Vehicular Communications Using DSRC: Challenges, Enhancements, and Evolution

Xinzhou Wu, Sundar Subramanian, *Member, IEEE*, Ratul Guha, Robert G. White, *Senior Member, IEEE*, Junyi Li, *Fellow, IEEE*, Kevin W. Lu, *Senior Member, IEEE*, Anthony Bucceri, and Tao Zhang, *Fellow, IEEE*

***Abstract*—Dedicated Short-Range Communications (DSRC) has been designed to support vehicular communications. In the U.S., DSRC operates in the 5.9 GHz licensed spectrum band. Its physical (PHY) and medium access control (MAC) layers, defined in the IEEE 802.11p standard, are based on the IEEE 802.11 family of Wi-Fi standards. Vehicular communication environments differ significantly from the sparse and low-velocity nomadic use cases of a typical Wi-Fi deployment. Thus, there are many challenges to adapt Wi-Fi technologies to support the unique requirements of vehicular communications such as achieving high and reliable performance in highly mobile, often densely populated, and frequently non-line-of-sight environments. The automotive and the communications industries, academia, and governments around the world have been devoting tremendous efforts to address these challenges, and significant achievements have been made. Remaining challenges can be addressed by the future versions of DSRC. In this paper, we investigate the current technologies used by DSRC to support vehicle safety communications, analyze existing and possible DSRC performance enhancements that can be realized in the near term, and provide a few initial thoughts on the DSRC evolution path.**

***Index Terms*—DSRC, dedicated short-range communications, vehicular networks, V2V, V2I, connected vehicle, vehicle safety, technology evolution.**

I. Introduction

DEDICATED Short-Range Communications (DSRC) is a wireless technology that has been designed to support new vehicular safety applications through vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. The U.S. Federal Communications Commission allocated 75 MHz of licensed spectrum in the 5.9 GHz band for DSRC [1]. The U.S. Department of Transportation (USDOT) has estimated that V2V communication based on DSRC can address up to 82% of all crashes involving unimpaired drivers in the U.S. [2] and about 40% of all crashes occurring at intersections [3]. These statistics point to the huge potential for this technology to reduce crashes and improve safety in the driving public.

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X. Wu, S. Subramanian, J. Li, and A. Bucceri are with Qualcomm Flarion Technologies, 500 Somerset Corporate Blvd., Bridgewater, NJ, 08807, USA (e-mail: xinzhouw, sundars, junyil, tbucceri@qti.qualcomm.com).

R. Guha is with Verizon, 1 Verizon Way, Basking Ridge, NJ, 07920, USA (e-mail: ratul.guha@verizon.com).

R. G. White is with Metriken, LLC, PO Box 161, Morristown, NJ, 07963, USA (e-mail: robert.white@metriken.com).

K. Lu is is with Broadcom Inc., 90 Matawan Rd., Suite 202, Matawan, NJ, 07747, USA (e-mail: luk@broadcom.com).

T. Zhang is with Cisco Inc., 170 West Tasman Drive, San Jose, CA, 95134, USA (e-mail: taozhang2@cisco.com).

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USDOT, auto-makers, and academia are actively pursuing research on DSRC to ensure that the technology is safe and effective when it is deployed in production vehicles [35]. The on-going USDOT Connected Vehicle Safety Pilot Program [4] is conducting tests and collecting data on the readiness and effectiveness of DSRC-based V2V and V2I communications for supporting collision prevention safety applications. This extensive program includes driver clinics in six US cities in which drivers are monitored in a controlled environment. The Safety Pilot also combines normal and professional drivers that drive in an area of public, highly congested roadways in Michigan, which have been equipped with DSRC-based infrastructure [36]. The results in the safety pilot program will lead to a potential DSRC mandate from NHTSA by late 2013.

DSRC uses IEEE 802.11p as its PHY and MAC layers; it is largely a half clocked IEEE 802.11a with small modifications in the quality-of-service (QoS) aspects by taking a few elements from IEEE 802.11e. The motivation for basing DSRC on the existing IEEE 802.11 standards was the vast availability of IEEE 802.11a chipsets, as well as performance and cost savings.

The typical use cases of IEEE 802.11 standards are sparse nomadic deployment with stationary channels. Consequently, existing commercial IEEE 802.11 chipsets are naturally optimized for best performance in such an environment. However, vehicular communications can happen among highly mobile vehicles, with multipath fading channel, and often in densely populated environments. Although existing field tests and safety pilot programs indicate that the DSRC standards and prototype devices based on commercial IEEE 802.11 solutions are adequate to address safety applications [10][34], there is definitely room for improvement and enhancement to the current DSRC solutions in PHY and MAC, under certain communication environments, e.g. when Line-Of-Sight (LOS) path is not available or when excessive delay spread is present in the communication channel.

In this paper, we first discuss the nature of the PHY/MAC challenges brought by the DSRC communication requirement from first principles. We then study existing or potential solutions to these challenges. In particular, here is a list of PHY/MAC challenges for DSRC we discuss in this paper:

1) Channel estimation in both frequency and time selective fading channel;
2) Convolutional code decoding without time interleaving in time selective fading channel;
3) Channel congestion in dense deployment with CSMA

as the underlining MAC protocol;
4) Adjacent band leakage in multi-channel operation.

Some of the solutions to the above issues are well studied in industry and academia and can be indeed incorporated as DSRC enhancements without the request for standards change. For the rest, we suggest to address them in future versions of DSRC, i.e., the evolution of DSRC.

Maybe we dont need this ?

Towards this end, we also provide a list of preferred features for DSRC evolution in PHY/MAC, which can further enhance the DSRC performance. A key issue for DSRC evolution is to ensure backward compatibility between all vintages of the DSRC technology, i.e., an older version of the DSRC device has to be able to understand the transmission from newer DSRC devices. Thus, having the ability to upgrade older generations of DSRC to be compatible with subsequent generations will ease the evolution transitions and improve safety in the future. In this paper, we discuss options to enable easy update of the deployed DSRC equipments, which can enable smooth technology transition for DSRC evolution. Further, we envision that a key component in DSRC evolution is to enable communications between vehicle and pedestrians, which can greatly enhance the safety feature of DSRC applications. We will also discuss key elements in DSRC evolution to support vehicle-to-pedestrian (V2P) communications.

