and Europe, authorities have allocated licensed spectrum for this purpose. In this section we present details of these allocations, including frequency ranges, channelization, power limits, and prescribed uses. Fortunately, many of these details are the same or similar between the US and Europe. The harmonization of spectral allocation facilitates common hardware platforms for deployment in both regions.

2.1 Allocation in the US

In the US, the FCC is responsible for spectrum regulation. In 1999, the FCC allocated 75 MHz of spectrum in the range 5.850-5.925 GHz (commonly called the 5.9 GHz band) for ITS, and specifically for the DSRC Service. In 2003, based on input from the ITS community and US Department of Transportation (DOT), the FCC issued licensing and service rules for the spectrum [28]. These rules include a division of the spectrum into seven non-overlapping 10 MHz channels, and a 5 MHz unused band at the low end. As shown in Fig. 1, these 10 MHz channels are numbered with even numbers 172 through 184. It is also permitted to operate in 20 MHz channels 175 and 181, each of which overlaps with two 10 MHz channels. Each channel includes a maximum conducted power and Equivalent isotropically radiated power (EIRP) limit; in some cases there are separate limits for public (i.e. government operated) devices and for private devices. While these power limits typically permit 33 dBm EIPR, or higher, key applications will more often use transmit power in the range of 10 to 20 dBm. These lower powers are chosen to achieve a desired transmission range without causing excess interference at longer distances.

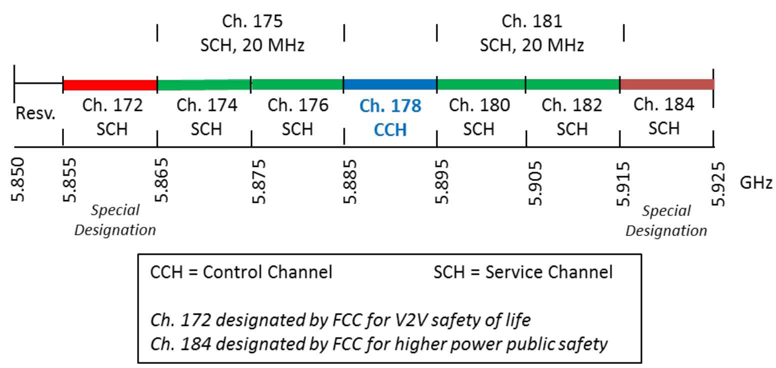


Fig. 1 Channels allocated in the US by FCC for ITS

Each channel is further classified as either a CCH or a SCH. Channel 178, in the middle of the seven 10 MHz channels, is the CCH. The other six 10 MHz channels are classified as SCHs, as are the two 20 MHz overlapping channels. The roles of the CCH and SCHs are not specified in detail in Fig. 1, but as explained below these distinctions are key to multi-channel operation in the US. The 2003 rules also require equipment to conform to the Physical (PHY) layer and Medium Access Control

(MAC) sublayer protocols defined in ASTM standard E2213-03. This standard was replaced in 2010 by the IEEE 802.11p-2010 Wireless Access in Vehicular Environments (WAVE) amendment [21] to the popular IEEE 802.11 standard. However, the FCC regulations have not yet been updated to require conformance to the new standard. The 802.11p amendment was subsequently incorporated into the integrated IEEE 802.11-2012 standard, which continues to be amended and revised. Conformance to the IEEE 802.11 standard in the 5.9 GHz band in both the US and Europe requires use of *communication outside the concept of a Basic Service Set (BSS)*, abbreviated as OCB, which is the principal novelty of the IEEE 802.11p amendment (See Chap. 3 and 4, respectively for details of the PHY and MAC standards).

2.2 Allocation in the EU

In Europe, the ECC is responsible for spectrum regulation, and the European Commission (EC) is responsible to enforce that the allocated spectra are made available in all states of the EU. In 2008, an ECC *Decision* [6] made 30 MHz of spectrum in the range 5.875-5.905 GHz (commonly called *ITS-G5A*) available for ITS restricted to safety-related communications, as well as an extra 20 MHz of spectrum in the range 5.905-5.925 GHz (commonly called *ITS-G5D*) for future ITS extensions. Also in 2008, An ECC *Recommendation* [7] made 20 MHz of spectrum in the range 5.855-5.875 GHz (commonly called *ITS-G5B*) available for ITS non-safety communications. Fig. 2 illustrates the ECC frequency allocation plan and and their different classes. As for the FCC spectrum allocation, the ECC allocation comprises of six SCHs and one CCH. Yet their EU-wide availabilities as well as their usage slightly differ from the FCC allocation.

As specified in [8], the ITS-G5A frequency band contains channels CCH, SCH1, and SCH2, which are restricted to ITS road safety-related communications. SCH3 and SCH4 are contained in the frequency band ITS-G5B and are intended for ITS non-safety communications. Finally, SCH5 and SCH6 are part of the frequency band ITS-G5D and reserved for future ITS extensions. At the time of writing, the ITS-G5A band is the only ITS spectrum currently usable European-wide following a 2008 EC Decision [1]. The other ITS bands (ITS-G5B, ITS-G5D) have been allocated but not enforced to be made available by this EC decision. Depending on the states in the EU, these bands may or may not be available and usable.

One important difference between the US and the EU is that BSMs in the US are not sent on the CCH but rather sent on Channel 172, a SCH specially designated for this purpose by the FCC, while the analogous CAMs and DENMs in the EU are sent on the CCH.

Another difference between the FCC and the ECC, is that although the ITS-G5A spectrum is restricted to safety-related communications, it is not restricted to a specific technology [6, 1]. In principle, if other technologies than ITS-G5 (e.g. 3GPP LTE, WiFi-Giga) could operate in 10MHz OFDM channel for traffic safety, they could operate in the ITS-G5A band. Complementary to the ECC allocation, the

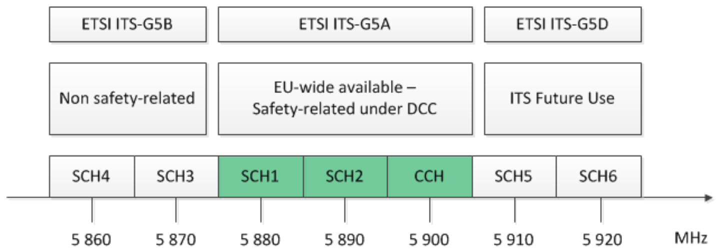


Fig. 2 ITS carrier frequencies in the EU [6, 7]; ITS-G5A is the only frequency band currently available EU-wide [1].

ETSI [14, 8] yet requires technologies operating on the ITS-G5A to operate under the control of the ETSI Decentralized Congestion Control (DCC) [9, 15] mechanisms, which are responsible for per-packet transmit power and rate restrictions (see Chap. 6).

As illustrated on Fig. 3, each ITS channel in the ITS-G5A, ITS-G5B and ITS-G5D bands have spectral power restrictions [14], which in turn restrict the ITS applications that can be operated in them. The CCH and SCH channels have a 23 dBm/MHz transmit power restriction (33 dBm EIRP on 10 MHz channel). Due to adjacent channel interferences, the SCH2 has a stronger spectrum power restrictions to 13 dBm/MHz (23 dBm EIRP on 10 MHz channel), which restrict any Inter-Vehicle Communication (IVC) to short range transmissions. The ITS-G5C band also follows the spectral power restrictions of the Radio Local Area Network (RLAN) bands (e.g. WiFi-5) as described in [11].

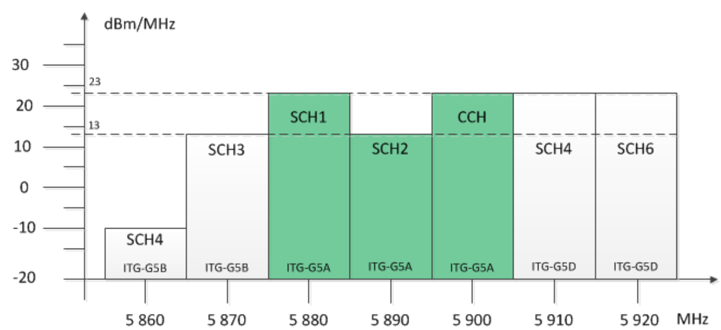


Fig. 3 Power spectral limits on each ITS channel [11], adapted from [13].

