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Impact of the radio channel modelling on the performance of VANET communication protocols

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Abstract The expected traffic safety and efficiency benefits that can be achieved through the development and deployment of vehicular ad-hoc networks has attracted a significant interest from the networking research community that is currently working on novel vehicular communication protocols. The time-critical nature of vehicular applications and their reliability constraints require a careful protocol design and dimensioning. To this aim, adequate and accurate models should be employed in any research study. One of the critical aspects of any wireless communications system is the radio channel propagation. This is particularly the case in vehicular networks due to their low antenna heights, the fast topology changes and the reliability and latency constraints of traffic safety applications. Despite the research efforts to model the vehicle-to-vehicle communications channel, many networking studies are currently simplifying and even neglecting the radio channel effects on the performance and operation of their protocols. As this work demonstrates, it is critical that realistic and accurate channel models are employed to adequately understand, design and optimize novel vehicular communications and networking protocols.

Keywords Wireless vehicular communications · Radio channel modeling · Dimensioning and optimization · System simulations

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1 Introduction

Vehicular Ad-Hoc Networks (VANETs) have been identified as a promising Intelligent Transportation System (ITS) technology to improve traffic safety and efficiency while providing Internet access on the move. To reach these ambitious goals, V2V (Vehicle-to-Vehicle) and V2I (Vehicle-to-Infrastructure) systems allow the wireless transmission of information among vehicles and with road infrastructure, which effectively enables vehicles that are not within direct sight of each other to exchange information that will help preventing any potential road traffic danger or improving road mobility. The potential of these new technologies is such that the IEEE is currently developing an amendment to the IEEE 802.11 standard (IEEE 802.11p) [1] and the European Telecommunications Standards Institute (ETSI) has established a technical committee to develop the new vehicular communication standards [2].

The potential impact of vehicular communications has been fueling lately important research work from the communications and networking engineering communities. Although hardware prototypes are being developed, the complexity of VANETs is such that most of the research is being conducted through simulations. Nevertheless, these simulation investigations are critical to adequately dimension and configure the operation of VANET systems, especially considering the strict reliability and latency requirements of traffic safety applications and the fast network topology changes due to the vehicles' mobility. The strict communication requirements of vehicular applications result in the need to carefully conduct VANET research studies using adequate and realistic models that ensure achieving accurate results. For example, it has been shown that vehicular mobility models can considerably impact the performance and operation of VANET simulations, and realistic mobility models are needed for a precise analysis of VANET protocols and applications [3].

Based on simulation, interesting studies have been conducted to analyse and improve the performance of the IEEE 802.11p protocol, such as in [4] and [5]. In particular, the work in [4] proposes the dynamic adaptation of the IEEE 802.11p backoff window sizes as a function of the number of vehicles in the transmission range to improve the throughput. The work in [5] evaluates the Enhanced Distributed Channel Access (EDCA) protocol of IEEE 802.11p, which considers service differentiation, taking into consideration the specific conditions of the control channel, and presents detailed results in terms of throughput, packet losses, buffer occupancy and delays. Based on IEEE 802.11p, other studies analyse the performance of multihop routing and data dissemination protocols in VANETs. For example, the work in [6] proposes and analyses the performance of small-scale and large-scale routing protocols in urban environments, considering realistic mobility models. The study presented in [7] proposes an adaptive reactive routing protocol for VANETs based on the traffic density estimation of the paths to be used, which has been shown to improve the performance of the protocol. In fact, for this type of protocols the traffic density (or the number of neighboring vehicles) can be an important parameter and has been analysed in other studies such as in [8], considering multipath and mobility effects in highway scenarios.

A key, but yet underexplored for vehicular environments, aspect of any wireless system is radio propagation. Radio propagation modelling has been shown to have a significant impact on the performance of communications techniques in traditional mobile and wireless communication systems [9] and ad-hoc networking systems [10]. In [10] the authors conduct an interesting investigation on the importance of propagation modelling to adequately study routing protocols in low mobility MANETs (Mobile Ad-hoc Networks). Although some interesting work has already being carried out to characterize the radio propagation for vehicular communication systems (see e.g. [11] and [12]), more research is needed to adequately understand the vehicular channel and develop channel models suitable for system level investigations. The creation of such radio channel models would represent a valuable resource for designers and developers, not only to properly evaluate the performance of advanced communication schemes, but also to fairly compare different novel proposals.

Despite the demonstrated importance of the radio channel modelling on the performance of traditional cellular systems, many VANET research studies significantly simplify, or even neglect, the impact of radio propagation on the operation and benefits that can be achieved through the use of VANET communications and networking protocols. This is particularly dangerous for vehicular networks due to unfavorable propagation conditions that can be experienced due to low transmission antenna heights in V2V communications and highly mobile ad-hoc communication networks.

In this context, this work is not aimed at developing new radio channel models for the vehicular environment but at investigating the impact of the radio channel modelling on the performance, dimensioning and operation of VANET communications and networking systems. In particular, the study focuses on the reliability and time-critical V2V safety applications and the challenging operation of VANET ad-hoc routing protocols. The final aim of this research is to provide information to the research community about the level at which radio propagation needs to be modeled to conduct valid investigations intended to design V2V and V2I systems. Interesting initial investigations on this topic have been presented. In [13], the authors conducted a simulation study to investigate the effects of realistic channel characteristics on packet forwarding strategies for vehicular ad-hoc networks. In particular, the authors analyzed these strategies using deterministic (Two-Ray-Ground) and probabilistic (Nakagami) radio propagation models and showed that the radio propagation model utilized can have a considerable, not always negative, impact on protocol performance. The authors have also analyzed this issue with regard to the capabilities of IEEE 802.11 to coordinate packet transmissions and avoid collisions [14]. In this context, this work complements these useful initial investigations considering a different analysis approach. In this case, this work gradually increases the radio channel modelling accuracy with the aim to identify and quantify the varying contributions of each radio propagation effect (pathloss, shadowing and multipath fading) on the dimensioning and configuration of VANETs. In addition, this investigation is not limited to the system level impact but also considers the radio channel modelling impact on the capacity to instantaneously guarantee the strict reliable communication requirements that characterize VANET systems.

To demonstrate the impact of the radio channel modelling on the performance, operation and understanding of VANETs, two key communication scenarios are considered. The first one represents an intersection V2V collision avoidance application. In this case, guaranteeing the correct reception, and hence the adequate configuration of the communication parameters, of a broadcast beaconing message from the potentially colliding vehicle with sufficient time for the driver to react is key to avoid the collision at the intersection. The second scenario implements a set of geographical-based VANET routing protocols to disseminate safety or traffic efficiency information among vehicles. The capacity to route information without the participation of road side infrastructure is a key feature for the initial and gradual deployment of VANET systems. It is interesting to note that the selected evaluation scenarios allow analyzing the impact of the radio channel modelling on both one-hop and multi-hop VANET communications.

This paper is organized as follows. Section 2 describes the main features of the IEEE 802.11p communications technology, which is being especially designed to operate in the vehicular environment, and is the basis of this study. Section 3 details the radio channel effects and models considered in this work. Section 4 analyses the impact of the radio channel modelling accuracy on the performance evaluation of 1-hop traffic safety VANET applications, including scenarios with and without channel congestion. Section 5 studies the effect of the accuracy of the radio channel modelling on the performance and operation of different multi-hop ad-hoc routing protocols in urban environments. Finally, Sect. 6 summarizes the main results obtained and concludes the paper.

2 Wireless access for vehicular environments

This work is based on the Wireless Access for Vehicular Environments (WAVE) technology which is being developed by the IEEE to adapt the IEEE 802.11 operation to the vehicular environment and is being adapted to the European context by ETSI TC ITS in the ITS-G5 standard. In the US, WAVE is based on seven ten-megahertz channels consisting of one control channel and six service channels in the 5.9 GHz band. Similarly, in Europe, 30 MHz have been reserved in the same frequency band for cooperative vehicular systems and are currently divided in one control channel and two service channels [15]. The service channels are used for public safety and private services, while the control channel is used as the reference channel to initially detect surrounding vehicles and establish all communication links. As a consequence, the control channel is mainly used to periodically broadcast positioning, movement and status information to surrounding vehicles by means of CAMs (Cooperative Awareness Messages) in Europe or Heartbeat WSMs (WAVE Short Messages) in the US [16].

The IEEE 802.11p [1] standard defines the WAVE physical and MAC (Medium Access Control) layers of the protocol stack. IEEE 802.11p is based on the DCF (Distributed Coordination Function) of IEEE 802.11 and consequently makes use of the CSMA/CA medium access mechanism to grant the vehicles access to the communications channel. IEEE 802.11p employs the EDCA mechanism from IEEE 802.11e to support service priority and QoS differentiation. Four different queues corresponding to four different service classes are provided. The ad-hoc mode is the only operational mode allowed in the control channel. At the physical layer, IEEE 802.11p uses Orthogonal Frequency Division Multiplexing (OFDM) with a maximum data transmission rate of 27 Mbps in 10 MHz channels. The default data rate used in the control channel is 6 Mbps, which corresponds to the QPSK transmission mode with a coding rate of 1/2.

