Cooperative Intelligent Transport Systems: 5.9-GHz Field Trials

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ABSTRACT | The mobile outdoor radio environment is challenging for vehicular communications. Although multipath propagation offers diversity and benefits in non-line-of-sight (NLOS) conditions, simultaneous multipath and mobility results in a doubly-selective fading channel. In practice, this means that the channel parameters vary significantly in both time and frequency within the bandwidth and typical packet durations used in 802.11p/WAVE standards for short-range vehicular communications. This paper presents the results of extensive field trial campaigns conducted in several countries, totaling over 1100 km. These field trials are scenario based, focusing on challenging low-latency, high-reliability vehicle-to-vehicle (V2V) safety applications including intersection collision warning, turn across path, emergency electronic brake light, do not pass warning, and precrash sensing. Vehicle-to-infrastructure (V2I) applications are also considered. The field trials compared the performance of off-the-shelf WiFi-based radio equipment with a more advanced 802.11p compliant radio employing more sophisticated channel estimation and tracking. Field trial results demonstrate significantly improved performance using the advanced radio, translating into greatly increased driver warning times and stopping distances. In fact the results show that off-the-shelf WiFi equipment fails to provide sufficient stopping distance to avert accidents in some cases. During the field trials, channel sounding data were also captured. Analysis of these channel measurements reveals the critical importance of accurate channel estimation, tracking the channel in both time and frequency within each packet. Delay spread and Doppler spread statistics computed from the channel measurements validate previously reported results in the literature. The results in this paper, however, provide the first instance of channel measurements performed simultaneously to application performance evaluation. The objective is to firmly establish the link between radio channel characteristics and the performance of critical V2V safety applications.

KEYWORDS | Channel estimation; channel models; time-varying channels; vehicle safety

I. INTRODUCTION

Road crashes are a leading cause of deaths worldwide. It is estimated that 1.2 million people are killed, and over 50 million are injured each year as a result of road crashes [1]. Road crashes are the second-leading cause of death in the 5–29 year old age group (second only to HIV/AIDS), and third in the 30–44 age group (surpassed only by HIV/AIDS and tuberculosis). Across all ages, road crashes rank as the 11th most common cause of death. Road safety is a serious public health problem, greater, or similar in magnitude to many serious diseases (which attract significant investment in research and treatment). The World Health Organization predicts that by 2020, road traffic injuries will increase in total number by 65% and will be the third...
highest cause of disability-adjusted life years.\textsuperscript{1} Worldwide, injuries due to road crashes result in an economic cost typically ranging between 1\% and 2\% of GDP, a global total that exceeds $145 billion per annum.

Cooperative safety systems based on vehicle-to-vehicle (V2V) communications have the potential to significantly reduce the number of road crashes. Australian statistics for the state of New South Wales show that in terms of the total number of crashes (all recorded fatal, injury and noninjury crashes), 61\% of crashes involve collision of two moving vehicles [2]. Furthermore, 46\% of all crashes occur at some kind of intersection (Cross, T-junction, Y-junction, or roundabout). The Australian National Crash In-Depth Study further reveals that 47\% of road fatalities and serious injuries are a result of collision between two or more vehicles [3]. Initial Organisation for Economic Co-operation and Development estimates indicate that emerging road safety technologies could reduce fatalities and injuries by as much as 40\% [4].

Of particular interest in this paper are V2V wireless communications systems that aim to prevent avoidable collisions, by identifying unsafe conditions and warning the driver (or even taking automatic intervention). In many high-risk safety scenarios, line of sight (LOS) between vehicles either does not exist, or is impaired. Clearly the most critical situations are where vehicles are in danger of collision, but the drivers cannot see the other vehicle.

This paper focuses on cooperative intelligent transport systems using the IEEE 802.11p Dedicated Short Range Communications/Wireless Access in Vehicular Environments (DSRC/WAVE) family of standards [5]–[9]. We present results of extensive field trial campaigns conducted in several countries, totaling over 1100 km. These field trials are scenario based, focusing on challenging low-latency, high-reliability V2V road safety applications including intersection collision warning, turn across path, emergency electronic brake light, do not pass warning, and precrash sensing. Vehicle-to-infrastructure (V2I) applications are also considered.

The main conclusions of these field trials are as follows.

1) DSRC/WAVE can provide highly reliable communications, and sufficient driver warning times in support of road safety applications.

2) Non-line-of-sight (NLOS) safety-critical conditions require careful attention to physical layer receiver processing in order to provide a safety benefit. Failure to accurately estimate and track the radio channel over the entire duration of a packet results in poor performance and greatly reduced potential for safety benefits.

In Section II, we give an introduction to cooperative intelligent transport systems and the DSRC/WAVE set of standards and protocols. In Section III, we describe the physical layer challenges presented by outdoor, mobile NLOS conditions. We also give an overview of technology solutions that can address these problems. Section IV describes the field trials, including the experimental methodology and test scenarios. We analyze the results of these trials in two different ways. First, in Section V, we analyze the packet error rate (PER) statistics collected during the field trials to determine the excess/deficit stopping time for each safety scenario. Comparative testing shows that accurate channel estimation and tracking within each packet is vital in order to deliver safety benefits. Second, in Section VI, we use channel sounding data collected during the field trials to characterize the radio channel at 5.9 GHz, in terms of delay/Doppler spread for both urban and highway environments. These results confirm the need for accurate channel estimation and tracking within each packet.

II. COOPERATIVE INTELLIGENT TRANSPORT SYSTEMS

Cooperative intelligent transport systems, also known as DSRC for WAVE are in the final stages of international standardization. Overviews of DSRC/WAVE can be found in [6]–[9].

With reference to Fig. 1 (which shows a schematic representation of an onboard unit), DSRC systems combine reliable, low-latency wireless connectivity, accurate positioning (via global positioning satellites and vehicle dead reckoning) and an onboard computer to allow vehicles to communicate directly\textsuperscript{2} with each other (V2V links), and with roadside units (V2I).

\textsuperscript{1}Average years of life lost, plus average years lived with disability.

\textsuperscript{2}This is a key difference to infrastructure-based WiFi and cellular systems, which mediate communications via access points or base stations.
Provision of a robust, low-latency radio connection, even in safety-critical, NLOS conditions gives vehicles the ability to “see around corners” and to “see through other vehicles.” Each vehicle can communicate with nearby vehicles as well as monitor the status of traffic lights, variable speed signs, location of roadworks, school zones, etc. Similarly, it enables infrastructure to obtain information about detailed traffic movements and to communicate with vehicles.