3 ITS Station Types and Restrictions

ITS stations have different features depending if they operate while moving or being static. Also, as a function of the number of transceivers available, ITS station may access different type of channels, implement different multi-channel mechanisms, and have different transmit restrictions. We describe in this section the access restrictions of DSRC devices in the US, as well as ITS Station (ITS-S) in the EU.

3.1 DSRC in the US

DSRC devices must be licensed to operate in 5.9 GHz band. The FCC recognizes two types of device, each with its own licensing status. OBUs are permitted to operate while in motion, and can operate anywhere vehicles or pedestrians are allowed. OBUs are licensed implicitly by rule according to Part 95 of the FCC regulations. By contrast, RSUs are required to be stationary when operating, and are licensed explicitly for operation at a site or in a region. RSU operations are specified in Part 90 of the FCC regulations. OBUs may use the 5.9 GHz spectrum to communicate with other OBUs or with RSUs. RSUs are only permitted to communicate with OBUs in the 5.9 GHz spectrum.

In February 2013 the FCC issued a Notice of Proposed Rulemaking (NPRM) [30] concerning operation of unlicensed devices in various portions of the 5 GHz band. In this NPRM, the FCC solicited comments about the possibility of unlicensed devices (e.g. IEEE 802.11 or other devices) sharing the 5.9 GHz DSRC spectrum, with a condition that no unlicensed device would be allowed to harmfully interfere with a DSRC device.

In 2006, again at the request of the ITS community, the FCC updated the 2003 rules by adding special designations to Channel 172 and Channel 184 [29]. Channel 172 is designated exclusively for vehicle-to-vehicle safety communication for accident avoidance and mitigation, and safety of life and property applications. Thus, Channel 172 is where vehicles will exchange BSM, as well as send and receive other messages integrally related to this mission (e.g., Intersection MAP (MAP) or Signal Phase and Timing (SPAT) messages[1] are likely to be sent by RSUs on Channel 172). As a historical note, in early phases of testing the BSM was sent on the CCH (Ch. 178), but following the 2006 FCC decision there was a change in concept of operation so that in the US the BSM is now sent on Channel 172.

Channel 184 is designated exclusively for high-power longer-distance communications to be used for public safety applications involving safety of life and property, including road intersection collision mitigation. One key application for Channel 184 is signal preemption by emergency vehicles. In this application, an emergency vehicle can send a message to a signal controller requesting that the signal state be set so that the emergency vehicle does not contend with other traffic. The option to

[1] See Chap. 5 for a detailed description of such messages.

use power up to 40 dBm allows this preemption request to reach a kilometer or more in many settings, which gives the signal controller time to safely clear the intersection. Note that Channels 172 and 184 remain classified as SCHs, along with these special designations.

3.2 ITS-S in the EU

The ETSI is responsible for the ITS-S plans in Europe, whether it is for static RSUs or mobile OBUs. This section describes the ITS-S architecture for operation in ITS-G5 band. An ITS-S station may contain one or more ITS G5 transceivers, each of them camping to one or more ITS channels. ITS-Ss may classified into three types depending on their functions: safety-related, traffic efficiency, commercial applications. The supported configurations (operating channels and channel switching) for ITS transceivers (number and type of supported ITS G5 transceivers) for ITS Stations are described in the ETSI specification [10]. At the time of writing, [10] was being re-opened to allocate channels for the ETSI ITS Day two applications. Without lost of generality, we provide one approach currently considered.

IVC communication on ITS-G5 should be capable of operating on single channels or on multiple channels according to the requirements of the ITS applications. As a scan mode does not exist in ITS-G5 transceivers, a base channel is specified for each transceiver configuration. This base channel corresponds to where an ITS-G5 transceiver may expect to receive unsolicited traffic.

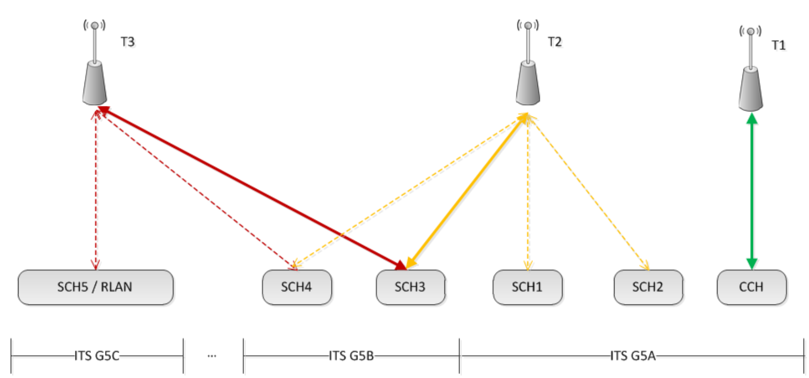


Fig. 4 ITS-S types and restrictions as defined at ETSI [10]

An ITS-S using one or more ITS-G5 transceivers shall operate each transceiver in one of the following configurations, as depicted in Fig. 4:

- *Transceiver Configuration 1 (T1)*: This configuration corresponds to a transceiver strictly operating for safety-related ITS applications. A T1 station never switches channels and must strictly remain on its assigned channel.

- *Transceiver Configuration 2 (T2)*: The transceiver can be tuned to arbitrary ITS-G5A or ITS-G5B channels. T2 transceivers may support synchronous or asynchronous channel switching mechanisms, described later in this chapter.
- *Transceiver Configuration 3 (T3)*: The transceiver can be tuned to arbitrary ITS-G5B or ITS-G5C channels. It is the only transceiver type than can share spectrum with WiFi on the RLAN bands.

The ETSI regulation mandates that at least one T1 transceiver of any ITS-S be constantly tuned to the CCH to send and receive CAM and DENM when the vehicle is considered *in traffic*. This clause is subject to interpretations. In Europe, being *in traffic* corresponds to having the engine *turned on*, regardless if moving or being static, being on the street or not.

Yet, T1 transceivers are not restricted to the CCH, and may be tuned to other ITS-G5A channels (SCH1 and SCH2) (not shown on Fig. 4) for other safety-related applications such as platooning or autonomous driving. For non-safety related and commercial traffic, T2/T3 transceivers are used. Service Announcement Messages (SAMs) [16] are required to let SCs become aware of the services offered by SCs, and which must be sent on a well-known channel to all SPs and SPs. Accordingly, T2/T3 transceivers have a base channel *SCH3* corresponding to where SAMs can be received, and which may also be used to coordinate ITS-G5 and any other type of networks (WiFi, LTE, etc..) if necessary.

Also, both T1 and T2 transceivers must support the ETSI DCC specification, while T3 transceivers do not, as T3 are primarily operating in the ITS-G5C band. Finally, depending on the context, an ITS-S may reconfigure transceivers. For example, a single transceiver ITS-S not considered *in traffic* may reconfigure its T1 transceiver to a T2 or T3 transceiver.

An ITS-S consists of one or more ITS-G5 transceivers, and vehicles or infrastructures may have one or more ITS-Ss. This leads to the following requirements:

- *Single ITS-S, single ITS-G5 transceiver -* The ITS-G5 transceiver must be T1 while *in traffic*. It can be reconfigured to T2 or T3 transceivers when not *in traffic*.
- *Single ITS-S, multiple ITS-G5 transceivers -* At least one ITS-G5 transceiver must be T1 while *in traffic*, while other transceivers may by of different types.
- *Multiple ITS-Ss, multiple ITS-G5 transceivers -* At least one ITS-G5 transceiver of at least one ITS-S must be T1 while *in traffic*, while other transceiver and the other ITS-Ss may operate in other bands.

