A Measurement Study of Time-Scaled 802.11a Waveforms over the Mobile-to-Mobile Vehicular Channel at 5.9 GHz

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ABSTRACT

We have studied the effects of the mobile vehicle-to-vehicle (V2V) channel on scaled versions of the current IEEE 802.11a standard to investigate how readily they can be applied to vehicular networks. In particular, measured parameters for the V2V channel at 5.9 GHz in suburban, highway, and rural environments are studied in the context of critical parameters for OFDM. Actual performance of scaled OFDM waveforms with bandwidths of 20 MHz (bandwidth of IEEE 802.11a), 10 MHz (bandwidth of the draft IEEE 802.11p), and 5 MHz (halved bandwidth of IEEE 802.11p) are described and interpreted in light of the channel parameters. At 20 MHz the guard interval is not long enough, while at 5 MHz errors increase from lack of channel stationarity over the packet duration. For these choices of the scaled 802.11a OFDM waveform, 10 MHz appears to be the best choice.

INTRODUCTION

With more than 40,000 annual traffic fatalities in the United States alone [1], improving automotive safety is one of the top concerns in modern life. While a number of existing technologies such as radar and camera systems are already available on many high-end vehicle models today, widely used inexpensive onboard devices are desired to further reduce injuries and fatalities for large deployments.

Along with the unrelenting advancements in semiconductor technology, the price of chipsets for IEEE 802.11 devices continues to drop, making it an economical networking option included in ever more devices, including in the vehicular context. Many governments and manufacturers envision that future vehicles will be equipped with 802.11-like devices to achieve dedicated short-range communications (DSRC). This allows vehicles on the road to communicate with each other for a number of safety and non-safety applications, forming a vehicular ad hoc network (VANET).

The growing interest in VANET research is also driven by the allocation of the spectrum at 5.9 GHz specifically for DSRC. The Federal Communications Commission (FCC) in the United States has allocated 75 MHz of spectrum at 5.9 GHz that will use IEEE 802.11p technology as wireless access for vehicular environments. This technology is still under development, and the current draft standard [2] proposes to use a variant of the existing 802.11a standard (widely used in the 5.2 GHz range, primarily for indoor environments). The key modification to the physical layer is to scale the channel bandwidth from 20 MHz (802.11a) to 10 MHz (draft 802.11p) to increase the tolerance to delay spread. In Europe, since some of the allocated band has been used for other purposes, tighter scaling to 5 MHz (p/2) is also proposed. In these proposals the entire temporal waveform is scaled, so the number of carriers is fixed, but other parameters such as carrier spacing and guard interval are scaled appropriately. Until now, to the best of our knowledge, there was no comprehensive field study on the performance of scaled 802.11 waveforms. Motivated by this observation, this article aims to answer the following questions:

- How well do scaled versions of IEEE 802.11a perform in the high-mobility vehicle-to-vehicle channel?
- What are the key characteristics of the VANET channel that impact DSRC performance?
- How can we mitigate performance problems in the design space of the scaled 802.11a waveforms?

To answer these questions, we first describe a system and methodology for measuring key fundamental channel properties such as coherence time, Doppler spread, coherence bandwidth, and

PHY parameter	Relevant channel parameters	Criteria for PHY parameter
Guard interval (GI)	Maximum excess delay (τ_e)	GI> τ_e
Carrier spacing D_f	Coherence bandwidth (B_c), Doppler spread (B_D)	$B_c > D_f >> B_D$
Interval between channel estimates (packet length T_p)	Coherence time (T_c)	$T_p < T_c$

Table 1. *Key parameters of the 802.11a family of OFDM waveforms and PHY requirements.*

Key parameters of the 802.11a family of OFDM waveforms include the length of the cyclic prefix or guard interval, the carrier spacing, and the time intervals between channel estimates and corresponding updates to the equalization.

delay spread. Second, we discuss these measurements in the context of critical parameters for orthogonal frequency-division multiplexing (OFDM) transmissions as implemented in scaled versions of the 802.11a waveform. Actual performance of scaled OFDM waveforms with bandwidths of 20 MHz (a), 10 MHz (p), and 5 MHz (p/2) are described and interpreted in light of the channel parameters. Understanding these relationships enables the design of a physical layer (PHY) that will provide the best quality of service for VANET applications. Finally, we use our observations to evaluate the viability of scaled 802.11a-like systems for DSRC applications. We also provide suggestions on how future systems could be adapted for best performance, and discuss the limitations and possibilities of 802.11a and subsequent systems.

