An Overview of the DSRC/WAVE Technology

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Abstract. Wireless vehicular networks operating on the dedicated short-range communications (DSRC) frequency bands are the key enabling technologies for the emerging market of intelligent transport system (ITS). The wireless access in vehicular environments (WAVE) is significantly different from the Wi-Fi and cellular wireless networking environments. The specifications defined by IEEE802.11P and IEEE1609 represent the most mature set of standards for DSRC/WAVE networks. This paper provides an overview of the current state of the art, and analyses the potential differences between application requirements and what can be offered by the current WAVE solutions. It is shown that the current solutions may be inadequate for large-scale deployment. The primary challenge is to develop scalable, robust, low-latency and high-throughput technologies for safety applications that will significantly reduce collisions and save lives and property loss. Further research ideas are proposed to address this challenge.

Keywords: WAVE, DSRC, IEEE802.11P, IEEE1609, VANET, OFDM, QoS, scalability, latency, throughput.

1 Introduction

There has been tremendous investment from government, academia and industry under the big umbrella of intelligent transport systems (ITS), leading to the development of safety and traffic management technologies in vehicles and road infrastructure. Wireless vehicular communications and networking is a key enabling technology for future ITS services. The International Organization for Standardization (ISO) TC204 WG16 is developing a family of international standards and architecture on communications access for land mobiles (CALM). It is expected that the future CALM system will make use of a wide range of technologies including satellite, cellular (GSM, 3G and 4G/WiMAX), Wi-Fi wireless local area network (WLAN) and its wireless access in vehicular environments (WAVE) evolutions (IEEE802.11P and IEEE P1609), Bluetooth wireless personal area network (WPAN), mm-Wave, infrared and radio frequency identification (RFID). In addition, many sensing technologies such as radar, imaging and video processing will be integrated into the CALM architecture. Most of the communication technologies in the CALM family are borrowed from other mature applications, with the exception of the recently proposed WAVE standards on the dedicated short range communications (DSRC) frequency band. DSRC/WAVE is the only wireless technology that can potentially

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meet the extremely short latency requirement for road safety messaging and control. The unique feature of low latency secures the role of DSRC, as an essential communication technology, in future CALM networks that will make use of multi-radios on multi-bands. However, the current DSRC solutions are not fully field proven. There are significant DSRC-related social and technical challenges that have to be dealt with before large-scale deployment.

There are two classes of devices in a WAVE system[1-2]: on-board unit (OBU) and roadside unit (RSU). They are equivalent to the mobile station (MS) and base station (BS) in the cellular systems respectively. There are two classes of communications enabled by the OBUs and RSUs: vehicle to vehicle (V2V) and vehicle to infrastructure (V2I). While a MS in the cellular environment normally communicates with another MS via the BS, the OBU in a vehicle normally directly communicates with other OBUs within the radio coverage area. This direct V2V communication reduces the message latency and low latency is an essential requirement for safety applications such as collision avoidance[3]. Another difference is that an OBU is more likely to be embedded and connected with other electronic systems of the vehicle via in-vehicle networking such as controller area network (CAN) and FlexRay, while a MS is normally detached from the CAN. In addition to improving safety, WAVE networks can play major roles in travel plan, traffic management, navigation, fleet and asset management, environment monitoring, logistics, congestion and emission reduction, toll collection, smart parking, emergency services and a wide range of other location-based services.

WAVE networks have a set of technical challenges not encountered in other wireless networks. One challenge is to use WAVE technology in collision avoidance between fast moving vehicles. For example, it can be used to warn the drivers at the crossing between roads and railways if there is a danger of collision. In V2V communication, the relative velocity between two vehicles moving in the opposite direction is the sum of their individual speeds. In addition, such V2V communication system has to be robust in extremely abnormal situations, as accidents and collisions are less likely to happen in normal situations. One example of such an abnormal situation is when two cars are traveling on a narrow two-way street towards each other at fast speed. Therefore V2V communication has deal with much faster fading and much more Doppler frequency spread than any other wireless systems. On the other hand, most other wireless communication systems such as the Wi-Fi and cellular systems are designed to work in well anticipated and even controlled environments. Fundamentally WAVE networks have to be extremely robust as their failure may cause the loss of life and property. Some messages transmitted on a WAVE network have a tight latency requirement, and a decision based on delayed information could be quite harmful. The WAVE networks may operate in a wide range of hash environments. The density can vary from a few vehicles to perhaps tens of thousands of vehicles in the radio coverage area. To meet these challenging requirements, a WAVE solution must be scalable, robust, low-latency, high-throughput and cognitive[4].