This classification enforces that the first category of ITS-Ss configurations can only support safety-related applications operating on the CCH. If other type of safety-related applications, such as platooning or highly autonomous driving, are required, at least another T1 transceiver must be available.

In the rest of this chapter, we will describe the mechanisms available for T1, T2 and T3 transceivers for multi-channel operations.

4 Multi-Channel Operations

Multi-channel operation means to tune a given transceiver to different wireless channels at different times. It is sometimes also referred to as channel switching. Given the large number of channels available for DSRC (US) or C-ITS (EU) communication, multi-channel operation is a desirable alternative to statically assigning one device to each channel, or to foregoing operation on some channels to which no device is statically assigned. This section describes the protocols and processes designed to facilitate multi-channel operation in the 5.9 GHz band.

4.1 US Regulations - WAVE 1609.3 & 1609.4

As shown in Fig. 1, there are seven 10 MHz and two 20 MHz channels identified in the US DSRC spectrum. Some of them have special designations, while others might be used to support a wide variety of services. The large number of channels provides not only a high aggregate data communication capacity, but also flexibility in the assignment of applications and services to specific channels. Road geometry, traffic movement, the location of RSUs and of various sources of interference, and the set of applications supported in a region may dictate a certain set of channel assignments at a given time and place, but changes to those variables might make an alternate assignment desirable at another time or place. A given vehicle or infrastructure device might find it useful to utilize all of those channels at one time or another, but over any short period of time (hundreds of milliseconds) the device likely will not need to utilize more than two or three of those channels. While one could theoretically build the device with nine radios, one tuned permanently to each of the channels, it would be an inefficient use of resources. An intelligent and efficient alternative is provided in the IEEE 1609 suite of standards. In particular, the IEEE 1609.4-2010 Multi-Channel Operation [19] and IEEE 1609.3-2010 Networking Services [20] standards define a flexible approach based on time division and channel switching.

4.1.1 Channel Switching Principles

As the DSRC technology does not support the WiFi *scanning* phase, any DSRC device must somehow become aware on which channel it can meet other DSRC devices. For BSM, the channel is well known (Channel 172). But for non-safety services, any of the other channel could theoretically be used. Accordingly, IEEE 1609 channel switching conveys service information using announcements

At a high level, IEEE 1609 channel switching uses the following paradigm. Time is divided into alternating intervals, and all devices that wish to participate are synchronized to a common clock so they know what interval is active at any given time. One type of interval is the *Control Channel Interval (CCH Interval)*. The other type of interval is the *Service Channel Interval (SCH Interval)*. During the CCH Interval, devices wishing to offer services (i.e. Provider devices) and devices wishing to utilize provided services (i.e. User devices) all tune a radio to the CCH (see Fig.1)so that Providers can advertise services via theWAVE Service Advertisement (WSA) and Users can listen to the advertisements. This can be referred to as a rendezvous operation, i.e. it is a way for devices to find each other without prior arrangement. A given WSA specifies on which SCH the Provider offers the service. If a User wishes to participate in an advertised service, it tunes a radio to the indicated SCH during the following SCH Interval, perhaps by switching the radio that was previously tuned to the CCH. During the next (or a subsequent) CCH Interval, the device switches a radio back to the CCH to again listen for advertised services.

At this high level one can see that this paradigm supports a single radio switching among any or all of the channels to access desired services, one channel at a time. Note that channel switching is optional within the IEEE 1609 standards. A single-radio device might use channel switching or not. A device might also have multiple radios, some of which switch and some do not. One configuration expected to be common for OBUs will be to have two radios, one of which is statically tuned to Channel 172 for safety communication and one of which follows the switching paradigm to access other services.

The IEEE 1609 standards describe an optional internal mechanism that a User device can utilize to manage its participation in services. The management function of the device maintains a list of service requests made by higher layers in the device. If a service in the service request list appears in a received WSA, the management function initiates a channel switching operation to the SCH indicated in the WSA. Services in the request list can also register a priority, which the management function uses to arbitrate requests in the case that more than one is available at the same time. The standards specify primitives for the maintenance of this service request list. The service request list is an optional mechanism, not required for over-the-air interoperability.

Services are identified in the WSAs, and in the service request table, using the Provider Service Identifier (PSID) value. Each PSID value is associated with an application area. Examples of application areas for which PSID values have been allocated are: *vehicle to vehicle safety and awareness*, *traveler information and roadside signage*, and *electronic fee-collection*. At the time of writing, the allocation of PSID values to application areas is documented in the IEEE 1609.12 Identifier Allocations standard [22]. In the future, this registration function may be performed by another organization, for example the *IEEE Registration Authority*. The IEEE 1609 WG coordinates the allocation of PSIDs from the same number space that ISO and ETSI allocate ITS Application Identifier (ITS-AIDs). The PSID is a variable length value, occupying one to four bytes. The format is specified in IEEE 1609.3. The PSID value is also used in the WAVE Short Message Protocol (WSMP)(IEEE 1609.3) [20] and in WAVE Security Services (IEEE 1609.2) [23].

Application areas are by design somewhat general. In order to include more specific information about an advertised service, the WSA may also include a Provider Service Context (PSC) field for each advertised PSID. The PSC is a variable length field, up to 31 bytes. The format of the PSC field is specific to the PSID value and is specified by the organization to which the PSID value is allocated, for example ISO or SAE.

The high level switching operation described above, in which a device tunes to the CCH during each *CCH interval* and to an SCH during each *SCH interval*, is described in the IEEE 1609 standards as *alternating channel access*. As noted, a device might also utilize *continuous channel access* to tune to one channel indefinitely. The standards provide for two additional channel access modes, *immediate channel access* and *extended channel access*. These latter two can be used in combination if desired. Fig.5 illustrates the four channel switching principles.

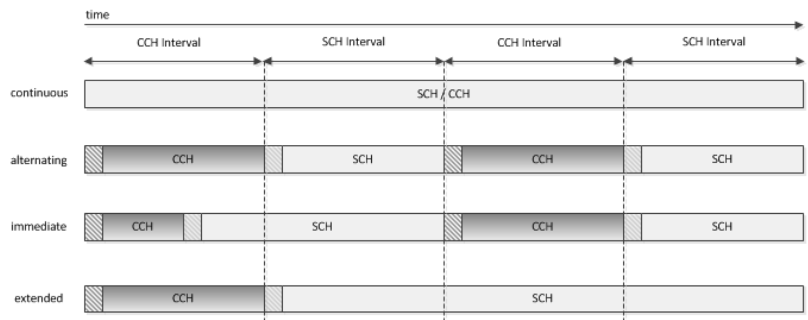


Fig. 5 Channel switching principles as defined in IEEE 1609.4 [19]. Adapted from [19]

In the case of *immediate channel access*, when a User device wishes to access a particular advertised service, it switches to the indicated SCH immediately, not waiting for the start of the next *SCH interval*. In the case of *extended channel access*, the User device remains tuned to the indicated SCH through one or more subsequent *CCH intervals*, until a specified time interval has expired. When extended access is completed the User device switches back to the CCH. These additional modes are designed to reduce the latency associated with accessing a service. A SP can indicate in the WSA whether it is capable of providing the service only during the *SCH interval*, or during *both* CCH and SCH intervals. The User device can use this information when deciding whether to initiate either immediate or extended access. A given device can utilize any of these channel access modes: continuous, alternating, immediate, or extended, and some devices will use different modes at different times. In this way the IEEE 1609 channel switching mechanism provides a User device with a high degree of flexibility in accessing DSRC services.

Figure 6 illustrates the time division associated with IEEE 1609.4 channel switching. Every 100 msec period, synchronized with the GPS second boundary, constitutes a *Sync Interval*. The first 50 msec of each sync interval is the CCH Interval, while the latter 50 msec is the SCH Interval. These durations are default values in the standard, and have been used in most testing. The standard permits other duration values, with the constraint that the ratio of 1 second to the Sync Interval be an integer.