In summary, the key points we want to make in this paper are as follows:

1) DSRC, with IEEE 802.11p at its PHY/MAC, has many challenges to address the vehicular communication environment. Some of these challenges have been addressed by introducing enhancements to current DSRC solutions, while others yet remains to be addressed in future versions of the technolgoy.
2) A key issue is DSRC evolution is the backward compatibility issue, due to the broadcast nature of the messages in DSRC safety applications. We discuss a few options to ease the difficulty in DSRC evolution, even before we start deploying the first generation of the technology.
3) Enabling vehicle-to-pedestrian communication can be an important extension of DSRC technolgies in the future since it can enhance the current DSRC safety applications to pedestrians, among many other non-safety critical use cases. A few key technical issues have to be addressed to ensure the prevailence of the technology.

The rest of paper is organized as follows. Section II discusses DSRC PHY and MAC layer challenges and existing solutions to address these challenges. Safety application performance and reliability in light of the PHY/MAC challenges is discussed in Section II-C. Section III provides some initial thoughts on DSRC evolution, including supporting vehicle-to-pedestrian (V2P) communications to improve pedestrian safety. The summary is given in Section IV.

We recognize the existence and importance of other challenges faced by vehicular communications, especially how to enable privacy-preserving security in a national scale vehicle communication network and how to cost-effectively achieve the positioning accuracy, which may be required by vehicle safety applications. However, these issues will not be covered in this paper due to space limits. Further, the concept of connected vehicle is in general broader than DSRC based V2x communications alone, and it also includes in-car communications for infotainment and connectivity based on cellular technologies and other variants of Wi-Fi. In this paper though, we will focus on DSRC communications and discuss issues for DSRC technology alone. It is very likely that some of the view points can be shared with the other elements of the general connected vehicle concept. A more futuristic looking at the V2V safety may also include non-communications based technologies to enhance the DSRC-based framework, e.g., computer vision sensors equipped on the vehicle or the roadside units. We leave these topics as future research areas for DSRC communications.

II. DSRC Challenges and Solutions

Over the last decade, there have been vigorous joint efforts from the industry, academia and government to validate the DSRC technology and also to identify and address key technical and business challenges. These efforts have confirmed the applicability of DSRC to improve vehicle safety. They also point to several areas for further improvements. In this section, we will discuss potential PHY and MAC layer improvements that can benefit future generations of DSRC.

A. PHY Layer

Vehicular communications occur in a challenging environment involving fast moving vehicles and a wide range of obstacles that can degrade radio performance such as buildings, surrounding bigger vehicles, intersections, tunnels, bridges. The channel models for vehicular communications have been extensively studied [5], [6], [7] and they in general have a very different behavior than the stationary channel models for typical IEEE 802.11 use cases.

Two key differentiating characteristics of vehicular communication environments are: multi-path delay spread and mobility. Delay spread leads to frequency selectivity of the channel while mobility causes time-selective fading channels.

Extensive studies have been done to characterize the delay spread of vehicular channels. Channel-sounding results reported in [6] describe the effect of reflections in Urban LOS environments. The results indicate that although a strong initial tap is observed at 250ns, a number of reflections are present. The Root Mean Squared (RMS) delay spread is approximately 500ns demonstrating the significant effect of the reflections from objects. On the other hand, on highways, the power delay profile has fewer taps due to reduced reflections and an RMS delay spread of 190 ns. Field trials have also reported the empirical distributions for the delay and the Doppler spread [8]. For urban NLOS environments, the RMS delay spread is less than 200ns with 99% probability. Also, the maximum delay spread is typically less than 1.4-1.6 microseconds. NLOS conditions result in larger delay spreads due to increased influence of scattering. NLOS situations on the highways have high probabilities of increased Doppler spread. In urban situation, the Doppler spread are typically less than 1000 Hz. Additionally, the RMS Doppler spreads in LOS highway scenario is small, since the high frequency

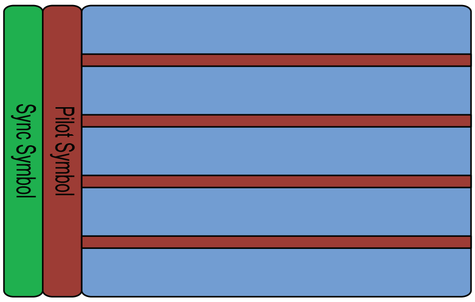
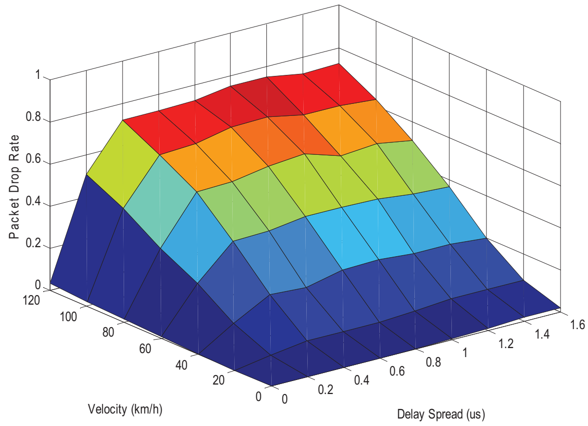
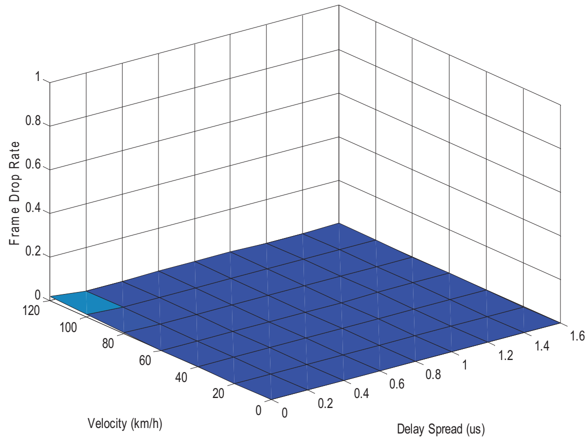


Fig. 1. IEEE 802.11p pilot structure.



(a) Conventional IEEE 802.11a implementation.



(b) Turbo receiver implementation.

Fig. 2. Performance of conventional IEEE 802.11a implementations vs. turbo receiver against mobility and delay spread.