This article is organized as follows. We review related work. Then we present a brief overview of the 802.11a OFDM format and key channel parameters influencing its performance. The measurement apparatus and environments studied are described. We present measured channel properties and their implications. We then conclude the article.

Related Work

The challenges for VANETs are discussed in [3]. The studies in [4] provide an overview of DSRC-based vehicular safety communications and propose a coherent set of protocols to address these requirements. The California PATH project in the United States, and the Fleetnet and Network-on-Wheels projects in Europe have investigated a range of issues relating to the medium access control (MAC) layer and routing protocols for VANETs.

The studies in [5, 6] develop theoretical mobile-to-mobile channel models from the existing analytical infrastructure-to-mobile studies. More precisely, [5] presents the double ring model, which assumes that the multipath components are mainly from dense clutter uniformly distributed around the two mobiles. This assumption may not be adequately satisfied in many on-road environments. Consequently, it is important to verify the applicability of these models to on-road system design.

On the empirical side, [7] discusses continuous-wave measurement campaigns at 5.2 GHz, and [8] presents joint Doppler-delay power profile measurements at 2.4 GHz. Measurements and modeling of the vehicle-to-vehicle (V2V) channel at 5.9 GHz at a specific highway location has also been reported [9]. Reference [10] reported empirical results from a study examining the effects of antenna diversity and placement on V2V link performance based on IEEE 802.11a radios.

To the best of our knowledge, the performance of scaled versions of 802.11a in multiple on-road environments has not been previously discussed. The previous empirical results either concern a different frequency band or were performed at a specific highway site. In contrast to the prior work, we consider varied on-road scenarios and measurements in the 5.9 GHz DSRC band. We present studies of basic channel parameters in both the time and frequency domains, as well as the performance of scaled 802.11a waveforms in these channels.

Key Channel Parameters for Scaled 802.11a Waveforms

DSRC Standards

The standardization work on information exchange between vehicle systems started in the ASTM group based on IEEE 802.11a. The resulting ASTM E2213-02 standard was approved in 2002 and formed the foundation for 5.9 GHz DSRC applications in the United States. The standard was reissued as ASTM 2213-03 and was transferred to the IEEE 802.11 working group as Task Group p for standardization in 2004. The work discussed here is based on the draft IEEE 802.11p-D1.4 version [2, 11].

From a physical layer perspective, the IEEE 802.11p standard under development uses an OFDM PHY derived as a variation of the IEEE 802.11a standard. It is aimed at providing both V2V and vehicle-to-infrastructure wireless communications over distances up to 1000 m, with absolute and relative velocities up to 30 m/s, and in a variety of environments (e.g., rural, highway, suburban, and urban). If scaled for operation in 10 MHz channels, data payload communication capabilities are from 3 to 27 Mb/s. If scaled to use the optional 5 MHz or 20 MHz channels, it allows data payload capabilities up to 13.5 Mb/s and 54 Mb/s, respectively.

Key parameters of the 802.11a family of OFDM waveforms include the length of the cyclic prefix or guard interval, the carrier spacing, and the time intervals between channel estimates and corresponding updates to the equalization. The relationship between these parameters and the channel properties are summarized in Table 1 and discussed in the follow-

There are multiple metrics that can be used to estimate the duration of the power-delay profiles. The mean excess delay and delay spread provide measures that can be considered to be related to the typical channel, while the maximum excess delay provides a worst-case estimate with respect to a particular threshold.

ing sections.

Multipath and the Guard Interval

The V2V channel is a multipath channel. The transmitted signal arrives at the receiver via various paths with different delays. Consequently, if a short pulse is transmitted, the received signal will contain many echoes with varying spacing and amplitude. In the limit of vanishingly short pulses, the received signal is referred to as the channel impulse response. Because of motion in the environment, the impulse response constantly changes. Averaging the magnitude-squared of the impulse response in an environment with stationary statistics yields the power-delay profile.

Statistics extracted from the power-delay profile include the mean excess delay, root mean square (RMS) delay spread, and maximum excess delay [12]. The mean excess delay is a measure of the average echo delay timed from the arrival of the first signal, and is obtained from the first moment of the power-delay profile. The RMS delay spread is obtained from the second moment of the power-delay profile and is a measure of the variation of the echo delays about the mean. The maximum excess delay is the maximum observed time between the first signal and the last echo whose amplitude exceeds a threshold chosen with respect to the strongest echo (not necessarily the first). With an adequate representation of the power-delay profile, system designers are able to simulate the channel to obtain either time- or frequency-domain responses [13].