DSRC-equipped vehicles broadcast basic safety messages [10] (typically ten times a second). These messages contain detailed dynamic information including latitude, longitude, speed, heading, four-way acceleration, brake status, steering wheel angle, throttle position, and vehicle size [obtained from global positioning system (GPS) signals and from the vehicle controller area network (CAN) bus]. Allowing vehicles to communicate with each other, and the broader environment, provides the vehicle with greater knowledge of its surroundings, and hence the ability to avert hazardous situations such as potential intersection crashes, rear-end collisions, dangerous overtaking, lane drift, or imminent road departure. Onboard units can alert drivers to hazardous situations, or can take automatic intervention, via interface to the vehicle control system (using the CAN bus), e.g., to automatically apply brakes to prevent a collision between vehicles, or between vehicles and DSRC-equipped road infrastructure such as bridges and tunnels.

In addition to these important road safety applications, DSRC provides a standardized platform for active traffic flow management, flexible road use charging, road and traffic condition monitoring, traffic scheduling, optimized route selection, and active ecodrive assistance for drivers. The low latency of DSRC enables tight coupling (i.e., real time, closed loop) of vehicular control systems with the systems that manage and control traffic flow and infrastructure utilization. This enables the interaction of these systems to cooperatively optimize resource utilization and minimize the impact on traffic infrastructure while also minimizing engine emissions. For example, smart infrastructure systems can provide environmental information to the control systems of vehicles entering an intersection or a tunnel. The vehicle control system can incorporate this information to reduce the fuel consumption and emissions of the vehicle based on known intersection timing, traffic congestion, and traffic flow through the tunnel. Such resource optimizations can be rapidly performed without involving the driver.

Dedicated short-range communications will operate in a protected frequency band at 5.9 GHz. Protection from interference is critical for road safety applications. In the United States, this band (5.850–5.925 GHz) has already been allocated [11], and licensing rules have been established (December 2003) [12]. In Europe, the band 5.875–5.925 has been allocated for protected access (August 2008) [13], and the industrial, scientific, and medical (ISM) band immediately below this (5.855–5.875) can also be used by nonsafety critical services in an unprotected fashion (in accordance with the usual rules for ISM bands). In Australia, the Australian Communications and Media Authority placed the 5.850–5.925 band under embargo in April 2008, and is currently considering the allocation and licensing arrangements for DSRC [14].

DSRC/WAVE standards are already in trial use, and products are already appearing. These standards are being adopted by car manufacturers and component suppliers to achieve an internationally harmonized technology landscape. This is critical for interoperability between all vehicles on the road.

The IEEE has standardized the wireless air interface under 802.11p [5], which is a variant of the IEEE 802.11a standard used for WiFi. The IEEE 1609 set of standards covers resource management [15], security [16], networking services [17], and multichannel support for very low-latency V2V connection [18]. This is critical for safety applications. The Collision Avoidance Metrics Partnership (CAMP) Vehicle Safety project concluded that “latencies of less than 100 milliseconds seem to be possible with DSRC, and many of the vehicle safety applications have latency requirements in this range” [19].

A dictionary of messages has been standardized by the Society of Automotive Engineers under SAE J2735 [10]. This provides the common language whereby vehicles can understand each other. In addition to basic safety messages and other specific applications (intersection collision warning, lane change warning, forward collision warning to name just a few), this standard defines messages for notification of approaching emergency vehicles and roadworks, as well as messages that allow traffic signals to communicate their state to vehicles (including time to change and the presence of pedestrians). Probe vehicle data messages have been defined that allow vehicles to transmit information about their driving history in support of active traffic management applications. Many other messages have been defined, as well as generic, extensible messages to provide for future applications.

Fig. 2 shows the WAVE protocol stack and its relation to the open system interconnect (OSI) layers 1–4.

The International Organization for Standardization (ISO) TC204 Working Group 16 is in the final stages of developing Communications Access for Land Mobile (CALM). This is an overarching set of protocols and standards for intelligent transport that includes IEEE 802.11p, as well as other standards such as cellular 2G/3G, Internet (IPv6), WiMax, Satellite, millimeter wave, and infrared. While IEEE 802.11p is uniquely placed to support critical safety and tightly coupled V2I control systems, a heterogeneous system incorporating other communications technologies provides a universal and open platform...
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Large consortium projects such as VII (now Intellidrive [20]), COOPERS [21], CVIS [22], CAMP, and Car-2-Car [23] have demonstrated the feasibility of DSRC/WAVE systems, as well as directly contributing to standards, technology, and application development. Large-scale field trials (hundreds of vehicles) are commencing this year in Europe (simTD, [24]) and the United States (CAMP).

III. PHYSICAL LAYER CHALLENGES

One of the key difficulties in the design of outdoor mobile communications systems is the impact of the propagation environment (channel) on the radio signal. The channel may distort the transmitted signal by altering its magnitude and/or phase. An introduction to the characteristics of the wireless channel can be found in [25, Ch. 3]. In this section, we give a brief overview of doubly-selective channels (which vary appreciably in frequency and time within the signal bandwidth and duration). We also describe how orthogonal frequency division multiplexing (OFDM) addresses frequency-selective fading in a computationally efficient manner. We also consider different receiver technologies for OFDM, including advanced schemes that can handle time selectivity.

A. Doubly-Selective Fading Channels

As a radio signal propagates through space, it may be reflected or refracted by scatterers in the environment. At the microwave frequencies of interest, the wavelength is of the order of 5 cm, and hence the urban or highway environment can present a rich scattering scenario. Furthermore, relative motion of transmitter, receiver, and scatterers can induce Doppler shifts in the various reflected paths. As a result, the receiver observes the superposition of many different delayed and frequency shifted versions of the transmitted radio signal. The baseband time-varying impulse response of the multipath channel may be modeled as

$$h(t, \tau) = \sum_{k} A_k(t)\delta(\tau - \tau_k)$$

where $A_k(t)$ is the time-varying complex amplitude (magnitude and phase) of tap $k$, with delay $\tau_k$. In this model, Doppler shifts manifest as linear variation of phase with time. The complex amplitudes $A_k$ can also aggregate very large numbers of unresolvable reflections, commonly resulting in Ricean or Rayleigh statistics for these coefficients.

For a given channel response, the root mean square (RMS) delay spread is the RMS power-weighted average of tap delays

$$\sigma_T = \sqrt{\frac{\sum_{k=1}^{K} P_k(\tau_k - \bar{\tau})^2}{\sum_{k=1}^{K} |A_k|^2}}$$

where

$$P_k = \sum_{k=1}^{K} |A_k|^2 \frac{\sum_{k=1}^{K} \tau_k}{\sum_{k=1}^{K} |A_k|^2}$$

is the normalized power profile and

$$\bar{\tau} = \frac{\sum_{k=1}^{K} \tau_k}{\sum_{k=1}^{K} |A_k|^2}.$$

From the time-varying impulse response, we can calculate the time-varying frequency response as the Fourier transform with respect to delay

$$H(t, f) = \mathcal{F}_\tau \{h(t, \tau)\}.$$
constant $|H(t, f)| \approx |H(t, f + \Delta f)|$ for $|\Delta f| < B_c/2$. Two frequencies separated by more than the coherence bandwidth have approximately uncorrelated magnitude response. Channels for which the coherence bandwidth is larger than the signal bandwidth are called flat. For such channels, the frequency response is constant over the entire signal band. Channels for which the coherence bandwidth is much smaller than the signal bandwidth are frequency selective. In the time domain, this manifests as intersymbol interference (since the RMS delay spread is larger than the symbol period).

