Chapter 12
Channel Models for Vehicular Communications

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Abstract Recent empirical studies have shown that correctly modeling the vehicular channel is imperative for realistic evaluation of VANET applications (Gozalvez et al., Telecommun Syst:1–19, 2010; Dhoutaut et al., Impact of radio propagation models in vehicular ad hoc networks simulations. VANET 06: Proceedings of the 3rd international workshop on Vehicular ad hoc networks, 2006). This is particularly the case for safety applications, where the correct reception of a single message can help avoiding an accident. With this in mind, this section focuses on vehicular channel and propagation models. We start by describing the basic propagation mechanisms that enable wireless communication. Next, we elaborate on specific considerations for vehicular channel modeling, including diverse environments where the communication takes place and the objects that impact channel modeling. We then classify the models based on the propagation mechanism scale, modeling approach, and suitability for a particular environment, among others. Using this classification, we overview the current state of the art in vehicular channel and propagation modeling and make a qualitative comparison between the models. Finally, to address the aspects of vehicular channel modeling that are not sufficiently explored, we provide some directions for future work.

Keywords VANET • Propagation • Free-space • Reflection • Diffraction • Fading • Scattering • Line of sight (LOS) • Non-line of sight (NLOS) • LOS obstruction • Ray-tracing • V2V • Multipath • Doppler spread

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12.1 Wireless Channel Basics

12.1.1 Wireless Propagation Primitives

As the wireless signal, in the form of an electromagnetic wave, travels or propagates through a medium, several mechanisms take place that affect the intensity and characteristic of the electric field of the transmitted wave. The mechanisms behind such propagation greatly affect the electric field of the electromagnetic wave observed at the receiving antenna. In general, such mechanisms can be attributed to free space propagation, reflection, diffraction, scattering, and penetration through material [2].

12.1.1.1 Free Space Propagation

Free space propagation describes the propagation mechanism of an electromagnetic wave in the scenario where a transmitter and a receiver are separated but have an *unobstructed, line of sight (LOS)* path. Free space loss depicts the decay of the signal as it propagates to the receiver and is usually expressed in terms of separation distance, signal frequency or wavelength, parameters associated with antennas, *but not* factors that are related to propagation environment. For instance, in a free space propagation model, the power received at a receiver antenna is given by the Friis free space equation:

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}, \tag{12.1}$$

where P_t is the transmitted power, G_t and G_r are the transmitter antenna gain and receiver antenna gain, respectively, λ is signal wavelength in meters, d is the separation distance in meters, and L is the system loss factor.

12.1.1.2 Reflection

In addition to attenuation caused by the propagation distance, the transmitted wave can also be affected by surrounding objects. Reflection describes a phenomenon that takes place when the radio wave impinges upon a medium that has different electrical properties and has large dimensions compared to the wavelength of the propagating wave. Therefore, the electromagnetic wave may be reflected from the surface of the ground, walls, etc. While part of the wave energy reflects, some of the energy penetrates into the second medium; and the amount of reflected and transmitted energy depend on reflection coefficients, R, which can be computed given material properties of the two mediums (i.e., relative permittivity, ϵ_r and permeability, μ_i), angle of incidence (θ_i), and signal frequency (f) or wavelength.

In the propagation scenario where the first medium is free space and both mediums have the same permeability (i.e., $\mu_1 = \mu_2$), the reflection coefficients can be simplified as follows for vertical ($R_{||}$) and horizontal ($R_{\perp}$) polarization, respectively [2]:

$$R_{||} = \frac{-\epsilon_r \sin\theta_i + \sqrt{\epsilon_r - \cos^2\theta_i}}{\epsilon_r \sin\theta_i + \sqrt{\epsilon_r - \cos^2\theta_i}} \tag{12.2}$$

and

$$R_{\perp} = \frac{\sin\theta_i - \sqrt{\epsilon_r - \cos^2\theta_i}}{\sin\theta_i + \sqrt{\epsilon_r - \cos^2\theta_i}}. \tag{12.3}$$

Note that in the systems with low antennas and hence, small incidence angle (θ_i), both reflection coefficients, $R_{||}$ and $R_{\perp}$ approach 1 regardless of ϵ_r for perfectly smooth surfaces. In other words, the earth (i.e., the ground) can be abstracted as a perfect reflector: as the propagating signal grazes the earth, the reflected wave will be equal in magnitude and between 0° and 180° out of phase with the incident wave, thus resulting in constructive or destructive interference. This phenomenon gives rise to the *two-ray ground reflection* model [2]. In practice, V2V measurements have shown that, while V2V communication in LOS conditions exhibits a behavior that can be modeled by the two-ray ground reflection model, the magnitude of the ground-reflected ray is considerably lower than that predicted by the theoretical model [3, 4].

12.1.1.3 Diffraction

While reflection describes how a wave behaves when it impinges upon an object such as the ground, diffraction describes the phenomena in which the signal propagation path between a transmitter and a receiver is obstructed by objects. In this situation, the wave diffracts and propagates around the surfaces of the objects (i.e., propagates behind the obstacles). Diffraction mechanism can be explained by the *Huygens–Fresnel principle* which states that the propagation of a wave can be visualized by considering every point on a wavefront as a point source for a secondary spherical wave [2]. Electric field magnitude of the diffracted wave is thus the vector sum of the electric field components of these secondary waves and in some cases, it is sufficiently strong to produce a useful signal.

In general, diffraction loss can be calculated based on the difference between the direct path and the diffracted path (i.e., secondary waves). These differences are described by the concept known as *Fresnel zone*. The nth Fresnel zone is defined as the region where path length of secondary waves are $n\lambda/2$ greater than length of the direct LOS path. As a rule of thumb, only diffraction rays caused by obstacles in the first Fresnel zone attribute to the electric field of the wave received at the receiving antenna. Furthermore, if 55 % of the first Fresnel zone is kept clear, further Fresnel zone clearance does not significantly alter the diffraction loss [2].

The simplest model used to estimate signal loss due to diffraction is the *knife-edge* diffraction model [5]. Instead of modeling the diffraction loss over complex terrains, this model assumes that the obstruction can be estimated by treating them as a diffracting knife-edge. As a result, the signal attenuation caused by the diffraction over a knife-edge can be computed as follows:

$$\frac{E_d}{E_0} = F(v) = \frac{(1+j)}{2}\int_{v}^{\infty} \exp((-j\pi t^2)/2)dt, \tag{12.4}$$

where E_d is the electric field strength of a diffracted wave, E_0 is the free space field strength, and ν is *Fresnel–Kirchoff* diffraction parameter which is given by

$$\nu = h\sqrt{\frac{2d}{\lambda(d-d_{\text{obs}})d_{\text{obs}}}}, \tag{12.5}$$

where h is the obstructing height of the objects, d_{obs} is the distance between the transmitter and the obstacle, and d is the separation distance between the transmitter and the receiver. While the single knife-edge diffraction model is applicable only to a scenario with a single obstructing object, the extended multiple knife-edge model can model signal attenuation due to multiple obstructions and is usually used in practice [5].