As mentioned above, the 802.11a protocol uses the OFDM transmission format. OFDM is a multicarrier transmission scheme that spreads the data over carriers that are spaced at the smallest possible frequency intervals for which the frequencies are orthogonal over the duration of a symbol. Multipath echoes of one symbol that extend into a subsequent symbol may not only cause intersymbol interference (ISI), but can destroy the orthogonality between the carriers. To combat this situation, in practice an OFDM symbol is typically prepended with a circular extension called a cyclic prefix. If the duration of the cyclic prefix is longer than the duration of the echoes, the orthogonality between symbols and carriers is restored. Thus, the cyclic prefix provides a guard interval (GI) for all multipath following the first arrival signal. Consequently we need to ensure that the durations of the expected power-delay profiles are shorter than the guard interval.

However, as suggested above, there are multiple metrics that can be used to estimate the duration of the power-delay profiles. The mean excess delay and delay spread provide measures that can be considered to be related to the typical channel, while the maximum excess delay provides a worst case estimate with respect to a particular threshold. This estimate can be made increasingly conservative by lowering the threshold used to compute the maximum excess delay. Ideally this threshold should be chosen so that only those echoes with sufficient energy to adversely impact reception are included. Since the guard interval reduces the channel throughput, the choice of GI represents a trade-off between available data bandwidth and reliability. Furthermore, each metric is represented by a cumulative distribution function (CDF), and the criterion can also be made more or less conservative by the choice of threshold on the CDF.

The criterion we use is that *the GI should be longer than 90 percent of the observed values of maximum excess delay*, but computed with the relatively high threshold of 15 dB below the maximum. We believe this somewhat conservative criterion reflects the requirements of safety applications without imposing an excessive overhead burden.

Coherence Bandwidth and Carrier Spacing

Multipath effects are also reflected in the frequency domain, resulting in what is known as frequency selective fading. One metric to describe this is to estimate how likely it is for the spectrum envelope at two frequencies separated by Δf to be correlated.

The value of Δf at which the autocorrelation of the spectrum envelope falls below a value x is known as the $100x$ percent coherence bandwidth. Here we use the 90 percent coherence bandwidth, where the value of Δf is obtained when the autocorrelation falls to 0.9. In general, the coherence bandwidth is inversely related to the duration of the power-delay profile.

The notions of flat fading and frequency selective fading are important for relating the coherence bandwidth to the performance of OFDM. In the flat fading case, the bandwidth of the signal is small compared to the scale of variations in the channel response. As a result, the overall amplitude of the signal can vary, but the signal is not distorted. On the other hand, for frequency selective fading, the bandwidth of the signal is large compared to the scale of variations in the channel response. As a result the overall amplitude of the signal does not vary greatly, but the signal is distorted. Equalization can be used to correct for the distortion, but can add considerable complexity to single-carrier receiving schemes. Furthermore, the equalization must be updated as the channel changes.

One of the advantages of OFDM is that the carrier spacing can be selected so that each carrier experiences flat fading, even though the spectrum of the OFDM symbol as a whole experiences frequency selective fading. In this case equalization simply consists of multiplying each carrier by a complex constant to correct its amplitude and phase with respect to the others.

Since equalization in the 802.11a PHY is implemented this way, we require that *the coherence bandwidth be greater than the carrier spacing to ensure flat fading on each carrier*. More specifically, we require the 90 percent coherence bandwidth to be greater than the carrier spacing 90 percent of the time. Again, we believe this represents a reasonable though somewhat conservative choice.

Coherence Time and Packet Duration

In the V2V scenario the vehicles travel along different paths at varying speeds. While doing so, radio signals transmitted between them may scatter from stationary objects (e.g., trees, houses, overhead bridges), as well as other vehicles in motion. Consequently, the propagation channel changes due to the relative motion between transmitter and receiver, the absolute speeds with respect to the environment, and the motion of the scatterers in the vicinity of the vehicles.

To be concrete, if a narrowband signal is transmitted through the channel, the received signal would experience severe changes in the amplitude and phase due to such motion. One metric to characterize this time variation is the coherence time, which describes the interval over which the channel can be considered unchanged.