The primary objective of this paper is to provide an overview of the current DSRC/WAVE technologies, identify their strength and weakness, and stimulate further research. The rest of the paper is organized as follows. In Section 2, we provide a short review of the spectrum allocation and its associated regulatory requirements. Section 3 is dedicated to the introduction of the IEEE802.11P and IEEE

1609 standards. We then analyze the latency, capacity and other requirements for large-scale DSRC deployment in Section 4. The requirement analysis is compared with the current DSRC solutions to identify their gap. Further research ideas are proposed to address this gap. Finally summary and conclusion are drawn in Section 5.

2 Regulatory Requirements

In US, 75 MHz of spectrum in the 5.9 GHz frequency band has been allocated for DSRC applications. Out of the 75 MHz spectrum, 5 MHz is reserved as the guard band and seven 10-MHz channels are defined as in shown in Fig. 1. The available spectrum is configured into 1 control channel (CCH) and 6 service channels (SCHs). The CCH is reserved for carrying high-priority short messages or management data, while other data are transmitted on the SCHs. The pair of channels (channel 174 and 176, and channel 180 and 182) can be combined to form a single 20-MHz channel, channel 175 and 181 respectively. The channel number (*CN*) is derived by counting the number of 5-MHz spectrum in the frequency band from 5000 MHz to the center frequency $f(CN)$ of the channel *CN*, i.e.,

$$f(CN)=5000+5CN \quad \text{(MHz)}.$$

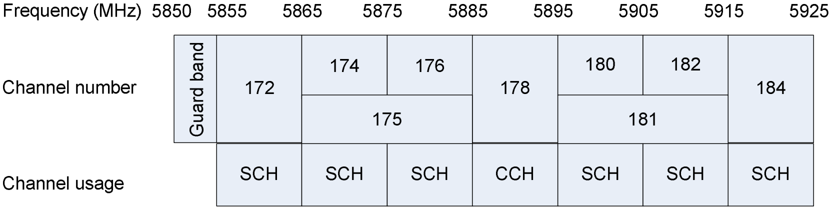

Fig. 1. The DSRC Frequency Allocation in US

In terms of transmitter (TX) power, four classes of devices have been defined whose maximum TX power ranges from 0 dBm to 28.8 dBm. The associated coverage distance by a single radio link depends on the channel environment, the TX power and the modulation and coding schemes (MCS) used. This distance may range from 10m to 1km. The details of OBU and RSU TX limits of equivalent isotropically radiated power (EIRP) also depend on the operating CN and applications. It is worth noting that the current FCC code of federation regulations (CFR) heavily refers to the American Society for Testing and Materials (ASTM) standard E2213-03, while the industry is adopting the IEEE802.11P and IEEE 1609 standard. The IEEE standard on the other hand refers to the FCC CFR for regulatory requirements. This means that implementers should address the channel and power limit defined in the ASTM standard. For example, FCC CFR specifies that the channel 172 and 184 shall be used for "public safety applications involving safety of life and property"[5] and this requirement is not fully compatible with the current IEEE1609.4 multi-channel operation where it is more natural to use channel 178 (i.e., the CCH) for such applications. Other than some minor differences in power level and spectrum mask requirements, ASTM standard E2213-03 and IEEE802.11P are both based on IEEE802.11A and they are effectively compatible.

Other frequency bands have also been used for DSRC applications even before the 5.9 GHz band allocation. They were typically used for highway or city central business district (CBD) toll collection. Of particular interest are the frequency bands defined in Table 1. It is worth noting that the DSRC regulatory requirements in many parts of the world are in the process of being finalized. There is a chance that similar spectrum allocation and requirements will be adopted world wide for DSRC applications. Spectrum harmonization is desirable for global inter-operability and low-cost DSRC services.