We can compute the deterministic scattering function by taking a Fourier transform with respect to time

$$S(\rho, \tau) = \mathcal{F}_t \{ h(t, \tau) \}.$$ 

The scattering function reveals the Doppler behavior of the channel (induced by relative motion of the transmitter, receiver, and scattering environment), where $|S(\rho, \tau_k)|^2$ is the energy at Doppler frequency $\rho$ corresponding to the tap at delay $\tau_k$. In other words, $|S(\rho, \tau_k)|^2$ is the Doppler power spectrum of tap $k$.

The Doppler bandwidth $B_D$ is the bandwidth over which $|S(\rho, \tau)|$ is essentially nonzero. The precise definition requires specification of “essentially nonzero.” Typically, some threshold is employed. The Doppler bandwidth is inversely proportional to the coherence time $T_c$ of the channel (via a constant that depends on the actual shape of the Doppler spectrum). This is the time interval over which the channel response is approximately constant $|H(t, f)| \approx |H(t + \Delta t, f)|$ for $|\Delta t| < T_c$. Two instances separated by more than the coherence time have largely uncorrelated channel response.

Wideband mobile radio channels are typically doubly selective, with coherence bandwidth less than the signal bandwidth, and coherence time less than the packet duration. This results in a channel response that varies in both frequency and time, and is a particularly difficult challenge for both physical layer waveform design and receiver implementation.

Fig. 3 shows an example of an actual measured 5.9-GHz channel, recorded in highway conditions during a Do Not Pass Warning trial (see Section IV for details of the scenario). The surface plot shows the magnitude of the time-varying frequency response $|H(t, f)|$ in decibels relative to the maximum value. Also shown are the gains and Doppler offsets of each multipath tap (relative to the LOS tap). As discussed in Section VI, the time variation of the multipath channel is completely characterized by the Doppler frequency of each tap (i.e., the tap gains and delays do not change appreciably during a packet). This example shows strong doubly-selective behavior, which is induced by the large relative Doppler of the fourth tap. Not only do we see strong frequency selectivity, but we also see that the frequency domain nulls move right across the signal bandwidth within the duration of the packet. A further example of this kind of behavior in an urban environment can be seen in Fig. 4.

B. The 5.9-GHz Outdoor Mobile Channel

Several measurement campaigns have already been conducted by different teams, focussing on characterizing the 5.9-GHz V2V channel in terms of delay spread and Doppler spread. There has also been significant effort towards developing statistical channel models. A good recent overview can be found in [26] and [27].

For channel modeling purposes, it is more typical to be interested in the statistics of the average power delay profile,\(^4\) which can be used as inputs to a statistical channel model for the purposes of simulation (provided a reasonable statistical model can be found). This was the methodology of [28]. In [28], broadband sounding using maximal length sequences was conducted in a number of different environments. Based on the empirical average power delay profile, Tan et al. measured RMS delay spreads between 300 ns (urban LOS) and 560 ns (highway NLOS) and average Doppler bandwidths (again measured from the empirical average spectrum) of 340–790 Hz.

However for real-world performance analysis, the distribution of the measured delay/Doppler spread is of much more interest. In that case, one is much more interested in the probability that each channel realization has difficult delay/Doppler characteristics. Median RMS delay spreads of 50 ns (suburban)/100 ns (highway) and

\(^{4}\) Our discussion in Section III is for the instantaneous, deterministic power delay profile.
corresponding median maximum excess delays of about 400 ns/600 ns were reported in [29], based on broadband channel sounding using zero correlation zone sequences. Similar results were reported in [30] (which also fits a number of statistical channel models to the empirical data). A channel sounding approach using both spread spectrum and OFDM signals was described in [31]. Note that results based on quantiles of the empirical cumulative distribution function cannot be directly compared to [28], since the latter are derived from the empirical average power delay profile. The importance of accurate consideration of the radio channel is highlighted in [32], where simulation-based evidence is given to show that safety systems performance may depend very strongly upon the choice of physical layer channel model.

Another extensive channel measurement campaign was carried out in [33] and [34], including multiple-antenna (4 × 4 MIMO) channel soundings [35]. This work led to a very attractive geometric-stochastic channel model [36].

Fig. 4 shows an example of actual measured frequency domain channel magnitudes for a two-antenna system with two vehicles approaching a blind intersection (see Section IV-B for a description of the test methodology). Beginning on the right-hand side of the diagram, we see the vehicles separated by 116 m, and in NLOS conditions (the test environment was urban, with two and three story buildings on all sides). The frequency domain channel magnitude responses are shown for each antenna (decibel relative to the maximum magnitude over both antennas), and are labeled with the average receive power. Each channel response is shown with frequency on the horizontal axis and time on the vertical axis. NLOS conditions induce deep fades in both time and frequency. We also see that the two antennas have quite different channel responses, which indicates the availability of space diversity.

As the vehicles approach, and are separated by 41 m, the channel is still double selective, but with less total variation. Finally, as the top vehicle passes the intersection, we have LOS conditions, and the channels are considerably “flatter.” It is important to note that, in this scenario, the most difficult radio channel presents at a time when it is most important to achieve reliable communications for safety applications.

C. Orthogonal Frequency Division Multiplexing

OFDM is an elegant modulation format that combines multicarrier transmission and a special guard interval to provide good performance and low complexity in frequency-selective channels. The basic idea is to partition the total bandwidth into a number of nonoverlapping (orthogonal) subcarriers, whose spacing is chosen to be less than the coherence bandwidth of the channel. As a result, each subcarrier experiences flat fading, requiring only a single tap equalizer per subcarrier. This takes care of the frequency domain effects of the channel’s time dispersion. In the time domain, OFDM employs a cyclic prefix, whose duration is chosen to be larger than the delay spread of the channel. The cyclic prefix is a guard interval, which is filled with a copy of the end of the OFDM symbol.

The cyclic prefix serves two purposes. First, it prevents intersymbol interference between successive OFDM symbols. Second, it converts the linear convolution of the channel response with the transmitted signal into a cyclic convolution. This ensures subcarrier orthogonality (prevents intercarrier interference) and allows the application of the discrete Fourier transform (via fast transforms) for implementation of the transmitter and the receiver.