12.1.1.4 Scattering

Scattering is used to describe a phenomena in which the transmitted wave encounters an object that has rough surface or object with dimensions that are small compared to the wavelength of the propagating wave. Surfaces of objects such as foliage, trees, street signs, lampposts, and vegetation can cause the reflected energy to scatter in all directions and provide additional signal energy at the receiver. Roughness of the surface is usually measured relative to a critical height, h_c, defined by the Rayleigh criterion [6]. A surface is considered smooth if its minimum to maximum disturbance is less than h_c and is considered rough otherwise. The critical height is expressed in terms of the signal wavelength, λ and incidence angle, θ_i:

$$h_c = \frac{\lambda}{8\sin\theta_i}. \tag{12.6}$$

For a rough surface, electric field intensity of the scattered waves can be computed in a similar manner as that of the reflected wave but with a modified reflection coefficient [7, 8]:

$$R_{\text{rough}} = \rho_S R, \tag{12.7}$$

where

$$\rho_S = \exp\left[-8\left(\frac{\pi\sigma_h \sin\theta_i}{\lambda}\right)^2\right] I_0\left[8\left(\frac{\pi\sigma_h \sin\theta_i}{\lambda}\right)^2\right], \quad (12.8)$$

where σ_h is the standard deviation of the surface height and I_0 is the Bessel function of the first kind and zeroth order.

12.1.1.5 Penetration Through Material

In addition to LOS, reflected, diffracted, and scattered rays, electric field intensity at the receiving antenna is also attributed to the waves that penetrate through materials (e.g., walls, buildings, foliage, etc.), noting that free space propagation and penetration through material are mutually exclusive. Models used to describe penetration loss are derived using empirical results, which can vary greatly depending on the type of environment (e.g., indoor or outdoor), wavelength, geometry, and the properties of the penetrated material. For instance, measurements have shown that windows can cause 6 dB attenuation loss on average and the presence of tinted metal in the windows could cause up to 30 dB additional penetration loss [9]. Transmission through trees also cause attenuation depending on the signal frequency and the penetration distance [10].

12.1.2 Wireless Channel Modeling

While it is impossible to precisely estimate signal attenuation caused by all of the aforementioned primitives (free space propagation, reflection, diffraction, scattering, and signal penetration loss), a number of models have been introduced that can reasonably predict the received signal strength. These models can be classified into three main types depending on the cause of signal attenuation: (1) a model to estimate *average* signal loss due to propagation distance, (2) a model to estimate *large-scale* variation caused by propagation environment, and (3) a model to estimate *small-scale* rapid fluctuation over a short period of time or distance. These models are often in the form of theoretical approximations that are adjusted and extensively validated by empirical measurements.

12.1.2.1 Path Loss

Path loss (PL) is a measure of the average RF attenuation as the electromagnetic signal travels from the transmitter to the receiver and is usually expressed in dB scale:

$$\text{PL(dB)} = 10 \log \frac{P_t}{P_r}, \quad (12.9)$$

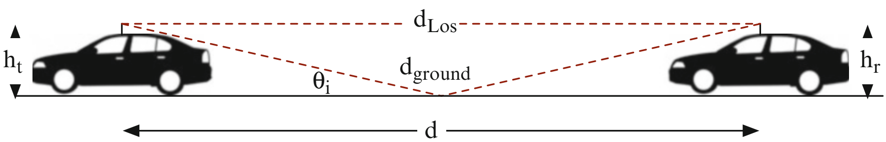

Fig. 12.1 Two-ray ground reflection model

where P_t and P_r are the transmitted and received signal power, respectively. While the Friis free space given in Eq. (12.1) provides a path loss estimate when the signal propagates in free space, measurements and theoretical studies have shown that in mobile radio channels, the average received power does not always follow the Friis space formula. Instead, the received power decreases *logarithmically* with separation distance. In other words, in the *log-distance* model, the average path loss for a given separation distance d, $\overline{\mathrm{PL}}(d)$ in dB, can be expressed as:

$$\overline{\mathrm{PL}}(d) = \overline{\mathrm{PL}}(d_0) + 10\gamma \log(d/d_0), \tag{12.10}$$

where $\overline{\mathrm{PL}}(d_0)$ is the average path loss (in dB) at a reference distance d_0, and γ is the path loss exponent, which denotes the power-law relationship between the separation distance and the received power. The value of γ is most often obtained from measured data and is usually in the range of 2–6, depending on the propagation environment.

Another widely used model in predicting path loss in mobile radio channels is the *two-ray ground reflection* model [2]. In contrast to a single direct path assumed in the log-distance model, in the two-ray ground reflection model, the signal received at the receiving antenna consists of *two rays*: the direct LOS ray and the ground-reflected ray (see Fig. 12.1). E-field (in volts per meter) for the two-ray ground reflection model is given by the following equation [2, Chap. 3]:

$$E_{\mathrm{TwoRay}} = \frac{E_0 d_0}{d_{\mathrm{LOS}}} \cos\left(\omega_c \left(t - \frac{d_{\mathrm{LOS}}}{c}\right)\right) + R_{\mathrm{ground}} \frac{E_0 d_0}{d_{\mathrm{ground}}} \cos\left(\omega_c \left(t - \frac{d_{\mathrm{ground}}}{c}\right)\right), \tag{12.11}$$

where $\frac{E_0 d_0}{d_{\mathrm{LOS}}}$ is the envelope E-field at a reference distance d_0, ω_c is the angular frequency ($\omega_c = 2\pi f$, where f is frequency), t is the time at which the E-field is evaluated, d_x represents distance traversed by ray x, and R_{ground} is the reflection coefficient of the ground-reflected ray. When the originating medium is free space, R_{ground} is calculated for vertical and horizontal polarization using Eqs. (12.2) and (12.3), respectively. The resulting received power Pr is equal to

$$\mathrm{Pr(dB)} = 20 \log(E_{\mathrm{TwoRay}}) + \mathrm{Gr}_{\mathrm{dB}} + 20 \log\left(\frac{c}{\sqrt{480}\pi f}\right), \tag{12.12}$$

where Gr_{dB} is antenna gain at the receiver and c is the speed of light. Note that the two-ray ground reflection model takes into account signal loss due to both signal propagation and reflection. Equation (12.12) assumes that the signal is reflected from the ground which is in the first Fresnel zone (as defined in Sect. 12.1.1.2).

12.1.2.2 Shadowing

The path loss model is one of the main ingredients of a propagation model. However, path loss model alone is not sufficient for predicting the received signal strength, since it does not take into account the rapid change in propagation conditions inherent in mobile systems and the resulting shadowing, diffraction, and scattering created by the environment.

Measurements have indicated that the average received power at the receiver antennas can be significantly different when measured at different locations despite having the same separation distance. This phenomenon is referred to as the *shadowing* effect.

