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Analysis of Approaches for Channel Allocation in Car-to-Car Communication

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Abstract

Car-to-car and car-to-infrastructure communication (C2X communication) has received considerable attention worldwide. The main goals of C2X communication are reduction of road accidents and fatalities and improvement of traffic efficiency. In Europe, the European Telecommunications Standards Institute (ETSI) is currently leading the spectrum allocation dedicated to road safety. It is expected that 30 MHz spectrum in the range from 5.875 to 5.905 GHz will be allocated for critical road safety and traffic efficiency applications. This paper provides a detailed analysis of channel allocation for the 30-MHz spectrum dedicated to safety-related C2X communication. Our contributions are:

(1) We provide a comprehensive overview of existing approaches on the usage of the 30-MHz frequency band dedicated for safety-related C2X communication.

(2) We analyze advantages and disadvantages of these approaches based on an extensive set of evaluation criteria.

(3) We provide a recommendation for the channel allocation of the 30-MHz frequency band dedicated for safety-related C2X communication in Europe.

1 Introduction and Motivation

Recently, C2X communication has received considerable attention in both academia and industry because it has the potential to improve road safety and to reduce road accidents and fatalities. For this purpose, the mature, inexpensive, and widely available IEEE 802.11 technology appears very attractive. In C2X communication, cars are equipped with IEEE 802.11-based wireless network interfaces and can spontaneously form an ad hoc network among themselves. Cars can use the ad hoc network to communicate with each other in order to support safety applications such as cooperative collision warning. This allows drivers to receive emergency warnings from the C2X communication system and reduce speed before they can actually see an accident or the brake light of the cars in front. Further, road side units (RSUs) equipped with sensors can also communicate with cars via the ad hoc network to provide warnings about road conditions or speed limit.

C2X communication is considered as an important part of future *Intelligent Transportation Systems* (ITS). An overview of the C2X communication system is depicted in Fig. 1. Beside enabling safety applications, the C2X communication system provides non-safety applications such as infotainment applications and Internet access. These will have lower priority than safety applications.

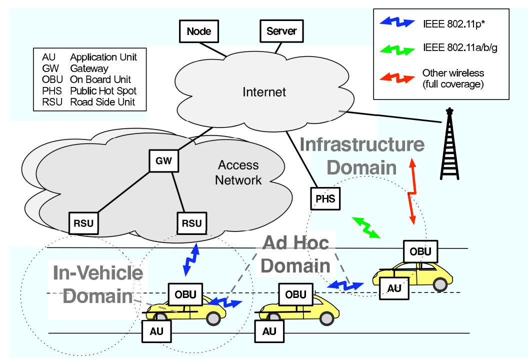


Figure 1. C2X communication scenario.

Since C2X communication's major goal is to support critical road safety applications, it is desirable that C2X communication experience as little interference from other wireless applications on the wireless medium as possible. For this reason, there are ongoing discussions that a spectrum allocation will be used as protected bandwidth for C2X communication (and ITS in general).

In Europe, it is expected that the frequency bands 5.855-5.875 and 5.875-5.925 GHz will be used for ITS non-safety and safety applications. Further, the frequency band 5.875-5.925 GHz will be divided into two parts 5.875-5.905 GHz and 5.905-5.925 GHz in an initial and a later deployment phase [5]. An overview of the expected spectrum allocation for ITS applications in Europe is illustrated in Fig. 2.

A number of proposals have been made for the usage of the 30-MHz frequency band dedicated for road safety and traffic efficiency. This paper provides an analysis of the channel allocation for the 30-MHz frequency band dedicated to safety-related C2X communication. Our contributions are:

(1) We provide a comprehensive overview of existing approaches for the usage of the 30-MHz frequency band dedicated for safety-related C2X communication.

(2) Based on a set of evaluation criteria for multi channel operation [7], we perform a detailed analysis of the existing proposals for channel allocation.

(3) We provide a recommendation for the channel usage of the 30-MHz frequency band dedicated for safety-related C2X communication. Our recommendation is intended as input for further discussions in different standardization bodies such as ETSI, ISO, and Car 2 Car Communication Consortium (C2C-CC).