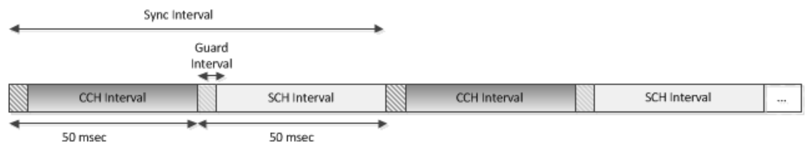


Fig. 6 *Alternating Channel Access* switching principle as defined in IEEE 1609.4 [19]

Each CCH interval and SCH interval begins with a short *Guard Interval*. This is to accommodate the switching of radio resources from one channel to another. Devices participating in channel switching are encouraged to abstain from transmitting during the Guard Interval, since the receiver(s) might not be able to receive yet. The default Guard Interval is 2 msec.

Another potential complexity associated with channel switching is that without special care there could be a large amount of traffic waiting to be transmitted at the start of a given SCH (or CCH) Interval. The channel access procedures of the IEEE 802.11 MAC protocol would arbitrate that access in a way that could result in an artificially high level of frame collisions, compared to a case in which that traffic was spread out over the Interval. To mitigate this, a device that enqueues a packet for a specific SCH (or CCH) Interval that has not yet begun declares the channel busy when the Interval begins. This forces the channel access to use the IEEE 802.11 backoff procedures to reduce the number of collisions. Furthermore, transmitters are encouraged to further spread out their channel access during the entire Interval.

Various studies investigated the performance of the IEEE 1609.4 switching mechanism. For example, in [18], Hong *et al.* investigated the performance of safety-related applications and proposed slight modifications to the IEEE 1609.4 standard to improve it. A similar study has been conducted by Di Felice *et al.* in [5], which proposed a modification of the MAC procedures to mitigate the influence of the switching mechanism. In [31] Wang and Hassan instead evaluated the 1609.4 capacity to support non-safety related DSRC traffic. Various other approaches were also proposed to enhance the switching mechanisms with different synchronous or asynchronous *rendezvous* mechanisms. They are surveyed in [3] and described in more details in [2, 4, 17].

4.2 EU Regulations - ETSI ITS

Multi-channel operations proposed by the ETSI bear many similarities with that of the IEEE 1609.4 and IEEE 1609.3. They yet fundamentally differ with the station architecture previously described, which enforces that at least one ITS-S T1 transceiver be always tuned to the CCH. Accordingly, this T1 transceiver cannot have multi-channel operations. The major advantage of this proposal is to maximize the safety-related communication capacity on the CCH. The synchronous channel switching mechanism specified in 1609.4 notably reduces the CCH channel capacity during the time the ITS-S is switched to a SCH. Considering that even a full capacity of the CCH might not even be sufficient to support safety-related applications (see Chapter 6), an ITS-S must always be capable of receiving on the CCH. The major disadvantage of this approach is that if an ITS-S also need to offer ITS services, it then requires to have at least two transceivers.

Compared to the situation in the US, the EU can only effectively use three 10 MHz channels at the time of writing. The benefit of having a second ITS-G5 supporting channel switching for operating on the other two SCHs is therefore less straightforward compared to having that ITS-G5A transceiver constantly tuned on one of the SCHs. Accordingly, the ETSI did not primarily focus on ITS service managements. Yet, considering the scarce channel resources on CCH from ITS *Day One* applications, and the availability of a second ITS-G5 transceiver constantly tuned on another ITS-G5A channel, the ETSI focused on providing mechanisms to mitigate channel congestions by benefiting from traffic offloading on two other ITS-G5A channels. Accordingly, we will first describe multi-channel congestion control, and then briefly introduce the general directions envisioned by the ETSI for multi-channel service management.

4.2.1 Multi-Channel Congestion Control

At the time of writing this Chapter, standards describing multi-channel congestion control at the ETSI were still being finalized. We provide here the current trends, but some details might evolve in the future. We suggest interested readers to refer to the corresponding standard [13, 15]. Also, at the time of writing this Chapter, very few studies could be found, which investigated the performance of safety-related traffic offloading on adjacent channels. One of them is provided by De Martini and Härri in [25].

As described in the Chapter 6 dedicated to congestion control, the load on the CCH must be regulated to keep a communication quality for safety-related applications. Regularly found mechanisms include regulating the transmit power or the transmit rate. Yet, when the channel load reaches a limit when packets either must be dropped by the ITS-G5 T1 transceiver, or cannot be generated according to the ITS application requirements, an alternative approach is to transmit these packets on alternate channels.

As illustrated in Fig. 7 depicting the ETSI DCC management architecture, the DCC-net block includes a Multi-Channel Function (MCF) on the management plane, and a Channel Routing Function (CRF) in the data plane. The MCF aims at providing the CRF with the load and remaining capacities for the CRF to be able to off-load a particular Traffic Class (TC) to an adjacent channel. The primary and alternate channels for a particular TC is known to all ITS-Ss and depicted in Fig. 8, where two fictional messages (Autonomous Driving Message (ADM) and Decentralized Localization Message (DLM)) have been used as examples. This figure shows that a typical TC, for instance $TC3$ corresponding here to a high priority CAM message, has the CCH as primary channel and Service Channel 1 (SCH1)

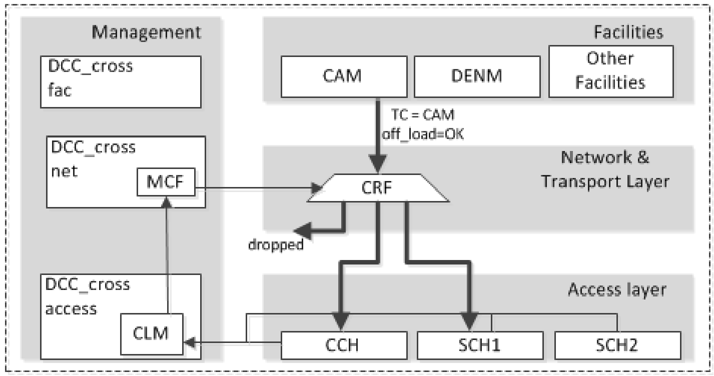


Fig. 7 Multi-Channel Congestion Control architecture based on the ETSI DCC architecture [15]

as secondary channel. In order not to perturb traffic on the secondary channels, a TC being offloaded may also loose priority. For example, the TC corresponding to a high priority CAM may become the lowest ITS-G5A Access Category (AC) on SCH1 to help mitigate congestion with a TC $TC5$ corresponding to an ADM. The selection of the primary and secondary channels, as well as their level of ITS-G5 AC priorities is out of the scope of the multi-channel mechanisms.

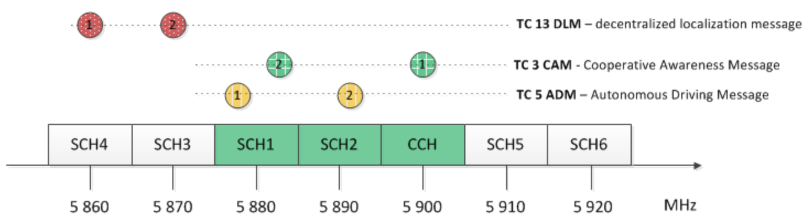


Fig. 8 Exemplary primary and secondary assignment concept illustrated with CAM and two fictional messages ADM and DLM. [Partial reproduction from P. Spaandeman [**?**]]

The CRF therefore takes as input from the MCF the load and remaining capacities on all channels under multi-channel operations, as well as the TC of a packet. As specified in the ETSI technical specification [13] and depicted on Fig. 9, the TC includes a 1-bit field *Channel Offloading Bit (COB)*, which indicates if the ITS application generating the packet tolerates multi-channel off-loading. In the negative, the CRF operate as a single channel DCC as described in Chapter 4. In the positive, depending on the status of the DCC function on the primary channel, the packet may be sent on the primary channel, off-loaded on a secondary channel or dropped.