The model that is commonly used to predict signal attenuation caused by the shadowing effect stochastically is the *log-normal* shadowing model. This model is based on empirical measurements which indicate that the path loss at a given location is random and distributed log-normally [11, 12]. The total path loss of Eq. (12.10) can be re-written as:

$$\overline{\mathrm{PL}}(d) = \overline{\mathrm{PL}}(d_0) + 10\gamma \log(d/d_0) + X_\sigma, \tag{12.13}$$

where X_σ is a zero-mean Gaussian distributed random variable (in dB) with standard deviation, σ (in dB). Similar to path loss exponent γ, the value of σ is usually obtained from measured data.

In vehicular networks, where both transmitter and receiver can be mobile, shadowing is more severe and dynamic compared to virtually any other network. For this reason, efforts have been made to calculate shadowing in a deterministic manner, using the information about the objects in the vicinity of the transmitter and receiver (e.g., [13, 39]).

12.1.2.3 Small-Scale Fading

In mobile radio channels, the signal received at the receiver antenna usually consists of multiple waves which are copies of the same transmitted wave but arrive at the receiver at different times and may have different amplitudes and phases. These multipath waves create the small-scale *fading* effects which cause the rapid fluctuation of the received signal over a short period of time or distance.

Fading is most pronounced in vehicular networks when there is no LOS path between the transmitter and the receiver. However, even in a scenario where a direct LOS path exists, the multipath phenomenon could also occur due to reflections from the ground and/or buildings. As a result, the severity of fading varies depending on the existence of a LOS path, structure of the surrounding environment, speed of mobile stations and surrounding objects, etc.

In general, the small-scale fading effect in mobile radio channels is described by either the Rayleigh or the Ricean distributions. The Rayleigh distribution is commonly used to describe the channel when there is no dominant LOS signal components and the random multipath waves may arrive at any angle. Probability distribution function (pdf) of the Rayleigh distribution is given by

$$p(r) = \begin{cases} \frac{r}{\sigma^2} \exp\left(-\frac{r^2}{2\sigma^2}\right), & \text{if } 0 \leq r \leq \infty, \\ 0, & \text{otherwise,} \end{cases} \tag{12.14}$$

where σ is the root-mean-square value of the received voltage and σ^2 is the time-average power of the received signal.

On the other hand, when a strong LOS path is present, the Ricean distributed signal envelope is used instead and the Ricean distribution:

$$p(r) = \begin{cases} \frac{r}{\sigma^2} e^{-\frac{r^2+A^2}{2\sigma^2}} I_0\left(\frac{Ar}{\sigma^2}\right), & \text{if } 0 \leq r \leq \infty, \\ 0, & \text{otherwise,} \end{cases} \tag{12.15}$$

where A is the peak amplitude of the dominant signal and I_0 is the modified Bessel function of the first kind and zeroth order.

Note that the measurements have shown that, on average, the received amplitude distribution gradually transitions from near-Ricean to Rayleigh as the separation distance increases and dominant path begins to fade away [14].

12.1.3 Propagation and Channel Modeling for Mobile Cellular Systems

A number of outdoor propagation models that take into account all the above factors have been introduced. Here, outdoor propagation models that are widely used in practice are presented. For example, the Longley–Rice model is a commonly used propagation model in the frequency range from 40 MHz to 100 GHz [15, 16]. In the Longley–Rice model, the two-ray ground reflection model is used to predict signal attenuation within the radio horizon and the knife-edge models are used to further account for diffraction loss caused by obstacles.

Okumura and Hata models are popular models for estimating signal attenuation in cellular mobile systems in city areas [17, 18]. Both of these models are based primarily on the classical free space path loss. In addition, correction factors are added to account for different terrains, antenna height, etc. Although Okumura and

Hata models provide very good signal loss predictions, both models are well suited only for the transmission between a stationary and elevated base station and a mobile station in cellular mobile systems.

Modeling channels in case of existence of LOS path (i.e., when the optical and electromagnetic path between the transmitter and receiver is unobstructed) is arguably a less difficult task than modeling non-LOS channels. A large number of studies tackled outdoor propagation modeling for mobile communication (for an extensive survey, see Sarkar et al. [19]). In terms of deterministic propagation modeling of non-LOS channels, research efforts often rely on Uniform Geometrical Theory of Diffraction [20]. One example is work by Anderson [21], where the author analyzed path loss induced by around-the-corner communication.

Erceg et al. [22] proposed a deterministic model for non-LOS communication in urban areas and validated it against measurements, whereas Durgin et al. [23] performed measurements and developed path loss models for non-LOS communication caused by residential buildings.

However, these models might not be best suitable for V2V communication, where both transmitter and receiver can be mobile and of similar, low height. To that end, the early work on mobile-to-mobile channels by Akki and Haber [24] is more relevant for modeling V2V communication.

12.2 Specific Considerations for Vehicular Channel Modeling

While a number of existing mobile channel models have been extensively used for cellular systems, they are not well suited for the vehicular systems, due to unique features of vehicular channels. For instance, difference in the relative height of transmitter and receiver antennas could lead to significant difference in the signal propagation behavior. Operating frequency and communication distance assumed in vehicular communications also differ from those of the cellular systems; i.e., vehicular communications systems operate mostly at 5.9 GHz and over short distance (100–500 m) whereas cellular systems operate at 700–2,100 MHz over a long distance (up to tens of kilometers) [25].

Because of the aforementioned differences, in this section we elaborate on specific issues that need to be considered for vehicular channel modeling. As depicted in Fig. 12.2, vehicular communication has distinct characteristics, such as varying surroundings that can include obstructing objects, thus creating a rich propagation environment, low height of both transmitting and receiving antenna, and potential mobility of the transmitter, receiver, and the surrounding objects. These characteristics result in highly variable quality of communication links. Figure 12.3 sheds light on the complexity of vehicular environment; even for single bounce (e.g., first-order) reflections and diffractions, the number of resulting rays is large. Calculating multiple-order rays results in nearly exponential increase of computational complexity. This example shows that capturing the complexities of vehicular channels is far from trivial.