OFDM is used in a wide array of modern standards, including 802.11 (WiFi), 802.16 (WiMax), and LTE. See [37] for an overview of the IEEE 802.11 family, and [38] for
a more recent update. The 802.11p physical layer is a variation on 802.11a, temporally scaled (via halving the clock rate) to result in 10-MHz channels. One of the main motivations for the half-rate clock is to increase the length of the cyclic prefix, to guard against longer delay spreads. It also halves the subcarrier spacing, which allows for greater frequency selectivity. Basing the standard in this way on 802.11a also allows easy technology migration for chip vendors. Table 1 lists the parameters of the 802.11p physical layer. The subcarrier structure is shown in Fig. 5. The structure is symmetric about subcarrier 0 (which is not used), and hence we have only shown the positive subcarriers. Subcarrier \(-i\) has the same pilot/training structure allocation as subcarrier \(i\).

Fig. 6 shows a simplified version of an OFDM transmitter, and the conventional receiver processing chain. At the transmitter, data are encoded and interleaved to protect against noise and interference. The data are then modulated and framed into packets, to which are added the short and long preamble, and pilot carriers (see Fig. 5).

The resulting sequence of OFDM symbols is then transformed into the time domain via an inverse FFT. After addition of a cyclic prefix to each symbol, the signal is transmitted over the channel. On the receiver side, initial coarse synchronization is achieved using the short preamble. The cyclic prefix is discarded, and the time domain signal is brought back into the frequency domain via an FFT. Frequency domain channel estimation is performed based on the long preamble, and this channel estimate is used for the entire packet duration. Phase tracking over the packet is facilitated by the pilot carriers. See [39] for an overview of OFDM and conventional algorithms.

<table>
<thead>
<tr>
<th>Table 1 IEEE 802.11p Physical Layer Parameters</th>
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<tbody>
<tr>
<td><strong>Parameter</strong></td>
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<tr>
<td>Data rates (Mb/s)</td>
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<tr>
<td>FEC rates</td>
</tr>
<tr>
<td>Modulation</td>
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<tr>
<td>Subcarriers</td>
</tr>
<tr>
<td>Bandwidth</td>
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<tr>
<td>Subcarrier spacing</td>
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<tr>
<td>OFDM Symbol Duration</td>
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<tr>
<td>Cyclic Prefix</td>
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<tr>
<td>FFT period</td>
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<tr>
<td>Preamble</td>
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<td>Pilot subcarriers</td>
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![Fig. 5. IEEE 802.11p frame structure. Only positive subcarriers are shown.](Image)
The 802.11a/p OFDM parameters and conventional receiver processing were designed to handle frequency-selective channels with a low complexity receiver. As we will see, however, they were not particularly designed with time selectivity in mind.

Based on empirical measurement studies of the 5.9-GHz channel, it has been concluded [40] that the IEEE 802.11p cyclic prefix is long enough to deal with the longest maximum excess delays encountered in practice (this conclusion is further supported by the results in Section VI). Similarly, measurements of the coherence bandwidth indicate that the 802.11p subcarrier spacing is small enough such that the assumption of flat fading within a subcarrier is approximately true most of the time. Delay spreads exceeding the cyclic prefix duration are difficult to handle, but OFDM receiver algorithms do exist for this scenario; see [41] for an overview.

One particular challenge for the conventional receiver in vehicular environment occurs if the coherence times/Doppler spreads are such that the channel changes significantly within a packet (typically a problem for longer packets). As recognized in [40], “...the PHY performs channel estimation at the beginning of the packet and the estimation is then used for all the OFDM symbols in the packet.” Further evidence of this problem can be found in [28], where it was calculated that packets of the order of 400 B would experience multiple temporal fades. Thus, we expect the conventional receiver, which bases its channel estimate only on the preamble, to suffer performance degradation on time-selective channels.

An example of this effect is shown in Fig. 7. The top blue trace shows the measured byte error performance (0 means correctly decoded, 1 means error). The frequency domain channel magnitude response (decibel relative to maximum) is shown with accurate time scaling compared to the error trace. At the start of the packet, the receiver is decoding correctly, with zero errors (despite a deep 20-dB fade). As time progresses, however, the location of this “null” moves, and eventually the initial channel estimates are sufficiently inaccurate to cause the decoder to fail. It is further interesting to note that the receiver cannot recover, since it has no way to reestimate the channel. Even when the channel becomes significantly better, around OFDM symbol 200, where it is quite flat, and also higher in total power, the receiver cannot decode properly because it is using outdated channel estimates. A number of advanced OFDM receiver algorithms have been proposed to deal with this problem.

One approach is to use pilot symbol aided methods [42]. These aim to interpolate channel estimates obtained from the pilot symbols. However, the frequency separation of the pilot subcarriers in 802.11p greatly limits the extent to which such receivers can track a frequency-selective channel (consider a channel with several nulls between two pilots).

A more sophisticated approach is to iteratively estimate the channel parameters based on outputs of the data decoder. See [43]–[50] for basic concepts of iterative decoding, demodulation, and channel estimation. This approach is shown schematically in Fig. 8 for a system with two receive antennas. In this system, the front end processing is identical to the conventional receiver, performing coarse synchronization using the short preamble. The channel estimator generates initial estimates using the long preamble (since no soft decoded outputs are available to begin with). The signals from the two antennas are diversity
combined (possibilities include maximum ratio combining, or linear minimum mean squared error methods), and “soft demodulated.” The resulting likelihood ratios are input to a soft-in/soft-out decoder, which outputs soft estimates of the transmitted bits. These soft estimates are in turn fed back to the channel estimator, which uses them (together with perfect knowledge of the long preamble and pilots) to update the channel estimate. Such algorithms use tentative decoder outputs as “noisy pilots” in order to improve the channel estimates. In turn, improved channel estimates improve the reliability of the decoder outputs. This is an application of the so-called “turbo principle” to the problem of channel estimation. Note that the channel estimation can be performed either in the frequency domain (which reduces complexity), or in the time domain, which can improve performance for channels with long delay spread [41]. Many variations on this theme of iterative decoding and channel estimation have been reported in the literature. A good contemporary starting point, containing a comprehensive literature review is [51]. Other recent variations on iterative channel estimation can be found in [52]–[58]. These iterative schemes can provide very good performance, potentially at the expense of additional implementation complexity.

Fig. 7. Example of conventional receiver measured byte error performance versus time for a packet with doubly-selective fading.

Fig. 8. Advanced receiver using iterative decoding and channel estimation.
The key ingredient for all of these approaches is the use of soft decoder outputs as extra (noisy) pilot symbols. This allows the receiver to accurately estimate the channel over the entire duration and bandwidth of the packet. In contrast, the initial channel estimate obtained from the long preamble (at the start of the packet) may become outdated. Note, however, that the initial channel estimate is still valuable, as it allows the iterative receiver to get started.

IV. FIELD TRIALS

During 2007–2010, we conducted a substantial campaign of scenario-based field trials. This paper reports the results of 35 trials, totaling over 1100 km for several distinct use-case scenarios. The trials were conducted on public roads in the United States, Germany, Austria, Italy, and Australia, providing a wide range of real-world traffic and environmental conditions.