Figure 10 illustrates the multi-channel congestion control benefits to regulate the load on safety-related channels. To obtain these results, the multi-channel congestion control mechanism has been implemented on the iTETRIS ITS simulation plat-

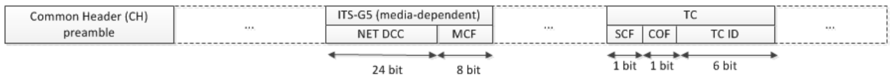


Fig. 9 ETSI GeoNetworking Common Header, and the multi-channel related fields: COB and MCF as defined in [12, 13]

form [27], configured with the channel load monitoring and offloading parameters indicated on Table 1. More detailed results are available in [25].

Parameter	Value
Simulator	iTETRIS (ns-3 + ETSI ITS stack)
PHY/MAC	ETSI ITS-G5
Channels	CCH, SCH1 (ITSG5A)
Switch delay	1 msec
Fading	log distance
Attenuation	2.3
Mobility	Highway, 3 lanes, 2 directions
$Generation^{vehicle}$	Erlang $\lambda = 2s$
$Speed^{vehicle}$	$[20m/s - 40m/s]$
T_{Sync}	1000 msec
T_{SAM}	200 msec
T_{offset}	$Uniform[0, T_{Sync} - T_{SAM}]$
$CCA_{Threshold}$	-85 dBm
T_{mon}	100 msec
$CL^{offload}_{threshold}$	20%
$CL^{offload}_{hist}$	5 %
SAM^{TX}	5 Hz
CAM^{TX}	10 Hz
SAM size	500 B
CAM size	500 B

Table 1 iTETRIS ITS multi-channel simulation parameters.

Each vehicle transmits a CAM at the intended 10Hz rate, where CAM primary and secondary channels are the CCH and SCH1 respectively. When the MCF indicates 50% channel load on CCH and less than 50% channel load on SCH1, the CRF offloads all CAM to SCH1. In order to avoid oscillating behaviors of the CRF offloading on the SCH1 when the channel load is slightly higher or lower than 50%, an hysteresis is added, which value is configurable. In the results shown in Fig. 10, the hysteresis corresponds to 10% of the target channel load. In that case, we can see that the channel load first increases on CCH, before a gradual offloading on SCH1 starts. If multi-channel offloading is not supported, we can see that the channel load reaches 30%[2]. But when offloading is triggered, the load generated by the CAM messages are shared between CCH and SCH1 and reach only 15%.

[2] The IEEE 802.11-2012 default value of the 802.11 Clear Channel Assessment (CCA) threshold has been considered for the measure of the ITS-G5A channel load

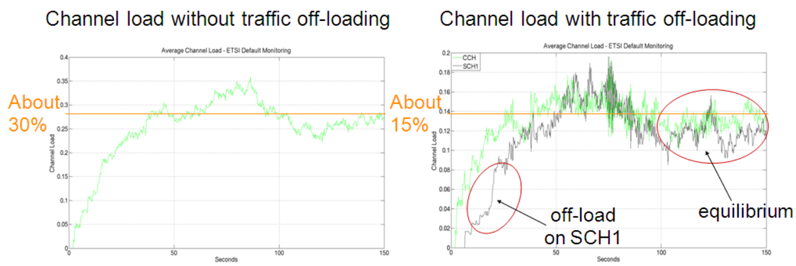


Fig. 10 Illustration, appeared in [25], of the potential reduction of channel load on the CCH from offloading traffic on a secondary SCH.

4.2.2 Channel Switching Principles

At the time of writing this Chapter, standards describing multi-channel switching at the ETSI were still being finalized. We provide here the current trends, but some details might evolve in the future. We suggest interested readers to refer to the corresponding standard [13, 15]. Also, at the time of writing this Chapter, very few studies could be found, which investigated the performance of the ETSI channel switching standard. One of them is provided by De Martini and Härri in [26].

According to the channel plans depicted in Fig. 2 services may be offered on four SCHs. The ECC regulations enforce that only safety-related services be transmitted on ITS-G5A channels (SCH1 and SCH2), but ITS-G5B channels (SCH3 and SCH4) are also open to non-safety-related traffic. Service management (safety-related or not) again bears similarities with IEEE 1609.3. A *Service Provider* announces the presence of an ITS service with a SAM [16] indicating the service and on which SCHs it can be found. *Service Consumers* interested in ITS services tune to the channel, where SAM are sent, and then go to the indicated SCH to consume the service. Service providers and service consumers must therefore first *rendezvous* for service announcement, and then *rendezvous* again where the service is actually being offers. While the SAM message indicates the channel on which the ITS service will be provided, service providers and service consumers must still agree on a common *rendezvous* channel for SAM. In EU, the channel on which SAM are sent correspond to the base channel of the respective ITS transceiver (see Fig. 4) and further referred to as Service Announcement Channel (SACH) in the rest of this Chapter.

As indicated in Fig. 8 and described in Section 4.2.1, road safety-related messages, such as CAM or DENM, may be offloaded or relayed on secondary SCH. ITS-Ss operating on the ITS-G5A spectrum and supporting multi-channel operations (i.e. the T2 transceivers as described in Fig. 4) are therefore enforced to monitor these channels. Considering the safety-of-life content of safety-related messages, even when off-loaded, channel switching must be synchronous between ITS-Ss to guarantee that all T2 ITS-Ss operating on ITS-G5A are on the same secondary SCH when safety-related messages are offloaded or relayed. The synchronous channel switching mechanism is very similar to IEEE 1609.4, but restricted on SCHs.

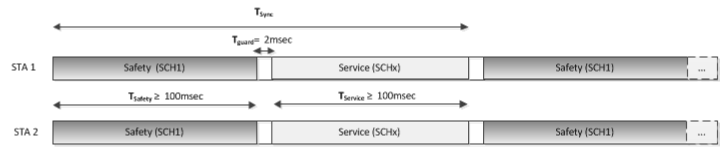


Fig. 11 Synchroneous Channel Switching for ITS-S Services, adapted from [13].

The synchronous channel switching mechanism for the ITS-G5A spectrum has two switching phases as depicted on Fig. 11:

- *Safety* - the ITS-S is tuned to the SCH1 during a *Safety* interval corresponding to T_{Safety}.
- *Service* - the ITS-S is tuned to any other SCHs during a *Service* interval corresponding to $T_{Service}$.

Similarly to IEEE 1609.4, ITS-S transceivers alternate between a safety phase and a service phase following two intervals T_{Safety} and $T_{Service}$, both configurable but widely known to all ITS-Ss. DCC requires a minimum channel load monitoring interval $T_{mon} = 100ms$. Accordingly, both T_{Safety} and $T_{Service}$ must be integer values of T_{mon}. A guard interval, T_{gard} will also be added for time synchronization reasons, during which both channels are unavailable. Finally, T_{Safety}, $T_{Service}$ and T_{gard} sum up to a T_{Sync}.

For ITS-S transceivers not operating on ITS-G5A, the strict and synchronous *rendezvous* on a SCH may be relaxed. The principle is similar to the synchronous mechanism previously described and is illustrated on Fig. 12. The *Safety* phase is replaced by a *SAM* phase, and ITS-S transceivers are only required to be on a *SAM* phase *globally* at the same time. This has two advantages: first, ITS-Ss do not need to be synchronized to operate in this mode. Second, the *SAM* phase may be adjusted at any time during the *synch interval* T_{Sync}. The length of a *SAM* phase is also not strict, but must be sufficient for channel load monitoring. So, $T_{SAM} > T_{mon}$.