The coherence time can be obtained by computing the auto-correlation of a received narrowband signal. We will use the 90 percent coherence time, determined by the time offset for which the autocorrelation function drops to 90 percent of its peak value. As with other experimentally determined parameters, the 90 percent coherence time is represented by a CDF. As before, we want to ensure that the 90 percent coherence time exceeds the required value 90 percent of the time.

In the PHY specification of IEEE 802.11a, channel estimates are performed and used to correct for flat fading on individual carriers. These estimates are obtained from training sequences in the packet header and are used for the remainder of the packet. Therefore, it is vital to ensure that *the duration of the packet is less than the coherence time for the corrections to remain valid*. Since the equalization is performed on individual carriers, coherence time measurements made using narrowband signals are directly applicable even though the entire OFDM symbol has much wider bandwidth.

Doppler Spread and Carrier Spacing

The time-varying properties of the channel manifest themselves in the frequency domain as well. Specifically, the received spectrum is spread by signals arriving from all directions due to the Doppler effect. One of the commonly used metrics in the frequency domain is the width of the resulting spectrum, referred to as the Doppler spread. The interference between frequency components also determines the coherence time. In particular, the Doppler spread and coherence time are inversely related.

The Doppler spread puts an additional constraint on OFDM carrier spacing. To avoid the scenario where a Doppler spread signal leaks into adjacent carriers and causes interference, *OFDM carrier spacing must be much larger than the maximum Doppler spread*.

Summary of Requirements

We can summarize the requirements from our discussion as follows (Table 1). First, the guard interval must be greater than the maximum excess delay; second, the carrier spacing must be smaller than the coherence bandwidth, but much larger than the Doppler spread; and finally, the intervals between channel estimation (the packet duration in 802.11a) must be smaller than the coherence time of the channel.

We believe the values and criteria we have used when evaluating these relationships to be reasonable but somewhat on the conservative side, reflecting an emphasis on reliability required by many proposed VANET applications (e.g., safety).

Measurement Apparatus and Environment Classification

While a formal analytical description is precise in meaning and amenable to performance analysis, ultimately the performance of transmission schemes must be evaluated using empirical campaigns. In previous work we reported on narrowband characterization of the V2V channel as well as the impact of driver behavior [14]. The RF platform has since been extended to allow broadband sounding. Working with different excitation signals, it is possible to extract channel properties that represent abstract behavioral descriptions from different perspectives. For example, using narrowband signals, the coherence time can be obtained from the time domain, and the Doppler spread can be obtained from the frequency domain. Similarly, using wideband signals the delay spread can be obtained from the delay time domain, and the coherence bandwidth can be obtained from the delay frequency domain. For wideband measurements we used spread-spectrum signals based on zero-correlation codes [15].

Integrating DGPS receivers using the Wide Area Augmentation System (WAAS) for differential position correction (with position accuracy of 3 m or less [14]), we were able to study on-road driving conditions across suburban, highway, and rural environments. These correspond to a rich set of representative on-road driving scenarios. A particular feature of our system is the ability to link instantaneous channel conditions with position and velocity.

Highway measurements were obtained with the aforementioned sounding platform between Pittsburgh and Grove City, Pennsylvania. The data were taken between about 3 p.m. and 8 p.m. on the days of the experiments, and the traffic was light to moderate. In this environment there are occasional overpasses but very few nearby buildings. The two cars were in steady high-speed driving with passing during the experiments.

The rolling countryside north of Pittsburgh was chosen as the site for rural field measurements. While remote hills and trees were constantly observed during measurements, the majority of nearby objects consisted of various kinds of low-height vegetation. The routes consisted of two-lane roads, and the vehicles were driven without passing during the measurements.

The environment in suburban areas is characterized by trees, houses, apartments, and office buildings. The majority of the buildings observed were two to three stories and set back about 10–12 m from the curb. The routes consisted primarily of two-lane suburban streets, and the sounding vehicles did not pass one another during the measurements.

If a narrowband signal is transmitted through the channel, the received signal would experience severe changes in the amplitude and phase owing to such motion. One metric to characterize this time variation is the coherence time, which describes the interval over which the channel can be considered unchanged.

Measurement Results

Time Delay Domain Measurements

As mentioned before, the maximum excess delay captures the time period during which the power delay profile falls to T dB below its maximum, where T is the threshold applied. Figure 1 shows the cumulative distributions of the empirically measured maximum excess delay over all environments under investigation, using a 15 dB threshold.

