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A SURVEY ON VEHICLE-TO-VEHICLE PROPAGATION CHANNELS

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The authors provide an overview of existing VTV channel measurement campaigns in a variety of important environments, and the channel characteristics (such as delay spreads and Doppler spreads) therein.

ABSTRACT

Traffic telematics applications are currently under intense research and development for making transportation safer, more efficient, and more environmentally friendly. Reliable traffic telematics applications and services require vehicle-to-vehicle wireless communications that can provide robust connectivity, typically at data rates between 1 and 10 Mb/s. The development of such VTV communications systems and standards require, in turn, accurate models for the VTV propagation channel. A key characteristic of VTV channels is their temporal variability and inherent non-stationarity, which has major impact on data packet transmission reliability and latency. This article provides an overview of existing VTV channel measurement campaigns in a variety of important environments, and the channel characteristics (such as delay spreads and Doppler spreads) therein. We also describe the most commonly used channel modeling approaches for VTV channels: statistical as well as geometry-based channel models have been developed based on measurements and intuitive insights. Extensive references are provided.

INTRODUCTION

Vehicle-to-vehicle (VTV) communications systems have recently attracted much interest, because they potentially improve efficiency and safety of surface traffic. The grand vision is that all future vehicles gather sensor data and share information on traffic dynamics with each other, and with the road infrastructure, via wireless links. Each vehicle can thereby receive and aggregate information from other vehicles to improve the capabilities of its braking system, enhance airbag functionality, and reduce fuel consumption and travel time. To this aim, vehicles have to build up ad hoc communication networks. Such networks, however, require reliable low-latency VTV communication links that are capable of meeting strict packet delay deadlines. An international standard, IEEE 802.11p, which is part of the Wireless Access in Vehicular Environments (WAVE) initiative, was recently published. Based on the popular WiFi standard, it is intended for both VTV and vehicle-to-infrastructure traffic telematics applications [1]. Systems based on IEEE 802.11p as well as alternative systems are also being developed in the European Union and Japan.

The simulation and performance evaluation of such ad hoc vehicular communications systems and their future enhancements require a deep understanding of VTV propagation communication channels. In the past, much research effort has been devoted to the *cellular* channel between a static base station and a mobile vehicle. It turns out, however, that the propagation characteristics of VTV communication channels are significantly different from those of cellular channels, especially in terms of the time and frequency selectivity and the associated fading statistics. Here, *time selectivity* describes the temporal fluctuations of the channel quality, whereas *frequency selectivity* relates to the occurrence of "spectral holes" in the channel; both are very important for system performance. Therefore, dedicated measurement campaigns are needed for the accurate characterization of VTV propagation aspects, and dedicated VTV channel models are urgently needed to evaluate the reliability and latency of data packet transmissions among vehicles.

Research into VTV channels was fairly low-key until about 2006, when the WAVE initiative and other potential commercial applications spurred interest in this important communications medium. Since then, dozens of papers have been published in this field by a number of different research groups all over the world. It is thus desirable to survey the recent progress and current state of the art. In this article we summarize methodology and results from the rele-

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vant measurement campaigns, as well as different types of channel models derived from those measurements. The goal of this article is to help communications system designers to gain an overview of the pertinent channel characteristics, and propagation researchers to assess where the most pressing needs for further work lie.

Key Issues in VTV Channels

The ultimate goal of VTV channel measurements and modeling is to enable performance characterization of VTV communications systems. This section thus first reviews the most important features and metrics that describe fading channels and how they impact system performance.

Propagation Channel Characterization

In a wireless system, the signals can propagate from the transmitter to the receiver via different paths, each of which can involve reflection, diffraction, waveguiding, and so on. The different paths give rise to multiple attenuated, delayed, and phase-shifted echoes of the transmitted signal arriving at the receiver. All these radio propagation effects are subsumed into the impulse response of the channel, which can be interpreted as the superposition of the contributions by all multipath components (MPCs). Note that the impulse response is time-variant because the propagation channel changes as transmitter, receiver, and scatterers move around. A complete description of the channel is therefore given by the time-variant channel impulse response [2].[1] However, a sequence of impulse responses is too cumbersome to work with directly. For this reason, several statistical channel metrics, which provide a more condensed characterization, have been derived and widely adopted: pathloss, fading statistics, Doppler spread, and delay spread.

Pathloss is the *average* attenuation (reduction in power) of a radio signal as it propagates. Pathloss includes the propagation losses caused by free space and effects due to absorption, diffraction, and others. It has been found in many experiments that the pathloss increases a function of distance d like d^n, where n is called the *pathloss exponent*. The pathloss is the single most important quantity of any wireless channel. As the pathloss increases, the signal-to-noise ratio (SNR) decreases; this restricts the achievable range and data rate of the system.

Fading statistics are used to describe the fluctuations in the received power over a distance (i.e., deviations from the power predicted by the simple pathloss law described above). Fast fluctuations, also called *small-scale fading*, can occur due to the interference of MPCs, which — depending on the exact location — can be constructive or destructive. Small-scale fading occurs during motion over short distances (approximately one wavelength), and leads to possibly reduced reliability, necessitating appropriate countermeasures (increasing transmit power, using frequency diversity or antenna diversity, etc.) [3]. Since exact characterization is usually too complicated, a description of the fading amplitude *statistics* is commonly used. The smaller the signal-power variations (i.e., the more "peaked" the probability density function of the fluctuations), the smaller the danger of system outage due to fading. Finding the fading statistics is a first step in identifying how serious the fading problem might become, and how much effort has to be put into the countermeasures. The most common model for small-scale fading is Rayleigh fading. *Large-scale fading*, or shadowing, is due to objects obstructing propagation paths. Such fluctuations are observed on locally averaged received powers.