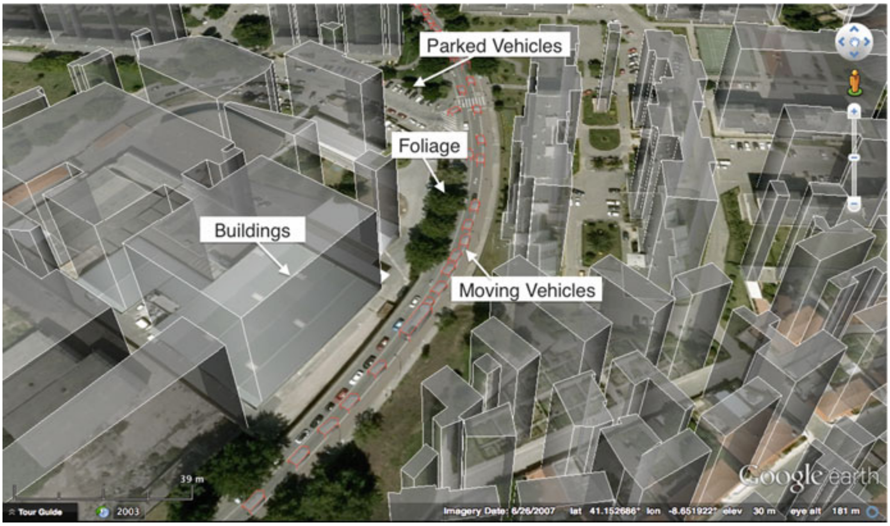

Fig. 12.2 Typical vehicle-to-vehicle communication environment. Building and vehicle overlays are generated using GEMV^2 [26]

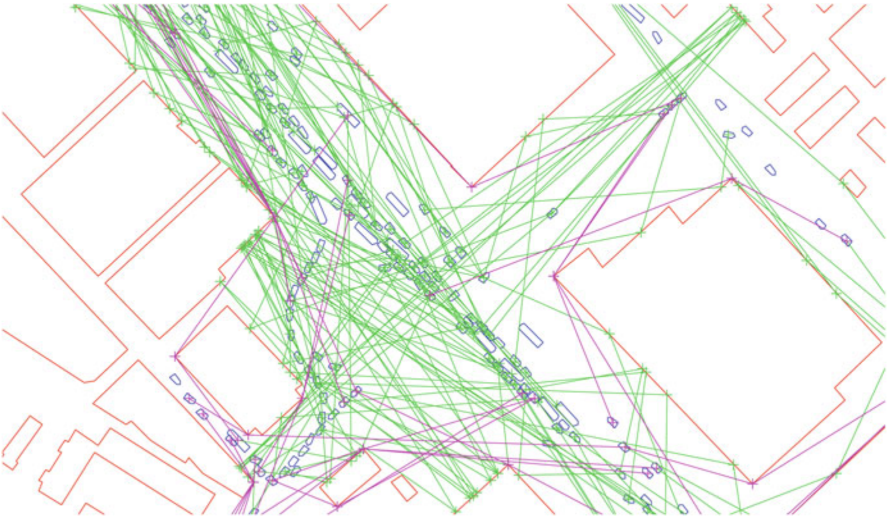

Fig. 12.3 Single bounce reflections (*green*) and diffractions (*magenta*) off buildings (*red*) and vehicles (*blue*) for a set of randomly selected transmit-receive vehicles. Results are generated using GEMV^2 [26]

12.2.1 Environments

Theoretical and measurement-based studies have indicated that environment has a tremendous impact on the characteristics of the mobile radio channels. For vehicular channel models, the propagation environments generally considered in the literature are rural areas, urban canyons, and highways. These environments are characterized by varying presence, locations, and density of roadside objects such as buildings, trees, parked cars, etc., as well as the velocity and density of traffic on the road. Considerably different propagation characteristics of these environments require that the channel models are designed for each of them separately.

For instance, V2V measurement campaigns have shown that the path loss exponents [i.e., γ in Eq. (12.10)] differ across various environment; measured path loss exponents were $2.3 \leq \gamma \leq 2.75$ in a suburban environment [27], $2.44 \leq \gamma \leq 3.39$ in an urban environment [28], and 3 in a parking garage [29].

12.2.2 Objects

As depicted in Fig. 12.2, the vehicular propagation environment may consist of a number of objects of different types and characteristics. We categorize these objects into two groups: (1) static objects such as buildings, trees, road signs, parked vehicles, etc.; and (2) mobile objects such as vehicles on the street. While both types of objects generally cause signal attenuation, the level of impact varies depending on the environment. For instance, mobile objects (i.e., vehicles on the roads) are more important objects to consider for modeling vehicular channels in highway environment, because communication between transmitting and receiving vehicles on highways usually happens over the road surface. On the other hand, in urban environment with two-dimensional topology, the communicating vehicles are likely to be on different streets. In this case, along with mobile objects, accounting for static objects is critical for modeling vehicular channels, since both types of objects are sources of shadowing, reflections, and diffractions [30].

12.2.3 Link Types

In addition to the nature of propagation environment, it is also important to distinguish between vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) channels as they exhibit vastly different propagation properties. In V2V channels, the transmitter and receiver antennas are usually mounted on the vehicle rooftop, whereas in the V2I channels, the base station (or access point) may be elevated.

The difference in relative height of the transmitter and receiver antennas poses significant difference in reflection, diffraction, and scattering patterns of the transmitted waves [31].

For example, in the V2I channels with elevated base stations, a transmitter and a receiver usually have a dominant LOS path which might not exist in the V2V channel, especially in a crowded urban area. In addition, since the elevated base station is usually not surrounded by scatterers, scattering effects leading to small-scale fading is reduced. For these reasons, the propagation channel in the elevated V2I system may be estimated using the existing cellular propagation models. Nevertheless, in some cases where the base stations are installed at the street level, the V2I channel experiences unique behavior [32].

A number of measurement campaigns have also indicated that the LOS condition is a key factor in modeling the V2V propagation channels. Measurements performed by Tan et al. [33] show that, regardless of propagation environment (e.g., highway or urban scenarios), non-LOS channel has noticeably larger delay spread than that of the LOS channels. This is due to stronger signal attenuation and multipath effects caused by an increasing number of reflections and scatterers. A detailed investigation on different link types and how they affect the vehicular channel modeling is given in the next sections.

12.3 Classification of Models

In an attempt to classify the models according to their most important characteristics, in this section we introduce and describe different "dimensions" we use to classify the models. While models may not necessarily fit into these categories perfectly, the categorization helps in understanding which model can be used for a particular purpose. Figure 12.4 shows different dimensions we use to classify the models.

12.3.1 Propagation Mechanism Scale

As described in Sect. 12.1.2, propagation models are typically divided by their scale into:

- *Path loss*, which is defined as distance-dependent signal attenuation;
- *Large-scale fading*, which includes signal variations due to shadowing by objects significantly larger than the carrier wavelength;
- *Small-scale fading*, which includes variations due to multipath and/or Doppler spread.