Table 2 summarizes the 90 percent threshold on the CDF plots from Fig. 1 for these environments. As we can see, the rural case exhibits the largest maximum excess delay. For 90 percent of the time the maximum excess delay τ_e is less than 1.5 μs for this environment.

The larger values of maximum excess delay in the rural case are likely due to reflections from objects such as hills that are located further away than typical objects in the suburban and highway environments. By the same token, as the scattering objects are more tightly distributed in suburban areas, the maximum excess delay values are smaller and saturate faster than the rural and highway cases.

As discussed earlier, the OFDM guard interval must be scaled to exceed the maximum excess delay in all of the above environments, since they represent typical scenarios and topologies where V2V is likely to be deployed. In our measurements the rural case has the most demanding requirements among the three (1.5 μs).

The guard intervals from the scaled 802.11a waveforms are summarized in Table 3. We can see from the table that the duration of the guard intervals in the 5 MHz and 10 MHz cases are both larger than the measured maximum excess delay. However, this is not the case for the 20 MHz bandwidth.

As we can see, while the 20 MHz guard interval of 0.8 μs is satisfactory for the suburban case, it is likely not to provide adequate protection for the rural and highway environments, thereby increasing the chances of errors due to multipath delay.

Environment	Suburban	Highway	Rural
Maximum excess delay	0.6 μs	1.4 μs	1.5 μs
Minimum 90 percent coherence bandwidth	750 kHz	410 kHz	420 kHz
Maximum Doppler spread	0.583 kHz	1.53 kHz	1.11 kHz
Minimum 90 percent coherence time	1 ms	0.3 ms	0.4 ms

Table 2. *Measured channel parameters.*

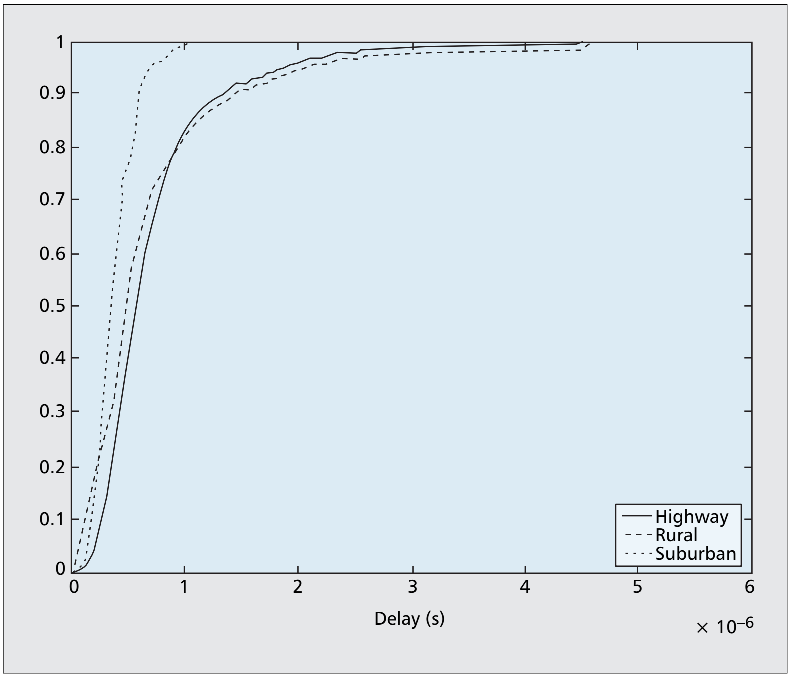

Figure 1. *CDF of maximum excess delay, using a 15 dB threshold. The highway curve is based on 16,785 measurements, the rural curve on 13,406 measurements, and the suburban curve on 23,427 measurements.*

Coherence Bandwidth

The measured coherence bandwidth is obtained from the autocorrelation functions of the measured frequency spectra.

Figure 2 depicts the cumulative distribution for the 90 percent coherence bandwidths for different environments. Given a horizontal line at $y = y_0$, for each environment one can estimate the coherence bandwidth at $100(1 - y_0)$ percent of the time. Following this procedure at $y_0 = 0.1$, we obtain the corresponding 90 percent coherence bandwidth for each environment. These values are summarized in Table 2.

As pointed out earlier, the carrier spacing should be less than the coherence bandwidth of the channel. Table 3 describes the carrier spacing obtained from the scaled versions of the 802.11a waveform. In each environment the requirement is satisfied.