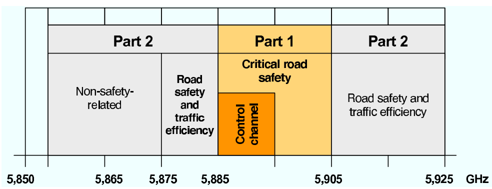


Figure 2. Anticipated spectrum allocation for ITS applications in Europe.

The rest of this paper is organized as follows. Section 2 reviews the background and requirements for C2X communication. Section 3 discusses related work. Section 4 presents our analysis. Section 5 concludes the paper.

2 Background and Requirements

In this section, we review the basic protocol operations and the requirements for C2X communication. This section covers the background in C2X communication before we present our analysis in section 4.

2.1 Background for C2X Communication

In vehicular ad hoc networks (VANETs) vehicles support safety applications by broadcasting and processing of two types of messages: periodic and event-driven safety messages [2]. These safety messages typically need to be delivered within a geographical area with certain reliability and delay limit. The periodic messages, also called beacons, carry vehicles' status information such as positions and speeds. Beacons can be generated at the application layer or at the network layer, and are used by neighbouring vehicles to become aware of their surrounding and to avoid potential dangers. Event-driven safety messages are generated when an abnormal condition or an imminent danger is detected, and disseminated within a certain area with high priority. Critical event-driven messages usually have strong reliability and delay requirements.

It is well known that vehicular communication environments are characterized by highly mobile vehicles, extremely frequent topology changes and a great variation in the number of vehicles in a certain region. To meet the specific requirements of V2X communications in such environments, geographical routing is applied. Geographical routing assumes that vehicles acquire information about their own positions (i.e. geodetic coordinates) via GPS or other positioning systems. If a vehicle intends to send data to a known target geographic location, it chooses another vehicle as message relay, which is located in the direction towards the target position. The same procedure is executed by every vehicle on a multi-hop path until the destination is reached. Results from extensive network simulations and measurements have indicated that geographical routing has good performance in realistic environments.

2.2 Requirements

Recently, a set of criteria for evaluating multi channel operation in C2C-CC has been proposed [7]. We review these criteria in this section and use them to evaluate different approaches for channel allocation in Section 4.

Usability: This criterion represents the main requirements for safety-related C2X communication: low latency and high reliability for critical safety messages. In Section 4, we will focus on latency since network and/or applications should be responsible for reliability.

Robustness: This criterion evaluates the wireless link's robustness in two aspects: (1) it has to be robust in terms of bit errors (e.g. the bit error rate should be as low as possible) and (2) it has to be robust in terms of interference.

Cost: This criterion considers the material costs for mass production and deployment. Obviously, an inexpensive solution is preferred in order reduce the market barrier.

Efficiency: This criterion evaluates the effectiveness of channel allocation in terms of bandwidth usage. Given the scarcity of available bandwidth allocated for C2X communication, this precious resource must be used effectively.

Scalability: This criterion evaluates the impact of channel allocation on the flexibility of the overall C2X communication system in different scenarios such as highways, cities, and rural areas.

Development effort: This criterion considers development costs apart from material costs. A solution for channel allocation that allows a simple design and implementation of the C2X communication system is clearly preferred.

3 Related Work

3.1 Spectrum Allocation and Measurement Reports in North America

In North America, a 75-MHz frequency band in the 5.9 GHz range is reserved for ITS. This spectrum may be allocated to seven 10-MHz bandwidth channels. One of the 10-MHz channels will be designated as a control channel (CCH) that is used to transmit critical safety applications and beacons. Other channels are used for other purposes such as traffic efficiency and infotainment and are called service channels (SCHs). It is also possible to obtain a 20-MHz SCH by combining two 10-MHz SCHs. Since wireless devices are usually incapable of simultaneously monitoring and exchanging data on different channels, the standard IEEE 1609 for Wireless Access in Vehicular Environments (WAVE) [3] suggests that wireless devices operate in the control channel during a periodic common interval.