Table 1. Spectrum Allocation for WAVE/DSRC Applications

Country/Region	Frequency Bands (MHz)	Reference Documents
ITU-R (ISM band)	5725-5875	Article 5 of Radio Regulations
Europe	5795-5815, 5855/5875-5905/5925	ETS 202-663, ETSI EN 302-571, ETSI EN 301-893
North America	902-928, 5850-5925	FCC 47 CFR
Japan	715-725, 5770-5850	MIC EO Article 49

3 DSRC/WAVE Standards

Collectively the IEEE 1609 family, IEEE802.11p and the Society of Automotive Engineers (SAE) J2735[6] form the key parts of the currently proposed WAVE protocol stack. The WAVE protocol architecture with its major components is shown in Fig. 2, and they are summarized as follows.

- IEEE P1609.0 “Draft Standard for Wireless Access in Vehicular Environments (WAVE) – Architecture.”
- IEEE 1609.1 “Trial Use Standard for Wireless Access in Vehicular Environments (WAVE) - Resource Manager.”
- IEEE 1609.2 “Trial Use Standard for Wireless Access in Vehicular Environments (WAVE) - Security Services for Applications and Management Messages.”
- IEEE 1609.3 “Trial Use Standard for Wireless Access in Vehicular Environments (WAVE) - Networking Services.”
- IEEE 1609.4 “Trial Use Standard for Wireless Access in Vehicular Environments (WAVE) - Multi-Channel Operations.”
- IEEE P1609.11 “Over-the-Air Data Exchange Protocol for Intelligent Transportation Systems (ITS).”
- IEEE802.11p Part 11: “Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications -- Amendment: Wireless Access in Vehicular Environments.”

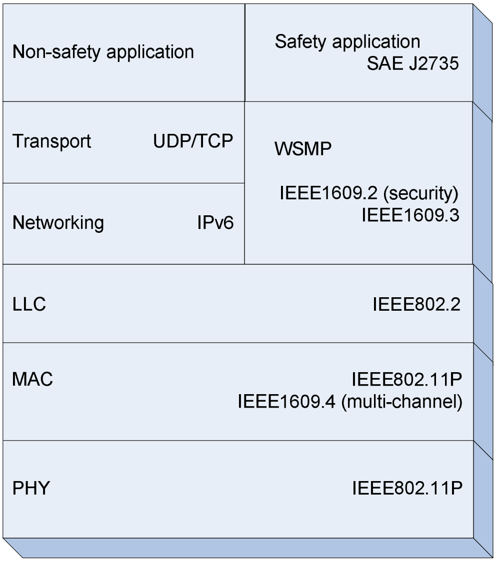

Fig. 2. The WAVE Protocol Stack and Its Associated Standards

3.1 The WAVE PHY

The current FCC CFR still refers the ASTM E2213 as the PHY standard. ASTM E2213 was published in 2003, and was based on the IEEE802.11A OFDM PHY. Since 2007 IEEE has consolidated all older versions of the PHY and the MAC into the IEEE 802.11–2007 edition. IEEE802.11P is an amendment to IEEE802.11-2007 for WAVE applications. Compared to IEEE802.11-2007, minimum change has been proposed in IEEE802.11P. In particular, IEEE802.11P only adopts the OFDM PHY on 10-MHz channels in the 5.9 GHz frequency band. On the other hand, the Wi-Fi industry normally implements the OFDM PHY on the 20-MHz channels, even though 5/10/20 MHz channels have been specified in IEEE802.11-2007. Compared to the 20-MHz Wi-Fi OFDM PHY, the subcarrier spacing and the supported data rate of IEE802.11P are halved while its symbol interval including cyclic prefix (CP) is doubled. Other parameter comparisons are shown in Table 2. In addition, IEEE802.11P requires the signal spectrum to decay faster to further reduce the adjacent channel interference. Different TX filtering may impact other TX performances such as error vector magnitude (EVM) to which a designer should pay attention.