3 Radio channel modelling

Accurate radio propagation models for system level investigations must properly reflect the effects of pathloss (*PL*), shadowing (*SH*) and multipath fading (*MP*) [17]. While the pathloss represents the local average received signal power relative to the transmit power as a function of the distance between transmitter and receiver, the shadowing models the effect of surrounding obstacles on the mean signal attenuation at a given distance. The multipath fading effect results from the reception of multiple replicas of the transmitted signal at the receiver. Previous research has demonstrated the importance of an accurate radio channel modelling to adequately evaluate communication techniques in traditional mobile and wireless communication systems [18, 19]. However, the relative youth of the research in the vehicular networking domain has resulted in that many vehicular communications and networking studies have been based on rather simple radio channel models that are not capable to accurately reflect the challenging vehicular channel conditions [20, 21].

The received signal power (*Pr*) can be calculated in dB using the following equation, that considers the transmission power (*Pt*) and the different propagation phenomena, and does not consider antenna gains and circuit losses:

$$Pr = Pt - PL - SH - MP. \tag{1}$$

To analyse the impact of the radio propagation modelling on the understanding and evaluation of vehicular communication protocols and communication techniques, this work implements different radio propagation models varying from deterministic propagation models to a more realistic channel model accounting for the variability present in the radio channel.

3.1 Pathloss

Many different pathloss models can be found in the literature and three of them have been considered in this work. One of the implemented pathloss models is the Two Ray Ground model, normally employed for Line-of-Sight (LOS) propagation conditions, which approximates the pathloss as:

$$PL(d) = \begin{cases} 10\log_{10}(\frac{d^2(4\pi)^2}{\lambda^2}) & \text{if } d < d_c, \\ 10\log_{10}(\frac{d^4}{h_A^2 h_B^2}) & \text{if } d \geq d_c \end{cases} \tag{2}$$

where

$$d_c = \frac{4\pi h_A h_B}{\lambda}, \tag{3}$$

d is the distance between transmitter and receiver, h_A and h_B are their respective antenna heights, and λ is the carrier wavelength, all of them in m. For $d < d_c$, this model is equivalent to the Free Space propagation model. The Two Ray Ground model has been considered as a reference model since it is widely used by the vehicular networking research community, such as in [22], and it is incorporated in ns2 [23], which is the simulation platform employed in this work.

To consider the higher losses experienced in urban environments, a log-distance pathloss model has also been implemented, based on the following expression:

$$PL(d) = PL(d_0) + 10n\mathrm{Log}_{10}\left(\frac{d}{d_0}\right) \tag{4}$$

with n being the pathloss exponent, usually determined by field measurements, and $PL(d_0)$ the pathloss experienced at reference distance d_0, calculated using the Free Space propagation model. Following the indications in [24], the pathloss exponent ranges from $n = 2.7$ to $n = 5$ for urban scenarios. For $n = 2$, this model is equivalent to the Free Space propagation model. This model is also implemented in ns2 and has been considerably used by the vehicular networking research community, such as in [25] or [26], especially for urban environments.

The previous two models are not capable to differentiate between LOS and NLOS propagation conditions, which has been proven to significantly influence the received signal. To this aim, a third pathloss model, named LOS/NLOS, that differentiates visibility conditions between transmitter and receiver due to the presence of buildings, has also been implemented. The LOS/NLOS pathloss is expressed under LOS conditions as [27]:

$$PL_{LOS}(d) = \begin{cases} 22.7\log_{10}(d) + 41 + 20\log_{10}(f/5) \\ \quad \text{if } d < R_{bp}, \\ 40\log_{10}(d) + 41 - 17.3\log_{10}(R_{bp}) \\ \quad + 20\log_{10}(f/5) \quad \text{if } d \geq R_{bp} \end{cases} \tag{5}$$

where

$$R_{bp} = 4\frac{(h_A - 1)(h_B - 1)}{\lambda} \tag{6}$$

and f is the carrier frequency in GHz. For NLOS conditions, the pathloss is expressed as:

$$PL_{NLOS}(d_A, d_B) = PL_{LOS}(d_A) + 20 - 12.5n_j + 10n_j\log_{10}(d_B) \tag{7}$$

where

$$n_j = \max(2.8 - 0.0024d_A, 1.84) \tag{8}$$

and d_A and d_B are the transmitter and receiver distances to the closest intersection.

Figure 1 shows the effect on the received signal level for the different pathloss models implemented in this work. It is important to highlight the high difference between the LOS and NLOS pathloss models (between 30 and 40 dB in average) because it considerably impacts the communications between vehicles depending on whether they are obstructed by a building or not.

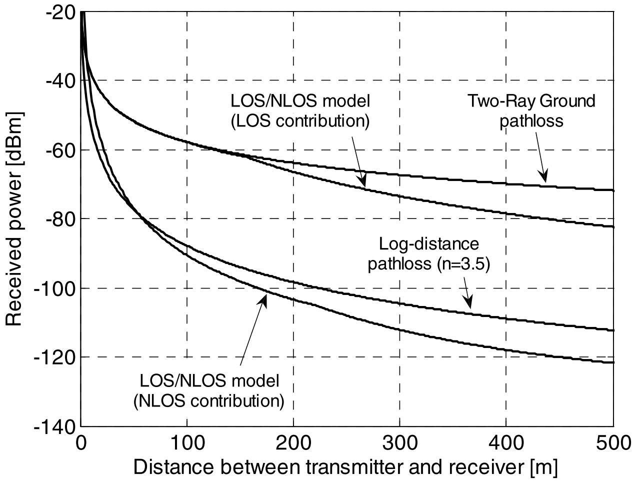

Fig. 1 Received power level for the various implemented pathloss models ($Pt = 1$ W $= 30$ dBm)

3.2 Shadowing

The shadowing is normally modeled following a log-normal distribution with a zero mean and a standard deviation σ that depends on the operating conditions, normally between $\sigma = 4$ dB and $\sigma = 12$ dB for outdoor propagation conditions [24]. Gudmunson also demonstrated that the shadowing is a spatially correlated process [28], which results in that the shadowing experienced by a mobile at a given position is correlated to that experienced at a nearby position. Given the impact of such spatial correlation on the performance of mobile and wireless radio systems, including vehicular communication systems [29], the Gudmunson model considering an exponential autocorrelation function has also been implemented for this work. This model describes the correlation of the shadowing process at a distance d as:

$$R_{yy}(d) = \sigma_s^2 \cdot \exp\left(-\frac{|d|}{d_S}\right) \tag{9}$$

where σ_S is the shadowing standard deviation and d_S equals $D/\ln(2)$, with D being the distance at which the normalized correlation is 0.5. To illustrate the effect of the shadowing spatial correlation on the received signal level, Fig. 2 compares the received power for a moving vehicle with and without considering the shadowing correlation.[1]

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[1] This figure has been plotted considering the NLOS contribution of the LOS/NLOS pathloss model.

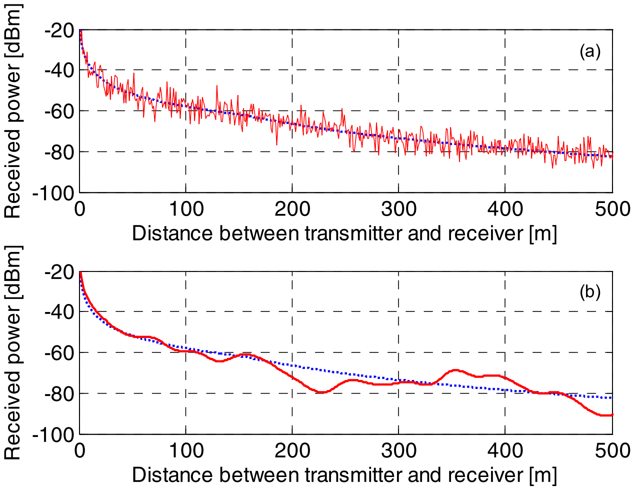

Fig. 2 Effect of shadowing correlation on the received signal level with $Pt = 1$ W $= 30$ dBm. (**a**) Uncorrelated shadowing. (**b**) Correlated shadowing

3.3 Multipath fading

The multipath fading effect resulting from the reception of multiple replicas of the transmitted signal at the receiver has also been shown to have a significant impact on the performance of mobile and wireless communication systems. As a result, a multipath fading implementation following the observations reported in [27] has also been considered. In particular, the multipath fading is modeled by means of a Ricean random distribution under LOS propagation conditions. The probability density function for the Ricean envelope r is given by:

$$PDF(r) = \frac{r}{\sigma^2} \exp\left(-\frac{r^2 + A^2}{2\sigma^2}\right) I_0\left(\frac{Ar}{\sigma^2}\right) \tag{10}$$

where I_0 is the zero-order modified Bessel function of the first kind. The parameters A and σ are related with the K parameter, which is normally used to describe a normalized Ricean distribution:

$$K = \frac{A^2}{2\sigma^2}. \tag{11}$$

Following the indications in [27], K depends on the distance between transmitter and receiver as follows:

$$K = 3 + 0.0142d \tag{12}$$

where d is expressed in meters and K in dB. Under NLOS propagation conditions, the signal variability is considerably higher than in LOS conditions and a Rayleigh random distribution has been considered in this case [27].