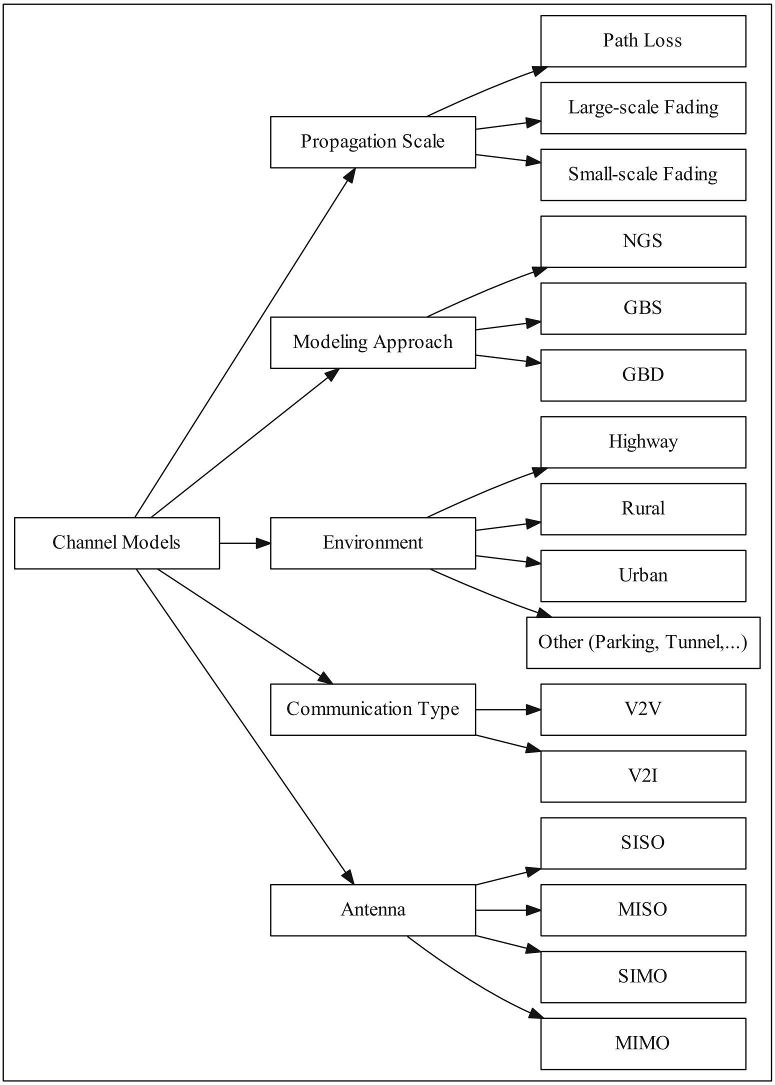

Fig. 12.4 Channel model classification

12.3.2 Modeling Approach

Depending on the use of geographical descriptors of the simulated area and on the approach to modeling the signal variations, the models can be divided into [14]:

- Geometry-based deterministic (GBD) models incorporate relevant objects in the simulated area and calculate the channel statistics in a completely deterministic manner. Ray-tracing method is an example of GBD models that requires a detailed description of propagation environment in order to reproduce the actual physical propagation process for a given environment [14]. By considering propagation factors caused by all possible paths, ray-tracing models can estimate the actual receive power within 3 dB standard deviation [39]. However, ray-tracing models are computationally expensive and not suitable for large-scale simulations. GBD models that are more scalable than ray-tracing have been proposed recently (for details, see Sect. 12.4).

- Geometry-based stochastic (GBS) models take into account the geometrical properties of the surroundings, but calculate the channel statistics according to the statistics extracted either from measurements or obtained through simulations. The simple GBS model used in V2V channel model is the *two-ring* model which assumes that scatterers are randomly placed in a *two-ring* structure, with one ring around the transmitter and one around the receiver [34]. A simplified ray-tracing method is then applied to this topology. In order to account for more realistic locations of scatterers in vehicular environment, another GBS model assumes that most of the scatterers such as buildings, trees, and houses are positioned along the sides of the road or the transmitter and receiver path. Furthermore, the model also takes into account different properties of these scattering objects [35].
- Non-geometrical stochastic (NGS) models generate channel statistics in a completely stochastic fashion, where both the geometrical properties and the channel statistics are generated stochastically. Examples of NGS models used for V2V channel modeling include a tapped-delay-line model. Each tap in this model represents signal received from several propagation paths; each with different delay and different type of Doppler spectrum [36].

12.3.3 Antenna and Small-Scale Fading Characteristics

Small-scale fading occurs due to multipath time delay spread and Doppler spread. If a channel model has the ability to model the statistics related to multipath time delay spread, including both flat and frequency-selective fading, we consider it as being able to model multipath delay spread. Similarly, if it is able to model the effects of Doppler spread, including both slow and fast fading, we consider it as being able to model Doppler spread.

Related to channel model's ability to incorporate small-scale fading is the ability to support different types of antenna configurations that exploit the positive and counter the negative effects of small-scale fading. Therefore, we include the information about the model's ability to support different antenna configurations (e.g., SISO, SIMO, MISO, MIMO).

12.3.4 Communication Type

Communication links considered in vehicular channels are usually classified into two groups: links between vehicles and links between a vehicle and a stationary (and potentially elevated) base station (i.e., infrastructure). Both of these models further distinguish communication links according to three conditions: line of sight (LOS), Non-LOS due to static objects (NLOSb), and Non-LOS due to vehicles (NLOSv).

The three LOS conditions lead to very different physical propagation behaviors. For a LOS link, power at the receiver is usually dominated by the direct LOS ray and the ground-reflected wave. In the absence of LOS, however, the most important rays in the NLOSb links are rays which are diffracted or reflected from *stationary* objects such as building, roadsigns, and streetlights. These diffraction and reflection phenomena are always present since the buildings are significantly taller than vehicles and can reflect the signal for any communicating pairs. While the waves can be reflected from vehicles, the reflected rays from stationary objects are often the dominating mechanism [37]. On the other hand, for a NLOSv link where the communication is blocked by vehicles only, reflection rays caused by tall vehicles should also be considered.

In addition to the large-scale variation, small-scale fading effects for different LOS conditions also vary depending on the richness of reflection environment (e.g., reflections in case of LOS, the number of obstructing vehicles in case of NLOSv, and deep or slight building obstruction in case of NLOSb [26]).

12.3.5 Environment

Vehicular channel models are mainly classified into the following categories based on the roadside environments and traffic characteristics:

- *Open space and highway* environment is characterized by one-directional, high-speed motion of vehicles. Roadside environment contains mostly vegetation with a few houses and street signs which are usually located far from the road.
- *Suburban* environment is a mixture of low-rise buildings and open spaces such as park areas and parking lots. These roadside objects are usually set further back from the curb as compared to the urban environment. Low to medium vehicle density and few pedestrians and bicyclists are assumed in this scenario.
- *Urban canyon* describes a scenario with high traffic densities and a higher density of pedestrians and cyclists. In contrast to open space and suburban street environments, urban vehicular channel models assume two-dimensional streets and consider the possibility that the communicating vehicles may be on different streets. In urban environments, objects such as buildings, houses, and street signs are densely scattered along the side of the road and tend to be located very close to the streets.