The vast majority of V2V and V2I experiments reported in the literature focus on channel measurements in the 5.9-GHz band, aiming to characterize statistical properties of the radio channel. In contrast, the principal objective of our field trials was to evaluate and compare system performance of IEEE 802.11p compliant equipment in real-world application scenarios.

In Section IV-A, we describe the details of the specific V2V safety scenarios and V2I test scenarios. We then present our experimental methodology in Section IV-B.

A. Test Scenarios

Standard V2V and V2I scenarios were considered [10]. Fig. 9 shows schematic representations of each of the test scenarios, which are described below. It is important to note that the high-risk safety scenarios are typically NLOS situations, where the drivers vision is blocked by traffic, buildings, or the environment. No only do NLOS conditions increase the risk of accident, but also they result in more challenging radio channels, as described in Section III. The crash risk (and radio challenge) are further increased by increased vehicle speed. This highlights the importance of DSRC equipment performance in highly mobile, NLOS conditions.

*Intersection movement assist (IMA) (also known as intersection collision warning);* Fig. 9(a): It warns drivers of potential side impact when entering an intersection. This scenario was executed in both closed intersections (buildings on all corners) and blind corner intersections (buildings on one corner only, between the approaching vehicles). Typically, the vehicle entering the intersection has low speed (or is stopped, waiting to enter), and the second vehicle is traveling at the speed limit. Impaired LOS between vehicles creates an unsafe situation, and additionally presents challenges for radio transmission.

*Turn across path (TAP);* Fig. 9(b): It warns a driver of an oncoming vehicle if turning across its path. This scenario was executed in closed intersections and open intersections. The turning vehicle is traveling at low speed, compared to the oncoming vehicle, which is traveling in accordance with the speed limit. Occluding traffic impairs LOS and creates a high-risk scenario. A large truck was used during field trials to create this situation.

*Fig. 9. Safety scenarios. (a) Intersection movement assist. (b) Turn across path. (c) Precrash sensing. (d) Do not pass warning. (e) Emergency electronic brake light.*
Precrash sensing (PCS); Fig. 9(c): Harm minimization in unavoidable intersection collisions. This scenario was executed in closed intersections and blind corner intersections. In contrast to TAP, in this scenario, both vehicles travel towards the intersection in accordance with the speed limit. Again, impaired LOS increases risk of collision.

Do not pass warning (DNPW); Fig. 9(d): It warns driver of an oncoming vehicle when overtaking or drifting from the lane. This scenario was executed on blind urban and hillside corners, blind corners in cuttings, and on an open highway with a truck blocking the view ahead. In all cases, all participating vehicles drove at the local speed limit.

Emergency electronic brake light (EEBL); Fig. 9(e): It warns a driver of hard braking by a vehicle ahead. This scenario was executed in highway conditions with an occluding truck. All participating vehicles traveled at the local speed limit.

**Roadside unit (RSU):** V2I communications. This scenario was executed with the RSU mounted in closed intersections and open intersections. The vehicle was driven past at the local speed limit.

The specific trial locations, safety scenarios, and environment types are listed in Table 2. Each data set has been assigned an identification (ID) number to facilitate presentation of results in Sections V and VI. The environments and speed parameters are explained in Section IV-B where we give details of the experimental methodology.

### B. Experimental Methodology

The test system architecture is shown in Fig. 10. For V2V trials, both the transmitter and the receiver are vehicle mounted. For V2I trials, the receiver is stationary.

All trials were conducted on public roads, in ambient traffic conditions with other vehicles present. Each

<table>
<thead>
<tr>
<th>Scenario</th>
<th>ID</th>
<th>Locations</th>
<th>Environment</th>
<th>Speed (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMA</td>
<td>1</td>
<td>San Diego, USA</td>
<td>Highway</td>
<td>104 (65 mph)</td>
</tr>
<tr>
<td></td>
<td>2, 3, 4</td>
<td>Adelaide, Australia (3 sites)</td>
<td>Urban</td>
<td>50</td>
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<td></td>
<td>5</td>
<td>Detroit, USA</td>
<td>Urban</td>
<td>56 (35 mph)</td>
</tr>
<tr>
<td></td>
<td>6, 7, 8</td>
<td>Milan, Italy (3 sites)</td>
<td>Urban</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>Hildesheim, Germany</td>
<td>Urban</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>10, 11</td>
<td>Hildesheim, Germany (2 sites)</td>
<td>Urban</td>
<td>50</td>
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<tr>
<td>TAP</td>
<td>12</td>
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<tr>
<td></td>
<td>13</td>
<td>Detroit, USA</td>
<td>Urban, Occluding truck</td>
<td>32 (20 mph)</td>
</tr>
<tr>
<td></td>
<td>14</td>
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<td>Urban, Occluding truck</td>
<td>60</td>
</tr>
<tr>
<td>PCS</td>
<td>15, 16</td>
<td>Adelaide, Australia (2 sites)</td>
<td>Urban</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>Detroit, USA</td>
<td>Urban</td>
<td>48 (30 mph)</td>
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<td>40</td>
</tr>
<tr>
<td></td>
<td>19, 20</td>
<td>Milan, Italy (2 sites)</td>
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<td>50</td>
</tr>
<tr>
<td>DNPW</td>
<td>21</td>
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</tr>
<tr>
<td></td>
<td>22</td>
<td>Detroit, USA</td>
<td>Highway, Occluding truck</td>
<td>88 (55 mph)</td>
</tr>
<tr>
<td></td>
<td>23</td>
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<td>Highway, Occluding truck</td>
<td>90</td>
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<td>Highway, Occluding truck</td>
<td>90</td>
</tr>
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<td></td>
<td>25</td>
<td>Wolfsburg, Germany</td>
<td>Highway, Occluding van</td>
<td>100</td>
</tr>
<tr>
<td>EEBL</td>
<td>26</td>
<td>Frankfurt, Germany</td>
<td>Highway</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>27</td>
<td>Graz-Vienna, Austria</td>
<td>Highway</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>Adelaide, Australia</td>
<td>Highway, Occluding truck</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>29</td>
<td>Hildesheim, Germany</td>
<td>Highway, Occluding truck</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>Adelaide, Australia</td>
<td>Urban, Occluding truck</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>31</td>
<td>Milan, Italy</td>
<td>Urban, Occluding truck</td>
<td>100</td>
</tr>
<tr>
<td>RSU</td>
<td>32</td>
<td>Detroit, USA</td>
<td>Urban, Occluding truck</td>
<td>56 (35 mph)</td>
</tr>
<tr>
<td></td>
<td>33</td>
<td>Milan, Italy</td>
<td>Urban, Occluding truck</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>34</td>
<td>Vienna, Austria</td>
<td>Urban, Occluding truck</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>Adelaide, Australia</td>
<td>Urban</td>
<td>60</td>
</tr>
</tbody>
</table>
scenario was conducted according to the descriptions in Section IV-A, with vehicle movements shown in Fig. 9. In all cases, moving vehicles were driven in accordance with local speed limits. Table 2 lists the nominal speed for each trial. For the IMA scenarios [Fig. 9(a)], the indicated speed was for the approaching vehicle, with the second vehicle stationary. Similarly for TAP [Fig. 9(b)], the indicated speed is for the approaching vehicle, with the turning vehicle proceeding at a lower speed. For PCS [Fig. 9(c)] the listed speed is the approach speed for both vehicles, with only one vehicle stopping (to avoid collision). For both DNPW [Fig. 9(d)] and EEBL [Fig. 9(e)], the indicated speed is for both test vehicles. For TAP, DNPW, and EEBL scenarios with occluding truck (see Table 2), an additional large truck or van (Mitsubishi 3 tonne moving van or similar) was driven as shown in Fig. 9(b), (d), and (e).