A realistic system propagation modelling has to include models for the pathloss, shadowing and multipath fading effects. The more complete model implemented in this work and referred to as realistic model, considers the LOS/NLOS pathloss model, correlated log-normal shadowing and the multipath fading implementation reported in this section. This complete model has been obtained from a detailed urban micro-cell propagation model developed in the WINNER project [27], which was extracted from field measurements in urban environments. This realistic model captures all radio propagation effects and therefore provides a close representation of real signal measurements. In this work, it will constitute the benchmark over which other channel models will be compared, in order to conclude whether they would provide different conclusions to those obtained in real systems. Despite not being developed for V2V communications, the operating conditions of the WINNER urban micro-cell model are to the authors' knowledge those that currently best fit the V2V communications scenario for a system level propagation modelling.[2] Moreover, despite considerable progress in V2V channel modelling [11, 12], to the authors' knowledge there is currently no complete system level channel model for wireless vehicular communications systems. To illustrate the radio propagation effects, Fig. 3 shows the combined effect of pathloss, shadowing and multipath fading on the received signal power for a moving vehicle receiving packets under LOS and NLOS propagation conditions considering the detailed WINNER urban microcell propagation model implemented.

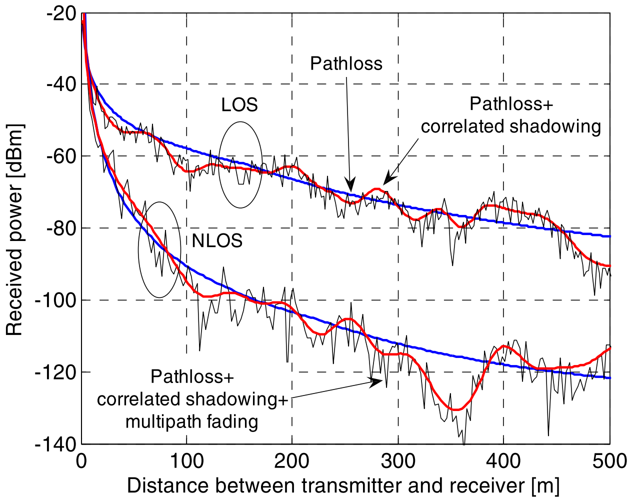

Fig. 3 Realistic propagation model based on WINNER ($Pt = 1$ W)

3.4 Physical layer implementation

To reduce the complexity of system level simulations, the effects of the physical layer (e.g. modulation and coding)

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[2] The model considers an operating frequency in the 5 GHz band and for antenna height as low as 5 meters.

resulting from the probabilistic nature of the radio environment are generally modeled by means of simplified Look-Up Tables (LUTs). These LUTs, extracted from link level simulations, map the Packet Error Rate (PER) to the experienced channel quality conditions. In this work, the PER performance has been included at the system level, following the results from [30], with the PER as a function of the effective Signal to Interference and Noise Ratio (SINR), E_{av}/N_0, which represents the SINR reduced by a factor α to model the effect introduced by the cyclical prefix attached to each OFDM symbol.

4 Impact of the radio channel modelling on the performance and dimensioning of time-critical VANET safety applications

One of the most important VANET applications is traffic safety, and in particular collision avoidance. In fact, VANETs are considered an active safety solution given their capacity to prevent road accidents through the message exchange between neighboring nodes. Traffic safety applications are characterized by their time-critical nature and the need for reliable instantaneous communications. In addition, such reliability cannot only be ensured at a statistical level but needs to be permanently ensured to avoid road accidents. As a result, it is crucial that vehicular communications are carefully configured and optimized to ensure their reliable and timely operation needed for traffic safety. Given that such reliable and timely operation heavily depends on the received signal levels, and thereby on the channel propagation conditions, the design of vehicular communication techniques for traffic safety applications needs to adequately model the radio propagation conditions. To demonstrate the impact of such modelling on the performance of traffic safety VANET applications, this study considers V2V communications in an urban intersection scenario.

4.1 Evaluation scenario

To investigate the impact of the accuracy of the radio channel modelling on the performance and dimensioning of VANET V2V communication protocols, a traffic safety application at a critical urban intersection scenario without visibility has been considered; US studies show that more than 25% of vehicles collisions occur at intersections [31]. In this case, two vehicles, A and B, are moving towards an intersection with a risk of collision (Fig. 4). To detect each other's presence, the vehicles periodically broadcast ten basic beacons per second on the control channel using the 6 Mbps 1/2 QPSK transmission mode. The packet size has been set to 100 Bytes, which is considered enough to support most V2V communications [32] and includes information such as the timestamp, vehicle's latitude, longitude, acceleration, speed module and heading, transmission power or message priority.

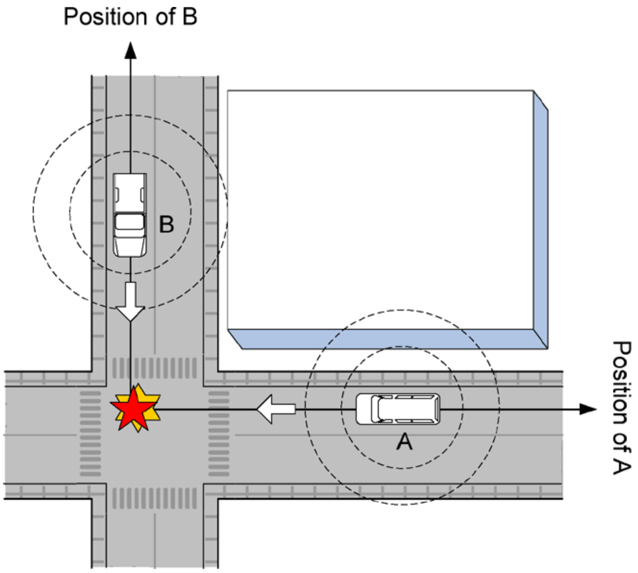

Fig. 4 Urban intersection scenario

The correct dimensioning of VANET protocols should guarantee the exchange of at least one of these messages between A and B with sufficient time for the drivers to react and avoid the accident at the intersection. In this context, we define the critical distance CD as the minimum distance to the intersection at which vehicle A needs to receive a broadcast message from vehicle B to avoid their potential collision at the intersection. Considering a uniform deceleration model, the critical distance can be computed as follows:

$$CD = v \cdot RT + \frac{1}{2}\frac{v^2}{a_{\max}} \qquad (13)$$

where v represents the vehicle's speed, RT the driver's reaction time and a_{max} the vehicle's emergency deceleration. In particular, these parameters have been fixed to $v = 70$ km/h, $RT = 0.75$ s and $RT = 1.5$ s, and $a_{\max} = 8$ m/s^2. In this scenario, this parameter definition will allow obtaining valuable traffic safety performance results.

In terms of system load, two scenarios have been analysed. The first one, modelling only the two vehicles approaching the intersection with a risk of collision, represents a scenario where radio transmission errors are just due to propagation effects and not to channel congestion. The second scenario, represented in Fig. 5, also considers other surrounding vehicles (100 vehicles/km) in order to emulate high density conditions where numerous vehicles broadcast their messages through the same control channel, thereby resulting in a higher channel congestion, and consequently, in an increased probability of packet errors due to packet

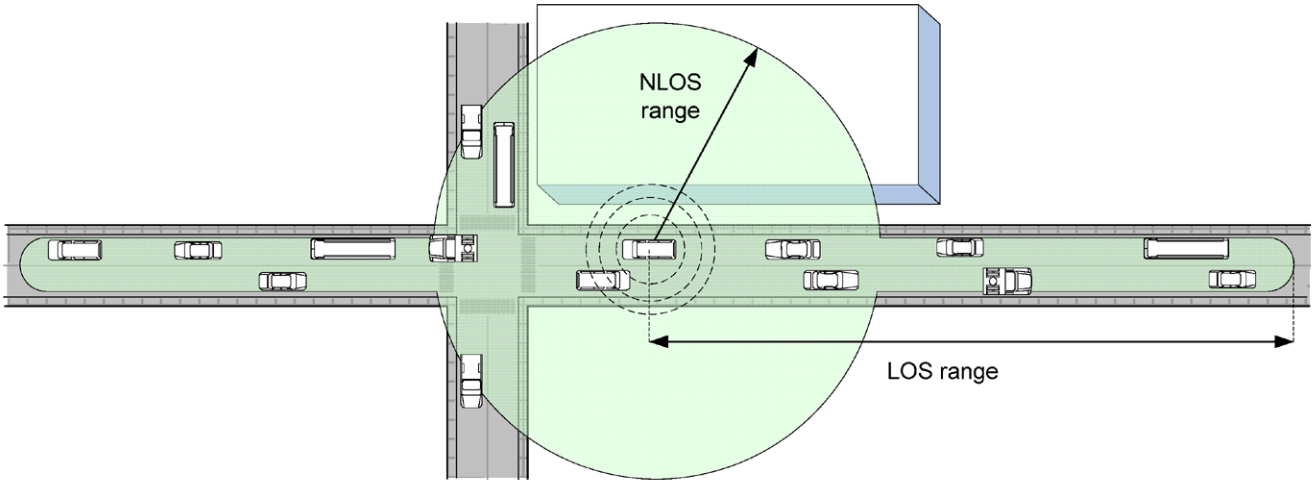

Fig. 5 High dense urban intersection scenario

collisions (specially due to the well-known hidden-terminal problem).