Doppler taps have reduced power. This is confirmed since the maximum Doppler spread is high for both LOS and NLOS highway scenarios.

In summary, the vehicular communication channel can be highly frequency selective – due to multipath delay spread, and highly time selective – due to vehicle mobility. It can be easily estimated that the 50% coherence bandwidth in some scenarios is roughly in the order of $\sim$1MHz and 50% coherence time can be as short as $\sim$0.2ms. This leads to two challenges of adapting the traditional IEEE 802.11 solution to vehicular communications:

1) Channel estimation error in vehicular environment due to time-selective and frequency selective fading;
2) Lack of time-interleaving in fast time-selective fading channels.

1) Channel Estimation in Vehicular Environments: To illustrate the channel estimation problem, let us look at the pilot structure in IEEE 802.11p PHY shown in Fig. 1. An IEEE 802.11p packet starts with a few wideband pilot symbols and then the data symbol and SIGNAL symbol, which carries the PLCP header. Only four out of the 52 subcarriers are used for pilots. In other words, for the 10MHz operation in IEEE 802.11p, two adjacent subcarriers are 2.4MHz away. Further, a typical safety broadcast message can take up to 0.5ms to transmit. Two observations can be made here:

1) The interspacing between two pilot subcarriers is significantly larger than the coherence bandwidth.
2) The packet transmission time (e.g., 300 bytes in approximately 0.5ms) can be longer than the coherence time, which can be as small as 0.2ms.

Typical IEEE 802.11p devices first obtain a wideband channel estimate from pilot symbols, and then monitor the residual channel variation using the pilot subcarriers. The latter is usually referred to as pilot tracking. In benign channel models, such algorithms are sufficient. However, in vehicular channels, after the coherence time, the channel estimates obtained from the pilot symbol becomes obsolete. However, the sparse pilot subcarriers are not sufficient to track the channel. Thus, the packet reception can fail even when the received power of the packet is well above the thermal noise. Fig. 2(a) shows the simulated results of the performance of a typical IEEE 802.11p receiver with conventional channel estimation implementation at different delay spreads and mobility. Packet drop rates shown in this figure are mostly caused by channel estimation errors which rise sharply with a combination of delay spread and mobility.

There are a few tools from modern coding theory to deal with channel estimation errors. One such method is to introduce a Turbo receiver [37], which iterates between channel estimation and decoding, instead of carrying out the two steps in a sequential order as in conventional receivers. The nature of the IEEE 802.11p PHY coding and modulation enables a natural way of implementing such a scheme. In particular, IEEE 802.11p uses convolutional codes with a short constraint length (7) and no time interleaving is allowed. This means that the receiver can reliably decode a particular information bit coded and transmitted earlier in the packet without waiting for the reception of the whole packet. Further, one can use the already-decoded bits as pilots for the remaining packets to improve channel estimation. Such a scheme is referred to as decision feedback and can track the channel variations significantly better than standard non-iterative schemes. As shown in Fig. 2(b), it almost removes entirely the channel estimation error caused by time and frequency selective fading. Note that either Turbo receiver or decision feedback receiver is a receiver algorithm enhancement and is fully compatible with the existing IEEE 802.11p standards.

2) Time Selective Fading without Time Interleaving: In the previous subsection, we discussed how we can take advantage of the fact that current IEEE 802.11p standard does not use time interleaving to rectify channel estimation errors. In this subsection, we look at the other side of the coin: no time interleaving leads to significant performance degradation in a time selective channel even without channel estimation errors. This is an outcome of using convolutional code with short memory without time interleaving. An information bit is only reflected by a small number of coded bits determined by the constraint length (7). Without time interleaving, most likely the encoded bits will be modulated and transmitted on the same or adjacent time symbols. In time-selective channels, if a symbol (or a few adjacent symbols) is in a deep fade, there is a very low probability for the receiver to recover the information bits encoded in the symbol. Thus, the packet reception rate is determined by the *minimum* signal-to-noise (SNR) across all symbols in the packet rather than the *average* SNR. On the other hand, in IEEE 802.11p, the packet length can be longer than the coherence time, which indicates that deep fades can happen within the transmission time of a packet with significant probability.

This problem is well understood in the wireless communication community and can be resolved using a better coding scheme (e.g. Turbo or LDPC code). However, this indeed requests a standard change and is better to be addressed in future versions of DSRC. We will elaborate more on this in Section III.

B. MAC Layer

In this section, we discuss the main challenges at the DSRC MAC layer and possible solutions. The primary issues are packet collisions and medium access congestion when a large number of devices are in each other's radio transmission ranges. We discuss the nature of the congestion problem and review the state of the art to address this problem. Finally, we discuss the potential benefits of using an algorithm based on a TDM overlay on top of the IEEE 802.11p PHY/MAC. A similar protocol has been designed to support device-to-device communications [9].

1) CSMA Behavior at High Node Density: Vehicle safety communication applications rely heavily on periodic broadcast of basic safety messages (BSM) which contain the positions, velocities, and other information about the vehicles. These messages with the PHY layer overheads typically measure around 300 bytes [10] and are expected to be transmitted up to once every 100ms. The periodicity is chosen to meet latency and accuracy requirements of vehicle safety applications. IEEE 802.11p uses CSMA/CA and a random back-off procedure to reduce collisions of over-the-air packets. At high densities of vehicles, the wireless medium can quickly become highly congested and collisions among packet transmissions may occur with high probability. The MAC layer congestion issues have been observed and reported in numerous studies in the literature [11], [12], [13], [14].

The main source for the collisions at high densities is the synchronous countdown of the back-off timers by any two transmitters within the carrier sense range of each other. At high densities, many devices observe the channel to become idle at the same moment and start counting down their timers to zero synchronously and then transmit at the same time, as shown in Fig. 3.

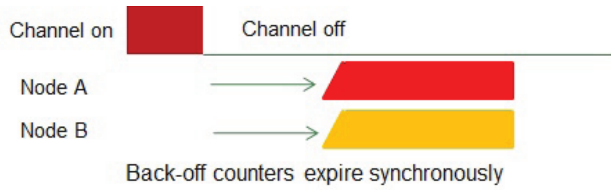


Fig. 3. Illustration of a collision scenario. Nodes A and B count their timers down synchronously and transmit simultaneously.