The power delay profile (PDP) is the squared magnitude of the impulse response, averaged over the small-scale fading. It thus describes how much power is carried, on average, by MPCs with a certain delay. We can further obtain the *root mean square (rms) delay spread* as the second central moment of the PDP, providing a very compact description of the delay dispersion (or frequency selectivity) of a channel (i.e., if we transmit a short pulse, how "spread out" is the received waveform?). The delay dispersion determines the available frequency diversity, and also dictates the required length of cyclic prefix (for an orthogonal frequency-division multiplexing, OFDM, system) or equalizer (for a single-carrier system).

The Doppler spectrum describes the widening of the spectrum that occurs because different MPCs experience different Doppler (frequency) shifts. The *rms Doppler spread* thus characterizes the channel's frequency dispersion or, equivalently, the time selectivity of the channel; to a rough approximation, a channel can be considered to be constant over a timescale that is the inverse of the Doppler spread. The Doppler spread is a quantity that is of interest in itself for OFDM systems, because it leads to intercarrier interference, as part of the signal emanating from one subcarrier is not "in the spectral nulls" of the adjacent subcarriers anymore. It is furthermore an important characterization method for the time variability of the channel.

PDP and Doppler spectrum (and therefore delay spread and Doppler spread) are obtained from an ensemble of impulse responses, under the assumption that the statistics of the channel do not change with time. This assumption is widely used in cellular communications channels, but violated in VTV channels: there, we have to define a PDP or Doppler spectrum that is only valid for a short time; a complete description of the channel then also has to include how they change with time.

Difference from Cellular Propagation

The characteristics of VTV channels, such as time selectivity or pathloss, differ from those of mobile cellular communications channels. These differences originate from the following specific features of VTV radio propagation:

- In VTV systems the transmitter (TX) and receiver (RX) are at the same height, and in similar environments (peer-to-peer communications). In cellular communications, on the other hand, communication is between a base station that is high above street level and a mobile station at street level. As a consequence, the dominant propagation mechanisms of the multipath

The Doppler spectrum describes the widening of the spectrum that occurs because different MPCs experience different Doppler shifts. The rms Doppler spread thus characterizes the channel's frequency dispersion, or equivalently, the time-selectivity of the channel.

[1] *Note, however, that for multi-antenna systems, a double-directional impulse response is required for a complete description of the channel.*

Figure 1. *Channel measurements in an urban environment (Lund, Sweden); the red pickup truck carries the receiver.*

components are different. For example, in cellular communications propagation of waves over rooftops is important, while in VTV systems propagation in the horizontal plane, with diffraction and reflection, for example, at street corners, is more important. Also, for a VTV channel, scattering can occur around both the TX and the RX, while for cellular channels, the area around the base station is usually free of scatterers. Furthermore, the distance over which communications can take place is much smaller in VTV channels (< 100 m) than in typical cellular scenarios (~ 1 km).

• In a VTV channel, both the TX and RX as well as many of the important scatterers are moving, whereas in cellular channels, only one of the TX or RX is moving, and moving scatterers have less relative importance. This implies that the channel fluctuations in VTV channels are faster and that commonly used assumptions on stationarity usually are not valid.

• VTV systems operate mostly at 5.9 GHz carrier frequency, while cellular communications occurs mostly at 700–2100 MHz. Due to their higher carrier frequency, VTV channels have higher signal attenuation, and specific propagation processes like diffraction are less efficient than in cellular radio.

ENVIRONMENTS

Channel characteristics of VTV channels are influenced by the properties of the environment around the communicating cars, as well as the typical traffic characteristics. Although classification of different traffic environments is somewhat arbitrary and there are sometimes large variations between different parts of the world, the following categories are often distinguished in the literature:

• *Highways* have two to six lanes in each direction, usually with middle dividers and no houses situated in their immediate vicinity. Speeds on highways are usually limited to 25–30 m/s in the United States, Asia, and large parts of Europe, but can be higher than 40 m/s in Germany and a few other European countries.[2] Traffic density is usually high on urban highways (up to 10,000 cars/h), but much lower on highways through generally rural areas (e.g., large parts of the interstate highway systems in the United States).

• *Rural streets* usually have two lanes, with few or no buildings on the side, although hills [4] or forests [5] can give rise to additional multipath components. Traffic density is usually very light, but velocities can be 20–30 m/s.

• *Suburban streets* are usually one or two lanes wide. In the United States houses are often set back 8–10 m from the curb [4], whereas in Europe and Japan houses can be much closer to it. Traffic density is light, and velocities are usually limited to 15 m/s or less. In contrast to the other environments, trucks are rarely found on suburban streets.

• *Urban streets* (Fig. 1) are characterized by wider streets (two to four lanes), houses closer to the curb, and higher traffic density than suburban streets. It must be noted that urban streets in Europe can be very narrow and winding, while in the United States they are usually wider and straight. Even though the building environment is the same, it is often worthwhile to separately model urban streets with light traffic and with heavy traffic; the presence of many cars, which may block both the line of sight (LOS) between TX and RX as well as other significant paths, can change the channel parameters significantly.

The distance between vehicles is strongly correlated with the speed, up to the official speed limit [4]. This can be explained by the fact that rational drivers keep a larger distance from the vehicle in front of them at higher speeds. As a consequence, any results that depend on speed and distance between vehicles are correlated.