The receiver design is typically out of the scope of the standard specification. However, due to significantly different channel environments, it is expected that a WAVE receiver may attract special design considerations. Compared to Wi-Fi OFDM receivers, the WAVE receivers have to deal with much higher Doppler spread which causes inter-carrier interference (ICI). The fact that the subcarrier spacing has been halved means that the WAVE OFDM receiver is more sensitive to carrier frequency offset and Doppler shift. Due to the higher Doppler spread and higher multi-path

Table 2. Comparison of WAVE and Wi-Fi OFDM Parameters

Parameters	WAVE	Wi-Fi
Frequency Band	5.9 GHz	5/2.4 GHz
Channel Bandwidth	10 MHz	20 MHz
Supported Data Rate (Mbps)	3, 4.5, 6, 9, 12, 18, 24, and 27	6, 9, 12, 18, 24, 36, 48 and 54
Modulation	Same as Wi-Fi	BPSK, QPSK, 16QAM and 64QAM
Channel Coding	Same as Wi-Fi	Convolutional coding rate: 1/2, 2/3 and 3/4
No. of Data Subcarriers	Same as Wi-Fi	48
No. of Pilot Subcarriers	Same as Wi-Fi	4
No. of Virtual Subcarriers	Same as Wi-Fi	12
FFT/IFFT Size	Same as Wi-Fi	64
FFT/IFFT Interval	6.4 µS	3.2 µS
Subcarrier Spacing	0.15625 MHz	0.3125 MHz
CP Interval	1.6 µS	0.8 µS
OFDM Symbol Interval	8 µS	4 µS

delay spread, the channel coherence bandwidth and channel coherence time become smaller, or in other words, the channel becomes more frequency-selective and faster fading. The following questions have to be addressed in designing a high-performance WAVE receiver.

- Is the CP sufficient to remove the inter-symbol interference (ISI) in the most hash WAVE environment with large multi-path delay spread?
- Can the fundamental requirement that the channel remains constant (or time invariant) during one OFDM symbol interval be met?
- Is the channel coherence bandwidth large enough so that the channel can be estimated on the pilot subcarriers and the estimates can be effectively interpolated to data subcarriers?
- Is the channel coherence time large enough to enable effective channel tracking? The fact that the OFDM symbol interval has been doubled and the channel is faster fading work against this condition.

Further field measurement, research and even change of the existing standardized parameters might be needed to achieve the satisfactory outcome.

3.2 WAVE MAC

In the architecture of IEEE802.11 networks, three kinds of service set (SS) are defined: basic service set (BSS), independent BSS (IBSS) and extended service set (ESS). The IBSS is formed by stations (STAs) without infrastructure, generally called an ad-hoc network. A BSS includes an access point (AP) that behaves as the controller/master STA. The ESS is the union of two or more BSSs connected by a distribution system (DS). A STA in the IBSS acting as the controller or the access point (AP) in the BSS periodically broadcasts a beacon that contains the service set ID (SSID) and other information. Other STAs in the SS receives the beacon and synchronize their time and frequency with those contained in the beacon. STAs can communicate with each other only if they are the members of the same SS. The same architecture of SS can be used for WAVE applications. However, forming a SS takes several steps including time and frequency synchronization, authentication and association. These steps take a time interval that is not affordable in some safety applications. In a vehicle traffic flow, two vehicles may be within the reach of the wireless link for less than a second. To minimize the message latency, a mode called “outside the context of BSS (OCB)” is introduced. The OCB mode applies to any two or more devices within the coverage area of a single radio link. A STA in OCB mode can send and receive data and control frames any time without forming or being a member of any SS. While enjoying the benefit of low-latency, the OCB mode does not receive the authentication, association or data confidentiality services on the MAC layer. The equivalent services have partially been moved to the higher layer as defined in IEEE1609.2.

From the receiver’s point of view, care must be taken on frequency synchronization. Currently IEEE802.11P does not specify a different frequency accuracy for the WAVE transceiver oscillators. In IEEE802.11-2007, the frequency accuracy is specified to be ±20 ppm, i.e., the maximum frequency difference between the TX and RX oscillator frequencies can be up to 40 ppm. For example, the center frequency difference of transceivers operating on channel 184 could be as high as $5920\times40\times10^{-6} = 0.2368$ MHz, greater than the subcarrier spacing of 0.15625 MHz. Without good frequency correction, the receiver error rate cannot be guaranteed even if the signal to noise ratio (SNR) is high. The preamble can be used to estimate the frequency offset. It is likely that WAVE radios may have access to other more accurate frequency sources such as the frequency derived form the GPS signal. The WAVE standard also support a timing advertisement frame, which can replace some of the features lost due to the lack of periodically sent SS beacon.