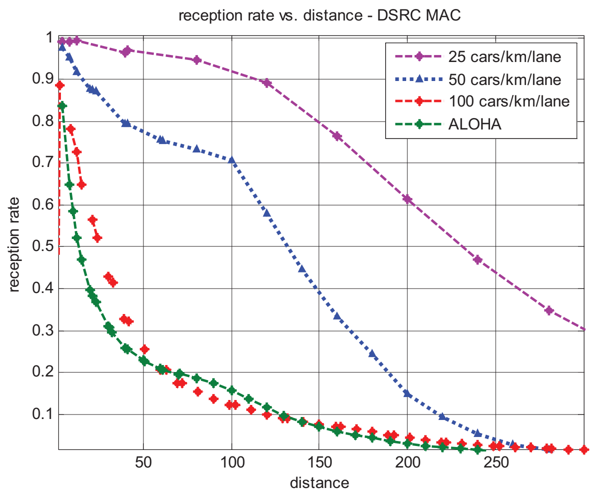


Fig. 4. Reception rate vs. distance. The plots demonstrate that at higher densities, the performance tends towards an ALOHA-like performance.

Fig. 4 shows the packet reception rate performance of the standard IEEE 802.11p MAC protocol for different vehicle densities. Packet reception rate, also commonly referred to as the discovery probability, measures the percentage of packets that can be successfully received by a receiver. The plots demonstrate that as the density increases, the discovery probability becomes degraded even at close-by distances. The performance appears to trend towards an ALOHA -like[1] behavior due to a lack of protection against nearby transmitters transmitting simultaneously. As the vehicle density increases, the discovery range will also reduce for the same packet length, periodicity and code-rate. The discovery range is the longest distance between a transmitter and a receiver for the receiver to receive packets with a given packet reception rate. Ideally, the discovery range should shrink in proportion to the density increase such that the number of discovered devices remains constant at all densities. However, the ALOHA type of collisions can lead to significant performance loss. Fig. 5 demonstrates the normalized discovery. The x-axis is the discovery distance in inter-car spacing (to normalize for a linear density increase with distance), and the y-axis is the probability of discovery. This degrading reception with increasing vehicle density can have a significant impact on the performance of vehicle safety applications in high vehicle density areas such as crowded intersections and highway segments.

[1]In ALOHA, each transmitter chooses to transmit with a probability that is independent of other transmitters around it implying that there is no guaranteeed protection zone around a transmitter.

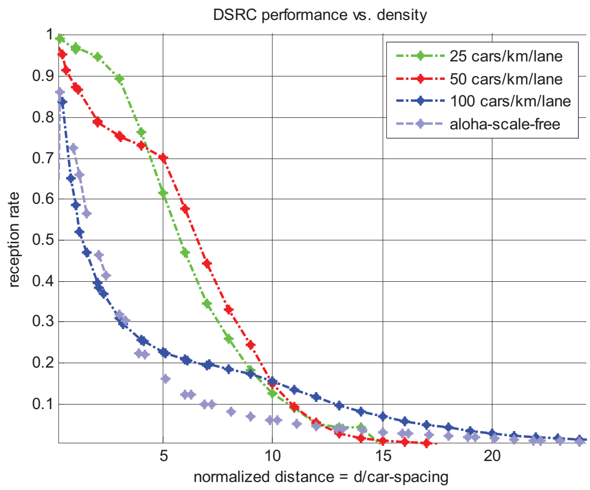


Fig. 5. Reception rate vs. normalized distance for a four-lane road of length 2 km under a typical two-slope radio path loss model and a transmit power of 20 dBm and a BSM frequency of 10 Hz. The packet size is assumed to be 300 bytes.

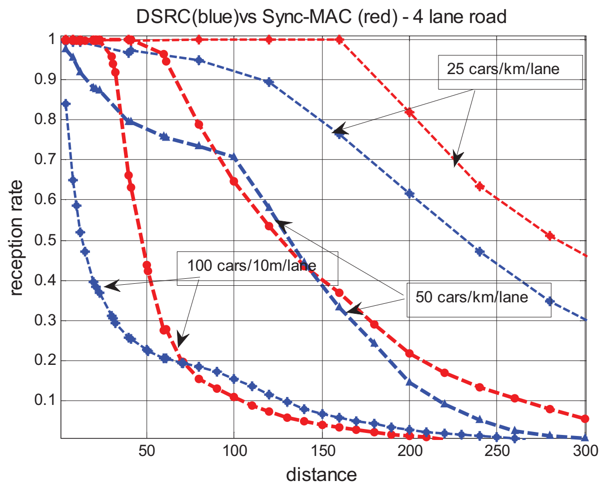


Fig. 6. Reception rate vs. distance, 4-lane road. Comparison of the discovery performance of the synchronous MAC with the DSRC approaches.

2) Potential Solutions to Congestion Control: A natural approach to reduce congestion is to reduce the number of transmitters within the carrier sense range of each device [11], [12], [13], [14], [15]. Examples of such schemes include (a) controlling the transmit powers of the devices to reduce the number of devices synchronously counting down, (b) reducing the periodicity of the safety messages, and (c) increasing the carrier sense threshold. The main tradeoff is how to ensure high channel utilization while reducing collisions.

A typical scheme to balance collisions and channel utilization is to use a distributed congestion control mechanism as described in [13], [15]. The basic idea is that each vehicle dynamically adjusts its transmission parameters (power, periodicity etc.) in response to the observed channel load. Typically, the response is to reduce the power or periodicity when a large channel load (based on channel busy time) is observed. Such schemes are shown to improve discovery performance over uncontrolled DSRC transmissions. However, identification of the optimal channel load and/or obtaining stable transmit-parameters without oscillations is not yet well understood.

Another promising method is to use a time-slotted synchronous system with a fixed set of broadcast resources. Synchronicity is already mandated as part of IEEE 1609.4 for channel switching and it is feasible to use a Global Positioning System (GPS) clock to synchronize MAC-layer packet transmissions as well. In a time slotted system, a fixed number of broadcast resource slots may occur in a periodic manner. One can employ a simple MAC protocol, [16], [17] to manage which transmitters should use which resources (e.g., time slots). A device may monitor and select the resource with the least observed energy indicating the resource is being used by the least number of other transmitters, thus maximizing the distance among transmitters sharing a resource in a distributed manner. Such an approach can significantly improve the packet reception rates. The main idea is to obtain a good spatial pattern of concurrent transmissions and maintain the same configuration for longer durations. The performance of a time-slotted media access control for vehicle communications is depicted in Fig. 6.