Coherence Time

We computed the coherence time using narrowband field measurements of the received envelope. The autocorrelation function $p(\tau)$ of the received envelope describes the correlation between the channel response to a sinusoid sent at time t_i, and the response to a similar signal sent at time t_j, with $t = t_j - t_i$.

The measured cumulative distribution of the 90 percent coherence time in each environment is shown in Fig. 3. If we draw a horizontal line at $y = y_0$, we can estimate the coherence time at $100(1 - y_0)$ percent of the time, for each environment. To be concrete, we illustrate using the suburban curve: if the horizontal line is specified at $y_0 = 0.1$, we can find the corresponding $T_{c,y0}$ value on the horizontal axis for the suburban environment, which reads to be about 1 ms based on the cumulative function. This means the coherence time stays above 1 ms for $(1 - y_0) = 90$ percent of the time; that is, the suburban V2V channel is likely to stay invariant over a time duration of 1 ms for 90 percent of the time. By the same token, we can obtain the values for the rural and highway environments from their

Scale	5 MHz	10 MHz	20 MHz
OFDM guard interval	3.2 µs	1.6 µs	0.8 µs
Carrier spacing	78 kHz	156 kHz	312.5 kHz
Test packet duration	3 ms	1.5 ms	0.75 ms

Table 3. *Scaled OFDM parameters.*

cumulative functions. Table 2 summaries the minimum 90 percent coherence time T_c for all three environments.

To analyze the waveform design implications, the test packet durations T_p for the scaled versions of 802.11a are given in Table 3. The same bits were used in each test packet, so halving the bandwidth doubles the packet duration. While the 20 MHz test packet duration (0.75 ms) is shorter than the minimum 90 percent coherence time in the suburban environment (1 ms), for all other cases the minimum 90 percent coherence time is shorter than the test packet duration.

Recall that the 802.11a PHY performs channel estimation at the beginning of the packet and the estimation is then used for all the OFDM symbols in the packet. Motivated by this observation, we analyzed the impact of the observed coherence time on the performance of OFDM transmission in V2V. We have shown in our prior work [14] that the Doppler spread can be predicted by the effective speed of two vehicles, where the effective speed is defined as

$$\upsilon_{eff} = \sqrt{\upsilon_T^2 + \upsilon_R^2}$$

(υ_T and υ_R are the velocities of the transmitter and receiver vehicles, respectively). Furthermore, our measurements demonstrated the inverse relationship between coherence time and Doppler spread. Therefore, by analyzing the bit error rate (BER) performance of our data using different scaled versions of 802.11a vs. the effective speed of the vehicles, the impact of coherence time on performance can be extracted.

We have also measured the average BER vs. the time of arrival of the OFDM symbol for various effective speeds. The BER performance for each scaled version of the waveform is shown in Fig. 4. The triangles are an estimate of the coherence time based on the effective speed.

In general, the BER curves increase steadily in the beginning, but saturate after a time interval that agrees well with an estimate of the coherence time obtained from the effective speed. The results show that since channel estimation occurs at the beginning of the packet, changes in the channel cause the equalization to expire before the end of the packet. With the same bandwidth, a higher effective speed implies higher Doppler spread [14]; hence, a shorter coherence time is expected. Therefore, the bit errors tend to rise within a shorter interval for higher effective speeds.

As we can see from Fig. 4, although none of the three bandwidth plans satisfy the requirement in terms of channel coherence time, 5 MHz seems to be the worst choice. With 5 MHz bandwidth, the test packet duration is much longer than the coherence time, causing poor equalization over the majority of the packet and resulting in a degraded BER. On the other hand, we argue that 10 or 20 MHz bandwidth might satisfy this requirement if the test packet length is appropriately adjusted.