Recent measurements evaluated the robustness of 802.11p's channel width (5, 10 and 20 MHz) against BER when operated in different scenarios: suburban, highway, and rural environments [10]. Measurements were conducted without channel interference. Analysis and measurements showed that 802.11p's guard interval is not long enough in a 20-MHz channel while errors increase from lack of channel stationarity over the packet duration in a 5-MHz channel. This study concluded that a 10-MHz channel is the best choice in terms of robustness against BER.

Regarding channel interference, a recent measurement study [9] reported that interference between adjacent channels leads to substantial packet error rates while interference between non-adjacent channels is much less of an issue, although still measurable in some environments. These results indicate that interference is a serious issue for deployment models employing adjacent channels.

3.2 Multi Channel Operation in NoW

In project Network on Wheels (NoW) [8], the task force *Multi Channel Operation* has investigated the channel allocation problem on how to use 2x10-MHz channels [1]. We observe that multi channel operation covers problems related to both the physical and network layer. Several possible channel usage scenarios are analyzed, namely, WAVE compliant mode, symmetric channels, priority and traffic channel, and combined channel mode.

WAVE compliant mode: this follows the WAVE standard [3] in the U.S. where channel switching is performed between a single CCH and multiple SCHs.

Symmetric channel layout: this considers the two channels as identical, and each transmitter decides which channel it uses or it may use the channels arbitrarily.

Priority and traffic channel: this uses one channel exclusively for high priority safety messages and the other channel for all non-priority safety messages.

Combined channel mode: this combines two 10 MHz channels to a single 20 MHz channel.

It is argued that the support of high priority low latency messages is vital for critical safety applications. Thus, the Priority and Traffic channel usage scheme is chosen for multi channel operation.

3.3 C2C-CC Channel Allocation Proposal

Within C2C-CC, there have been intensive discussions on the usage of 30-MHz frequency band. There are a number of proposals. Generally saying, three basic approaches have been discussed: (1) Single 30-MHz channel, (2) one 20- and one 10-MHz channel, and (3) three 10-MHz channels. However, the single 30-MHz channel approach requires new hardware that supports 30-MHz bandwidth. It is envisaged that considerable amount of development efforts are needed. Thus, it is not a preferred solution.

Table 1. Spectrum mask (in dBc)

MHz	4.5	5.0	5.5	10	15
Class A	0	-10	-20	-28	-40
Class B	0	-16	-20	-28	-40
Class C	0	-26	-32	-40	-50

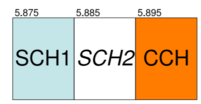


Figure 3. Proposed channel allocation for 30-MHz frequency band in C2C-CC

Recent discussions in C2C-CC tend to propose the following channel usage (Fig. 3): a service channel (SCH1) in the frequency band 5.875 - 5.885 GHz will be used for low-priority safety messages and traffic efficiency applications, another service channel (SCH2) in the frequency band 5.885 - 5.895 GHz will be used for transmission in small distances and with low transmit power to minimize the interference to SCH1 and CCH, and a control channel in the frequency band 5.895 - 5.905 GHz will be used for high-priority safety messages and beacons.

3.4 Spectrum Mask and Link Budget

For better understanding of channel interference, we will review the relevant specification of IEEE 802.11p and methods for calculating link budget in vehicular environments.

ETSI has specified the emission limits of different classes of IEEE 802.11p radio equipment. The maximum radiated power for Class A, B and C is 10, 20 and 33 dBm, respectively [5]. The transmit spectrum masks for these classes follow IEEE 802.11p [6] and are listed in Table 1. The minimum receiver sensitivity in a 10-MHz channel is also listed, e.g. -85dBm for data rate of 3 Mbits/s and $-72dBm$ for data rate of 6 Mbits/s.