To analyse the impact of the different radio propagation effects on the performance and dimensioning of V2V traffic safety applications, the log-distance pathloss model with uncorrelated log-normal shadowing has been used as a reference, since it is one of the basic urban propagation models included in the ns2 simulator, widely used by the VANET community. Starting from this model, this study sequentially analyses the effect of considering more realistic pathloss, shadowing and multipath fading models. This approach will enable identifying the most relevant propagation effects with regard of accurately dimensioning VANET systems designed for improving road safety. As it will be demonstrated in this section, changing the propagation model modifies the characteristics of the signal propagation and therefore the properties of the received signal level, following the implications of the different radio propagation effects highlighted in Sect. 3. As a result, the propagation model employed can considerably impact the performance and operation of the protocols or applications under study. To conduct this study, the following four radio propagation models have been analysed (with model 4 corresponding to the realistic model described in Sect. 3 and based on the WINNER results):

- Model 1: log-distance pathloss ($n = 3.5$) and uncorrelated log-normal shadowing ($\sigma = 4$ dB) radio model.
- Model 2: LOS/NLOS pathloss and log-normal shadowing ($\sigma = 3$ dB and $\sigma = 4$ dB for LOS and NLOS conditions, respectively).
- Model 3: same as model 2 but including the shadowing correlation as proposed by Gudmunson.
- Model 4: same as the model 3 but including the multipath fading following the WINNER indications (Realistic model).

Models 1 and 2 have been selected to analyse the impact of obstructing elements on the capacity of V2V communication technologies to provide reliable and time-critical safety applications. Such applications are based on the correct reception of at least one broadcast message from the potentially colliding vehicle at least with sufficient time for the driver to react. Since vehicles constantly broadcast messages on the control channel, the probability of receiving such alert depends on the probability to correctly receive at least one of the various broadcast messages. In this case, the potential channel correlation can have a significant impact on the instantaneous and reliable performance of V2V traffic safety communication techniques, and as a result, the third model has also been included. Finally, model 4 has been considered to analyse the performance and dimensioning of V2V communication techniques under realistic propagation conditions, since it includes all propagation effects and therefore realistically represents the signal propagation.

4.2 Dimensioning V2V systems under no traffic load

The results included in this section correspond to the scenario where only vehicles A and B are broadcasting messages on the control channel (packets errors are only produced by radio propagation effects). Figure 6 shows, for a transmission power level of $Pt = 0.75$ W and for the different radio propagation models, the cumulative distribution function (CDF) of the distance to the intersection at which a vehicle correctly receives the first broadcast message from the potentially colliding vehicle. The figure also shows the critical distances (CD), i.e. the distances from the intersection at which a vehicle needs to have correctly received a broadcast message to avoid an accident, considering the two driver's reaction time values analysed. A direct comparison of the first and second channel propagation models shows,

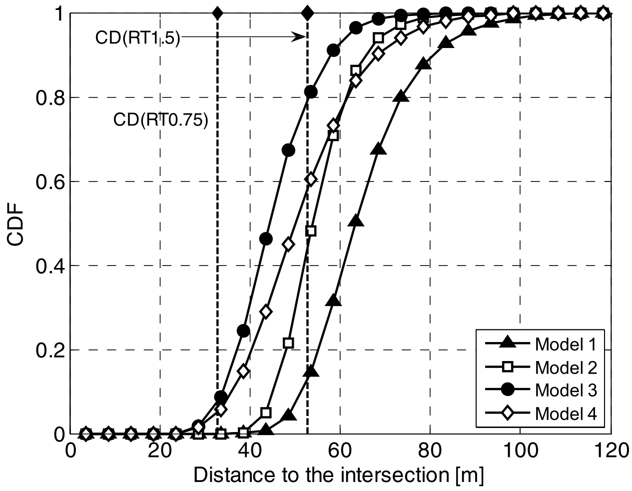

Fig. 6 CDF of the distance at which the first message is received ($Pt = 0.75$ W)

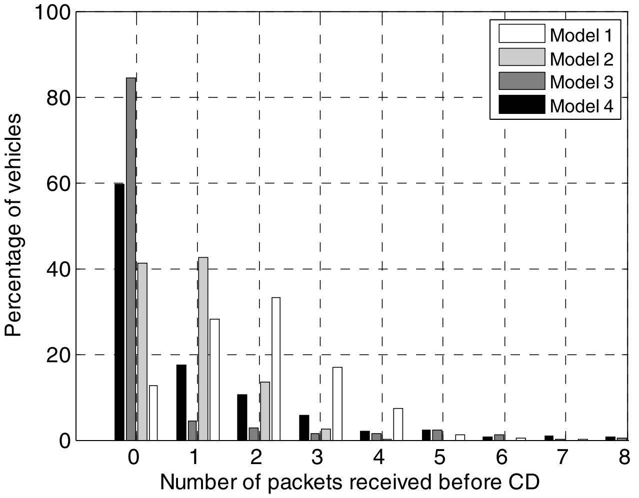

Fig. 7 Percentage of vehicles that receive a particular number of broadcast messages before CD ($RT = 0.75$ s and $Pt = 0.75$ W)

that in the considered scenario and operating conditions, there is a significant difference in the traffic safety application results obtained with the current communications configuration considering the log-distance pathloss model and the LOS/NLOS model proposed in [27] (note that A and B are under NLOS propagation conditions). In fact, the realistic pathloss model produces higher power level loses at long distances between transmitter and receiver, while both present a similar behavior at close distances, as it could be observed in Fig. 1 of Sect. 3, where the pathloss effect was analysed. This results in a reduction of the distance to the intersection at which the first packet is correctly received and therefore in a decrease of the application performance when considering the realistic pathloss model The results obtained clearly show that while this transmission power level would seem sufficient to receive alerts with enough time for the driver to react considering the simplistic pathloss model, the results using the realistic model show that this is not the case, in particular for $RT = 1.5$ s.

The shadowing correlation demonstrated by Gudmunson and included in propagation model 3 can significantly affect the traffic safety performance results, as depicted in Fig. 6. In particular, the shadowing correlation results in that the shadowing experienced by a vehicle at a given position is correlated to that experienced at a nearby position, resulting in a reduction of the signal variability, as detailed in Sect. 3. As a result of the reduction of the signal variability, the number of broadcast messages correctly received before reaching the critical distance is decreased (see Fig. 7). This increases the risk of collision due to the reduction of the distance to the intersection at which the first broadcast message is received (Fig. 6). In fact, while the first broadcast message was always received before reaching the critical distance for short reaction time values ($RT = 0.75$ s) if shadowing correlation was not modeled, considering the shadowing correlation present in radio environments induces that in around 8% of emulated iterations (vehicles approaching a dangerous intersection), the first broadcast message was not received with sufficient time for the driver to react. These results clearly highlight the importance of modelling the shadowing correlation effect, since not doing so can significantly overestimate the performance of wireless V2V communications in terms of its ability to prevent traffic collisions.

The impact of multipath fading modelling on the performance and dimensioning of wireless vehicular communications can be extracted from Fig. 6. The multipath fading effect results in an increased variability of the received signal level, as previously illustrated in Fig. 3 of Sect. 3. Although such increased variability can result in important instantaneous signal level drops, it can also provoke important increases in the received signal levels. As a result, the increase of the signal variability can be a positive effect to guarantee the correct reception of at least one broadcast message with sufficient time for a driver to react in front of a road danger, as it can be observed in the results shown in Fig. 6. For example, the probability of not receiving a message before reaching the critical distance was reduced from 0.81 to 0.6 when the multipath fading effect was modeled, as it can be observed in Fig. 6 when propagation models 3 and 4 are compared for $RT = 1.5$ s. The results illustrated in Fig. 6 show such positive effect despite the fact that the channel variability is also at the origin of a reduced probability of successful reception of a broadcast message for short distances to the intersection, as illustrated in Fig. 8. It is important to note that, in this case, the obtained results show that not including the multipath fading results in a pessimistic dimensioning of wireless V2V communications for safety applications.

