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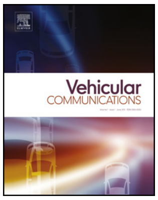

Invited paper

Generic stochastic modeling of vehicle-to-vehicle wireless channels

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ABSTRACT

We present a generic statistical characterization of the vehicle-to-vehicle (V–V) wireless channel by adopting a stochastic modeling approach. Our approach is based on the doubly underspread (DU) property of non-wide sense stationary uncorrelated scattering (non-WSSUS) wireless channels, with V–V channels pertaining to this category. DU channels exhibit explicit frequency and time intervals over which they are approximated as WSSUS. We call these intervals restricted time interval (RTI) and restricted bandwidth (RBW), and variations taking place inside them are characterized as small scale variations. Large scale variations take place outside RTI and RBW. In this paper, we focus on small scale variations, thus, our modeling finds its applicability within RTI and RBW. As practical V–V channels exhibit rapid temporal fluctuations due to the inherent mobility of transmitter (Tx), receiver (Rx) and surrounding scatterers (e.g., other vehicles), we analyze the relevant second order statistics characterizing temporal variability, namely, the a) temporal correlation function (CF) (or autocorrelation function (ACF)), b) power spectral density (PSD) (or Doppler spectrum), c) level crossing rate (LCR) and d) average fade duration (AFD). Our analysis considers three-dimensional (3-D) scattering at the Tx and Rx together with random scatterers' mobility. Illustrative examples demonstrate the usefulness and flexibility of our analysis, which is further validated by fitting the theoretical LCR to an empirical, obtained at a US interstate highway. We show that significant Doppler frequencies can arise due to scatterers' mobility exceeding the respective maximum and minimum values when considering only Tx and Rx mobility. Also scatterers' mobility causes more rapid temporal variations when it becomes more intense. The latter is also true when 3-D scattering at the Tx and/or Rx spreads over a greater range of angular sectors and becomes less directional.

1. Introduction

The number and type of wireless communications applications continues to grow. One application of great current interest is Intelligent Transportation Systems (ITS), and within this broad area is communications between vehicles, or vehicle-to-vehicle (V–V) communications [1]. In V–V communications, the idea is that vehicles form networks exchanging information directly between each other in an ad-hoc manner. Thus, a wide range of safety, convenience and entertainment services can be supported, such as emergency braking, notifications of hazards, notifications of traffic congestion, internet access for information and entertainment, etc. Information delivery requires a message from a source vehicle to propagate reliably in high-speed and on-road environments and this imposes a great challenge in designing robust V–V communication systems. This facilitates the necessity of accurate, and on the same time, generic V–V channel characterization.

For any wireless communication system, the channel is typically "uncontrolled" by the system designer and user. It is well known that the channel plays a critical role in communication reliability, and for V–V communications the channel will often be distorting, lossy, and rapidly time-varying. All these characteristics make it challenging for system designers to ensure reliable and timely communication. Hence, models for these channels represent vital tools for system developers [2]. These channels are the focus of this paper.

Currently planned V–V applications are expected to be short range, with link distances from a few meters to a kilometer. The three traditional channel effects that are used to characterize terrestrial wireless channels are propagation path loss (attenuation), large scale shadowing (or, obstruction), and small-scale (multipath) fading. These characteristics have been the focus of much analysis and many measurement campaigns, and research is currently ongoing.

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The V–V channel can be very dynamic, with time variation rates up to double those of conventional cellular radio channels. For typical vehicles, V–V antenna heights will be low relative to other land mobile radio systems, and this will yield more frequent obstruction of the radio line of sight (LOS) between transmitter (Tx) and receiver (Rx). These effects can cause the V–V channel to yield more rapid and more severe fading than cellular channels. In light of the rapid time variation, the V–V channel is often best modeled as statistically non-stationary.

This paper describes characteristics of the physical wireless channel for V–V communication applications. In the remaining parts of this Introduction we first define the V–V channel and some common settings. We then describe some initial V–V communication technologies, followed by a brief summary of the unique features of the V–V channel. In Section 2, we describe the state of the art in V–V channel modeling, and Section 3 provides a discussion of the V–V reference stochastic model. In Section 4, we present a second-order statistical characterization of small scale fading together with some illustrative examples. In Section 5, we validate our modeling approach by fitting the theoretical LCR to an empirical obtained at a US interstate highway [16] and in Section 6, we draw the conclusion.

1.1. The V–V channel

The V–V channel is the wireless channel between two terrestrial vehicles, such as two automobiles, trucks, vans, buses, etc. Initial V–V communications will take place on established roads in cities, suburbs, highways etc. We do not consider "off-road" settings in this paper. Such "off-road" areas, e.g., forest or mountainous regions, will exhibit differences in the form of greater attenuation and obstruction. The channel may include a line-of-sight (LOS) path between Tx and Rx, or it may be an obstructed, or non-LOS (NLOS) link. Either or both vehicles may be in motion.