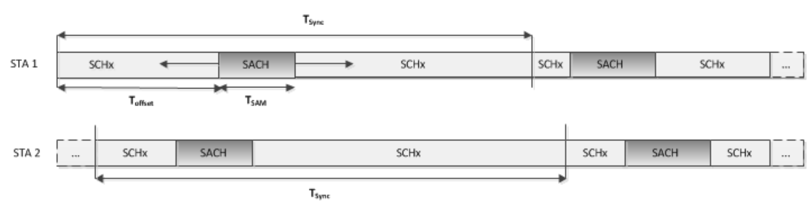
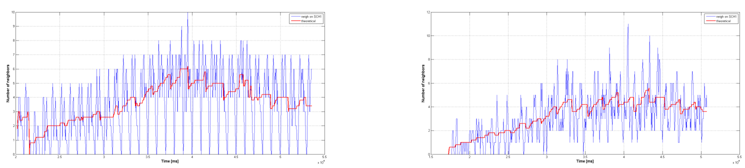


Fig. 12 Asynchronous Channel Switching mechanism, adapted from [13]

The *rendezvous* of ITS-Ss during a *SAM* phase is yet statistically enforced. The start of a SAM phase is triggered according to a *time offset* T_{offset} randomly assigned in an interval $[0,(T_{Synch}-T_{SAM})]$. When an ITS service provider announces a service, it cannot expect to have all ITS-Ss tuned on the SACH, but may statistically estimate the number of neighbors that will be present at any time instant on the SAM phase as: $N_{Nb}^{SAM} = N_{Nb} * \frac{T_{SAM}}{T_{Synch}}$.

The channel switching principles described here have been implemented on the iTETRIS ITS simulation platform [27], configured according to the parameters indicated on Table 1. An illustration the impact of the T_{offset} on the probability of finding a neighbor on the reference channel is depicted on Fig. 13. Considering that ITS-Ss are not synchronous, enforcing a SAM phase at the beginning of the T_{Synch} interval shows a high variance in the number of ITS-Ss jointly being on the SACH during a SAM phase. When a time offset is applied, we can see that the variance is significantly reduced, which is a stability indicator for ITS service providers to offer services on a SACH during a SAM phase. More detailed results are available in [25].



(a) No Offset (b) Random Offset

Fig. 13 Illustration, appeared in [25], of the impact of the offset parameter in increasing the chances of a Rendezvous point.

4.2.3 Multi-Channel Service Management

Multi-channel service management is the process for SPs or SCs to offer and consume ITS services, following the synchronous or asynchronous channel switching mechanisms previously described. In this section, we provide an example of how these mechanisms interact for SPs and SCs to operate ITS services inspired from the ETSI multi-channel operation mechanisms, even though ITS service management is not standardized by the ETSI at the time of writing.

As previously described, most of the ITS services need to be a priori advertised on a SACH on which SPs and SCs must *rendezvous*. The challenge is therefore to evaluate the time before which SPs and SCs manage to rendezvous, and the time required to start consuming an ITS service. Fig 14 depicts this process, where one SP offers a service to three SC. As SPs are not synchronized on the SAM phase, it takes multiple *synch intervals* before all SC are on the SACH at the same time as the SP. On the first *synch intervals*, only SC3 receives a SAM, while SC1 and SC2 are on different channels. During the second *synch intervals*, SC2 is able to receive a SAM, but still not SC1. In this figure, we also illustrate the probability (even though highly unlikely) that a SC, here SC1, never receives a SAM. Once SC have received a SAM, they switch to the SCH on which the service provided by SP1 is offered.

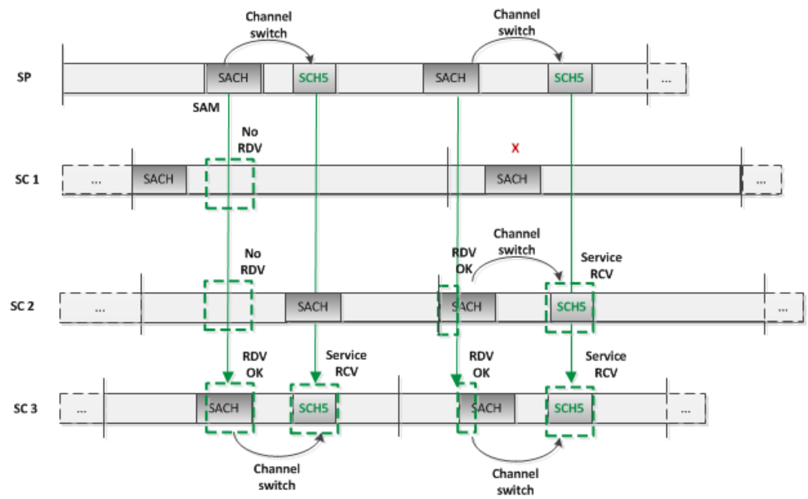


Fig. 14 Illustration, appeared from [13], of ITS service management between a SP and SCs considering a asynchronous channel switching mechanism.

The time required for this process therefore depends on various criteria (e.g. T_{Synch}, T_{SAM}, periodicity of SAM, etc..), one important one being whether the SP and SCs are already on the same SACH when the SAM message is sent or if they are on different channels. We can note that the case where SPs and SCs are on the same SACH is conceptually similar to a synchronous channel switching mechanism, whereas when they are on different SCHs, it corresponds to an asynchronous switching mechanism.

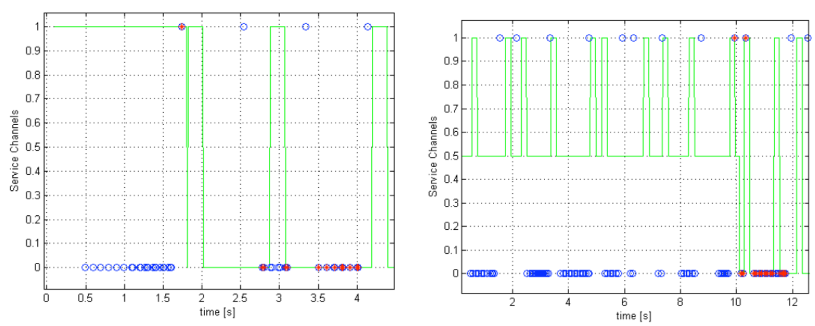
Services are identified in SAMs using an ITS-AID. At the time of writing, there is no clear process or responsible entity to administrate ITS-AID. This duty is shared by the various standards organizations (IEEE, ISO, SAE, ETSI). A list of existing ITS-AIDs are maintained by the International Organization for Standardization (ISO)[3]. At the time of writing, the ITS-AID is a fixed length value occupying three bytes, although there are ongoing proposals to make ITS-AID a variable length value occupying one to three bytes in order to allocate them on ETSI ITS packet headers.

We illustrate the performance of this ITS service management in Fig. 15. The service management has been implemented on the iTETRIS ITS simulation platform [27], configured wit the service management parameters indicated on Table 1. The x-axis corresponds to the simulation time, the green lines represent the channel

[3] ISO 17419: Available ITS-AIDs - http://standards.iso.org/iso/ts/17419/TS17419%20Assigned%20Numbers/TS17419_ITS-AID_AssignedNumbers.pdf

switch operated by the ITS-S, and the y-axis corresponds to channels, on which the ITS-S is currently tuned: the y-label *1* corresponds to the SACH, the y-label *0* corresponds to the Service Provider Service Channel (SP-SCH), while the y-label *0.5* corresponds to any other SCH. Also, the blue, respectively red circles, on the SACH (Channel '1') are SAM being sent, respectively received. The blue, respectively red circles, on the SP-SCH (Channel '0') are SP packets being sent, respectively received. Accordingly, by observing transitions of the blue circles to red circles, we can see the service management mechanisms in operation.