We note that slotted TDM systems are typically well suited for periodic transmissions of roughly equal size packets for prolonged durations. While the current DSRC standard does not specify the need for such synchronization, the addition of such “hooks” into the standard can be beneficial.

C. Multi-channel Operations

The 5.9 GHz DSRC spectrum is divided into seven 10 MHz bands. A main motivation behind such channelization is the ability to utilize the market penetration of existing Wi-Fi chipsets that operate over 20MHz channels. The original chips can be run ‘half-clocked’ to achieve a 10 MHz bandwidth and be made more suitable for the highly mobile and frequency selective vehicular channels. With the availability of multiple channels, a mechanism is needed for the devices to use the different channels. For example, the vehicle safety messages from one vehicle are intended to be heard by all nearby vehicles, and if each vehicle has only one radio, all radios will be required to be tuned to use the same common control channel (CCH) at the same time. The IEEE 1609.4 MAC extension layer (multi-channel operations) was created to enable the use of multiple channels by the upper layers of a DSRC device to support safety and other applications [18]. IEEE 1609.4 provides mechanisms for obtaining timing and for synchronous channel switching among other roles.

The investigation into multi-channel operation has been limited since the primary focus of the industry has been to validate and improve the safety channel performance. In this section, we discuss the challenges of the IEEE 1609.4 multi-channel operation approach and propose a few potential improvements.

1) Single Radio Devices: When DSRC systems were envisioned initially, each vehicle was expected to be equipped with a single 10 MHz DSRC radio. The idea was to use one of the 10 MHz channels - Channel 178 the common control channel (CCH) – to safety messages and use the remaining channels as service channels (SCH) to support point-to-point communications. To allow all vehicles to hear each other's safety messages, it required that a common time period be utilized for safety message transmissions. This leads to the initial design where a sync-interval of 100 ms is divided into CCH and SCH intervals via time domain orthogonalization and all devices tune to the CCH channel in the CCH interval. In the SCH interval, the devices could use any of the service channels.

The main issue with the above scheme is the reduced capacity to support the broadcasting of safety messages. All devices can use a 10 MHz channel for only a fraction of the time (CCH/sync-interval). All safety and control message transmissions have to occur within this time interval. Many simulation studies have shown that to support vehicle safety broadcasts in typical vehicle densities, most or all of the sync-interval would be required. Some studies [19], [20] indicate that even with a fully dedicated 10 MHz channel for safety and control, the channel congestion issues still remain. Further, the above method is highly spectrum inefficient as six of the seven channels are underutilized during the CCH interval, as all radios have to be tuned to receive in CCH.

2) Multiple Radio Devices: Due to these issues, the industry is seen moving towards a '1609.4 optional' route [21] where all devices use the Channel 172 (different from the CCH channel) for safety broadcasts. Vehicles with dual radios can use one radio on Channel 172 for safety message broadcast and the other radio for control transactions and service transactions in a completely different channel.

This approach puts safety applications as a higher priority and makes more capacity available for safety message broadcast. However, the simultaneous operation of multiple radios on the same vehicle imposes further challenges. One issue to be address is that the reception in the safety channel may be influenced when a vehicle is transmitting over a separate radio channel, for example, to support any other application. For example, consider a device using channel 172 for safety and channel 174 for other applications. Then, due to the energy spillage from channel 174 to channel 172, the reception of safety data in Channel 172 can be affected while transmissions over channel 174 occur.

The transmit power mask requirements [22] as shown in Fig. 7 in the IEEE802.11p standard only require that the adjacent channels are -50 dB compared to the original transmitted power. Given that the dual radios in a vehicle may be located in close proximity, and assuming coupling losses between the radios to be in the order of 20 dB, the interference magnitude can be comparable to -70 dB. For a transmit power of 20 dBm, this amounts to a noise level of -50 dBm at the collocated radio in an adjacent channel. With typical Wi-Fi receiver sensitivities at -91 dBm, the interference level can impact the receiver sensitivity, reducing the discovering range. Roughly speaking, raising the sensitivity by 10dB leads to losing of the discovery range. 40dB difference can account up to a factor of 16 in loss of discovering range, which is significant. The spillage of power into adjacent bands when transmitting is depicted in Fig. 8.

The problem of self-interference cancellation is attracting a lot of attention in the academic society recently in the context of a full duplex modem [23], [24], [25], where concurrent transmitting and receiving are enabled in the same band. The adjacent band leakage problem here in DSRC is a much simpler problem. Certain techniques, which are well studied in the full duplex context, including analog cancelation and digital cancelation can be applied here. However, these algorithms are still in prototype stage and are not included in the off-the-shelf chip solutions. Future study of cost-effective implementations in DSRC chips still requires attention from the industry.

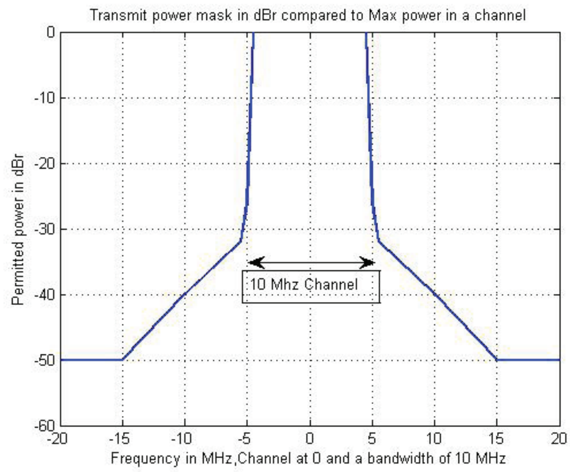


Fig. 7. DSRC multi-channel power mask for a Class C transmitter.