VEHICLE TYPES AND ANTENNAS

Two other important "environmental factors" are the type of vehicle that wants to communicate and the location of the antennas on the vehicle. The combined effect of these factors determines not only the influence from the subject car, but also how much the channel is influenced by other, obstructing, cars, because it impacts which multipath components can reach the antenna. Most car-mounted antennas for current applications are located either on the roof or near the rear window (e.g., for GSM communications or FM radio), although some cars have additional antennas in the bumper (mainly for radar applications) and possibly on the dashboard. In light of this, it is noteworthy that practically no existing VTV measurement campaigns have been performed with antennas that are actually in use in commercial vehicles. Rather, most campaigns in the literature make use of antennas placed either at an elevated position within a van [6, 7] or on top of a van [8]. Antennas placed inside a car (e.g., on a seat or near a dashboard) have been found to lead to higher pathloss (5–10 dB [9]) and stronger multipath propagation [8]. It should be noted, however, that the packet error rate is quite sensitive to the exact antenna position [10]. Trucks would allow placing the antennas even higher above the ground, so they presumably could communicate over the roofs of passenger cars, thus

[2] *1 m/s corresponds to 3.6 km/h or 2.25 mi/h.*

enabling larger communications ranges; however, this aspect seems to have drawn little attention in the literature up to now.

MEASUREMENTS

Measurements are vital for the understanding of propagation channels, either giving direct insights, or by verifying (or disproving) theoretical considerations. We thus first describe the type of measurement equipment that is being used for obtaining channel characteristics. The output of those measurement devices is usually a time-variant transfer function or time-variant impulse response [11], from which the channel parameters discussed earlier can be obtained. More detailed insights can be obtained from intricate channel models that might be parameterized from measurement campaigns; this will be discussed in the "VTV Channel Modeling" section.

MEASUREMENT EQUIPMENT

The type of measurement equipment that can be employed for VTV channels is mostly the same as that for cellular channels. Just like in cellular channels, the required equipment depends, naturally, on which channel characteristics we want to measure — the more general the desired measurement result, the more complex (and expensive) the required equipment.

Narrowband measurement systems try to identify the channel gain and Doppler shift experienced by a narrowband (sinusoidal) signal; by definition they cannot measure other parameters such as frequency selectivity. Narrowband measurement systems can be based on a sine wave generator combined with a vector signal analyzer [4, 12, 13] or spectrum analyzer [14].

Wideband sounders determine the impulse response (or transfer function) of the channel and the parameters derived from it, such as delay spread, as well as the narrowband parameters. The most popular form is correlative channel sounders, which transmit a pseudo noise (PN) sequence and correlate the received signal with the same PN sequence at the RX. It can be shown that if the channel is time-invariant for the duration of the PN sequence, the output of the RX correlator is the convolution of the channel impulse response with the autocorrelation function of the PN sequence; if the PN sequence has suitable properties, this output approximates the channel impulse response [3].

A correlative sounder can be either a dedicated device, as in the measurements of Ohio University [8], or constructed from an arbitrary-waveform generator (working as TX), as in the measurements of Carnegie-Mellon University (CMU) [15], Georgia Tech [16], Berkeley [17], and Heinrich-Hertz-Institut (HHI) [18]. A 50 MHz chip rate (i.e., inverse duration of the +1 and –1 of the PN sequence) has often been used for VTV measurements. A vector signal analyzer or sampling scope can be used as RX. With a sampling scope, sampling is usually done at twice the chip rate, but with strict synchronization and a repeated TX signal, undersampling can be used to virtually create a high sampling rate and allow for large bandwidth

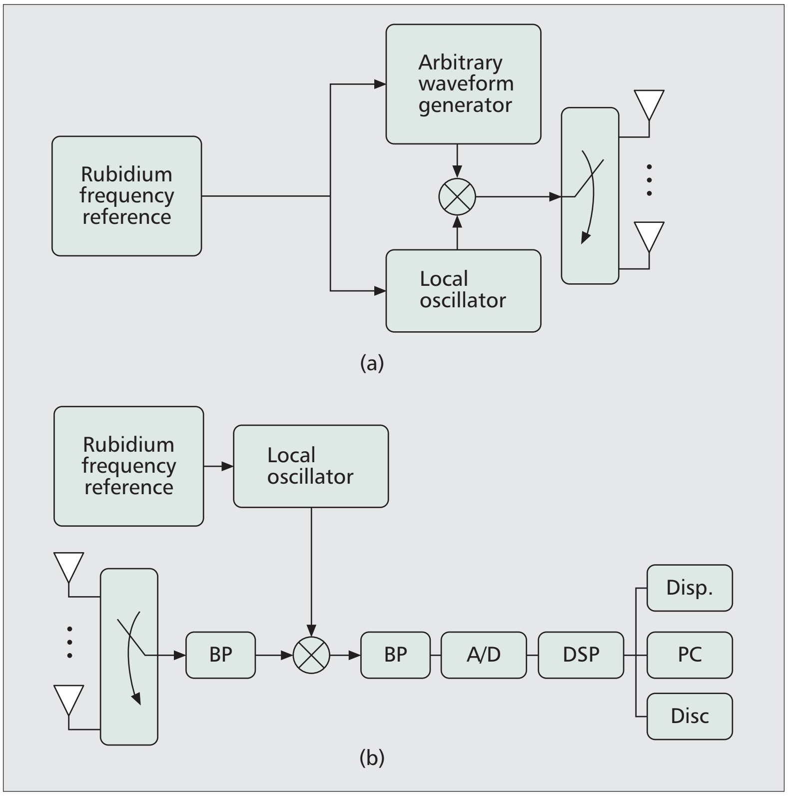

Figure 2. *Block diagram of a wideband multitone sounder based on the switched array principle: a) the transmitter; b) the receiver.*

[18]. The correlation of the received signal with the PN sequence is most often performed offline on a computer or workstation.

A different wideband sounding principle is multitone sounding, which is based on sounding signals similar to those of OFDM systems [6]. Sounding with multitone signals requires more complicated equipment, but provides channel characterization that is of equal quality in all parts of the considered bandwidth, while PN-based sounding is less accurate near the band edges. It must also be noted that channel sounding by means of vector network analyzers (VNAs), which is very popular for the measurement of impulse responses in indoor environments, is not viable for VTV channels, as such channels change much faster than VNAs can measure.