The results shown in Figs. 6 and 7 correspond to a transmitting power of 0.75 W. The use of higher transmission

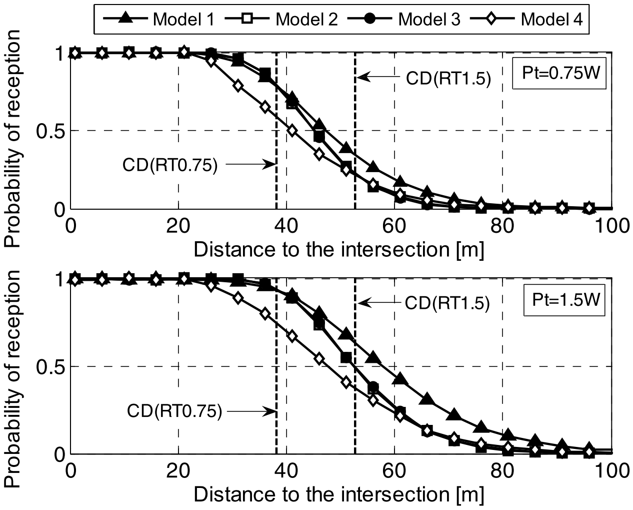

Fig. 8 Probability of successful reception between vehicles A and B

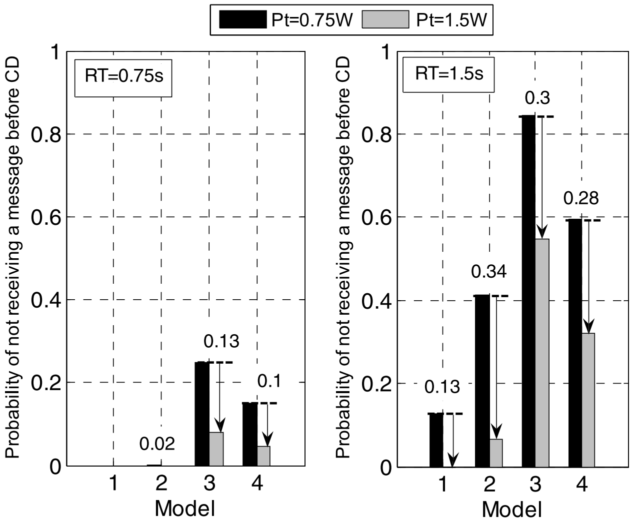

Fig. 9 Probability of not receiving a message before CD for various transmission power levels

power levels increases the transmission range and the distance at which messages are received (see Fig. 8). As a result, the application performance is increased, i.e. the probability of not receiving any broadcast message before CD is reduced, as Fig. 9 demonstrates. This performance improvement with higher transmission power levels is independent of the propagation model considered. Figure 9 also highlights the need of considerably high transmission powers to obtain adequate application performance levels under realistic propagation environments (model 4), especially for high driver reaction times. Despite the general performance improvement obtained with higher transmission powers, the same conclusions regarding the effect of the radio propagation modelling on the performance and dimensioning of wireless V2V communications can be reached for high

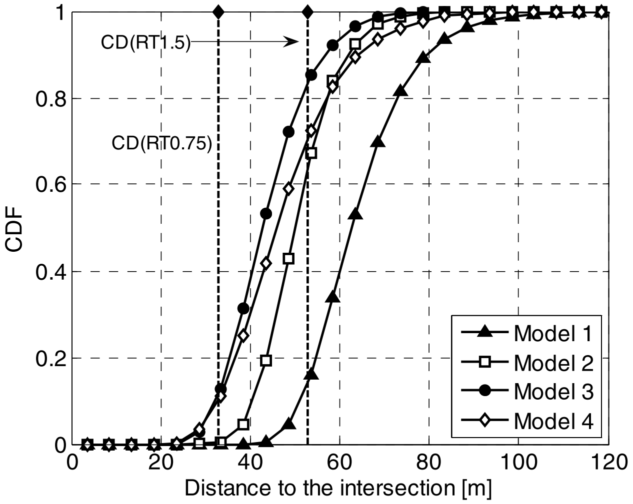

Fig. 10 CDF of the distance at which the first message is received under high channel load ($Pt = 0.75$ W)

transmission powers, according to the results previously shown and the signal variability characteristics identified in Sect. 3 where the different radio propagation effects were analysed.

4.3 Dimensioning V2V systems under high traffic load

While the previous results showed the system performance for scenarios where no surrounding vehicles were modeled, this section is aimed at demonstrating the impact of the radio channel modelling under high traffic densities. When all vehicles are periodically transmitting broadcast messages on the control channel, the obtained results are not only affected by the radio channel effects, but also by channel congestion and packet collisions. Despite the performance degradation generally observed with higher system loads, the conclusions regarding the channel modelling effect on the dimensioning of wireless vehicular communication systems are maintained, as shown in Fig. 10. However, the impact of surrounding vehicles transmitting on the control channel can considerably vary depending on the channel model employed. As shown in Fig. 11, there is an important difference between the propagation models studied when the reduction of the probability of reception due to packet collisions is analysed. As it can be seen in Fig. 11, model 1 presents a considerable difference when compared with the rest of the models due to the fact that models 2, 3 and 4 differentiate between LOS and NLOS propagation conditions, providing with a higher transmission range along the streets and hence with more potential interfering vehicles. Such difference between model 1 and models 2, 3 and 4 can also be observed in Fig. 12 in terms of the total rate of packets detected per second and per vehicle. Since this rate of detected packets quantifies the amount of time a vehicle's communications interface is occupied receiving packets from other vehicles (with

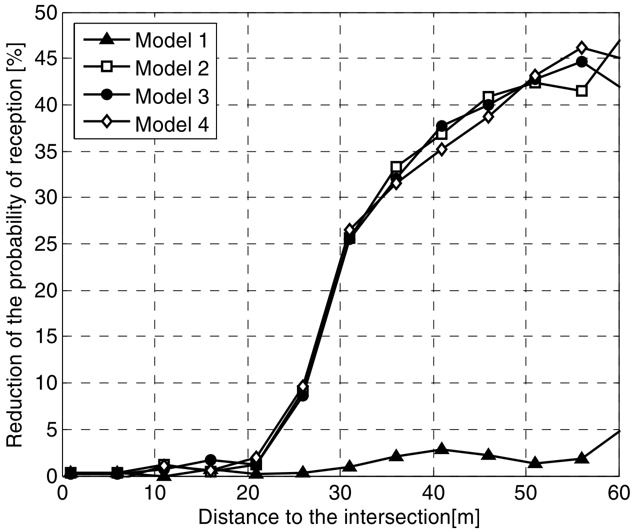

Fig. 11 Reduction of the probability of reception ($Pt = 0.75$ W)

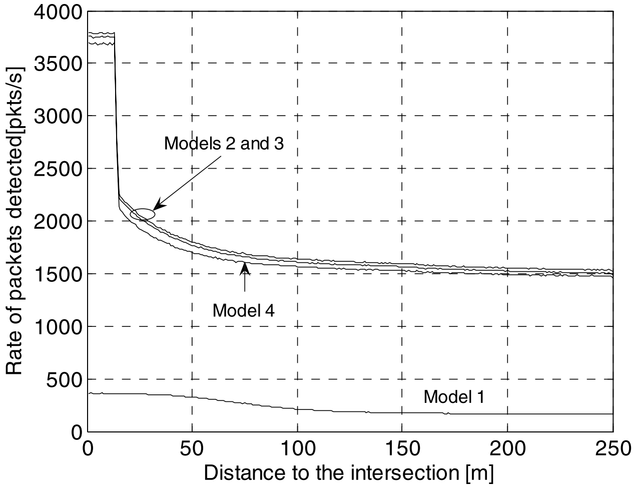

Fig. 12 Total rate of packets detected per second under high channel load ($Pt = 0.75$ W)

or without error), the use of a simplified propagation model that does not differentiate between LOS and NLOS propagation conditions not only influences traffic safety performance results, but can also provide inadequate indications about the channel load observed by each vehicle.

As it was expected from the results of Fig. 11, the results obtained using model 1 present the lowest increase of the probability of not receiving a packet with enough time for the driver to stop before the intersection when a high channel load is emulated, as illustrated in Fig. 13. Despite the fact that models 2, 3 and 4 present practically equal reduction of the average probability of reception due to packet collisions, the system performance degradation observed for traffic safety applications is considerably different. This is produced because the percentage of vehicles that receive a small quantity of broadcast messages before the critical distance considerably vary between one model and another when no surrounding vehicles are emulated, as previously depicted in Fig. 7. Such vehicles are the most sensitive to extra packet losses due to packet collisions. As a consequence, model 2 presents the worst performance degradation. As it can be observed in Fig. 13, these effects are independent from the transmission power used. As in the case without surrounding vehicles, the increase of the transmission power improves the application performance since it decreases the probability of not receiving a packet before the CD distance. However, the performance degradation due to packet collisions is higher as the transmission power increases, as it can also be observed in Fig. 13. This is due to the fact that increasing the transmission range increments the number of potential interfering vehicles, and hence the probability of packet losses due to radio collisions.