With regard to the applicability of a model to different environments, we distinguish between channel models that were calibrated by extracting the pertinent parameters from measurements at a specific set of locations and those that have the ability to model effects beyond those captured at particular locations. Since the former category depends on the measurements, it can be used to model the channel in locations similar to those where measurements were performed. However, these models can give no accuracy guarantees for locations with considerably different characteristics. On the other hand, models that take into account geometry-specific information of the simulated area can give some insights for environments beyond those characterized by the measurements. For this reason, we add another classification category named "Fitted to measurements," to describe the ability of the model to generalize to environments beyond those (similar to) the measured environments used to fit the model.

12.4 State-of-the-Art Vehicular Channel Models

Key distinguishing aspects of vehicular channels are varying path loss across space (e.g., different environments) and time (e.g., different time of day), potentially high Doppler shift, non-stationarity, and shadowing by both mobile objects (surrounding vehicles) and static objects (e.g., buildings, foliage) [26, 38–40]. Because modeling all of these aspects is a complex task, the most common approach thus far has been piecemeal modeling, wherein the problem is split into manageable parts and modeling is done on one or some of those parts. Therefore, certain models suit certain applications better than the other. For example, if the goal of a study is to evaluate system-wide performance of an ITS application involving hundreds or more vehicles, it is infeasible to use a detailed modeling approach such as the one described by Mittag et al. [41], where fine-grained statistics are calculated for each transmitted message (e.g., OFDM modulation and modulation, interleaving, convolutional decoding, etc.). On the other hand, such approach is well suited for precise modeling of intra-packet statistics in a small network over a short period of time.

Based on the classification described in Sect. 12.3, in this section we describe relevant channel models for vehicular communication. Specifically, in line with vehicular channel model surveys by Molisch et al. [25], Wang et al. [14], and Mecklenbräuker et al. [42], we group the models based on their modeling approach into NGS models, GBS models, and GBD models. Furthermore, we include both propagation models (which are concerned with physical characterization of radio wave propagation) and channel models (which also include the transmitting and receiving antenna characteristics, including any diversity methods). Table 12.1 summarizes the state-of-the-art vehicular propagation and channel models that are further described in the subsequent sections.

Table 12.1 Classification of channel models

Model	Propagation mechanism scale	Modeling approach	Ability to classify link types	Differentiation btw LOS/NLOS models	Antenna	Environment	Fitted to measurement	Per-link comput. complexity
Cheng et al. [27]	Large- and small-scale	NGS	No	No	SISO	Suburban	Yes	O(1)
Acosta and Ingram [43]	Small-scale	NGS	No	No	SISO	Urban, rural, highway	Yes	O(1)
Bernadó et al. [44]	Small-scale	NGS	No	No	MIMO	Urban, highway, suburban, tunnel, bridge	Yes	O(1)
Sen and Matolak [45]	Small-scale	NGS	No	No	SISO	Urban, highway	Yes	O(1)
Otto et al. [46]	Path loss and large-scale	NGS	No	Yes	N/A	Urban, suburban, open road	Yes	O(1)
Karedal et al. [30]	Path loss	NGS	No	No	N/A	Rural, highway, urban	Yes	O(1)
Matolak et al. [47]	Small-scale	NGS	No	No	SISO	Urban, highway	Yes	O(1)
Karedal et al. [35]	Path loss and small-scale	GBS	Yes (Stoch.)	Yes	MIMO	Rural, highway	Yes	$O(R+V)$
Cheng et al. [48]	Large- and small-scale	GBS	Yes (Stoch.)	Yes	MIMO	Rural, highway	N/A	$O((R+V)^2)$
Abbas et al. [49]	Path loss, large- and small-scale	GBS	Yes (Stoch.)	Yes	N/A	Highway	No	O(1)
Wang et al. [50]	Small-scale	GBS	Yes (Stoch.)	Yes	N/A	All	No	O(1)
Maurer et al. [39]	Path loss, large- and small-scale	GBD	Yes (Det.)	Yes	All	All	No	At least $O((R+V)^2)$

(continued)

Table 12.1 (continued)

Model	Propagation mechanism scale	Modeling approach	Ability to classify link types	Differentiation btw LOS/NLOS models	Antenna	Environment	Fitted to measurement	Per-link comput. complexity
Biddlestone et al. [51]	Path loss, large- and small-scale	GBD	Yes (Det.)	Yes	All	Urban	No	At least $O((R+V)^2)$
Mangel et al. [52]	Path loss and large-scale	GBD	No	Yes	N/A	Urban intersections	Yes	O(1)
Boban et al. [13]	Path loss and large-scale	GBD	Yes (Det.)	Yes	N/A	Highway	No	$O(V)$
Giordano et al. [53]	Path loss and large-scale	GBD	Yes (Det.)	Yes	N/A	Urban grid	No	$O(R)$
Cozzetti et al. [54]	Path loss	GBD	Yes (Det.)	Yes	N/A	Urban grid	No	O(1)
Pilosu et al. [55]	Path loss	GBD	No	No	N/A	Urban	N/A	O(1)
Boban et al. [26]	Path loss, large- and small-scale	GBD	Yes (Det.)	Yes	N/A	All	No	$O(R+V)$

R and V denote the number of roadside objects and vehicles, respectively. "Ability to classify link types" indicates whether or not the model includes a mechanism that can detect the LOS property of a link while "Differentiation between LOS/NLOS models" indicates whether or not the channel models use different modeling mechanisms for LOS and NLOS links

12.4.1 Non-geometrical Stochastic Models

Most NGS models conform to the following recipe: measuring the channel characteristics in a specific environment and adjusting the parameters of well-known path loss, shadowing, and small-scale fading models (e.g., log-distance path loss [56], two-ray ground reflection, Rayleigh/Rice/Nakagami fading [2], etc.). The studies below are not an exception: their computational complexity is usually low (e.g., O(1) per link.)

Cheng et al. [27] performed narrowband measurements of the V2V channel in the 5.9 GHz frequency band in a suburban environment. In the study, the measurement data was fitted to a dual slope piecewise log-distance path loss model; different fading statistics were also extracted from measurements. Acosta-Marum and Ingram [43] developed small-scale channel models that capture delay and Doppler characteristics of V2V communication. The models are based on extensive measurements for urban, suburban, and highway environments in the 5.9 GHz frequency band. The authors also develop packet error rate models for each of the channels. Bernadó et al. [44] performed extensive measurements in urban, highway, suburban environments, as well as measurements in a tunnel and on a bridge. Delay and Doppler statistics were extracted from measurements for each of the environments.