While the WAVE standard foresees only a single antenna element at the TX and RX, the trend to higher reliabilities and data rates lets us anticipate the future use of multiple antenna elements at the transmitter and receiver. For such multiple-input multiple-output (MIMO) systems we need to (quasi-)simultaneously record the impulse responses from each transmit to each receive antenna element. Appropriate *MIMO sounders* can be constructed from wideband sounders by one of two principles:

- Using multiple parallel RF chains at the transmitter and receiver
- Using the switched-array principle

The former case allows the reception of multiple signals *simultaneously* at the receiver, while different transmit signals (e.g., an *m*-sequence with different offsets [19]) are put onto the TX anten-

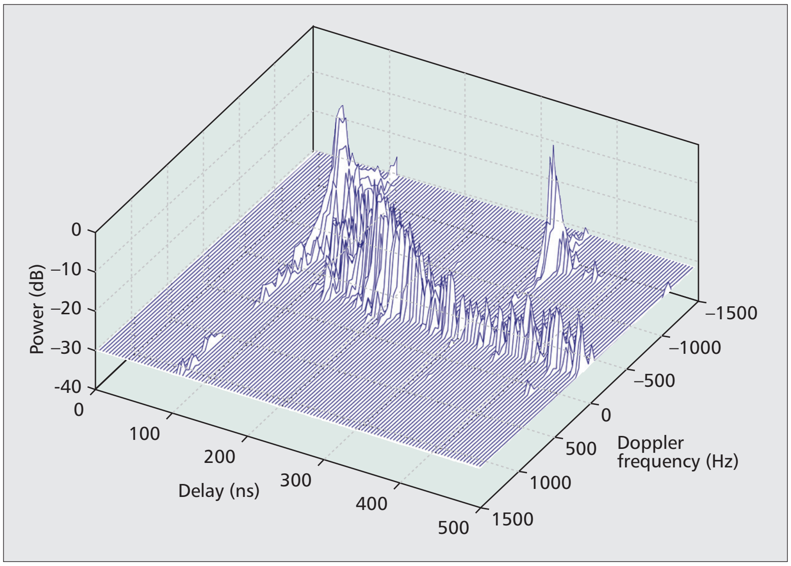

Figure 3. *Example of Doppler-resolved channel impulse response. TX and RX are driving in opposite directions.*

nas through parallel TX chains. In a switched-array sounder, a single available radio frequency (RF) chain (at TX and RX, respectively) is connected sequentially to the elements of an antenna array through an electronic switch [6] (Fig. 2). While cheaper and easier to calibrate, such sounders have the drawback of requiring a longer time period to record a complete MIMO snapshot (from each TX to each RX element), due to the sequential nature of the sounding. This drawback is more important in VTV environments than in cellular channels due to the higher Doppler frequency.

Measurement Results

As previously mentioned, the fast temporal variations of VTV channels impacts channel characterization, since channel parameters often vary with time. Much research effort has thus been spent on establishing connections between parameters and time-variant environment effects such as car densities, speed, and TX-RX separation. However, consistent conclusions are yet to be established in a statistically reliable way.

•*Pathloss*: Pathloss exponents around n = 1.8–1.9 were observed in light traffic highway environments [7, 20–22] as well as rural environments [20, 22], which is in reasonable agreement with two-ray models [20, 22].[3] Reference [21] also analyzed crowded highways, and found the pathloss to be more severe and experience larger variations. For an urban environment, [20] found that $n = 1.6$, whereas [21] used a breakpoint model. A breakpoint model was also found suitable for a suburban environment: pathloss coefficients of n = 2–2.1 up to a distance of 100 m, and around $n = 4$ beyond that distance [4]. The pathloss coefficients for rural, highway, and urban environments are similar to values measured for cellular channels under line-of-sight (LOS) conditions, while the suburban results mentioned above are comparable to non-line-of-sight (NLOS) cellular channels. Note that many results for VTV channels do not distinguish between LOS and NLOS conditions; rather, all channel samples are lumped together in the analysis.

•*Fading statistics*: The narrowband small-scale fading statistics in VTV communications have been subject to considerable debate in the literature. Reference [4] argues that small-scale and large-scale fading cannot easily be distinguished, and proceed to suggest the Nakagami distribution for the compound fading statistics. The Nakagami m-factor can be quite high (3–4) if the distance between TX and RX is less than 5 m, which means that fading is not very pronounced. However, when the distance exceeds 70–100 m, the Nakagami m-factor was observed to be less than unity, which means that fading is "worse than Rayleigh" ($m = 1$ corresponds to Rayleigh fading). Other authors did distinguish between small-scale and large-scale fading, eliminating the large-scale (shadowing) fading before analyzing the small-scale distributions. For the narrowband fading statistics, [14] found good agreement of measured data with either the Nakagami or Rice distributions. Note that narrowband fading statistics in cellular channels are commonly assumed to be Rayleigh (for NLOS) or Rice (for LOS).

A somewhat different problem is the analysis of fading in wideband measurements, where it is useful to consider a discretized channel impulse response,

$$h(t,\tau) = \sum_{i=0}^{N} c_i(t)\delta(\tau - i/B),$$

where B is the system bandwidth, and $c_i(t)$ are the (complex) amplitudes of the "resolvable delay bins" or "taps"; that is, we "lump together" all multipath components that are arriving at the RX within a time interval that is approximately the inverse bandwidth of the considered system. Most wideband receivers (e.g., a code-division multiple access, CDMA, receiver, or a receiver for a single-carrier system with appropriate equalizer) can process the signals arriving in different delay bins separately; it is thus meaningful to also analyze the fading statistics of *each* bin. Reference [8] fitted the measurement results to a Weibull distribution, whereas [23] fitted data to Weibull and Nakagami distributions. References [24, 25] describe the fading in each resolvable delay bin as Rician, and show from their experiments that the Rice factor in the first delay bin can be very high (up to 20 dB), while it is much lower for later delay bins. Reference [23] found that the fading can also be Rician for later delay bins; a similar behavior is found in [5] where fading of individual scatterers is studied. Summarizing, we can say that in LOS situations, the first delay bin shows "better than Rayleigh" fading characteristics, whereas bins with longer delays show a large variety of "fading depth," with distributions ranging from Rician to Rayleigh fading, with "worse than Rayleigh" also occurring in a significant percentage of cases; this qualitative behavior is similar to that of cellular channels.