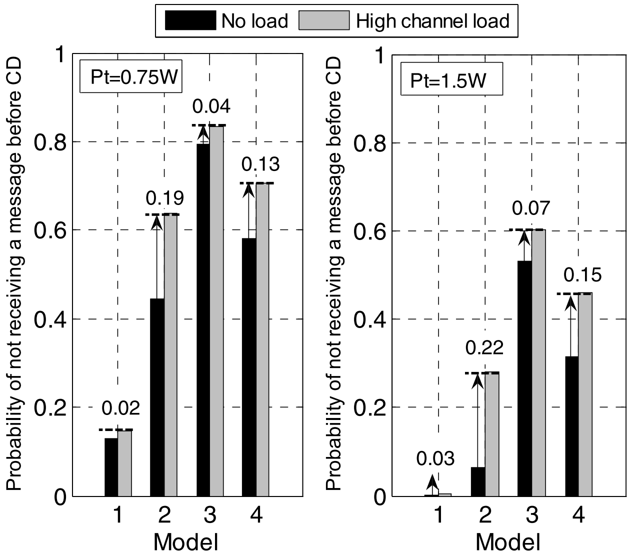

Fig. 13 Probability of not receiving a message before CD ($RT = 1.5$ s)

The results depicted in this section have clearly shown that the radio channel modelling has a significant impact on the performance and dimensioning of V2V communications and traffic safety applications. Considering the strict application and communication requirements of VANET traffic safety applications, the VANET community should carefully model the radio channel to adequately configure VANET communication protocols.

5 Impact of radio channel modelling on the performance and operation of VANET routing protocols

Ad-hoc routing protocols are a key feature of VANETs due to their capability to rapidly disseminate road safety or traffic conditions information in a given geographical area without the need for any road side infrastructure. The performance and efficiency of these routing protocols is heavily influenced by the selection process of the neighboring nodes that are candidates to relay the information from source to destination, the density of neighboring nodes, the radio link reliability and the number of relaying nodes needed to send the data packet from the source to the destination node. Given that these operational parameters are heavily influenced by the received signal level in VANETs, it is crucial, as this section will demonstrate, to adequately and accurately model the radio propagation conditions to understand, design, evaluate and optimize VANET routing protocols.

5.1 Evaluation scenario

To analyse the effect of the radio channel modelling on the performance and operation of vehicular ad-hoc routing protocols, a Manhattan-like urban scenario consisting of a uniform grid of 6 × 6 blocks has been employed (Fig. 14). In this case, all streets have two lanes except the horizontal street which consists of four lanes and has traffic lights at the intersections. In addition to the periodic broadcast transmissions,[3] data packets are generated every $Td = 3$ s at the source node. The source node seeks then to forward these data packets to the destination node (see Fig. 14) using an ad-hoc routing protocol.

Given that the performance and operation of ad-hoc routing protocols can be strongly influenced by the network topology, this study implements realistic vehicular mobility patterns extracted from the open source microscopic road traffic simulator SUMO (Simulation of Urban Mobility) [33]. SUMO is based on a collision free vehicle movement model, and supports different vehicle types, multi-lane streets and junction-based right-of-way rules, which significantly influence the vehicle's mobility. In this case, an average vehicular traffic density of 12 vehicles/km/lane is simulated, corresponding to a typical medium density urban scenario.

In the evaluation of VANET ad-hoc routing protocols under the influence of the diverse radio propagation effects, the following radio propagation models have been considered:

- Model A: Two Ray Ground pathloss model without shadowing or multipath fading.
- Model B: LOS/NLOS pathloss model without shadowing or multipath fading.
- Model C: Realistic model including LOS/NLOS pathloss, correlated shadowing and multipath fading (same as model 4 in Sect. 4).

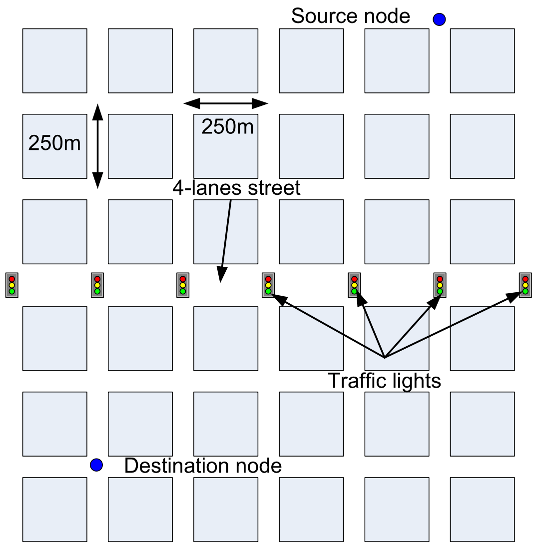

Fig. 14 Urban Manhattan-like scenario

Depending on the radio channel model employed, the characteristics of the signal propagation are modified following the different effects described in Sect. 3. This results in different protocol operation and performance when the radio channel model is changed. As for the V2V traffic safety communications dimensioning study presented in Sect. 4, it is crucial to analyse the impact of visibility conditions on the performance and operation of routing protocols. To this aim, the pathloss models A and B have been considered in this work to illustrate the importance of differentiating the radio visibility conditions. The simplistic pathloss model A is different from model 1 chosen in Sect. 4 since models A and 1 are the most commonly used simplistic propagation models by the VANET community and it was the intention of the authors to check their varying influence. As a result, each model has been used for a different evaluation scenario. Differently from the models A and B, which simplistically reproduce the radio propagation effects, model C is employed to accurately measure the impact of realistic propagation conditions on the study of VANET routing protocols. In this section, model C is the same as model 4 in Sect. 4 and captures all propagation effects. It therefore provides the closer representation of real signal propagation and the performance and operation of VANET routing protocols obtained with this model will be compared with those obtained with the rest of the models.

In this case, the shadowing correlation effect has not been studied separately since its impact on routing protocols is not expected as crucial as for traffic safety applications that require reliable and instantaneous V2V communications. In the case of routing protocols, several timely separated retransmissions are allowed.

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[3] Beacons are transmitted every $T_s = 0.1$ s at a transmission power of 0.5 W in the considered scenario. Given the unrealistic high transmission range that de Two Ray Ground model reproduces when using a transmission power of 0.5 W, the power level for this particular model has been set to obtain a 400 m transmission range.

5.2 Vehicular ad-hoc routing protocols in urban scenarios

Several authors have demonstrated the potential benefits of position-based routing protocols over traditional topology-based ad-hoc routing protocols in VANETS. This is derived from the highly dynamic nature of vehicular networks which prevents topology-based routing protocols to effectively operate in such environments [34]. Consequently, to analyse the impact of the radio channel modelling on the performance and operation of multihop routing protocols, three position-based wireless ad-hoc routing protocols have been employed and implemented in this study. One of the most referenced position-based routing protocols is GPSR (Greedy Perimeter Stateless Routing) [35]. In GPSR, packets generated at the source node are routed to the final destination node using positioning information. In GPSR, each intermediate node selects the following forwarding node based on the position of the destination node and the position of its neighboring forwarder-candidate nodes; the neighbors' positions can be obtained with a periodic beaconing algorithm such as the one employed in WAVE. By default, all nodes employ the greedy forwarding strategy and forward the data packet to the neighbor geographically closest to the destination. If a node cannot find any neighbor closer to the destination than itself, it follows the perimeter forwarding strategy in order to overcome the area with absence of neighboring nodes [35].

In spite of the fact that road topology can influence the mobility of the selected relaying node towards the destination, routing protocols such as GPSR do not normally consider the street layout in the forwarding node selection process. In order to include road topology information on the routing process, [36] proposes the SAR (Spatially Aware Routing) protocol. In SAR, the source node forces data packets to be routed through specific intermediate intersections in the path towards the destination. Intermediate intersections are normally chosen following the shortest path between the source node and the destination node.

Both GPSR and SAR are position-based unicast routing protocols that base their forwarding decisions on the positions of all the neighbors in the transmission range of the forwarding node. However, due to the high vehicle's mobility and the consequent varying topology dynamics, this information can be frequently outdated, decreasing the packet delivery ratio. To solve this problem, the CBF (Contention Based Forwarding) protocol was proposed in [37]. In CBF, a forwarding node transmits the data packet as a single-hop broadcast message. All vehicles that correctly receive the broadcast packet start a timer with a duration proportional to their distance to the destination. As a result, the timer of the closest neighbor to the destination will expire in first place and this node will broadcast/forward the message to be transmitted. All the other nodes receiving such broadcast message cancel their timers and thereby do not forward the packet again.

