A Survey on Vehicle-to-Vehicle Propagation Channels

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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-
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]. 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 small-scale fading is a quantity that is of interest in itself for enabling system design and countermeasures (increasing transmit power, reducing reliability, necessitating appropriate countermeasures).

The Doppler spread 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. 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 frequency bands 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 channel's frequency dispersion, or equivalently, the time-selectivity of the channel.

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

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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 correllative 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 [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 response 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-
n = 4 for break-point model, with 3 Reference [22] uses a
Example of Doppler-resolved channel impulse response. TX and RX
Figure 3.
>~ 220 m.

between LOS and NLOS conditions; rather, all
results for VTV channels do not distinguish
sight (NLOS) cellular channels. Note that many
urban environments are similar to values mea-
sured for rural, highway, and
and around n = 4 beyond that distance [4]. The
pathloss coefficients for a suburban environment: pathloss coef-
ficients 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 mea-
sured 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 litera-
ture. Reference [4] argues that small-scale and
large-scale fading cannot easily be distinguished,
and proceed to suggest the Nakagami distribu-
tion 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 analyz-
ing the small-scale distributions. For the narrow-
band fading statistics, [14] found good agree-
ment 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 togeth-
er” all multipath components that are arriving at
the RX within a time interval that is approxi-
mately 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 appro-
priate 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 distribu-
tions. 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 “fad-
ing depth,” with distributions ranging from
Rician to Rayleigh fading, with “worse than
Rayleigh” also occurring in a significant percent-
age 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

MEASUREMENT RESULTS
As previously mentioned, the fast temporal vari-
atations of VTV channels impacts channel charac-
terization, 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 separa-
tion. 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 environ-
ments [20, 22], which is in reasonable agreement
with two-ray models [20, 22]. 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 break-point
model. A break-point model was also found suit-
able for a suburban environment: pathloss coef-
ficients 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 mea-
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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 \( f_{\text{rms,D}} \) with the “effective speed” of the TX and RX, 

\[
v_{\text{eff}} = \sqrt{v_{\text{TX}}^2 + v_{\text{RX}}^2},
\]

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 \( \mu s \) on highways [6], other campaigns showed a very high maximum excess delay (up to 5 \( \mu s \) occurred in rare circumstances) in highway and urban environments [15, 17]. 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”

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Pathloss exponent</th>
<th>Delay spread (mean)</th>
<th>Delay spread (10%-90%)</th>
<th>Doppler spread (mean)</th>
</tr>
</thead>
</table>

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

Figure 4.

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 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.

Modeling Approaches

• Narrowband stochastic channel models: Narrowband stochastic channel 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.

...
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].

![Figure 5](image.png)

**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 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.

The non-stationarities of the channel have a 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) channel models 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 propa-
gation aspects of vehicular environment categories are expected to vary regionally due to differences in speed limits, road and building configuration, 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 near future.

REFERENCES


**BIOGRAPHIES**

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