To transmit a frame either as a member of a SS or in OCB mode, the STA shall compete for the channel using the IEEE802.11 carrier sense multiple access/collision avoidance (CSMA/CA) mechanism. Another major MAC layer extension for WAVE applications is the multi-channel operation defined by IEEE1609.4. This extension makes use of the concept of frequency/time division multiple access (FDMA/TDMA), where the 7 FDMA channel frequencies are as shown in Fig. 1. The TDMA channel is shown in Fig. 3. The time is divided into repetitive periods of 100 ms. During each 100ms, 50 ms is allocated to CCH and another 50 ms is allocated for SCH, including 4 ms guarding interval (GI) for switching between CCH and SCH. The motivation is to accommodate single-channel radios in the WAVE system to access both CCH and SCH services. A single-channel radio is defined as a radio that can either transmit or receive on a single 10-MHz channel but not simultaneously. On the CCH frequency (i.e., channel 178) and during CCH time (i.e., the 46 ms), only two kinds of messages can be sent.

- Short messages, primarily for safety applications, as defined by the WAVE short message protocol (WSMP).
- WAVE service advertisement (WSA) messages used to announce the services available on other SCH frequency channels.

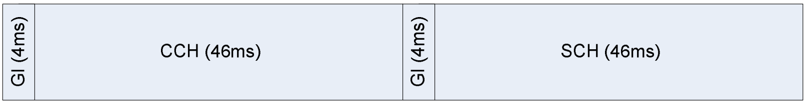

Fig. 3. The TDMA Extension of WAVE MAC

A single-channel radio can switch to other SCH frequencies for services during the SCH time and switch back to the CCH frequency during the CCH time for sending or receiving safety and other critical messages. The TDMA extension does not mean that the channels are idle for about 50% of the time. All SCHs can be active all the time to exchange service data and the CCH channel can be active all the tine to exchange control, management and other short messages. Practically it does mean a loss of time for safety messages sent on the CCH frequency. It cannot be guaranteed that all other STAs shall be listening on the CCH frequency during the SCH time, and as such safety messages sent on the CCH frequency during SCH time can be ineffective. Therefore it would be desirable to concentrate all safety messages on the CCH frequency and during CCH time, i.e., only 460 ms out of a second. This represents a capacity reduction for safety messages.

3.3 The WAVE WSMP

In addition to the standard IPv6 networking protocols operating over the SCHs, a WAVE-specific protocol called WSMP has been developed to carry messages on both the CCH and the SCHs. Unlike the standard IP protocol, the WSMP allows the applications to directly control the lower-layer parameters such as transmit power, data rate, channel number and receiver MAC addresses. To further shorten the latency, WSMP over the CCH can skip the steps for forming a WAVE BSS (WBSS) that delivers IP and WAVE short message (WSM) traffic on the SCHs.

The primary motivation for developing the WSMP is to reduce the overload. A WSMP packet is shown in Fig. 4. The overhead is 11 bytes, compared to a minimum of 52 bytes of a UDP/IPv6 packet. If a device receives a WSMP packet that has a WSM Version number not supported by the device, the received WSMP packet shall be discarded. The Security Type identifies if the packet is Unsecured, Signed or Encrypted. The Channel Number, Data Rate and TX Power allow the WSMP to directly control the radio parameters. The purpose of the provider service ID (PSID) field serves the similar role as the port number of the UDP/TCP packet, i.e., to identify the application that will process the WSM Data. The Length field indicates the number of bytes in the WSM Date, which might have been security-protected as specified in IEEE1609.2.

WSM Version (1 Octet)	Security Type (1 Octet)	Channel Number (1 Octet)	Data Rate (1 Octet)	TX Power (1 Octet)	PSID (4 Octets)	Length (2 Octets)	WSM Data (Variable)

Fig. 4. The Format of a WSMP Packet

4 Further Research Ideas

In this section we look at how the DSCR/WAVE technologies can be used to solve practical problems and specially safety applications. We identify the areas that need further research and verification.

4.1 Latency and Capacity Requirement

There have been a lot of safety applications proposed and studied in many projects. However a full scientific analysis of the latency and capacity requirements imposed to DSRC systems is still lacking. Currently the IEEE 1609.4 specifies the reoccurrence of the CCH at the rate of every 100 ms. If the OBU on each vehicle can capture the CCH during each CCH time, it can send its beacon and update its status to its neighbors at the rate of 10 Hz. The question is if the capacity of the DSRC system is large enough to accommodate all vehicles with a 10 Hz beacon. Additionally, have the latency requirements of all safety applications been met if the DSRC system can guarantee that all vehicles can update their beacons at 10 Hz? We believe that these questions have not been properly answered.