The vehicle-mounted transmitter consists of a Cohda Wireless MK1 802.11p DSRC unit\(^5\) with single antenna, a GPS receiver, and a laptop for control and logging. As described in Section III, the performance of an OFDM receiver can depend strongly on the radio channel characteristics and its ability to accurately estimate and track a time-varying channel. One of our objectives for these trials was to test the hypothesis that simultaneous large delay spread and Doppler spread would cause receivers using conventional channel estimation techniques (based only on the preamble) to fail. The receive side of the experimental setup includes two radios under test: the Cohda MK1 unit, which uses advanced channel estimation and tracking (Fig. 8), and a commercial off-the-shelf (COTS) 802.11p unit, which uses conventional OFDM channel estimation, based only on the preamble (Fig. 6). Both radios under test are fed by the same two antennas (Nippon Antenna part number DEN-HA001-001), connected by radio-frequency (RF) splitters. This is to make sure that each radio observes the same radio frequency signals. Antenna placement is shown in Fig. 11 (not to scale). The Cohda MK1 receiver combines the signals received from both antennas according to Fig. 8. The COTS receiver uses switched diversity.

Test packets are broadcast from the transmit vehicle to the receive vehicle. The radios under test are placed in receive-only monitor mode. All successfully received packets for each radio are independently logged. After the test has been completed, the transmit and receive logs are compared to determine which packets were successfully received by each radio. Additionally, position, speed, and heading data are logged for both vehicles using the GPS receivers.

---

\(^5\)The variation in system performance reported in this paper is due to differences in receiver signal processing. The transmitter, which must conform to IEEE 802.11p, only affects performance through its EIRP. We have verified that we obtain the same results when using other 802.11p transmitters.
At each test location, multiple repetitions (typically between five and ten) of the same safety scenario were run in succession. During each test, we transmit all nine combinations of 50-, 400-, and 2000-B packet lengths [MAC Service Data Unit (MSDU) length], and 3-, 6-, and 12-Mb/s data rates. The cycle is 50 B (3, 6, 12) Mb/s, followed by 400 B (3, 6, 12) Mb/s, then 2000 B (3, 6, 12) Mb/s. For most cases, an aggregate 400 packets/s are transmitted, resulting in a packet interval of 22.5 ms for each packet type. All packets are transmitted in broadcast mode (as opposed to unicast), which is the mode that would be used by basic safety messages in an operational system.

For the 35 data sets listed in Table 2, a total of 9,528,327 packets were transmitted, with over 12.5-h airtime and covering over 1100 km on the road.

The technical parameters of the test equipment are summarized in Table 3.

Postprocessing software uses the transmit and receive logs to compute several performance statistics, including PER versus range (distance between the two vehicles), and PER versus receive power level.

In order to focus on the particular scenarios of interest, we use the recorded GPS position information, to remove any packets transmitted outside the identified scenario “test zone.”

PER versus range and PER versus receive power are calculated separately for each MSDU length/data rate combination. Results are averaged over all of the multiple passes of the same scenario for each test location.

## V. FIELD TRIAL RESULTS

### A. Safety Scenarios

For each test location, we determine the maximum reliable range from the measured PER statistics (PER statistics are averaged over all passes at the test location). We define the maximum reliable range between two vehicles as the largest separation distance (range) below which the PER remains under 10% for the remainder of the pass. In other words, when the vehicles are closer than the maximum reliable range, the measured PER remains under 10%. Fig. 12 shows indicative results for PER versus range, and versus received power. The PER versus range results in Fig. 12(a) are labeled with the maximum reliable range (meters).

The PER versus received power plots in Fig. 12(b) show how the performance of the conventional OFDM receiver does not monotonically improve with increasing received power. As exemplified in Fig. 7, this is because even when the received power is high, temporal variations in the channel cause the receiver’s channel estimates to become outdated, and the receiver to fail. Also observe the “bathtub” behavior of the PER observed for the COTS receiver with 400- and 2000-B packets. This is due to the well-known two-ray effect due to reflection from the road, which causes a deep fade at about 88 m for a 5.860-GHz transmitter at a height of about 1.5 m.

In contrast, the advanced receiver, which accurately estimates and tracks the channel over the entire packet duration exhibits classic waterfall behavior. This clearly indicates that the advanced processor is providing performance that is somewhat independent of the actual fading conditions, and depends only on the total received power level.

Table 4 summarizes the field trial results for the intermediate 6-Mb/s, 400-B packet case. The ID numbers refer to the list of trials in Table 2. For each trial, Table 4 lists the measured maximum reliable range for both the COTS (conventional) and the Cohda Wireless (advanced)

<table>
<thead>
<tr>
<th>Test Equipment Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle-to-Vehicle</td>
</tr>
<tr>
<td>Infrastructure-to-Vehicle</td>
</tr>
<tr>
<td>Channel bandwidth</td>
</tr>
<tr>
<td>Center frequency</td>
</tr>
<tr>
<td>Transmit power</td>
</tr>
<tr>
<td>Transmit cable loss</td>
</tr>
<tr>
<td>Transmit antenna gain</td>
</tr>
<tr>
<td>Transmit EIRP</td>
</tr>
<tr>
<td>Receive antenna gain</td>
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<td>Receive cable loss</td>
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<td>Splitter loss</td>
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<tr>
<td>Receiver sensitivity</td>
</tr>
<tr>
<td>Data rate</td>
</tr>
<tr>
<td>MSDU size</td>
</tr>
</tbody>
</table>

Note that we generate PER versus range and PER versus received power charts for all test cases, however these are omitted for reasons of space. The results presented in Table 4 and Fig. 13 summarize the findings from these charts.
The maximum reliable ranges were computed from the empirical PER curves as follows. For every test location in Table 2, the empirical PER curves [e.g., Fig. 12(a)] were averaged over all passes (typically between five and ten passes per location; see Section IV-B). The maximum reliable range for each test location is then computed from these averaged PER curves.