•*Doppler spreads*: VTV channels tend to show higher Doppler spreads than conventional mobile-radio channels, because the relative

[3] *Reference [22] uses a break-point model, with* $n = 4$ *for* $d >\sim 220$ *m.*

Scenario	Pathloss exponent	Delay spread (mean)	Delay spread (10%–90%)	Doppler spread (mean)
Highway	$n = 1.8$ [7] $n = 1.85$ [20] $n = 1.9/4\ 0^a$ [22]	247 ns [7] 41 ns [20] 141–398 ns^b [17] 165 ns [27] 53/127 ns^d [8]	120–340 ns [7] 50–190 ns [15] 30–300 ns [27] 0.3/0 5–90/260 ns^d [8]	92 Hz^f [20] 120 Hz [14] 761–978 Hz^b [17]
Rural	$n = 1.79$ [20] $n = 2.3/4\ 0^a$ [22]	52 ns [20] 22 ns [17]	20–150 ns [15]	108 Hz^f [20] 782 Hz [17]
Suburban	$n = 2.5$ [4] $n = 2.1/3\ 9^a$ [4]	104 ns [27]	40–110 ns [15] 20–230 ns [27]	
Urban	$n = 1.61$ [20]	47 ns [20] 158–321 ns^c [17] 373 ns [27] 126/236 ns^e [8]	30–1100 ns [27] 3/20–250/570 ns^e [8]	33 Hz^f [20] 86 Hz [14] 263–341 Hz^c [17]

[a] Breakpoint model; [b] TX-RX separations of 300–400 m; [c] TX-RX separations of 200–600 m; [d] low/high traffic density; [e] antenna outside/inside car; [f] median value

Table 1. *Summary of reported parameters for VTV propagation channels.*

velocities of TX and RX can be higher, and because many important scatterers actually move (which often causes even higher Doppler shifts) in VTV channels (Fig. 3). Mean rms Doppler spreads are usually on the order of 100–300 Hz (Table 1), though results close to 1000 Hz have been reported in highway environments [17]. The high mobility also leads to large variations of the Doppler spread during a measurement; a log-normal distribution has been found a suitable description for rural, urban and highway environments [20]. The Doppler spread is also connected to the velocity of TX and RX. A linear dependence between the average rms Doppler spread $f_{\mathrm{rms},D}$ with the "effective speed" of the TX and RX,

$$v_{eff} = \sqrt{v_{\mathrm{TX}}^2 + v_{\mathrm{RX}}^2},$$

has been observed [13], whereas the Doppler shift of the LOS component was found, not surprisingly, to be exactly explained by the relative speed of TX and RX [7, 13].

•*Delay dispersion*: Statistics of the rms delay spreads and maximum excess delays, as well as the coherence bandwidth, were measured in a number of VTV campaigns. The distribution of the rms delay spread can often be fitted by a log-normal distribution [26]. In general, median rms delay spreads are on the order of 100–200 ns (Table 1), although [20] measured approximately 50 ns. Among the various environments, suburban and rural environments show the lowest delay spreads, while highways display slightly higher results [15, 17, 27] (Fig. 4). The delay spread in urban environments can be considerably higher; a median value of 370 ns was observed in [27]. These results are comparable to the range of delay spreads that have been observed for urban and rural cellular propagation channels.

The maximum excess delay has also been analyzed. While some measurements found only 0.5 μs on highways [6], other campaigns showed a very high maximum excess delay (up to 5 μs occurred in rare circumstances) in highway and urban environments [15, 17].[4] The large variations of the results can be explained by the fact that faraway objects (which can lead to very high excess delays) exist only in certain locations. Measurements in a variety of morphologies are thus essential to get better insights into the statistical importance of these effects.

•*MIMO measurements*: As previously stated, multiple antenna elements can be used to increase robustness against fading, and possibly achieve higher data rates. In either of those cases, the correlation coefficient of the fading at the antenna elements gives insights into the achievable gains. Usually, a low correlation coefficient results in a large performance improvement.

Evaluations on the correlation coefficient are scarce in the literature. Reference [5] evaluated the correlation coefficient between the elements of a four-element patch array that are pointing in different directions, and found them to exhibit considerable variations with time. The same conclusion was drawn regarding the multipath richness (sum of the logarithms of the eigenvalues) by [9] — this quantity is especially useful for assessing the potential of using multiple data streams over one link. The channel richness was increased when the antennas were placed inside the cars. Reference [23] did not specify any values of correlation coefficients, but evaluated the stationarity of VTV MIMO channels through the *correlation matrix distance*.