ETSI also specifies method for link budget calculation. Without considering the gain of antenna, the link budget is calculated in dBm as

$$P_e = P_s + L_0 + L_l, \tag{1}$$

where Pe is the received power in dBm, P_s is the transmit power in dBm, L_0 is the path loss in dB up to the breakpoint distance d_0, L_l is given by

$$L_l = -10log(d/d_0)^n, \quad (2)$$

where d is the distance between a transmitter and a receiver, n is the path loss factor, which is typically 2.7 for vehicular environments [5]. In the 5.9-GHz band, the breakpoint distance is given as $d_0 = 15m$ and accordingly $L_0 = -71dBm$.

4 Analysis of Different Approaches

4.1 Overview of Existing Approaches

Considering the basic channel usage scenarios from C2C-CC, we can eliminate some scenarios based on qualitative observations. First, since the 30-MHz channel scenario requires new hardware and would incur significant development cost, it must be ruled out. Second, the measurement study for channel interference [9] indicates that the simultaneous usage of two adjacent channels causes significant packet loss and hence is unacceptable for ITS safety applications. Although measurements have been conducted only for 10-MHz channels, we expect that simultaneous usage of 20- and 10 MHz channels will have similar effects and should also be avoided. Further, since measurement results [10] show that 20-MHz channels are more susceptible to BER than 10-MHz channels, usage of 20-MHz channels will not be further considered in our analysis.

While the usage of adjacent channels is possible, certain mechanisms such as WAVE channel switching have to be in place to prevent simultaneous transmissions on these channels. Although interference also occurs between non-adjacent channels, it is much lower than in the case of adjacent channels. We believe that this smaller interference acceptable as packet losses caused by interference between non-adjacent channels can be recovered by reliability mechanisms at the network layer and/or applications.

From recent measurement results [9, 10] presented in Section 3 and our reasoning above, we analyze and compare two channel usage schemes in the rest of our paper: SCH1 + SCH2 + CCH (Scheme A) and CCH + 2 * SCH with WAVE channel switching (Scheme B). Scheme A needs two transceivers while scheme B requires one transceiver performing WAVE channel switching.

4.2 Usability

4.2.1 Latency

Scheme A: Both SCH1 and CCH experience the media access latency according to 802.11 (denoted as T_m). SCH2 has lower priority and will also be subject to adjacent channel interference from both SCH1 and CCH. A node using SCH2 may sense channel as busy if other nodes are transmitting on SCH1 or CCH. The channel access latency of SCH2 depends on activities on SCH1 or CCH, and its minimum value is T_m. The latency for CCH and SCH1 is

$$T_A = T_m. \quad (3)$$

Scheme B: CCH and each SCH have the switching cycle of 100ms and are only active every $T_c = 50ms$. A message may arrive when CCH is either active or inactive. We assume that the arrival time of a message is uniformly distributed within a switching cycle. Thus, the probability that a message finds CCH to be active or inactive will be the same, and the average time between the arrival of a message and the end of an active or inactive period is $0.5T_c$.

When CCH is active, the message will not experience channel switching latency. Here we assume that the channel load is low and the message can be transmitted in a switching cycle. Otherwise, the message will experience a switching delay (denoted as T_s) and the media access latency T_m depending on the channel load. When CCH is inactive, the message will experience an additional average waiting time of $0.5T_c$. Since the probability of these two cases are equal, the average waiting time before CCH becomes active is $0.25T_c$. Therefore, we get the total average channel access latency for CCH is

$$T_{BC} = 0.25T_c + T_s + T_m. \quad (4)$$

For latency on SCH, we note that each SCH will be active after its service announcement on CCH. We assume that a SCH is activated immediately after a CCH's active period. Applying the same method in calculating Eq. (4), we get the total average channel access latency for SCH

$$T_{BS} = T_c + T_s + T_m. \quad (5)$$

For latency, scheme A is preferred over scheme B.

4.2.2 Prioritization of Different Message Types

Since both scheme A and B can support prioritization of different message types by using CCH and SCHs for different priorities, there is no preference between the schemes.