Fig. 5 shows the current WAVE over-the-air frame format. Let's assume that we can pack the 46 ms of CCH time with frames one after another with 58µs distributed inter-frame space (DIFS) between them. The combination of DIFS, Preamble and Signal fields takes 98µs, which can be considered as the minimum overhead to send a frame over the air. The Payload fields of Service, PSDU, Tail and Pad in Fig. 5 take a variable time depending on the size of the protocol service data unit (PSDU) and the MCS. Let's define the minimum air-time overhead ratio (OR) as the minimum overhead (98µs) divided by the time used for sending the Payload.

Preamble (32 µs)	Signal (8 µs)	Service (16 bits)	PSDU (variable)	Tail (6 bits)	Pad (variable)

Fig. 5. WAVE Over-the-Air Frame Format

Table 3 shows the capacity in terms of the maximum number of frames that can be sent over the air during the 46 ms of the CCH time that is allocated for short safety messages and service advertisement. To minimize the air time overhead, we prefer longer frames, and as a result less number of frames can be sent. This simple analysis shows that between 67 and 234 frames can be packed into this 46-ms time period. This analysis did not consider the time that will be lost when STAs compete for the wireless medium under the CSMA/CA MAC scheme, and therefore it represents the most optimistic capacity limit.

Table 3. The Capacity Analysis of the CCH

Payload Duration	Min Overhead Ratio	Max No. of Frames
98 μs	100%	234
196 μs	50%	156
294 μs	33.3%	117
392 μs	25%	93
490 μs	20%	78
588 μs	16.7%	67

Table 4 shows the number of vehicles that can exist in the coverage area of a single-link radio system. By comparing Table 3 and 4, we can easy identify many scenarios where the capacity is insufficient to allow each vehicle a chance to send its status every 100 ms. Is 100 ms latency good enough for all safety applications? Let's imagine a scenario of emerging collision of two cars speeding at 180 km/h on a two-way street towards each other in two adjacent lanes and one of them suddenly loses control. Within 100 ms, their distance can be shortened by 10m and if their starting clearance were less than 10m they would have collided within less than 100ms. In a practical system, the total latency is the sum of the time taken for sensing the event, communicating the event to the drivers and taking reactive control by the drivers. The total latency shall definitely be more than 100 ms of the network latency. We therefore conclude that the current DSRC solutions may be inadequate for large-scale deployment. Future research should focus on scalable solutions in terms of latency and capacity.

Table 4. The Number of Vehicles in a Radio Coverage Area

Coverage Radius	Area per Vehicle	No. of Vehicles
100 m	300 m^2	105
200 m	250 m^2	503
400 m	200 m^2	2513
600 m	150 m^2	7540
800 m	100 m^2	20106
1000 m	50 m^2	62832

4.2 The Social Science of DSRC

DSRC together with other technologies can enable smart applications we as a society never experienced before. Starting with simple applications like automatic toll collection, smart infrastructure can be built out that will significantly reduce traffic congestion, travel time, on-road accident, emission, driver stress and other unhealthy social behaviors. Unlike a human driver who can become bored, distracted and tired, a digital driving assistant (DDA) can stay alert and remain concentrated all the time. It can also have much better sensing and therefore information of the immediate and even far-reaching environment. For example, the DDA can see and understand the all-around 3-D environment with multiple video cameras and advanced signal processing algorithms. An aging/faulty component can alert the DDA that a break-down is about to happen unless corrective actions are taken. With the advancement of microelectronics and digital signal processing (DSP), a DDA can capture, store, process information and react to unexpected events faster than human drivers. Gradually the DDA will alleviate the driver more and more from the chores of driving until the vehicle becomes totally autonomous. Another scenario is remote driving. A driver could drive the vehicle or perhaps multiple vehicles from the comfortable office. DSRC networks enable the transparent control of the vehicles from anywhere in the world.