For each scenario, Table 4 also lists the worst case avoidance range requirement $d_{\text{avoid}}$, which is the total distance required to bring the vehicle to complete stop from the indicated absolute vehicle speed $v$, including

$\text{Note that this is worst case in the sense that it assumes that both vehicles must come to a complete stop in order to avoid collision. In many cases, less drastic intervention may suffice.}$
This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

human reaction and braking time. Human reaction time (the time required in order to comprehend a warning and to take action) is conservatively taken as $T_{\text{react}} = 2\, \text{s}$ [59], [60]. Braking distances are calculated according to [61].

This gives the following expression for avoidance range requirement:

$$d_{\text{avoid}} = T_{\text{react}} v + 0.1v + 0.006v^2$$ meters (1)

where $v$ is the absolute vehicle speed in meters per second.

From the measured maximum reliable range, and the vehicle speeds, we similarly compute the excess stopping plus reaction time. We define this as the time to impact (assuming no deceleration), minus required braking time at current speed [61], minus human reaction time [59], [60]. Note that a negative excess stopping plus reaction time indicates an unavoidable collision. We refer to such times as deficit stopping plus reaction time [reaction and braking times are computed from (1)].

The result for each trial is shown in Fig. 13. The conventional COTS receiver (blue bars) provides excess stopping plus reaction time in nine out of 35 trials. For the

<table>
<thead>
<tr>
<th>ID</th>
<th>Location</th>
<th>Speed (km/h)</th>
<th>Avoidance Requirement (m)</th>
<th>Reliable Range (m)</th>
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<td></td>
<td></td>
<td></td>
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<td>Conventional</td>
</tr>
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<td>San Diego</td>
<td>104</td>
<td>133.1</td>
<td>139</td>
</tr>
<tr>
<td>2</td>
<td>Adelaide</td>
<td>50</td>
<td>47.8</td>
<td>39</td>
</tr>
<tr>
<td>3</td>
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<td>50</td>
<td>47.8</td>
<td>74</td>
</tr>
<tr>
<td>4</td>
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</tr>
<tr>
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<td>Detroit</td>
<td>56</td>
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<td>125.6</td>
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</tr>
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<td>31</td>
<td>Milan</td>
<td>100</td>
<td>125.6</td>
<td>45</td>
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</table>
remaining 26 trials, the COTS receiver fails to provide sufficient stopping plus reaction time.

The green bars in Fig. 13 are the results for the Cohda Wireless MK1 receiver, which uses advanced channel estimation and tracking as explained in Section III-C. For all trials, there is excess stopping plus reaction time.

Fig. 14 summarizes the results of Fig. 13 according to receiver type and safety scenario. For each safety scenario, Fig. 14 shows the worst case (minimum), average, and best case (maximum) stopping plus reaction time. Note that the minimum, average, and maximum are computed from the results in Fig. 13, combining all trial locations for each safety scenario. We remind the reader that (as described above) the individual results for each trial location were obtained by averaging over all passes at that location.

These results very clearly show the importance of advanced receiver processing for cooperative ITS safety applications. As we will see in Section VI, the safety scenarios of interest all exhibit sufficiently rich doubly-selective fading such that the 5.9-GHz radio channel characteristics change within the duration of a packet. As expected, the susceptibility of the conventional receiver to doubly-selective fading decreases for shorter packets, and increases for longer packets.

B. Roadside Unit

Although communication with a roadside unit may be part of a V2I safety application, our RSU experiments focus on bulk data transfer. This is of interest in many commercial and road management applications, e.g., the
upload of traffic snapshot data. For the roadside unit scenario (consisting of a vehicle driving past the RSU, occluded by a truck), we determined the total duration for which the PER was better than 10%. For the advanced receiver, at 50 km/h, this was on average 44 s (reliably connected over a total travel distance of 600 m). For the conventional COTS receiver, the average duration was 7.6 s (reliable connection for a total travel distance of 106 m). Comparing to the results in [62] and [63], we see that the presence of traffic and occluding vehicles has a significant effect on the conventional receiver.

VI. CHANNEL CHARACTERIZATION

In this section, we analyze channel sounding data captured during the field trials to obtain delay and Doppler spread statistics. Several channel measurement campaigns have already been reported in the literature, and we will see that our results are in broad agreement with previous results. We believe, however, that our results provide the first instance of channel measurements performed simultaneously to application performance evaluation in V2V safety scenarios. The objective is to firmly establish the link between radio channel characteristics and the performance of critical V2V safety applications. The results of this section reveal the underlying cause of the poor performance of the conventional receiver, described in Section V. They also confirm the need for accurate channel estimation and tracking over the duration of a packet.

As described in Section IV-B, every few seconds, complex (I/Q) base band samples (40 M samples/second) corresponding to entire known transmitted packets were logged. This allows accurate estimation of the channel impulse response. Note that this approach differs from the usual channel sounding methodology. First, our channel sounding signals are IEEE 802.11p signals, rather than specially designed wideband sounding sequences (e.g., m-sequences [28] or zero correlation zone sequences [29]). Second, actual 802.11p transceiver hardware and antennas are used to transmit and receive the signals, rather than specialized test equipment. Finally, the signals were transmitted in the 5.9-GHz spectrum at power levels conforming to regulatory requirements (in contrast, many channel sounding experiments use higher gain antennas and transmission powers than would be allowed by an operational DSRC system).

We do not propose this approach as a replacement for standard channel sounding campaigns, rather we have opportunistically collected a significant amount of empirical data in real-world operating conditions. Our approach has several benefits. It yields channel measurements that correspond to the actual channel seen by the DSRC radio.

**Fig. 14. Summary of excess/deficit stopping plus reaction time by scenario.**
It also allows us to correlate the radio channel parameters to the different trial safety scenarios. Finally, it allows us to analyze some failure modes of the DSRC equipment under test.

### A. Analytical Methodology

For each packet of complex baseband samples collected, we estimated the time-varying frequency domain channel response, i.e., the complex amplitude of each active subcarrier for each OFDM symbol (using the entire known transmitted data packet as “training”).

Standard spectral analysis of these empirical frequency domain channel responses (taking a 2-D discrete Fourier transform to obtain an empirical scattering function), although simple, is problematic. The 802.11p subcarrier spacing is too wide to obtain accurate delay estimates and similarly, the 8-μs symbol period does not yield good Doppler resolution. In addition, since we have only 52 active subcarriers, Fourier transform edge effects cannot be ignored, and windowing introduces significant artifacts.