Fig. 1 illustrates an urban V–V scenario, in which the numbered lines indicate conceptual radio propagation paths. One Tx and one Rx are indicated; in general all vehicles will have both Tx and Rx. In suburban areas, the density of vehicles would generally be smaller, with buildings set farther back from the street. On expressways, vehicle density is time-dependent, especially near urban areas that see morning and evening "rush hours." Vehicle density will affect the V–V channel characteristics.

1.2. Initial V–V systems

Although V–V communication could conceivably operate in any frequency band from VHF through SHF, spectrum is scarce and regulatory constraints yield limits to specific bands. The primary spectral band currently planned for V–V applications is the 5.9 GHz band, which has been allocated in the US and Europe. This band is cited in the Dedicated Short Range Communication (DSRC) standard [3], originated by the US Dept. of Transportation, but moved to the IEEE under the 802.11p group [4]. The standard is also known as Wireless Access for Vehicular Environments (WAVE) [5].

The DSRC band is from 5.85–5.925 GHz. It was originally divided into seven, 10-MHz channels, one of which is reserved for priority messages. Channels of width 20 MHz are also possible. The DSRC/802.11p standard is a modified version of the IEEE 802.11 wireless local area network (WLAN) standard. As such, modifications for higher mobility had to be developed. The standard specifies the physical (PHY) and the medium access control (MAC) layer requirements. The modulation/multiplexing is orthogonal frequency division multiplexing (OFDM) with several modulation orders. Multi-access is via time division.

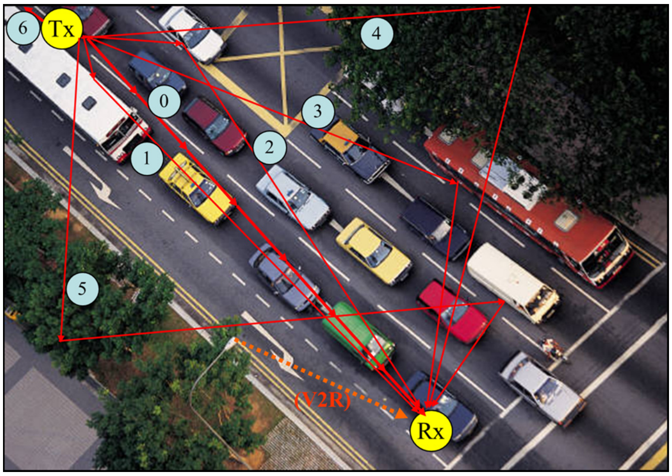

Fig. 1. Conceptual V–V channel between transmitter (Tx) and receiver (Rx) in urban area.

1.3. V–V vs. the conventional land mobile channel

Traditional land mobile radio channels have one end of the communication link fixed (non-mobile) at a so-called "base station" (BS). Such fixed stations typically have antennas atop tall towers, and access to ample electric power. The former characteristic will not apply in the V–V case where antenna heights will be only a few meters. Another physical feature distinct from traditional land mobile is that the V–V channel can have obstacles near/around both Tx and Rx, not just around the mobile unit.

In the V–V channel, obstacles to LOS propagation can be other vehicles, terrain, or buildings or other infrastructure (see Fig. 1). Link distances in urban areas are expected to be short, up to a few hundred meters or often much less. Link distances in suburban and expressway settings will often be larger (yet still less than the several kilometers of rural cellular). An additional unique feature of the V–V channel in comparison with cellular is that both Tx and Rx may be in motion. This can increase the rate of time variations in the V–V case to be double that of cellular. As noted, this more rapid time variation will often violate the conventional wide-sense stationarity (WSS) of the channel.

1.4. Channel characterization significance

As noted, regardless of the application or transmission technology, the wireless channel should be quantitatively characterized in order to optimize signaling design and performance [6]. Mathematical channel characterization results are typically employed in comparisons of competing technologies, and can aid design decisions on packet durations and format, channel bandwidths, etc. Models for the channel can also be used in analysis and computer simulations to estimate system performance, which in turn guides remedial measures (e.g., equalization, diversity) and system improvements.

Even with modern adaptive communication systems, channel impairments can severely degrade performance if not accounted for. Such performance degradations include a bit error probability "floor" or lower limit, and unacceptably large message latency. Long latencies can often be deemed link outages, which can sever multi-hop links. Thus, the V–V channel characteristics should be modeled as accurately as possible, since they affect system performance at multiple levels.