4.3 Robustness

4.3.1 Channel interference

Scheme A: Here we present a theoretical analysis of channel interference similar to [1]. We assume that a message will be correctly received if the received power from the transmitter is over 10dB higher than that of the interfering node. Based on the link budget calculation model presented in (1), if the transmit power of the transmitter on one channel is 20dBm, the received power will be -85dBm at the distance of $276m$. This means, the transmitter has a communication range of $276m$, in which the data rate of 3Mbits/s is supported. Depending on the distance between the transmitter and the interference node, there may be a jammed area within the communication range of the transmitter, where the reception from the transmitter will fail due to the interference node as shown in Figure 4.

Figure 4(a) shows the jammed area caused by the interference node in an adjacent channel with centre frequency offset 10MHz. The light-grey areas are the communication range of the transmitter without interference, the grey areas indicate the jammed area of class A/B equipment (with spectrum mask -28dBc) and the black areas indicate the jammed area of class C equipment (with spectrum mask -40dBc). We may observe that the jammed area is relatively large for class A/B equipment, especially when the distance between the transmitter and the interference node is large. Because class A/B equipment from non-adjacent channels with channel spacing 20MHz also has the same spectrum mask of -40dBc, its jammed areas are the same as the jammed areas in black.

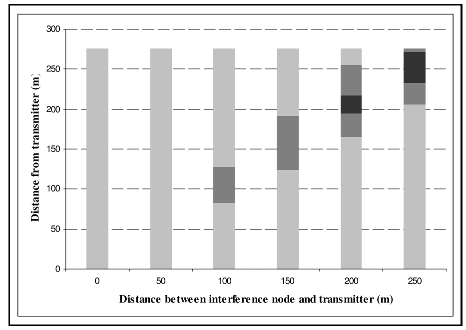
Figure 4(b) shows the jammed areas caused by the interference node with transmit power 10dBm in an adjacent channel. The light-grey areas are the communication range of the transmitter without interference, the grey areas indicate the jammed area of class A/B equipment (with spectrum mask -28dBc). Further analysis shows that in case the transmit power is 5dBm in an adjacent channel, no jammed area will be observed.

Comparing the theoretical analysis with field measurements [9], we have several observations. We find that the measurement of the non-adjacent channel interference is slightly different from theoretical analysis, but all indicating that non-adjacent channel interference is rather small if the frequency offset is over 20 MHz. However, theoretical analysis shows that there is no jammed area between adjacent channels if the distance between the transmitter and the receiver is below $50m$ (Figure 4(a)). But field measurements show that packet loss probability is considerably high if the distance between the interference node and the receiver is below $10m$. One possibility to cope adjacent channel interference is to reduce interference power. Theoretical analysis shows that in case the transmit power in adjacent channels is 15dB less, no jammed area will be observed, but no similar measurement data are available.

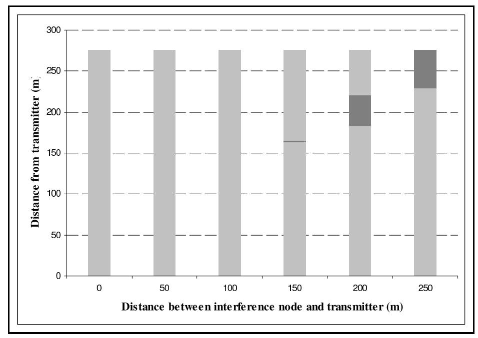
For scheme A, we conclude that: (1) There is very limited interference between the CCH and SCH1 if an interference node is over 2m away from a receiver. (2) Theoretical analysis shows that if the transmit power in SCH2 is 15dB lower than that of the CCH and SCH1, the CCH and SCH1 will be free from interference. It is still necessary to measure adjacent channel interference with relatively small interference power in order to use SCH2 with other channels simultaneously. (3) SCH2 will suffer severe interference from the CCH and SCH1.

Scheme B: If the CCH is located between two SCHs, there will be no adjacent channel interference since WAVE does not allow simultaneous transmissions in the CCH and a SCH. However, there exists non-adjacent channel interference similar to the case shown in Figure 4(a).

Here scheme B slightly outperforms scheme A.