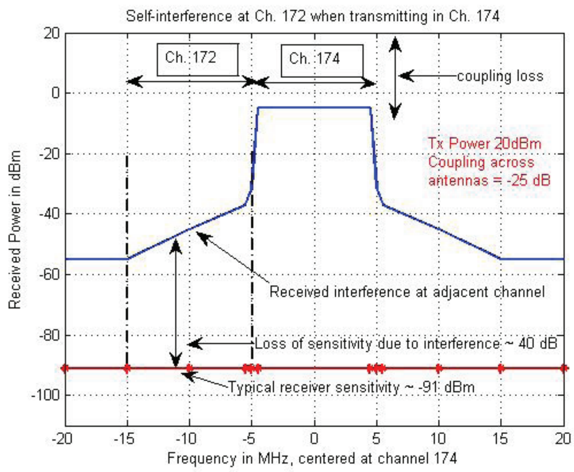


Fig. 8. The transmission in an adjacent channel (174) can spill into safety channel (172) increasing the interference level by more than 40 dB from the thermal noise floor significantly reducing the discovery range.

III. DSRC Evolution

As the industries and governments worldwide are considering the deployment of DSRC-based vehicle safety communication capabilities, a natural question is – What is next, i.e. what will be the evolution path of DSRC? In this section, we list a few key preferable components of the evolution and discuss the possible paths to include these components into future version of DSRC.

A. PHY/MAC

In Section II, we discuss a few key technical challenges to applying 802.11 solutions to vehicular communications and the standard compliant enhancements to PHY/MAC which can address these challenges. Although the DSRC solution with these enhancements seems to be adequate to address safety applications, there are still opportunities for further improvement.

Here are a few such enhancements we believe are important for future versions of DSRC:

Better channel interleaving and channel coding. In vehicular communication environments, the current channel coding and interleaving mechanisms defined in IEEE 802.11p lead to performance loss since the packet reception error is determined by the worst channel condition during the packet transmission rather than the average channel condition. A straightforward improvement is to enforce time-domain interleaving. The downside of such an approach is longer packet decoding delays since the receiver might have to wait for the reception of the entire packet before starting decoding. The delay can be a concern for unicast packets since according to the standard, the ACK signal has to send back by a receiver rather quickly ~10us in an atomic way after receiving each packet. But such a concern does not exist for the majority of the DSRC safety applications that rely on broadcast rather than unicast. Thus, a simple approach would be to enforce time interleaving for broadcast packet only. Meanwhile, LDPC code has been developed and implemented in the more modern versions of IEEE 802.11 family standards, e.g. 802.11n, which has significant performance gain against convolutional code used in IEEE 802.11 providing an effective solution for improving DSRC PHY performance.

Migration to more modern PHY technologies including MIMO support (802.11n) and multiple stream support (802.11ac). Multiple antenna support can bring a lot of value to DSRC systems. For example, both transmitter and receiver beamforming can increase the link budget and the transmission range. This is especially valuable for non-line-of-sight communication between vehicles, since the modems can track and beam form to the non-LoS path to enhance the reception reliability. Further, multiple streaming support similar to IEEE 802.11ac can enable the vehicle to receive multiple packets simultaneously, further enhancing packet reception rate.

More flexibility in channelization. The 10MHz channelization is chosen at the very early stage of DSRC development mainly to find the most economical way to increase cyclic prefix using the technology available at that time. However, such an approach underutilizes the capability of current technology. The latest generation of IEEE 802.11 chips mostly supports wideband operations to provide higher data throughput. For example, IEEE 802.11n supports 40MHz channelization and 802.11ac supports 80MHz channelization. Meanwhile, the 10MHz channelization used by the current DSRC also limits the efficiency of the DSRC frequency band (75MHz in US): one needs multiple DSRC radios to be able to use multiple channels. The most common DSRC devices on the market today or on the roadmap have one or two DSRC radios, which means it can support vehicle safety communications in a dedicated safety channel and potentially switch between the other channels to transmit or receive on the other available channels. This, however, limits the data throughput for DSRC communications and introduces unnecessary additional complexities for managing channel switching between different channels.

Better MAC congestion control protocols: Congestion remains one of the key issues to be resolved to ensure dependable DSRC safety broadcast. Multiple solutions to adapt packet transmissions according to changing congestion levels are currently being tested and evaluated by automakers and vendors. Unlike PHY enhancements introduced in some of the existing DSRC solutions, which can remain proprietary solutions, the MAC protocols should be standardized to be an effective part of the DSRC evolution. Multihop forwarding in conjunction with power control can bring further performance improvements in vehicular environments. Such mechanisms can improve message reception rate while mitigating the effect of both channel impediments and MAC congestion, since the distance and the relative speed between communicating nodes is reduced. Effective use of multihop and relaying techniques require cross-layer approaches along with assessment of delay trade-offs and could be considered for future DSRC systems.

Decoupling of DSRC upper layer with 802.11p PHY/MAC to support multiple potential technologies. Cellular data services can be used to support an increasing range of vehicular communication applications [28]. Feasibility of certain safety applications such as road hazard warning has also been demonstrated in today's 3G and 4G networks [29]. An analysis of long-term evolution (LTE) network capacity for vehicle communications showed the feasibility of using LTE to support event-triggered vehicle-to-vehicle hazard warning messages but also revealed significant overload due to periodic messages that were sent every 100 milliseconds [30]. Other possible technologies for vehicular data communication are Wi-Fi technologies. Thus, for DSRC evolution, there is value to decouple the upper layers (1609.x protocol stacks) and applications from the lower layers so that the actual data transmission can use any radio technology that best fit the application needs rather than being limited to IEEE 802.11p.

Another important challenge to evolve DSRC is **backward compatibility:** future DSRC devices have to be able to communicate with the legacy DSRC devices. How do we ensure that legacy devices and future devices can communicate with each other? This backward compatibility issue is significantly different from the compatibility issues that people faced in the conventional enterprise networks, telecommunications networks, or the Internet. In the conventional networks, the mobile devices communicate through infrastructure networks and servers, which are controlled by the operators. An upgrade of the infrastructure network can be sufficient to allow legacy devices and new devices to communicate with each other. Further, the newer devices usually support multiple radio technologies.