5.3 Routing protocols performance

The impact of the different propagation models analysed on the performance of the three implemented vehicular ad-hoc routing protocols can be observed in Fig. 15. The figure differentiates between packets correctly routed to the destination, and packets that could not reach the destination. For the unicast protocols (i.e. GPSR and SAR), the packets that cannot reach the destination node can be dropped by an intermediate node because the intermediate node does not have any neighbor node to forward the packet (Dropped RTR) or because the maximum number of retransmissions at the MAC level is reached (Dropped MAC). For the CBF protocol, a data packet is not able to reach the destination when a broadcasted message could not find any node to further rely the packet to the destination. The figure clearly shows that the considered radio propagation models strongly influence the vehicular ad-hoc routing performance and thereby the protocol's operation. In fact, the figure highlights that the number of packets lost due to the lack of neighboring vehicles in the case of unicast protocols significantly increases under the LOS/NLOS (model B) and Realistic (model C) radio propagation models, with respect to the Two Ray Ground model (model A). Accurately modelling buildings as obstacles to determine the visibility conditions between the transmitter and the receiver reduces the number of neighbors that each node detects, as depicted in Fig. 16 for the analysed unicast protocols. This effect is due to the fact that propagation models B and C adequately differentiate between LOS and NLOS propagation conditions, which results in higher signal losses under NLOS conditions, and consequently in

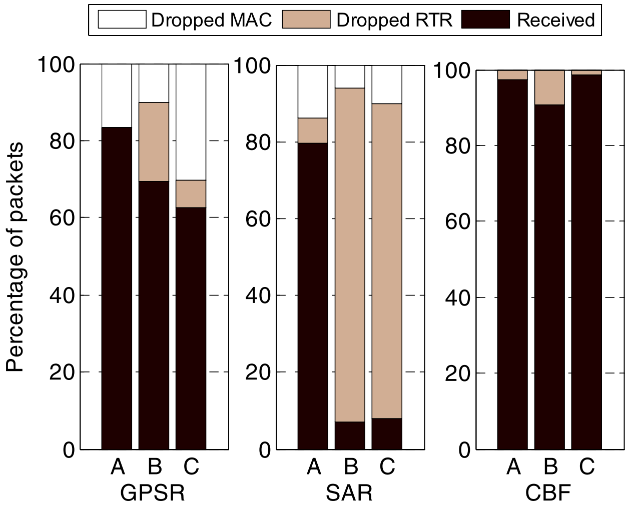

Fig. 15 Routing protocols packet delivery ratio for the various radio propagation models analysed

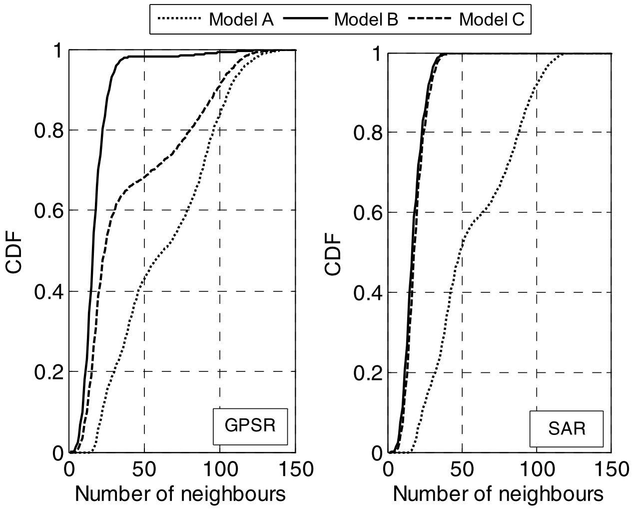

Fig. 16 Cumulative Distribution Function (CDF) of the number of neighbors detected by any wireless vehicular node; i.e. nodes that fall within its radio coverage

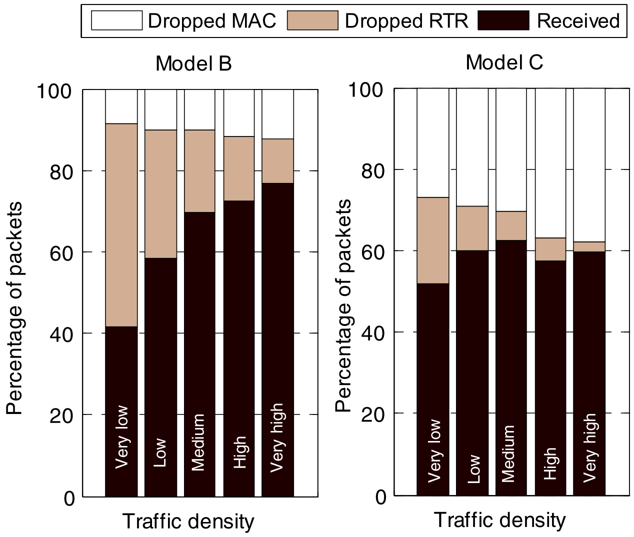

Fig. 17 GPSR protocol packet delivery ratio for different traffic densities

a reduced capability for vehicles to communicate through buildings and detect neighboring nodes. It is important to highlight that while GPSR and SAR achieved similar performance under the simplistic Two Ray Ground model, SAR's performance is considerably degraded under realistic propagation due to a significant degradation in the number of potential relaying neighbors resulting from an adequate modelling of NLOS conditions and the predetermined SAR route selection.

When evaluating the performance of any wireless ad-hoc routing protocol, it is important to analyse the different packet dropping factors in order to provide indications on how to improve and optimize it. In this case, depending on the signal variability and propagation modelling, packet dropping for unicast protocols is due to different factors. For example, in GPSR the percentage of packets dropped at the RTR level is lower considering propagation model C than considering propagation model B due to the increased signal variability of the realistic propagation model that occasionally makes possible the communications between distant vehicles and thereby increases the number of neighboring nodes available to route the packet to the destination (Fig. 16). However, the signal variability reduces the link's reliability, and therefore increases the number of packets dropped at the MAC level. In the case of SAR protocol, the signal variability introduced by the realistic radio propagation model does not result in an increased number of neighbors due to the restrictive SAR path selection route. As a result, SAR performance degradation for propagation models B and C is mainly due to the RTR packet dropping. These results clearly show how unicast protocols' performance can considerably vary depending on the propagation model used in the analysis.

Contrary to unicast protocols, the CBF protocol performance presents a much more limited variation across the different propagation models due to its relaying node selection process based on actual correct reception of broadcast messages by relaying candidates. In fact, unicast protocols can only reach similar performance levels under simplistic propagation models that ignore important radio propagation effects. On the other hand, Fig. 15 shows that such effects can actually benefit the performance of broadcast protocols that achieve their higher performance under the realistic propagation model C. The results shown in this section highlight that underestimating the propagation effects can yield inadequate routing protocols performance estimations, while also providing incorrect indications about the actual inefficiencies of unicast vehicular routing protocols.

The impact of traffic density on the performance of routing protocols can also considerably depend on the channel model considered, as shown in Fig. 17 for GPSR protocol. For deterministic propagation models such as the LOS/NLOS model, the higher the traffic density, the larger the percentage of packets correctly received at the destination mainly due to the reduction of packets dropped at the routing layer. However, when considering the Realistic propagation model, the signal variability notably increases packet losses at the MAC level and the maximum percentage of packets successfully received is produced at medium traffic densities. These results clearly show the considerable impact of the radio channel model also when analysing the effect of traffic density on the performance of VANET routing protocols.

It is also interesting to analyse the impact of the radio channel modelling effects on the performance of VANET routing protocols when changing the transmission power, and hence the transmission range. When the transmission power is increased, the performance of the routing protocols is generally improved, as it can be observed in Fig. 18 for the GPSR protocol and considering medium traffic density. However, the figure also shows that the transmission power increase does not cause the same impact on the routing protocols performance depending on the channel model considered. Increasing the transmission power considering static models can significantly increase the percentage of packets correctly received at the destination. Conversely, a much more limited increment is obtained considering realistic models, mainly due to the higher signal variability and packet losses at the MAC level. As Fig. 18 shows, the propagation model considerably impacts the packet dropping reason irrespectively of the transmission power considered, which could be a critical factor for the protocol improvement and optimization.

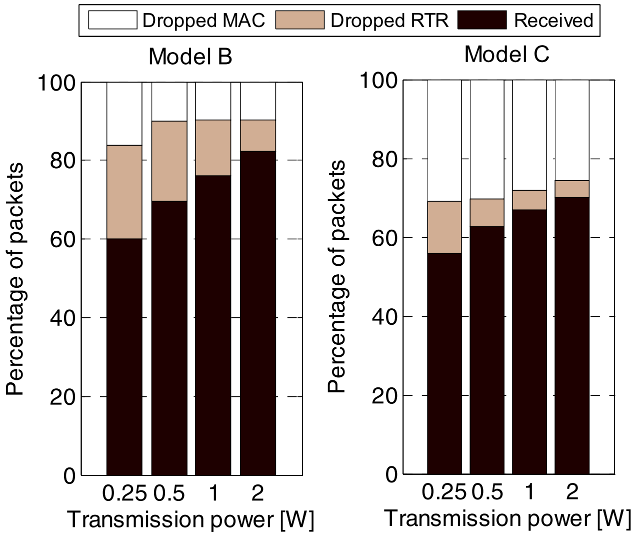

Fig. 18 GPSR protocol packet delivery ratio for different transmission power levels and medium traffic density

5.4 Routing protocols operation

After analysing the impact of radio propagation modelling on the performance estimation of broadcast and unicast vehicular routing protocols, this section studies their operation to better understand the radio propagation effects. Such understanding will help in subsequent research to design ro-

Fig. 19 Routing path from the source node to the destination node in the emulated urban scenario