(a) Adjacent channel: class A/B (-28dBc) and class C (-40dBc) with transmit/interference power $20dBm$



(b) Adjacent channel: class A/B (-28dBc) with transmit/interference power 20dBm/10dBm

Figure 4. Adjacent channel interference

4.3.2 Reliability

In Scheme B, all nodes need to synchronise with a reference time system such as UTC. Unsynchronized nodes or synchronization inaccuracy could render WAVE channel switching inoperable. Since scheme A has no requirement on synchronization, it is preferred over scheme B.

4.4 Hardware and Development Effort

Both scheme A and B will be based on standard IEEE 802.11p hardware and are equal regarding availability. However, scheme A needs two wireless network interfaces where scheme B requires only one. On the other hand, scheme A can use off-the-shelf IEEE 802.11 drivers whereas scheme B requires an implementation of WAVE synchronized channel switching. Here it is likely that scheme B is slightly preferred over scheme A. However, depending on deployment scenarios, the hardware cost can outweigh the development effort or vice versa.

4.5 Efficiency

Bandwidth usage efficiency. In order to compare the bandwidth usage efficiency we define the following metrics.

$$E \triangleq \sum \text{bandwidth} \times \text{percentage of active time} \quad (6)$$

For Scheme A, both the CCH and SCH1 can be active the same time. In this case, SCH2 will suffer from interference. Thus, the efficiency for Scheme A is

$$E_A = 2 * 10MHz * 100\% = 10MHz * 200\% \quad (7)$$

For Scheme B, every channel can only be active half of the same. Due to channel switching, not all the active time can be used for transmission. Assume the channel switching time is $x\%$, the efficiency for Scheme B is

$$E_B = 3 * 10MHz * (50\% - x\%) < 10MHz * 150\% \quad (8)$$

Here scheme A is preferred over scheme B.

4.6 Scalability

4.6.1 Node Density

With high node density, the amount of data traffic has to be controlled. This requires proper congestion control mechanisms, such as reducing packet size, packet generation rate and transmit power. Since available congestion control mechanisms appear to be applicable for both schemes, there is no preference for neither scheme A nor scheme B.

4.6.2 Additional Frequency Band

Addition frequency band, especially the additional 20-MHz bandwidth between 5.905GHz and 5.925GHz will have different implications on the allocation schemes. With scheme A, the lower part of the additional bandwidth may be used as a SCH with low transmit power similar to SCH2, and the higher part may be used as a SCH with relative higher power similar to SCH1. This will add the channel usage efficiency by $10MHz * 100\%$. With scheme B, another two SCHs with 10-MHz bandwidth will be available. However, the two new channels, along with the SCH between 5.895GHz and 5.905GHz, cannot be used simultaneously due to high adjacent channel interference. One possible approach to reduce adjacent channel interference between these three channels is to reduce the active time of the channels, e.g. to limit the activity on the SCH between 5.905GHz and 5.915GHz. This will only add channel usage efficiency by $10MHz * 50\%$, which is much less than that of scheme A. Here scheme A is preferred over scheme B.

5 Summary and Conclusion

We present a comprehensive overview of channel allocations for the spectrum allocated to C2X communication in Europe. We use an extensive set of evaluation criteria for channel allocation and present an analysis of some proposals. In particular, we consider and compare two channel usage schemes: SCH1 + SCH2 + CCH (Scheme A) and CCH + 2 * SCH with WAVE channel switching (Scheme B). Scheme A requires two transceivers and uses low transmit power on SCH2. Scheme B needs one transceiver performing WAVE channel switching. Overall, the advantages of scheme A outweigh those of scheme B. We recommend scheme A for C2X communication in Europe.

An issue that is not considered in this paper is the interference caused by transmissions in the 30-MHz frequency band dedicated to safety-related C2X communication to other frequency bands (below 5855 MHz and above 5925 MHz). This issue was investigated in a related study [4]. When results of this study is taken into consideration, one possible solution is to swap CCH and SCH1 (as shown in Figure 3). The main results of our analysis still hold.

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