VTV Channel Modeling

For system simulations and system testing, detailed channel models need to be established that quantify the effect of the propagation channel more precisely than the "single-number"

[4] *Reference [8] did not evaluate the maximum excess delay, but found rms delay spreads up to 1.7 μs, and 90 percent delay windows [28] of up to 2.5 μs.*

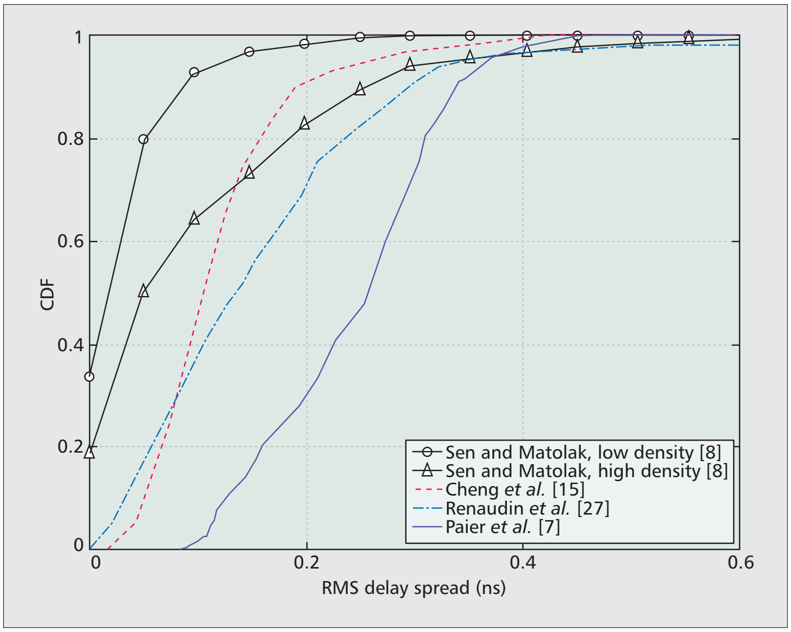

Figure 4. *Cumulative distribution functions (CDFs) of highway delay spreads reported in various measurement campaigns.*

descriptions discussed earlier. Just like in channel modeling for cellular systems, there are three fundamental approaches to channel modeling: deterministic (e.g., ray tracing), stochastic, and geometry-based stochastic. The deterministic approach computes the realization of the propagation channel in a specific location and environment. In the *stochastic* approach the statistics of the propagation characteristics are modeled rather than a site-specific realization. Finally, the *geometry-based stochastic* approach has a similar output as the stochastic approach, but uses (simplified) ray tracing together with random placement of scatterers to obtain it. For an extensive discussion of their principles, advantages, and drawbacks, the reader is referred to [3, 29]. A key difference between cellular and VTV communications channels is that VTV channels often exhibit non-stationary channel statistics; that is, not only the impulse responses, but also their statistical properties such as small-scale fading distribution, PDP, and Doppler spectrum change. Any model should thus be able to handle the rapid fluctuations typical for VTV communications channels. Below, we discuss how the different modeling approaches handle this important issue. In the following we first describe the main modeling approaches separately (Fig. 5). Subsequently, we compare them, and describe the pros and cons for different applications.

Modeling Approaches

•*Narrowband stochastic channel models*: Narrowband stochastic models do not characterize the frequency selectivity of the propagation channel, but rather focus on characterization of the fading statistics together with the Doppler spectrum — the latter being the key quantity that distinguishes a VTV channel from a cellular channel.

In cellular channels, where Doppler shifts are created mainly by movement of the mobile station, the most common model for the Doppler spectrum is the Jakes spectrum, which is based on the assumption of a uniform angular power spectrum (i.e., multipath components arriving at the mobile station from all directions with equal strength) and an omnidirectional antenna pattern at the mobile station [30]. The Jakes spectrum has a characteristic "bathtub" shape, with strong contributions at $\pm f_c v/c_0$, where f_c is the considered carrier frequency, v the velocity of movement, and c_0 the speed of light.

Generalizing this approach to VTV channels, [31] considered a situation where both TX and RX are moving, the angles of incidence are independent at transmitter and receiver, and the angular power spectrum and antenna pattern at TX and RX are uniform. The resulting Doppler spectrum does not show the "bathtub" shape, but is somewhat smoother. Further interesting results and generalizations are given in [32, 33].

Channel simulators need to create channel realizations whose Doppler spectra have the correct shapes, or equivalently have the correct autocorrelation function [34]. Two fundamentally different approaches have been developed: a statistical simulation model that essentially performs simplified ray tracing (see also the geometrical models below); the autocorrelation function is satisfied in this model when an expectation over different scatterer locations is taken. An alternative is a *deterministic* channel model, which adds up a number of sinusoids with different parameters and creates the correct temporal correlation function of the resulting fading when *time-averaged* correlation is considered. The relative advantages and disadvantages of these two approaches are rather subtle, and we refer to [35] for a detailed discussion.

•*Wideband stochastic channel models*: Wideband stochastic channel models provide the statistics of the power received with a certain delay, Doppler shift, and possibly even angle of arrival. In particular, the tapped delay line model, which is based on the wide-sense-stationary uncorrelated scattering (WSSUS) assumption [11], is in widespread use for cellular system simulations. This model describes the channel impulse response by means of a finite impulse response filter with a number of discrete taps, each of which is fading according to a prescribed probability density function (usually complex Gaussian) and Doppler spectrum (Fig. 5d). In particular, the IEEE 802.11p channel models employ the 6- and 12-tap models developed by Ingram and coworkers [16, 25] in different types of environments. Since each tap can contain several paths (where each path can have a different type of Doppler spectrum), this allows almost arbitrary Doppler spectra to be synthesized for each tap even though the spectrum of each path is selected from a small class of shapes. Tapped-delay-line models are popular due to their low complexity, although they may suffer from less accurate representation of the non-stationarities in VTV channels.