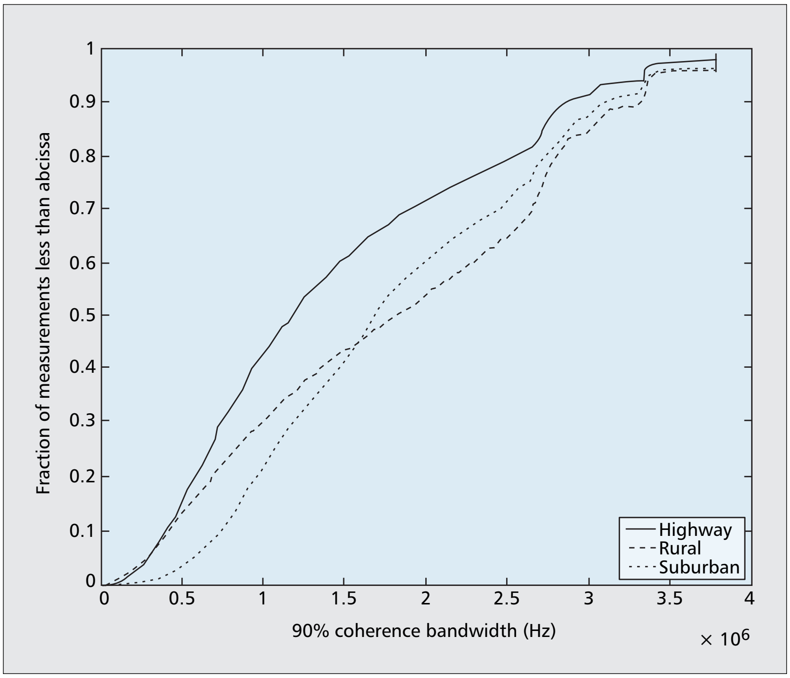

Figure 2. *Cumulative distribution of the 90 percent Coherence Bandwidth. The highway curve is based on 16,785 measurements, the rural curve on 13,406 measurements, and the suburban curve on 23,427 measurements.*

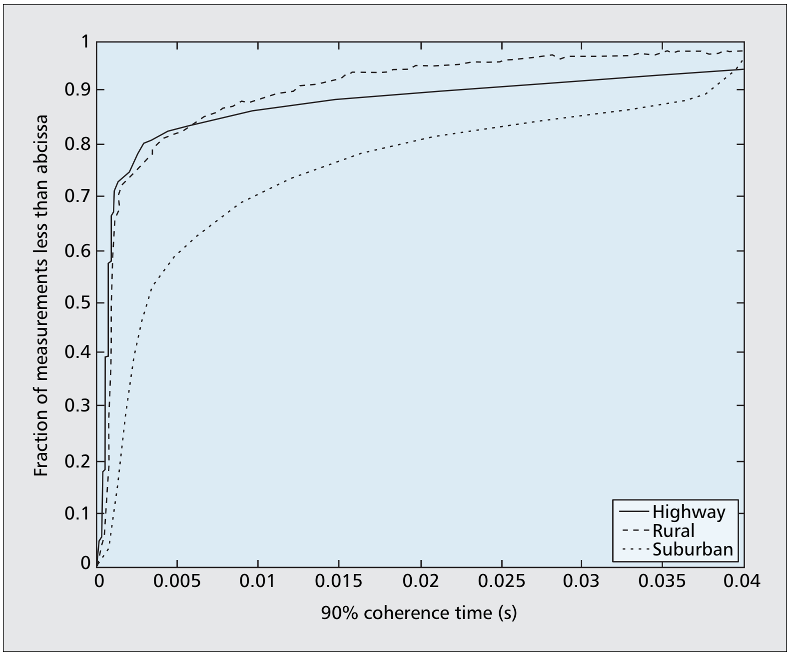

Figure 3. *Cumulative distribution of the 90 percent coherence time (overall). The highway curve is based on 6247 measurements, the rural curve on 3296 measurements, and the suburban curve on 6456 measurements.*