On the left side (Fig. 15(a)), we can see that as both SP and SC are camping on the SACH at the same time, it only takes one SAM transmit interval to switch to the target SCH (SP-SCH) and consume the service. On the right side (Fig.15(a)), we can see that, as SP and SC are away on different SCHs, it requires multiple iterations of the asynchronous channel switching mechanism before both SC and SP *rendezvous* on the SACH and then switch to the SP-SCH. From a time aspect, the difference between asynchronous and synchronous channel switching mechanisms bring an order of magnitude five to the service management convergence time. It should yet be noted first that this time penalty strongly depends on the SAM phase time T_{SAM} and the synch interval T_{Synch}. In this simulation, $T_{SAM} = 200msec$ and $T_{Synch} = 1sec$. Shorter synch intervals automatically gives a faster *rendezvous* convergence. Also, when a SC or even SPs are away on a different channels, it also means they are either consuming or producing already other services, so this does not correspond to wasted time. More detailed results are available in [25] and in [26].



(a) SP and SC start camp on SACH (b) SP and SC start on different SCHs

Fig. 15 Illustration, appeared in [26], of the distributed rendezvous between a SP a SC as function of their initial channel.

5 Coexistence Issues & Future Challenges

In 2013 the US FCC issued a NPRM concerning the use of the 5 GHz spectral band by *Unlicensed National Information Infrastructure (U-NII)* devices. Devices that implement the IEEE 802.11 protocols, frequently referred to as Wi-Fi, are the most common type of U-NII device. The need for more spectrum in which Wi-Fi devices can operate was the primary motivation behind the FCC NPRM. It divides the 5 GHz band into several sub-bands, as shown in Fig. 16. U-NII operation has been permitted in the following sub-bands by previous FCC decisions: U-NII-1, U-NII-2a, U-NII-2c, and U-NII-3. The NPRM proposed a variety of changes to U-NII operation in those bands. It also asked whether U-NII operation should be permitted, and if so on what basis, in the U-NII-2b and U-NII-4 sub-bands, where U-NII operation was not previously permitted. U-NII operation in the 5 GHz band is sometimes referred to as *spectrum sharing*, because the U-NII devices use spectrum that is allocated on a primary basis to licensed devices in these sub-bands. U-NII operation, according to Part 15 of the FCC rules, must not lead to harmful interference of any licensed communication.

The 5.9 GHz DSRC band shown in Fig. 1 is designated by the FCC as U-NII-4 for purposes of the NPRM. This band is allocated on a primary, licensed basis to DSRC services as well as to some radar and satellite services. The IEEE 802.11ac-2013 [24] amendment defines high bit rate Wi-Fi that utilizes *80 MHz* and *160 MHz* channel bandwidths. The Wi-Fi community was especially interested in gaining access to the U-NII-4 band. The combination of the U-NII-3 and U-NII-4 sub-bands would permit one additional 80 MHz channel and one additional 160 MHz channel, both with upper frequency 5.895 GHz. The potential for spectrum sharing in the DSRC band created significant concerns in the DSRC community. Many DSRC stakeholders worried that U-NII devices using the band would interfere with the DSRCs safety-of-life mission.

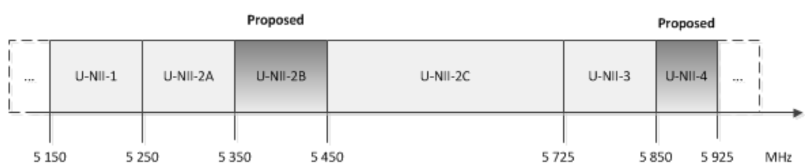


Fig. 16 The US U-NII bands, and coexistence with RLANs and DSRC spectra.

A similar proposal was made to allow Wi-Fi RLANs to operate in the ITS-G5 spectrum (Fig. 2) in Europe. In September 2013, the European Commission mandated the European Conference of Postal and Telecommunications Administrations (CEPT) to investigate the issue. The task was assigned to CEPT Spectrum Engineering Group 24 (*SE-24: Short Range Devices*). A major limitation of this proposal in Europe is related to the existence of the Comité Européen de Standardization (CEN) DSRC allocated spectrum for toll collection, which would not be able to coexist with other technologies sharing its dedicated spectrum. At the time of writing, SE-24 continues to study the issue of sharing ITS-G5 spectrum between C-ITS and RLAN devices.

In early 2013 key DSRC stakeholders in the US reached out to the Wi-Fi community to initiate discussions about whether sharing is possible and how it might be regulated. This led to DSRC experts providing educational tutorials at IEEE 802.11 Standards Working Group (WG) meetings, as well as several face-to-face meetings between the DSRC and Wi-Fi stakeholders. In August 2013 the IEEE 802.11 WG formed a technical *Tiger Team* to investigate coexistence between DSRC and Wi-Fi devices.

Wi-Fi members proposed two types of sharing solutions in the Tiger Team. One called for DSRC devices operating in the U-NII-4 band to detect the presence of DSRC transmissions, and to stop using the band for a period of time when DSRC devices were detected. Since DSRC is based on the IEEE 802.11 protocol, detection of DSRC can be done using the IEEE 802.11 *listen before talk* Carrier Sense Multiple Access / Collision Avoidance (CSMA/CA) MAC protocol (see Chapter 4). The CSMA function for detection is called Clear Channel Assessment (CCA), so this sharing proposal is known as the CCA proposal. The second proposal, called the *Rechannelization* proposal, calls for the DSRC community to move BSM communication from Channel 172 into one of the channels above 5.895 GHz, and to use two 20 MHz channels between 5.855-5.895 GHz, the portion of the spectrum that IEEE 802.11ac devices also want to use. It also calls for the FCC to draw the upper edge of the U-NII-4 band at 5.895 GHz instead of 5.925 GHz, so that the upper 30 MHz of the DSRC band does not overlap with U-NII-4.

The DSRC community has indicated to the Tiger Team, to the FCC, and to other US Government decision makers that it is opposed to the *Rechannelization* proposal for a number of reasons, but that it thinks the CCA proposal has potential to enable sharing without harmful interference. The DSRC community has encouraged the Wi-Fi community to further develop the CCA proposal into a complete sharing solution, so that it can be tested with DSRC devices. All parties agree that any potential sharing solution must be rigorously tested before sharing could be allowed. The FCC has not completed its consideration of U-NII device sharing of the DSRC band. At the time of writing, the Tiger Team is discussing these proposals according to the feedbacks from the DSRC community.

6 Conclusion

We reviewed in this Chapter the basic multi-channel mechanisms for vehicular communications, as standardized in the US and in Europe. Although sharing similar objectives and bearing resemblance to many aspects, the source of their difference is to be found in the different spectra allocated in the US and in the EU: the US has seven allocated DSRC channels, which makes it critical to have multi-channel switching mechanisms, as it is economically impossible to operate all seven with different DSRC transceivers. In Europe, only three ITS-G5 channels have been allocated since 2008, and due to the reduced spectrum, multi-channel switching appeared less critical. The ETSI therefore rather focused on mitigating channel congestion by offloading traffic on the other available channels. We first introduced the channel allocations and different ITS stations (i.e. RSUs and OBUs), we then described the channel switching principles proposed by IEEE 1609.4 and IEEE 1609.3 in the US and ETSI TS 724-4-2 and ETSI TS 103 165 in Europe. We illustrated the performance of potential multi-channel congestion control and showed how offloading or relaying part of the safety-critical traffic from the ETSI CCH on secondary SCH is another viable mechanism to regulate the load on CCH. We also proposed and tested an asynchronous multichannel service management compliant with the current standards and emphasized its flexibility for service providers and consumers to rendezvous and consume services.

Although mildly followed and supported, efficient multi-channel mechanisms are expected to become critical at the eve of the ITS Day Two applications, and mostly with the expected future requirement for DSRC to coexist and share the ITS spectrum with alternate technologies (i.e. WiFi-Giga or LTE-A). It is expected to be highly unlikely that all ITS bands be strictly assigned to a particular type of traffic. Early proposals already suggest to rely on cognitive principles to dynamically move traffic between channels as function of the co-existence with other type of traffic. It is therefore expected that the very mechanisms described in this chapter to evolve and expand to support a larger category of ITS services, spanning from safety-related to fully commercial traffic. If the initial years of the the DSRC/ITS-G5 technology have been focused primarily on single channels and on congestion *control*, the future years are expected to be focused on multi-channels dynamic spectrum sharing and on congestion *avoidance*.