It is usually true that technologies that bring huge benefits if used appropriately can cause huge damage if abused. Therefore how to prevent the abuse of DSRC-enabled systems is a critical factor for the success of this new technology. PCs and mobiles phones are the two most popular devices for mass communication, and they are subject to abuse and malicious attacks. However, the damage caused by such attacks on PCs and phones cannot be compared with the fact that a terror organization can remotely drive a fleet of heavy trucks through DSRC networks. Physical and information security, user privacy[7] and other DSRC-related social sciences are the key issues to be addressed before large-scale deployment can be accepted by the government and the public. The legal impact of DSRC-enabled systems is another area needing further investigation. For example, we have to address the insurance policy, the legal procedures after the happening of on-road accidents and the legal liability of autonomous vehicle owners before such vehicles can be put on road. The psychology of driver behavior in interacting with DDA is another research area that will ultimately create the true requirements for DDA products and DSRC system design. We do believe that the social and technology problems related to DSRC systems can be solved and as a result future drivers will experience a fundamentally different driving experience.

4.3 Cross-Layer Optimization of DSRC Protocol Stack

The different layers of the DSRC/WAVE protocol stack and its regulatory requirements are developed by several working groups at different times. There is not enough evidence that the protocol stack is optimized in terms of scalable capacity and latency[8-9].

The current PHY was effectively a re-use of the 10-MHz channel Wi-Fi OFDM PHY without any change of parameters. It is advantageous to have compatibility between WAVE and Wi-Fi systems, and such re-use obviously has shortened the time to define the standard. However, the WAVE and Wi-Fi operating environments are significantly different. Ideally the PHY should be designed based on the measurement and modeling of the wireless channel[10-12]. The WAVE channel environment is very much diversified in terms of vehicle density, vehicle velocity, TX power, path-loss, multipath components, coverage range and the environmental electromagnetic interference (EMI). There are conflicting requirements, for example, longer CP is good for removing the ISI due to strong multipath, but bad for spectrum efficiency.

One improvement is to adapt the OFDM parameters to the real-time operating environment. DSRC radio is usually integrated with other sensing technologies such as GPS and therefore has sufficiently reliable information to optimize the PHY parameters real-time. Currently the application layer has control of the channel number, data rate and TX power. It can be expanded to include other parameters such as antenna gain, directivity and polarization. From example, the electronic braking signal should be sent to the vehicles behind rather than in front. By physically focusing the beam to the desired directions, we can save energy, and the same spectrum can be simultaneously reused in other directions. Orthogonal frequency division multiplexing (OFDM) has a disadvantage of large peak to average power ratio (PAPR) and almost all transmitters are peak power limited. This peak power limit, as an important parameter of the TX, is readily available to the application layer. When the application layer determines the average power used for the sending the message, it has to make a pre-defined back off from the peak power. In other words, the average power limit is less than the peak TX power limit by, e.g., 10 dB. The current application layer will never try to exceed the average power limit. Such an approach is sub-optimum, and a better approach might be for the application layer to set the coverage range and latency requirement and let the lower layers figure out the optimum set of parameters to achieve the coverage and latency requirement.

We use the example of peak power reduction of OFDM signals to demonstrate the advantages of having the lower layers to control the power. The PAPR of an OFDM signal is a random variable whose values are generally greater than one, but depends on the data that created the modulated waveform. On many occasions the peak power limit of the TX is not reached, either because the required average power to reach the coverage area is low or because the particular set of data happen to create a low-PAPR OFDM signal. Occasionally the peak power exceeds the limit, and if not properly dealt with, will cause in-band distortion that will reduce the error performance of the concerned channel and cause signal spillage into adjacent channels that will reduce the error performance of other channels. There are many PAPR reduction schemes that can be applied to reduce the peak power and as a result to boost the average power if required. One simple approach is to use the tone reservation (TR) scheme that trades the combination of data tones and tones reserved for PAPR reduction. It is better to let the PHY make the trade-off decision, and by doing so a more scalable dynamic range in the average power (and consequently the coverage area) can be achieved. In Fig. 6 we show an example of peak reduction scheme. The average power has been normalized to 1 mw (or 0dBm). The X-axis shows a threshold for the peak power. The y-axis shows the probability that the peak power of an OFDM modulated signal is higher than the threshold. A variable number of iterations (0, 5, 10, 15 and 20) using the TR scheme[13] has been illustrated with 0 standing for the original OFDM signal. It is shown that more than 3 dB of peak power reduction can easily be achieved. In the PAPR reduction experiment we have used only two data tones and the unused virtual tones for peak power reduction, causing minimum sacrifice in net data rate loss. It has been shown that the peak power can be reduced by more than 6 dB by sacrificing about 20% of the data tones for peak power reduction[13]. There is an apparent trade-off between effective data rate and peak power reduction.