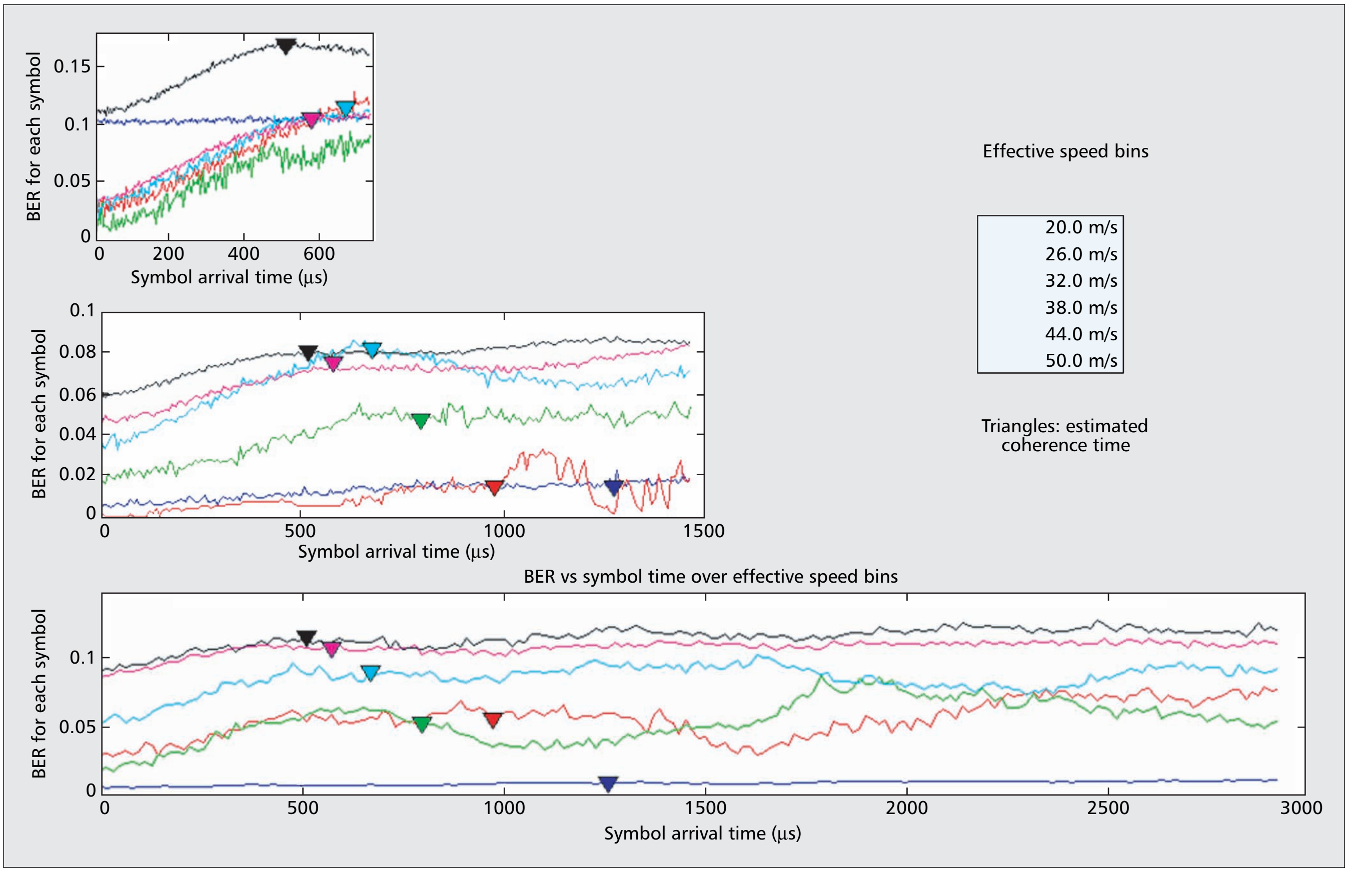

Figure 4. *Average BER for each OFDM symbol as a function of the time since the first symbols arrival for different effective speeds.*

DOPPLER SPREAD

The maximum values of Doppler spread for our experiments are summarized in Table 2. In this case we have simply presented the maximum observed Doppler spread in each environment. Due to the small values of Doppler spread, a detailed statistical analysis is not needed for our purposes.

Comparing Tables 2 and 3, we see that all of the carrier spacings are much larger than the observed Doppler spreads. We conclude that in all cases the carrier spacing meets the requirements imposed by both the maximum Doppler spread and the coherence bandwidth, although with different design margins.

SUMMARY AND CONCLUSIONS

In this article we have presented a systematic study concerning the effects of a mobile V2V channel on scaled versions of the current IEEE 802.11a standards. Aiming to investigate how readily the scaled versions of the 802.11a waveform can be applied to vehicular networks, we have extracted, quantified, and analyzed measured parameters for the V2V channel at 5.9 GHz in suburban, highway, and rural environments. The critical design parameters for the 802.11a PHY have been examined in detail along with the actual performance of scaled waveforms with bandwidths of 20 MHz (a), 10 MHz (p), and 5 MHz (p/2).

We have shown that the guard interval at 20 MHz should be extended for best performance in highway and rural environments. At lower bandwidths (e.g., 5 MHz), packets tend to be longer, and errors increase due to time variations in the channel degrading the equalization. Based on these results, we believe that if the choice is simply between discrete scaled versions of 802.11a, 10 MHz is a reasonable choice.

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