Acknowledgments

EURECOM acknowledges the support of its industrial members: SFR, Orange, ST Microelectronics, BMW Group, SAP, Monaco Telecom, Symantec, IABG.

The authors would also like to thank Laura De Martini for her support in the simulation results of the ETSI channel switching mechanisms, as well as the members of the ETSI Specialist Task Forces (STF) 420, 447 and 469, and the Editors of this Book for their fruitful suggestions and remarks.

References

[1] 2008/671/EC European Communication (EU) (2008) EU Decision of 5 August 2008 on the harmonized use of radio spectrum in the 5 875-5 905 MHz frequency band for safety-related applications of Intelligent Transport Systems (ITS)”. Decition 2008/671/EC, EC

[2] Bi Y, Liu KH, Cai L, Shen X, Zhao H (2009) A multi-channel token ring protocol for qos provisioning in inter-vehicle communications. Wireless Communications, IEEE Transactions on 8(11):5621–5631

[3] Campolo C, Molinaro A (2013) Multichannel communications in vehicular ad hoc networks: a survey. Communications Magazine, IEEE 51(5):158–169

[4] Chu JH, Feng KT, Chuah CN, Liu CF (2010) Cognitive radio enabled multichannel access for vehicular communications. In: Vehicular Technology Conference Fall (VTC 2010-Fall), 2010 IEEE 72nd, pp 1–5

[5] Di Felice M, Ghandour A, Artail H, Bononi L (2012) On the impact of multichannel technology on safety-message delivery in ieee 802.11p/1609.4 vehicular networks. In: Computer Communications and Networks (ICCCN), 2012 21st International Conference on, pp 1–8

[6] ECC/DEC/(08)01 Electronic Communications Committee (ECC) (2008) ECC Decision (08)/01 on the harmonized use of the 5875-5925 MHz frequency band for Intelligent Transport Systems (ITS). Decision ECC/DEC/(08)01, ECC

[7] Electronic Communications Committee (ECC) (2008) ECC Recommendation (08)01:”Use of band 5855-5875 MHz for Intelligent Transport Systems (ITS). Recommendation ECC/REC/(08)01, ECC

[8] European Telecommunications Standards Institute (2009) Intelligent Transport Systems (ITS); European profile standard for the physical and medium access control layer of Intelligent Transport Systems operating in the 5 GHz frequency band. ES 202 663 V1.1.0, ETSI

[9] European Telecommunications Standards Institute (2011) Intelligent Transport Systems (ITS); Decentralized Congestion Control Mechanisms for Intelligent Transport Systems operating in the 5 GHz range; Access layer part. TS 102 687 V1.1.1, ETSI

[10] European Telecommunications Standards Institute (2012) Intelligent Transport Systems (ITS); Harmonized Channel Specifications for Intelligent Transport Systems operating in the 5 GHz frequency band. TS 102 724 V1.1.1, ETSI

[11] European Telecommunications Standards Institute (2012) Broadband Radio Access Networks (BRAN); 5 GHz high performance RLAN; Harmonized EN covering the essential requirements of article 3.2 of the R&TTE Directive. EN 301 893 V1.7.1, ETSI

[12] European Telecommunications Standards Institute (2013) Intelligent Transport Systems (ITS); Vehicular communications; GeoNetworking; Part 4: Geographical addressing and forwarding for point-to-point and point-to-multipoint

communications; Sub-part 1: Media-Independent Functionality. TS 102 636-4-1 V1.1.2, ETSI
[13] European Telecommunications Standards Institute (2013) Intelligent Transport Systems (ITS); Vehicular Communications; GeoNetworking; Part 4: Geographical addressing and forwarding for point-to-point and point-to-multipoint communications; Sub-part 2: Media-dependent functionalities for ITS-G5. TS 102 636-4-2 V1.0.0, ETSI
[14] European Telecommunications Standards Institute (2013) Intelligent Transport Systems (ITS); Radiocommunications equipment operating in the 5 855 MHz to 5 925 MHz frequency band; Harmonized EN covering the essential requirements of article 3.2 of the R&TTE Directive. EN 302 571 V1.2.0, ETSI
[15] European Telecommunications Standards Institute (2015) Intelligent Transport Systems (ITS); Cross Layer DCC Management Entity for operation in the ITS G5A and ITS G5B medium; Cross Layer DCC control entity. TS 103 165 V1.0.0, ETSI
[16] European Telecommunications Standards Institute (in progress) Intelligent Transport Systems (ITS); Facilities layer function; Part 2: Services announcement specification. TS 102 890-2, ETSI
[17] Han C, Dianati M, Tafazolli R, Liu X, Shen X (2012) A novel distributed asynchronous multichannel mac scheme for large-scale vehicular ad hoc networks. Vehicular Technology, IEEE Transactions on 61(7):3125–3138
[18] Hong K, Kenney J, Rai V, Laberteaux K (2010) Evaluation of multi-channel schemes for vehicular safety communications. In: Vehicular Technology Conference (VTC 2010-Spring), 2010 IEEE 71st, pp 1–5
[19] IEEE Standard (2010) IEEE Standard for Wireless Access in Vehicular Environments (WAVE) - Multi-channel Operation. Tech. Rep. 1609.4-2010, IEEE
[20] IEEE Standard (2010) IEEE Standard for Wireless Access in Vehicular Environments (WAVE) Networking Services. Tech. Rep. 1609.3-2010, IEEE
[21] IEEE Standard (2010) IEEE Wireless LAN MAC and PHY Specifications: Amendment 6: Wireless Access in Vehicular Environments. Tech. Rep. IEEE 802.11p-2010, IEEE
[22] IEEE Standard (2012) IEEE Standard for Wireless Access in Vehicular Environments (WAVE) - Identifier Allocations standard. Tech. Rep. 1609.12-2012, IEEE
[23] IEEE Standard (2013) IEEE Standard for Wireless Access in Vehicular Environments (WAVE) - Security Services for Applications and Management Messages. Tech. Rep. 1609.2-2013, IEEE
[24] IEEE Standard (2013) IEEE Wireless LAN MAC and PHY Specifications: Amendment 4: Enhancements for Very High Throughput for Operation in Bands below 6 GHz. Tech. Rep. IEEE 802.11ac-2013, IEEE
[25] Laura De Martini and Jérôme Härri (2013) Design and Evaluation of Multi-Channel Mechanisms for Efficient ITS Spectrum Usage. Tech. Rep. RR_13_289, EURECOM

[26] Laura De Martini and Jérôme Härri (2013) Short paper: Design and evaluation of a multi-channel mechanism for vehicular service management at 5.9 ghz. In: Vehicular Networking Conference (VNC), 2013 IEEE, pp 178–181
[27] Rondinone M, Maneros J, Krajzewicz D, Bauza R, Cataldi P, Hrizi F, Gozalvez J, Kumar V, Röckl M, Lin L, Lazaro O, Leguay J, Härri J, Vaz S, Lopez Y, Sepulcre M, Wetterwald M, Blokpoel R, Cartolano F (2013) iTETRIS: A modular simulation platform for the large scale evaluation of cooperative ITS applications. Simulation Modelling Practice and Theory 34:99–125, DOI 10.1016/j.simpat.2013.01.007
[28] US Federal Communications Commission (2003) DSRC Licensing and Service Rules. Tech. Rep. FCC-03-324A1, FCC
[29] US Federal Communications Commission (2006) Memorandum Report and Order. Tech. Rep. FCC-06-110, IEEE
[30] US Federal Communications Commission (2013) Notice of Proposed Rulemaking. Tech. Rep. FCC-13-22, IEEE
[31] Wang Z, Hassan M (2008) How much of dsrc is available for non-safety use? In: Proceedings of the Fifth ACM International Workshop on VehiculAr InterNETworking, VANET '08, pp 23–29