Instead, we directly estimated the complex amplitude $A_k$, delay $\tau_k$, and Doppler frequency $\omega_k$ of each multipath tap $k = 1, 2, \ldots, K$ of the time domain channel impulse response modeled as follows:

$$h(t, \tau) = \sum_{k=1}^{K} A_k e^{j \omega_k \tau} \delta(\tau - \tau_k).$$

This model reduces the time variation of the impulse response to the Doppler frequency of each tap (i.e., the tap energy and delay remain constant over a packet, but the phase varies). Since we are only interested in the channel response on a packet-by-packet basis, our observation window is much shorter than that typically used in classical channel sounding campaigns [27]. Classically, each tap is modeled as having a Doppler spread, however for short time durations, we only see an instantaneous Doppler frequency. As a result, for sufficiently short durations, (2) is accurate. Indeed, this model is consistent with the geometric–stochastic model presented in [36] for short observation windows. Using a $K = 6$ tap model, we found that we were able to very accurately reproduce the actual measured channel responses, further validating this simplified model.

We also emphasize that our objective here is not to derive a new channel model. Rather, our aim is to analyze empirical data in order to explain the higher layer performance characteristics reported in Section V. Hence, we are more interested in the analysis of the channel realization on a per-packet basis, rather than long-term average statistics (typically reported in classical channel measurement campaigns).

The parameters $A_k$, $\tau_k$, and $\omega_k$ define the instantaneous empirical power delay profile and Doppler spectrum for each packet. For each packet, we compute the instantaneous RMS delay spread $\sigma_T$ and Doppler spread $\sigma_F$ according to

$$\sigma_T = \sqrt{\sum_{k=1}^{K} P_k (\tau_k - \bar{\tau})^2}, \quad \sigma_F = \sqrt{\sum_{k=1}^{K} P_k (\omega_k - \bar{\omega})^2}$$

where

$$P_k = \frac{|A_k|^2}{\sum_{k=1}^{K} |A_k|^2}$$

is the normalized power profile and

$$\bar{\tau} = \sum_{k=1}^{K} P_k \tau_k, \quad \bar{\omega} = \sum_{k=1}^{K} P_k \omega_k$$

are the power-weighted average delay and Doppler. We also compute the maximum excess delay $\max_j \tau_j - \min_j \tau_j$ and maximum Doppler spread $\max_j |\omega_j|$. Note that in the literature the term Doppler spread usually refers to what we have called here the maximum Doppler spread. We believe that it is important to additionally consider the RMS Doppler spread, since taps with large Doppler but low power do not cause much time variation in the frequency domain channel response. Conversely, large RMS Doppler spread indicates the presence of a powerful tap with significant Doppler, which will cause strong temporal variations of the channel response.

### B. Results

Using the methodology of Section VI-A, we analyzed the entire database of baseband channel captures obtained during the field trials listed in Table 2, discarding taps 30 dB below the strongest tap. Data were categorized according to urban and highway test environments as listed in Table 2. Fig. 15 shows the resulting empirical cumulative distribution functions for RMS delay spread [Fig. 15(a)], maximum excess delay [Fig. 15(b)], RMS Doppler spread [Fig. 15(c)], and maximum Doppler spread [Fig. 15(d)].

We see that urban LOS environments result in greater probability of larger RMS delay and maximum excess delay than their highway counterparts. This is due to the richer scattering environment. Although our direct estimation method is able to resolve delays beyond the cyclic prefix, we note that 0.999 of measured maximum excess delays were less than 1.6 μs. This confirms that the cyclic prefix duration is adequate for 802.11p in these scenarios.
It is also interesting to note that in highway environments, there is a larger probability of encountering near-flat fading (zero, or very small delay spread). This is to be expected for cases where scatterers may be absent, or very distant.

Considering Doppler spread, urban LOS, urban NLOS and highway LOS environments exhibit very similar RMS Doppler characteristics, with only NLOS highway environments resulting in significantly larger probabilities of higher RMS Doppler spread. Despite large highway vehicle speeds, the statistics of the RMS Doppler for LOS conditions are not too dissimilar to the lower speed urban environments. Again, this is probably due to the weak power of higher Doppler frequency taps (relative to the LOS component) in a highway environment. In contrast, the maximum observed Doppler for both LOS and NLOS highway conditions is skewed more toward higher frequencies. This confirms that large Doppler reflections do exist, however in LOS conditions, they are not strong enough to significantly affect the RMS Doppler.

The doubly-selective nature of the channel is confirmed in Fig. 16, which is a scatter plot of RMS Doppler versus RMS delay spread. Doubly-selective channels occur when both delay and Doppler are high. Clearly, a reliable system needs to be able to handle simultaneous frequency and time selectivity.

Table 5 provides a numerical summary of the delay/Doppler results, listing median (50% quantile) and 90%
quantile values of RMS delay spread, maximum excess delay, RMS Doppler spread, and maximum Doppler spread. From Fig. 15 and Table 5, we see that our measured delay spreads for urban scenarios are in agreement with previously reported results, e.g., [27] and [64]. Our highway results are slightly lower, however this is most likely due to the fact that our highway results were collected mostly in Australia and Europe, in relatively rural conditions. Our Doppler spread results are in broad agreement with previously reported results.

Based on narrowband channel measurements, Cheng et al. [64], [65] propose an empirically fitted linear relationship between effective velocity and average Doppler bandwidth

$$B_D \approx \frac{0.428}{\lambda \sqrt{2}} v_{\text{eff}} + 11.5$$

where $v_{\text{eff}} = \sqrt{v_{TX}^2 + v_{RX}^2}$. Fig. 17 shows scatter plots of our measured RMS Doppler spread (for both urban and highway environments) versus relative velocity and effective velocity. These results show that, for a wideband OFDM signal, there is in fact no strong correlation of the specific realization of Doppler spread with either relative velocity or effective velocity. In both urban and highway environments, we see from Fig. 17 that it is possible to experience high RMS Doppler at low relative/effective speeds, and conversely there are instances of low RMS Doppler spread at high speeds. The figure (especially the highway environment) does however reveal a linear correlation of effective speed with the maximum observed RMS Doppler spread, with larger effective velocities giving a higher probability of higher Doppler spreads.

VII. CONCLUSION

This paper presents results for 35 field trial data sets collected in Australia, Italy, Germany, Austria, and the United States, covering over 1100 km on the road in a wide variety of physical environments. Each trial was scenario based, focusing on particular standard road safety applications. The trials compared the performance of two sets of 802.11p compliant equipment: one receiver employing conventional OFDM physical layer processing, and the second employing more sophisticated channel estimation and tracking. The performance results reveal that DSRC/WAVE can provide highly reliable communications, and sufficient driver warning times in support of the targeted road safety applications. However, analysis of channel sounding data collected during the field trials shows that NLOS safety-critical conditions require careful attention to physical layer receiver processing in order to provide a safety benefit. Failure to accurately estimate and track the radio channel over the entire duration of a packet results in poor performance and reduced potential for safety benefits.

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Fig. 17. RMS Doppler spread versus relative speed and effective speed.

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