An extensive measurement campaign was performed by Sen and Matolak [45] in urban, suburban, and highway environments with two levels of traffic density (high and low). Based on the measurements, the authors proposed several V2V channel models that apply to a specific environment and vehicle traffic density. The study also points out the effect that the antenna location has on the channel characteristics. This leads to several antenna diversity techniques proposed to improve the packet reception in vehicular environment [57, 58]. Karedal et al. in [30] estimated path loss by performing measurements in rural, highway, suburban, and urban environments. Two-ray ground reflection model [2] was found to be the best fit for path loss in rural environment with low traffic density; in other environments, higher traffic density often created non-LOS conditions, thus the results did not conform to the two-ray model. Similar study was performed for V2V communication in the 2.4 GHz frequency band by Otto et al. in [46], where the authors perform measurements in urban, suburban, and open road environments at different times of day. Based on the measurements, the authors extract the path loss exponent and shadowing deviation for each environment. Due to the varying density of vehicles in different times of day, both path loss exponent and shadowing deviation were higher in case of measurements during daytime, when there were more surrounding vehicles. Different from other NGS models, the work in [46] makes a distinction between a LOS and non-LOS links. Based on the link condition, different channel parameters (i.e., median path loss exponent and shadowing standard deviation) are then estimated for each environment. It is important to note that the model is unable to detect the actual LOS condition of the link; rather, it assumes that the link type is known a priori. Lack of the geometry consideration and thus the inability to classify/detect the LOS condition of a link is one distinguishing factor between the NGS and geometry-based models, as discussed in the next subsections and shown in Table 12.1.

12.4.2 Geometry-Based Stochastic Models

Karedal et al. [35] designed a model for the V2V channel based on extensive measurements performed in highway and suburban environment in the 5.2 GHz frequency band. The model distributes the mobile scatterers (vehicles) and static scatterers at random locations and analyzes four distinct signal components: LOS, discrete components from mobile objects, discrete components from static objects, and diffuse scattering. While path loss, multipath, and Doppler spread are modeled, the existence of LOS component is assumed; therefore, the model does not distinguish between LOS and non-LOS conditions.

With regard to characterizing small-scale fading using actual scatterer locations, Wang et al. [50] employ aerial photography to determine the location and the density of scatterers in the environment. The scatterer density serves as the indicator of small-scale signal variation. The authors point out that aerial photography can be used to model static scatterers, whereas mobile scatterers need to be incorporated using a complementary technique.

Cheng et al. [48] proposed a MIMO V2V channel model that takes into account the LOS, single-bounced rays, and double-bounced rays by abstracting the scatterer positions using a combined two-ring and ellipse model. The model can be used in different V2V environments, provided that the appropriate parameters for a given environment are available.

Abbas et al. [49] designed a model that incorporates shadow fading for V2V communication. The distinction between LOS and non-LOS conditions is modeled using a probabilistic model based on Markov chains; transition probability between conditions is extracted from the probability distributions of the LOS and non-LOS conditions measured in different environments. The model demonstrates the importance of differentiating a LOS link from a non-LOS link as well as energy contributed from LOS and non-LOS rays.

12.4.3 Geometry-Based Deterministic Models

One of the first efforts to describe V2V channels in a fully deterministic manner was by Maurer et al. [39]. The authors propose an optical ray tracing model that uses a geographic database of all relevant objects in the simulated area. It calculates the channel statistics by analyzing the 50 strongest propagation paths between the transmitter and receiver. The model showed close agreement with the measurements performed in the same location. However, the model is computationally complex and requires a precise and detailed geographical database. A similar study was performed by Biddlestone et al. [51], where authors propose a propagation model that employs ray-tracing. Outlines of buildings are used to determine LOS conditions and perform reflections and diffractions to estimate the received power in LOS and non-LOS conditions. The model matches well the small-scale measurements performed by the authors. However, the computational complexity of the model remains an issue.

Several models were proposed with the goal of reducing the computational complexity and the need for complex geographical databases, at the same time keeping the beneficial characteristics of deterministic modeling (e.g., modeling effects of shadowing by actual objects). Below we overview these models.

The largest variation in path loss arises due to changing LOS conditions [28, 49, 59]. In particular, the rapid transitions between LOS and non-LOS conditions create considerably different channel statistics in terms of path loss as well as small-scale fading (e.g., delay spread). This has a significant impact on the performance of V2V applications [4, 32]. To that end, the following propagation models attempt at modeling the LOS obstruction in an efficient manner.

Urban intersections are a particularly interesting scenario when it comes to channel modeling. From the application point of view, the vehicles that are in shadowed, non-LOS region are arguably the most interested in receiving a message, particularly in case of safety messages, where receiving the message can prevent an accident. To that end, Mangel et al. [52] developed VirtualSource11p, a model that incorporates the relevant information about street intersections (e.g., street width, existence of buildings on intersection corners, etc.). The model is fitted to the measurements that the authors performed at representative intersections. Cozzetti et al. in [54] extend this model to account for propagation across multiple intersections in an urban grid environment. The model is able to emulate the hidden terminal phenomenon that leads to an unexpected drop in packet receptions at the center of intersections.

In highways, static objects rarely obstruct LOS for V2V communication. However, LOS is often blocked by surrounding vehicles, in particular large commercial vans and trucks. Measurement results showed that the LOS obstruction due to a van could cause up to 20 dB attenuation, whereas a large truck can cause in excess of 30 dB attenuation [59]. Boban et al. [13] developed a model that deterministically calculates the additional attenuation due to obstructing vehicles by abstracting vehicles as diffracting objects using the multiple knife-edge diffraction model [5]. The model was validated against measurements in open space and on highways.

In terms of channel modeling on a city-wide scale, Giordano et al. propose CORNER [53], an efficient propagation model for a grid-like urban environment. CORNER separates the links into three categories, based on the LOS obstruction level caused by buildings near the road intersections. The authors compared CORNER to measurements in terms of packet success ratio and found good agreement. Pilosu et al. [55] propose RADII, a propagation model that incorporates a preprocessing technique for ray-tracing simulations. RADII can simulate propagation for an arbitrary urban geometry at different levels of granularity. RADII was implemented in the NS-2 network simulator [60]. In an attempt to model signal propagation in the complete set of environments where V2V communication can occur (e.g., highway, rural, urban, complex intersections, etc.), Boban et al. developed $GEMV^2$ [26], a computationally efficient propagation model that uses outlines of vehicles, buildings, and foliage to distinguish the following three types of links: LOS, non-LOS due to vehicles, and non-LOS due to static objects. For each link, $GEMV^2$ calculates the large-scale signal variations deterministically, whereas the small-scale signal variations are calculated stochastically based on the number and size of surrounding objects. For links whose LOS is obstructed by other vehicles, $GEMV^2$ implements vehicles-as-obstacles model [13]. $GEMV^2$ can simulate city-wide vehicular networks with thousands of communicating vehicles. It was validated against extensive measurements performed in urban, suburban, highway, and open space environment.

Note that the propagation models above can serve as a basis for a more fine-grained channel modeling, where small-scale effects are incorporated. This can be achieved by assigning small-scale channel statistics (e.g., delay and Doppler spreads) to each link based on the detected link properties (e.g., LOS obstruction, environment, etc.). The per-link-type statistics can be obtained from measurements (e.g., [61–63]).