Vehicle safety applications rely heavily on V2V message broadcast directly among vehicles All broadcast packets are meant to be decodable by all neighboring devices around you. No intervening infrastructure networks or devices will be there to assist communication between legacy and new

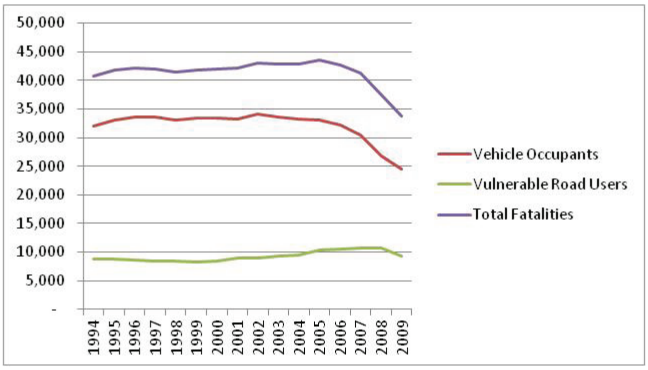


Fig. 9. Traffic fatalities in the U.S. from 1994 to 2009.

devices. Therefore, one must carefully plan the hardware and software to be used for the initial DSRC deployment. The Wi-Fi industry has moved much further ahead of IEEE 802.11a or 802.11p after 802.11p was selected as THE technology for DSRC a decade ago. The current IEEE 802.11a compliant chipsets on the market are much more powerful and at very affordable prices. Many chips support other newer generation of IEEE 802.11 standards in addition to 802.11a. Thus, when the DSRC market is ready for commercial deployment, the 802.11 chips will likely have much more hardware in them beyond what is required for the current IEEE 802.11p. Therefore, rather than using IEEE 802.11a chipsets for the initial DSRC deployment as most existing DSRC implementations do, a better approach will be to use, for example, IEEE 802.11n or 802.11ac chipsets so that advanced capabilities, such as LDPC code and decode and MIMO capabilities, can be available in the initial DSRC deployment. Although the initial DSRC communication is carried out using the current 802.11p standards, the chips will be ready for many advanced features that are likely to be needed in the future.

B. Vehicle to Pedestrian Safety

The world road traffic crashes kill nearly 1.3 million people and injure 20 to 50 million more every year. Nearly half (46%) of those dying on the roads are "vulnerable road users" including pedestrians, cyclists and motorcyclists [31]. In the U.S., 28% of the traffic crash fatalities in 2009 were vulnerable road users, up from 20% before 2000 [32]. Fig. 9 shows the U.S. traffic fatalities by vehicle occupants and vulnerable road users. This suggests that a key mission for DSRC evolution is indeed to extend vehicle safety applications from vehicle occupants to vulnerable road users. A natural evolution step is from V2V/V2I to V2P (Vehicle to Pedestrian) communications.

As the market penetration of cell phones increases, a vast majority, if not all, of pedestrians and cyclists would have cell phones. Therefore, a natural question is how to make cell phones part of the vehicular communication network. There are many new challenges to achieve this goal, some of which are listed below.

- The DSRC enabled phones could either operate as listen-only devices or have both transmit and receive functionalities. The phones could silently monitor the vehicular safety messages in the neighborhood and generate warnings when necessary. Since the receiver is the main source of the battery drain, it may be required for even the listen-only phones to control their duty-cycle. The cell phones may not need to monitor the 5.9 GHz channel every 100 milliseconds. The monitoring period can be adjusted dynamically and intelligently, for example, depending whether there are any nearby vehicles or whether the cell phone users are approaching traffic intersections.
  For cellphones that also transmit safety messages, controlling the channel congestion is one of the main concerns. Since pedestrians and cyclists do not move as fast as vehicles, they may not need to transmit every 100 milliseconds. It may be beneficial to separate the time slots used by vehicles from those used by pedestrians and cyclists. This will require modifications to the DSRC MAC protocol to manage the transmissions from cellphones to better control congestion. In particular, cell phones should be context-aware to know when they need to transmit and when it is sufficient to just keep silent.
- Application layer issues. In a vehicle, an onboard unit can use sophisticated user-machine interfaces to present alerts to the driver. However, pedestrians and cyclists do not look at their cell phones all the time. Innovative user interface designs will be necessary for pedestrians and cyclists to receive alerts of nearby vehicles without overwhelming the users with excessive unnecessary vehicular information.

To address these challenges, we contemplate a few possible solutions.

First, consider network-assisted solutions. Roadside devices can collect vehicle position and trajectory information by, for example, listening to V2V safety messages in the neighborhood. The roadside devices can forward the information to a network server. Pedestrians and cyclists can send their locations to the network server through cellular networks. The server can forward the safety information from nearby vehicles to cell phones of the pedestrians and cyclists, using unicast, multicast, or broadcast.

New cell phones can also be equipped with a 5.9 GHz DSRC radio, which add value to the cell phone users by enabling vehicle safety applications. Those cell phones can operate in a listening-only mode in 5.9 GHz. They silently monitor vehicle safety messages transmitted by nearby vehicles to be aware of the approaching vehicles, detect potential dangers, and alert their users when necessary. In addition, for power-saving purpose, cell phones may not need to monitor the 5.9 GHz channel every 100 milliseconds. The monitoring period can be adjusted dynamically and intelligently, for example, depending whether there are any nearby vehicles or whether the cell phone users are approaching traffic intersections.

Taking one step further, a subset of 5.9 GHz enabled cell phones can transmit their positions in the 5.9 GHz DSRC safety channel to alert approaching vehicles. Since pedestrians and cyclists do not move as fast as vehicles, they may not need to transmit every 100 milliseconds. It may be beneficial to separate the time slots used by vehicles from those used by pedestrians and cyclists. This will require modifications to the

DSRC MAC protocol to manage the transmissions from cell phones to better control congestion. In particular, cell phones should be smart enough to know when they need to transmit and when it is sufficient to just keep silent.

IV. Summary

In this paper, we reviewed the challenges, enhancements, and evolution of vehicular communications using DSRC. The current DSRC technology has been shown to be very effective in supporting vehicular safety applications in numerous field trials, and holds the promise for significantly reducing crashes. The technology is undergoing extensive research by the automakers, academia, and the government to ensure that the technology is safe and effective when it is deployed on production vehicles.

Even with such extensive research and testing, there will remain challenges to the performance of DSRC in some difficult RF environments. We reviewed the challenges of using DSRC technology in a highly mobile, dense deployment. Specifically we looked at channel estimation and lack of time diversity in the PHY layer, and packet collisions and congestion in the MAC layer. In addition, we noted that multichannel operations in the DSRC band impose new challenges. We discussed a few solutions to address those challenges based on existing DSRC standards. We also noted that some challenges will remain even after DSRC is deployed on production vehicles.