•*Ray tracing*: Ray tracing for VTV systems, which was pioneered by Wiesbeck and coworkers [14, 37–38], solves (a short-wavelength approximation to) the wave equation for specific

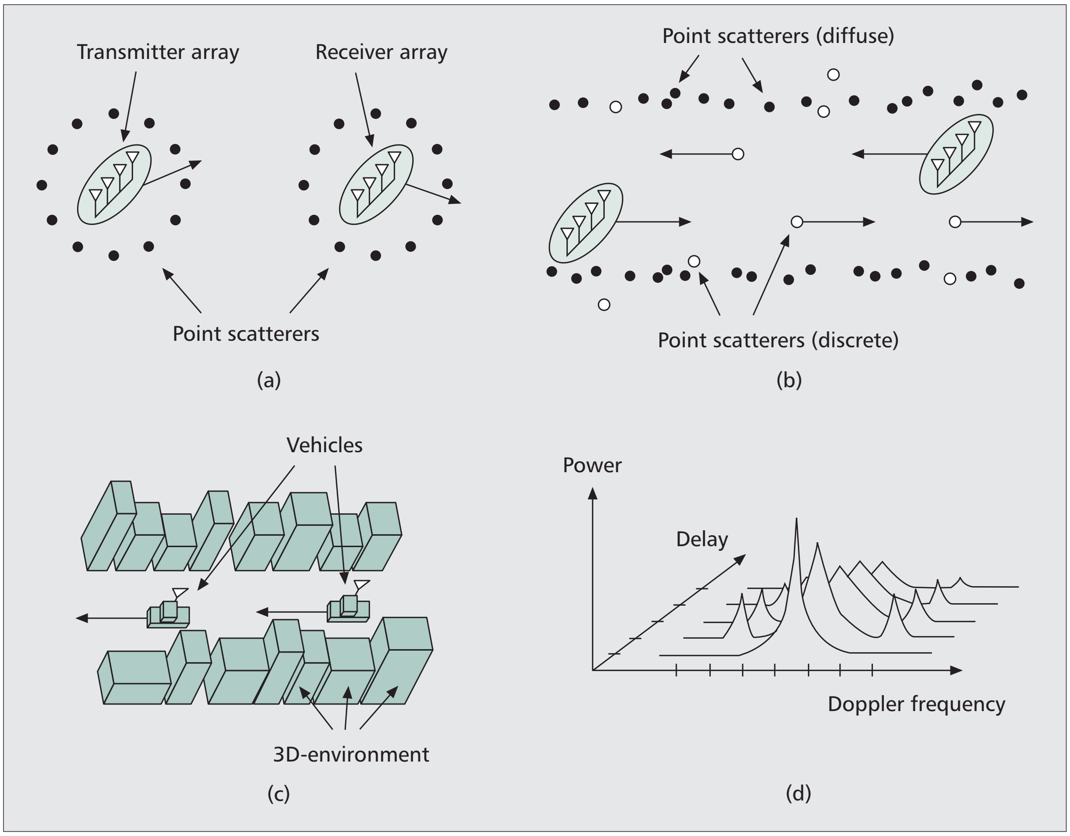

Figure 5. *Overview of some common VTV modeling approaches: a) geometry-based stochastic with scatterers on regular shapes; b) geometry-based stochastic with scatterers in realistic positions; c) ray tracing; d) stochastic (tapped delay line).*

The conventional two-ring model assumes that all scatterers are placed in the horizontal plane, i.e., have zero elevation. This need not be a realistic assumption, especially in NLOS situations in urban environments.

scatterer locations and associated boundary conditions. Such a deterministic approach provides a site-specific, very realistic simulation of the propagation channel. By appropriately modeling the environment (houses, traffic signs, parked cars, etc.; Fig. 5c), agreement between measured and simulated receive powers can be brought within 3 dB standard deviation [36, 38]. Ray tracing has also been used to investigate the effects of different antenna positions on the vehicles [39]. The main drawback of ray tracing lies in its computational demands.

• *Geometry-based stochastic channel models*: VTV geometry-based stochastic channel models (GSCMs) are based on the "classical" GSCM approach, simulating the channel by randomly placing (according to suitable statistical distributions) scatterers around TX and RX, and then performing simplified ray tracing. The simplest geometrical VTV channel model is the two-ring model, where one ring of scatterers is placed around the TX and one around the RX (Fig. 5a). Generalizations allow for the existence of an LOS component [40], single-scattering either near the TX or the RX, where the relative strengths of those processes are model parameters [41], or inclusion of additional scatterers on an ellipse [42]. A geometrical model, in particular the two-ring model, also allows a joint space-time correlation function to be derived, from which the temporal evolution of the correlation coefficient between the antenna elements in a MIMO system can be derived [43].

The conventional two-ring model assumes that all scatterers are placed in the horizontal plane (i.e., have zero elevation). This might not be a realistic assumption, especially in NLOS situations in urban environments. A generalization of the two-ring model to the three-dimensional case was analyzed in [44], which considered the double-scattering case, as well as a series of papers by Zajic and Stuber (e.g., [45, 46]).

The reference models described above do not aim to reproduce the physical reality, but rather are intended for the comparison of different transmission schemes. A more realistic model is proposed in [5], where location as well as properties of scatterers are closely adapted to measured results (Fig. 5b). This model makes a distinction between discrete and diffuse scattering (more precisely, interaction), where discrete scatterers are typically cars, houses, road signs, and other significant (strong) scattering points along the measurement route, whereas diffuse scattering is found to mainly stem from smaller objects at the sides of the measurement route (TX-RX path); the importance of the latter type of objects was also pointed out in [47]. A similar approach was suggested independently in [48].