12.4.4 Which Model to Use and When?

Models listed in Table 12.1 differ in many aspects: from stochastic models that do not include any information about the specific propagation environment under investigation, to environment-specific models with parameters extracted from measurements, to geometric models that can give good estimates of channel statistic even in locations that have not yet been surveyed with measurements. The decision on which model to use should ultimately depend on the type of application and/or protocol that needs to be evaluated [1]. However, practical issues of the availability of the required data (be it geographical or measurements data) and required processing power also dictate which models can be used in practice. Below we discuss several use-cases and give recommendation on which type of model to use.

- Application requirements
  - If system-wide networking performance statistics are of interest (e.g., overall packet delivery rate, average end-to-end delay, etc.) AND simulation speed is important, then measurement-derived NGS models may be used.
  - If network topology statistics are of interest (e.g., determining the number and size of clusters of directly communicating vehicles, determining average neighborhood size, etc.), then either GBS or GBD models may be used. Conversely, NGS models are not able to generate such statistics correctly, because of their location-agnostic channel estimation, which leads to “averaging” of the resulting network statistics (e.g., number of vehicles per cluster would be roughly equal in a built-up urban area and in an open space containing two-dimensional roads of similar structure to the urban area).

  - If analyzing performance of a routing protocol in a large area with rapid channel fluctuations (e.g., city with high-rises), simplified GBD models are best suited for the purpose, due to their ability to quickly and correctly distinguish where and when messages can be relayed between two vehicles as a result of the surroundings.
  - If simulating safety-critical application that disseminates information about a specific safety event (e.g., emergency breaking, blind intersection warning, etc.), then GBD models should be used.

- Geographic data and processing limitations

  - If detailed geographic information is available (e.g., locations, dimensions, and material properties of vehicles, buildings, foliage, and other roadside objects) AND processing speed is not an issue (either due to small simulation area or availability of computing power), very detailed channel model based on ray tracing method can be used (e.g., Maurer et al. [39]).
  - If limited geographic information is available (e.g., outlines of vehicles and objects surrounding the road), with processing speed being important (though not critical), then simplified GBD models can be used (e.g., Boban et al. [26]).
  - If geographic information is not available, but the qualitative type of simulated environment are known (e.g., performing highway, urban, or rural simulations), GBS models [35, 48, 49] may be used—apart from environment type, these models require only the information about the density of the scatterers and roadside objects.

However, as the evaluation of vehicular communication moves from the academic sphere (where certain level of lower-layer abstraction might be allowed to increase simulation performance) into the real world (where application and protocols are simulated to assess their suitability for deployment), the necessity to use realistic channel models increases. Therefore, using non-geometric models is only suitable for applications constrained to a single real-world propagation environment whose statistics do not change considerably over space and time (e.g., tunnel with low density traffic, unobstructed open space communication, etc.). In all other situations, geometry-based models should be used that are, at minimum, able to account for dynamic link transitions from LOS to NLOS conditions (large-scale signal variations) and that can model dynamic small-scale variations based on the transmitter and receiver surroundings.

12.5 Future Directions

This section has provided an overview of mechanisms that govern wireless vehicular communication and its modeling. We introduced the basic wireless communication primitives and we discussed the characteristics that distinguish the vehicular communication from other types of wireless communication. We then classified and summarized the state-of-the-art vehicular channel and propagation models. While there has been a lot of work in the area of vehicular channel modeling, below are some areas where further research efforts are welcome.

12.5.1 Measurements and Models for Diverse Vehicular Environments

While there exist numerous channel measurement and modeling studies dealing with the most common environments (e.g., urban, suburban, highway), there is a need for more systematic studies in other environments. For example, V2V signal propagation measurement in a parking garage has been performed in one study to date [29]; similar applies to V2V communication in tunnels, where one of the rare studies was done by Maier et al. [64] and bridge environment (a few studies, including one by Bernadó et al. [44]). Overpasses, multi-level highways (see Fig. 12.5 for an illustrative example), as well as more complex parts of known environments (e.g., roundabouts in urban environment, shadowed on-ramp highway access, etc.) are not well explored.

12.5.2 Measurements and Models for Different Vehicle Types

Research community has been performing channel measurements and modeling primarily focused around personal cars. Studies dealing with other types of vehicles (e.g., commercial vans, trucks, scooters, and public transportation vehicles) are rare, despite them having considerably different dimensions and road dynamics. For example, the mobility of scooters and motorcycles is notably different than that of personal cars [65]. Combined with their smaller dimensions and lack of roof for antenna placement, the mobility of scooters indicates that the propagation characteristics for scooters can be significantly different than that of personal cars. Similarly, recent studies have shown that, in the same environment, commercial vans and trucks experience different channel propagation characteristics than the personal cars. This resulted in different reliable communication range and packet error rates [66, 67]. Therefore, further studies are needed that investigate channel characteristics for vehicles other than personal cars.

12.5.3 V2I

Apart from some recent efforts (e.g., by Chelli et al. [68]), V2I channel modeling is not nearly as well-researched as V2V—for example, all models described in Table 12.1 focus on V2V communication. Part of the reason is that V2I resembles

Fig. 12.5 The High Five Interchange in Dallas represents a complex environment where vehicular communication can improve safety and efficiency. Modeling this and similar environments is a complicated, but important task. Photo by austrini, available under a Creative Commons Attribution license

existing cellular systems, where one of communicating entities (base-station) is stationary while the other (user equipment) is mobile. However, typical positioning of static (infrastructure) nodes in V2I communication is unique for vehicular communication: in highways, road side units (RSUs) will be placed close to the road and at heights considerably lower than that of cellular base stations (see, e.g., current efforts within the Amsterdam Group: https://www.amsterdamgroup.mett.nl). In urban areas, the most beneficial locations are near large intersections. Furthermore, a study performed by Gozalvez et al. [32] showed that V2I communication in urban areas is highly variable, with both static and mobile objects creating a considerably changing channel over both space and time. Therefore, there exists a need for further studies investigating the V2I channels.

12.5.4 Tools for Realistic Large-Scale Simulation

As the deployment phase in main markets is getting closer [69], realistic channel modeling for large-scale simulations is necessary for effective evaluation of applications before they are deployed in the real world. However, channel and propagation models currently used to simulate V2V and V2I communication in VANET simulators (e.g., NS-3 [70]) are based on simple statistical models (e.g., free space, log-distance path loss [2], etc.) that are used indiscriminately for all environments where communication occurs. These models cannot capture the complexities of the vehicular channel, namely rapid transitions between LOS and non-LOS conditions, changes in delay and Doppler spread, etc. Consequently, simple models were shown to exhibit poor performance in terms of link-level modeling, particularly in complex environments [71]. A way forward in this respect would be to combine geometry-based scalable propagation models (e.g., [26, 49]), which are able to distinguish between different LOS conditions and environments, with small-scale channel models, which are able to provide appropriate delay and Doppler statistics for each representative environment (e.g. [27, 44]). Finally, attempts should be made to implement such realistic models in large-scale network simulators in order to enable realistic evaluation of protocols and applications.

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