We suggested some initial thoughts on the DSRC evolution path to ease multi-generational interoperability in the future. In addition to V2V/V2I communications, which has been the focus of DSRC, V2P communications could extend enhanced safety to pedestrians and cyclists.

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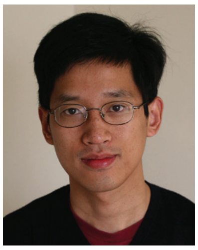


Xinzhou Wu received the B.E. degree from Tsinghua University, China, in 1998, and the M.S. and Ph.D. degrees from the University of Illinois at Urbana-Champaign in 2000 and 2004, respectively, all in electrical engineering. From 2005 to 2006, he was a Member of Technical Staff at Flarion Technologies, which pioneered OFDMA based cellular technologies. He is currently a Principal Engineer/Manager at Qualcomm Research. He currently holds 60 US patents and has more than 100 pending US patent applications in the area of wireless communications and wireless networking. He is a co-author of the book *OFDMA Mobile Broadband Communications - A Systems Approach*.

Sundar Subramanian (M'04) received his M.S. and Ph.D. ('08) from the University of Texas at Austin in electrical and computer engineering. His areas of expertise include distributed scheduling and networking techniques for heterogeneous networks, randomized algorithms, and PHY layer algorithms for cellular and mobile communications. Sundar joined Qualcomm Inc. in 2008 and has worked in many areas including PHY/MAC design for D2D systems like vehicular networks. He has one granted patent and over 40 patents pending.

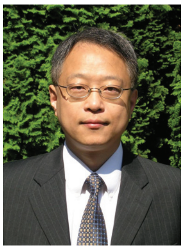
Ratul K. Guha has extensively contributed to the field of wireless and vehicular communication. Most recently, he has been working as a Senior Research Scientist at Telcordia, pursuing a multi-year research program for the application of wireless networks to vehicular communication, and he also holds 3 U.S patents. Dr. Guha has presented his work at major international conferences including the ITU-T fully networked car at the Geneva International Motor Show in 2010 and 2011. He received the B.Tech. in electrical engineering from the Indian Institute of Technology, New Delhi, India, in 2002, and the M.S and Ph.D. in electrical and systems engineering from the University of Pennsylvania in 2004 and 2007, respectively.

Robert (Bob) White is the Director of ITS Solutions at Metriken, LLC, developing systems, algorithms, and software focused on mobility, safety, and sustainability for intelligent transportation systems. He has worked in telecommunications, telematics research, automotive and transit systems, and new wireless technologies for over 30 years. He holds numerous US and international patents for inventions in wireless communications, digital security, and network systems. He has published extensively on technical and business topics in telecommunications and transportation. He began his career at Bell in 1980 after getting his doctorate in mathematics from Michigan State University. He joined Bellcore in 1984 and Telcordia Technologies in 1997. He is a founding member of Metriken, which he joined in 2012. He is a senior member of IEEE.

Junyi Li is vice president of engineering at Qualcomm. He holds over 180 U.S. patents and has more than 400 pending patent applications. He was a founding member of Flarion Technologies. Prior to that, he was a Member of Technical Staff at Bell Labs' Digital Communications Research Department in Lucent Technologies. He has a Ph.D. degree in electrical engineering from Purdue University and an M.B.A. from the Wharton School at the University of Pennsylvania. He received the 2012 Outstanding Electrical and Computer Engineering Award from Purdue University. He is a Fellow of IEEE.

Kevin W. Lu is a senior principal scientist for mobile wireless systems design at Broadcom. As the IEEE ComSoc director of standards development (2012–2013), Kevin chairs the ComSoc Standards Development Board that sponsors standards in communications and networking technologies and applications. He was chair (2007–2010) of the TIA TR-48 engineering committee on vehicular telematics, setting directions of standards development for interoperable connectivity between vehicles, infrastructure, and mobile devices. He contributed to the 2011–2014 strategic plan for the USDOT standards program on intelligent transportation systems and the connected vehicle sub-team of the ATIS M2M focus group. He was a liaison to the US technical advisory group for ISO/TC204 on intelligent transport systems, and to the SAE DSRC technical committee. Kevin had worked for over 27 years for applied research at Bellcore and Telcordia as a member of technical staff (1984–1995), director of broadband access network engineering (1995–1999), executive director of integrated access and operations (1999–2003), and chief scientist of emerging technologies and services (2003–2012). He received the B.S. degree in control engineering from National Chiao Tung University, Taiwan, and the M.S. and D.Sc. degrees in systems science and mathematics from Washington University, St. Louis.

Anthony Bucceri is a program manager with Qualcomm Corporate R&D and has responsibilities for advanced engineering and vehicular communications projects for the New Jersey Research office. Previously, Tony was a product manager at Flarion Technologies for Flash-OFDM, providing equipment for one of the first IP based cellular networks. In addition, he has held various positions at Lucent Technologies and NYNEX Mobile, culminating in more than 30 years of experience in the field of wireless telecommunications. Tony started his career as an RF engineer at Sperry Gyroscope in Great Neck, New York, after graduating with a B.E. in electrical engineering from City College of New York.



Tao Zhang is the Chief Scientist for Smart Connected Vehicles at Cisco Systems and a Fellow of the IEEE. For over 25 years, he has been directing and conducting research and product development in mobile Internet and vehicular networks. He holds 31 U.S. patents on wireless and vehicular networking and co-authored two books *Vehicle Safety Communications: Protocols, Security, and Privacy* and *IP-Based Next Generation Wireless Networks* published by John Wiley & Sons in 2012 and 2004, respectively. Dr. Zhang is the Chair of the IEEE Communications Society Technical Sub-Committee on Vehicular Networks and Telematics Applications. He has been serving on editorial boards or as a guest editor for several leading technical journals including the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, the IEEE JOURNAL OF SELECTED AREAS IN COMMUNICATIONS, and the *Journal of Wireless Networks*. He was a founding member of the board of directors for the Connected Vehicle Trade Association in the US and has served on the industry advisory boards for several research organizations. He has been an adjunct professor at several universities.