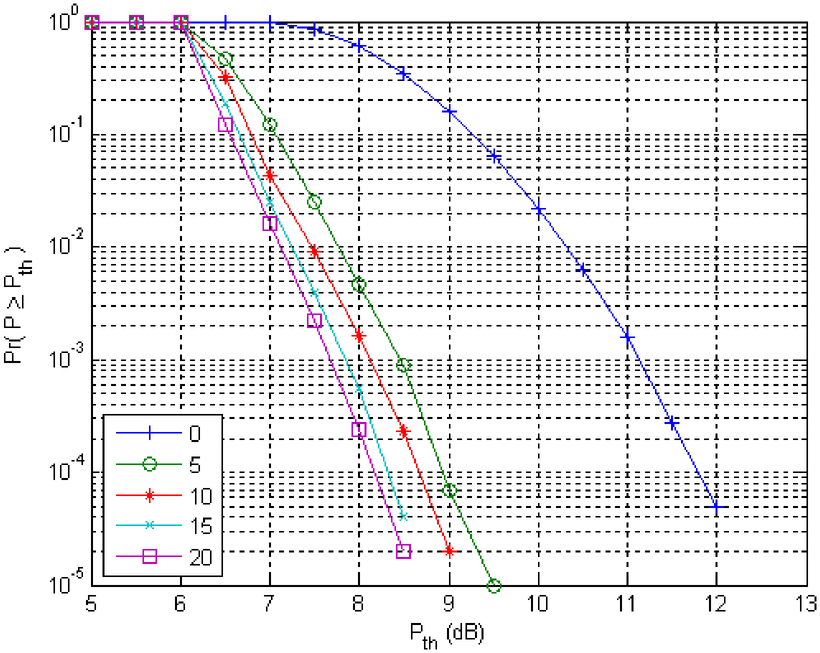

Fig. 6. PAPR Reduction of OFDM Signals by TR method

The objective of cross-layer optimization is to develop a scalable system that can capture the full diversity gain of frequency, time, space and antenna polarization. In general, from a capacity point of view, it would be more advantageous to adopt a broad-band approach. It is worthwhile to research OFDMA approach, treating the 70-MHz spectrum as a single channel, which might produce more improvement than treating it as seven separate channels[14-16]. Such an approach may increase the DSP complexity by requiring faster data converters and processors. However, DSP and application-specific integrated circuit (ASIC) technologies are now advanced enough to handle such broad-band channels. In fact, much wider channel bandwidth at about 2.16 GHz has been proposed in other gigabit wireless systems such as IEEE802.11AD.

It is hard to verify the impact of cross-layer optimization without a physical network. As a result, computer modeling and simulation will continue to be the primary tools for verifying the research results[17-18]. This is especially true if we have to verify the costs and benefits of a national ITS deployment to convince the government and the general public to invest in the infrastructure. Therefore large-scale system modeling and simulation including applications, communication protocol stacks and macro and micro controls will continue to be an outstanding research challenge.

5 Summary and Conclusions

We have provided a high-level overview of the current DSRC/WAVE regulatory requirements, protocol stacks and related standards of IEEE802.11P and IEEE1609. The key differences between WAVE and Wi-Fi or cellular wireless networking environments have been high-lighted. WAVE requires much more secure operation due to its role in safe-guarding human life and public property from road accidents. The strongest measure has to be taken to ensure that a DSRC-enabled ITS system cannot be abused or attacked. WAVE devices have to cope with fast frequency-selective fading due to faster mobility, larger Doppler spread and multipath delay spread. We have analysed the differences between application requirements and what can be offered by the current WAVE solutions. It is shown that the current solutions may be inadequate for large-scale deployment. The primary challenge is to develop scalable, robust, low-latency and high-throughput technologies for safety applications that will significantly reduce collisions and save lives and property loss. To address this challenge, further future research will include application requirement analysis, ITS-related social science study, cross-layer protocol stack optimization and large-scale system modelling and simulation.

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