Non-Stationarities

As discussed previously, one of the most important points that distinguishes VTV channels from conventional cellular channels is the non-stationarity of the channel, that is, the channel statistics (not only the instantaneous channel

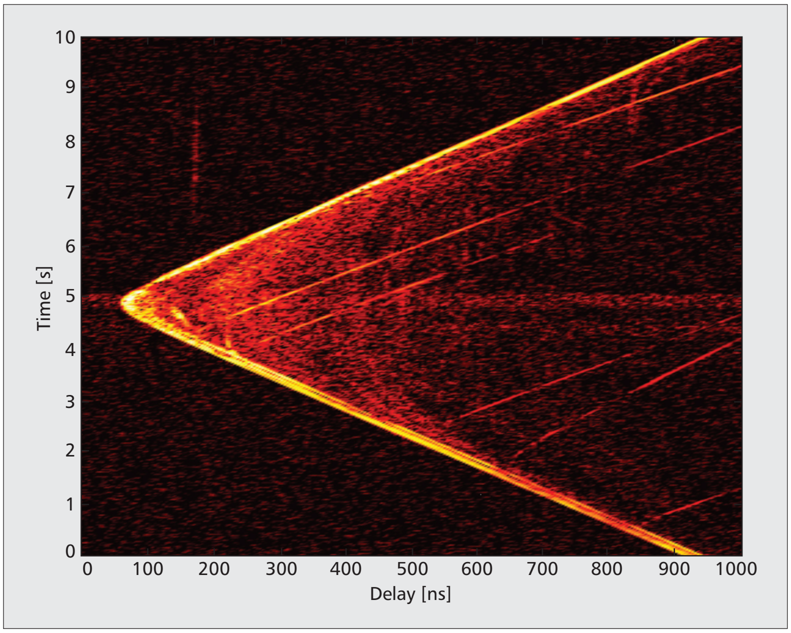

Figure 6. *Example of the time-varying power delay profile (average squared magnitude of impulse response), where the Doppler spectrum in Fig. 3 is calculated around 5.2 s. The delay of the first taps varies as the TX and RX approach each other, meet, and move away from each other. It can further be observed that while the LOS tap experiences fading, the interposition between strong components (clusters) and the LOS tap changes with time, and there is splitting of clusters over time as well.*

impulse response) can change within a rather short period of time (Fig. 6); therefore, the WSSUS assumption, which is widely used in the description and modeling of cellular communications channels, cannot be used. Rather, the channel statistics are valid only for a short period of time ("region of stationarity"). For example, in each region of stationarity, the Doppler spectrum of the first delay tap can be different, because the Doppler shift of the LOS component can change. If we would just average the Doppler spectra over the different regions of stationarity, a broadening of the spectrum of the first tap (which has no correspondence to physical reality) would result. The non-stationarities can be modeled by:

- A *birth/death process* to account for the appearance and disappearance of taps [8]; it must be noted that while this approach provides a non-stationary description, it does not account for the "drift" of scatterers into a different delay bin, and can also lead to a sudden appearance and disappearance of strong multipath components (MPCs)
- *Defining different tap models* for regions of a measurement route that have significantly different delay spreads, or whose power delay profiles (PDPs) lead to significantly different bit error rates (BERs) [24]; however, such an approach does not provide a continuous (with time) characterization of the channel
- Using GSCMs or ray tracers, which take non-stationarities into account automatically [5]

The non-stationarities of the channel have a significant impact on system performance. It has been found that the assumption of WSSUS leads to (erroneous) optimistic BER simulation results in single-carrier and multicarrier systems [49]. Also, [24] showed that if the simulation model is based on a single averaged PDP from which the realizations are drawn, the resulting BERs in a system simulation deviate considerably from the BERs resulting from the raw measured channel data.

Selecting a Suitable Modeling Method

Each of the channel modeling methods mentioned above has specific advantages and drawbacks. Analytical models for the narrowband Doppler spectrum, as well as models based on two-ring geometries, are suitable for analytical computations and provide reference channels that can be used for calibrating a simulator; however, they do not reflect realistic behavior of VTV channels. Tapped delay line models are somewhat more realistic and can be parameterized in a flexible way to describe channels in different environments. A main problem is that many tapped delay line implementations, most notably the IEEE 802.11p channel models, do not describe non-stationarities of the channels. Furthermore, correlation between antenna elements of MIMO systems is not provided in the 802.11p models, and generally would require additional modeling effort in tapped delay line models. These problems do not occur in GSCMs, which implicitly model non-stationarities and antenna correlations. However, generation of realizations of channel impulse responses from a GSCM requires more computer time than tapped delay line models. Finally, the ray tracing approach, which also implicitly includes non-stationary channel statistics, constitutes the most realistic channel model; drawbacks are the considerable simulation time and the requirement of an accurate terrain database as well as models for cars and other scatterers in the environment.

Summary and Conclusions

The VTV propagation channel has strong impact on the coverage, reliability, and real-time capabilities of VTV networks. Wrong assumptions about fading lead, for example, to erroneous conclusions on the dependability of intervehicle warning systems at intersections [50]. Thus, it is vital to use well characterized measurement-based models of VTV communications channels. Much progress has been made since 2005: it is now well understood that VTV channels are usually non-stationary, and that performance predictions based on stationary (WSSUS) channels are optimistic. Similarly, channel estimators and any other signal processing algorithms that rely on channel statistics have to be modified in light of this insight. Delay spreads have been investigated in various environments, and while under many circumstances the channels provide appreciable delay diversity, there are a significant number of cases where such diversity is not available, motivating the use of multiple antenna elements for enhanced robustness.

Despite all this progress, many open topics remain. The small amount of available VTV channel measurements do not allow the formulation of statistically significant statements about real-world VTV channels. Moreover, the propagation aspects of vehicular environment categories are expected to vary regionally due to differences in speed limits, road and building construction, vehicle population, and traffic statistics. It will therefore be important to perform extensive measurement campaigns in different parts of the world. A comparison of what an "urban" channel looks like in, say, Tokyo, Rome, and Los Angeles, would be of great interest.

Also little explored is the impact of vehicles between the TX and RX in VTV links (which lead to shadowing of the desired paths), the effects of the placement of antennas on vehicles, and the gains from multiple antennas. Measurement campaigns for this purpose, possibly augmented by full electromagnetic simulations for analyzing the interactions between antennas and cars, are desirable. For channel modeling, it would be important to derive a model that combines the flexibility of GSCM with the fast simulation times of tapped delay line models. This abundance of open issues, combined with the increasing importance of VTV communications, will make sure that VTV propagation channels will remain a vibrant research area in the next years.

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