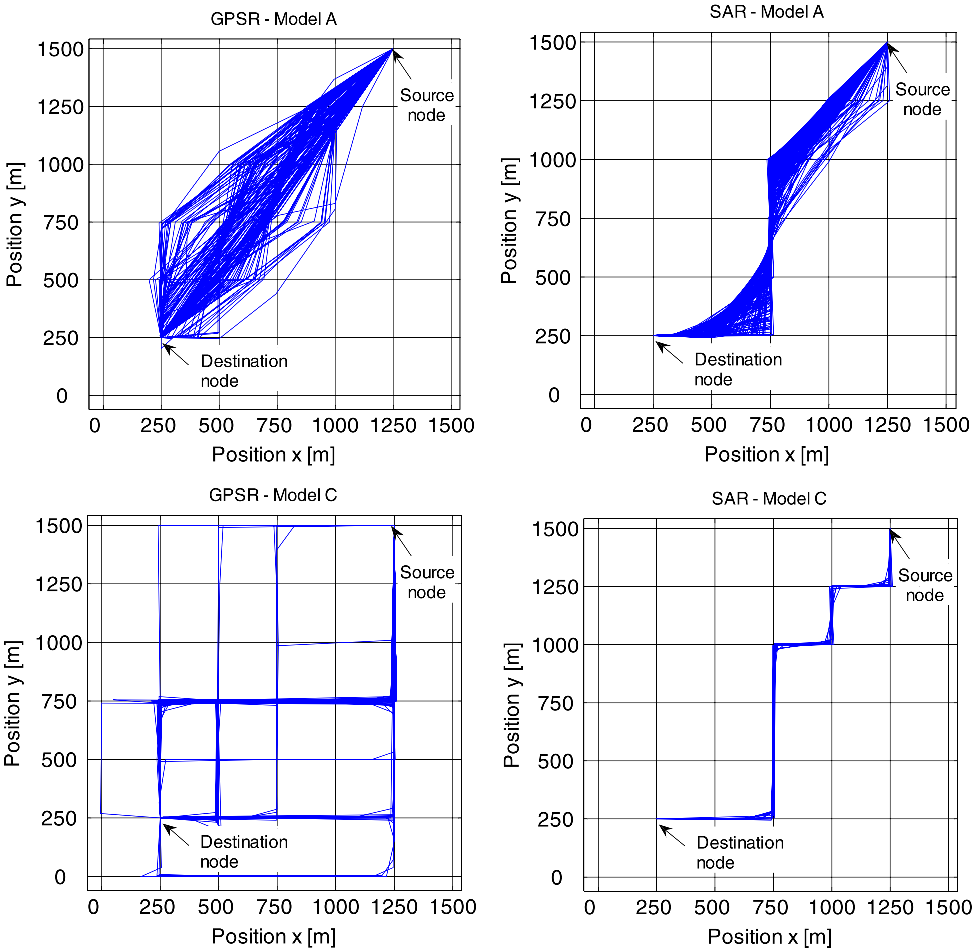

Fig. 20 Geographic distribution of packet retransmission attempts

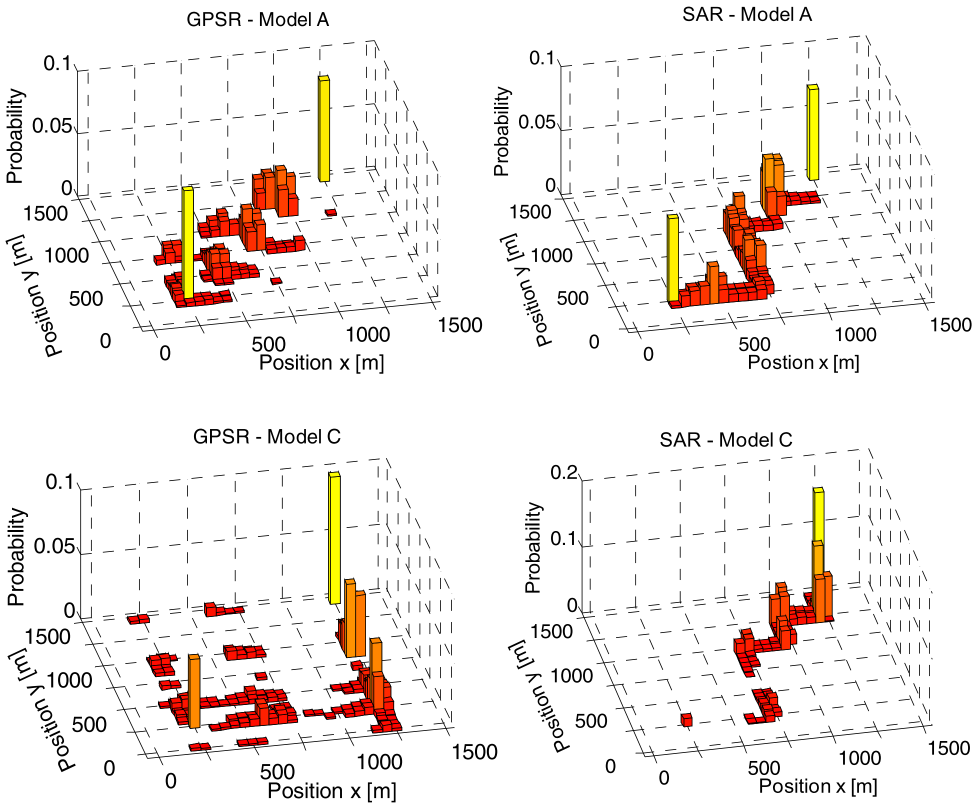

Table 1 Average data replicas received at destination node for different protocols and medium traffic density

Routing protocol	Radio propagation model		
	Model A	Model B	Model C
GPSR	1	1	1
SAR	1	1	1
CBF	1.64	2.17	3.54

bust and efficient vehicular routing protocols that overcome the current proposals limitations highlighted in this paper. Figure 19 clearly shows that differentiating between LOS and NLOS propagation conditions considerably affects the path that the data packets use to reach the destination. Considering the simple propagation model A, the data packets tend to follow a straight line between the source and the destination node, which includes V2V communications across buildings. On the other hand, a realistic propagation modelling prevents such communications and thereby confines V2V communications to routes following the underlying streets. This also results into an interesting observation of the CBF operation and performance under various propagation models. While with unicast routing protocols only one data packet replica per generated data packet is received at the destination node, more than one can be received in the case of broadcast routing protocols. Moreover, a different number of data replicas can be obtained depending on the propagation model considered, as shown in Table 1. As this table shows, the number of replicas significantly increases when considering propagation models that differentiate LOS and NLOS conditions. This is due to the fact that radio signals are confined to the underlying streets, which increases the probability of splitting the routing path at the intersections. In this case, the same data packet can be routed through different paths, which explains the higher number of replicas received at the destination. The results shown in Table 2 demonstrate that the number of replicas received at the destination node and thereby the number of unnecessary data packet transmissions can considerably increase with traffic density due to the higher probability of having vehicle neighbors in perpendicular streets.

According to the different routing path selections obtained with the various propagation models depicted in Fig. 19, the geographic distributions of the channel load vary depending on the propagation model considered. Figure 20 illustrates the geographic distribution of packet retransmission attempts or GPSR and SAR routing protocols. As it can be observed, a very different geographic packet distribution can be obtained with simplistic and realistic propagation models, especially for the GPSR protocol, that does not predefine any routing path to reach the destination. This emphasizes the importance of adequately consider physical layer effects to correctly estimate the performance of vehic-

Table 2 Data replicas received at destination node for CBF protocol and different traffic densities considering realistic propagation model C

Parameter	Traffic density				
	Very low	Low	Medium	High	Very high
Average	2.95	3.35	3.54	3.72	3.84
Standard deviation	1.31	1.33	1.30	1.28	1.27

Table 3 Routing metrics for GPSR

Parameter	Radio propagation model		
	Model A	Model B	Model C
Average travelled distance from source to destination	1665 m	2281 m	2273 m
Average distance between forwarding nodes	368.1 m	399.0 m	506.7 m
Average number of forwarding nodes	4.55	5.63	4.54

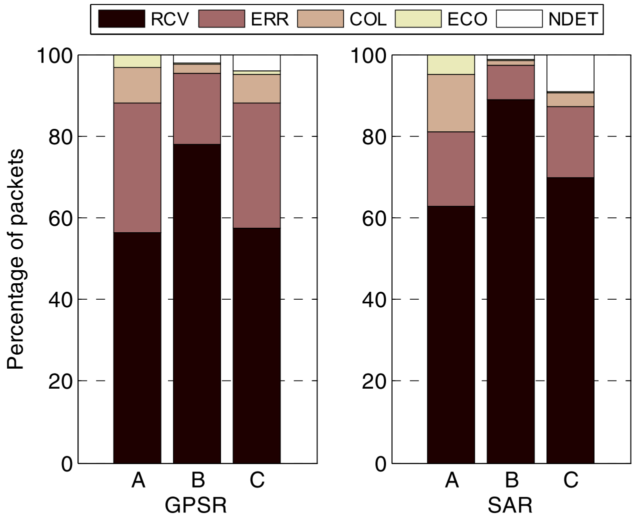

Fig. 21 Packet distribution at MAC level for unicast protocols

ular ad-hoc routing protocols and, in particular, to predict most likely channel congestion areas.

Considering the GPSR example, Table 3 further illustrates the need of accurate propagation models when studying the operation of vehicular routing protocols. In particular, Table 3 shows that propagation models differentiating between LOS and NLOS conditions significantly increase the travelled distance between source and destination given that the packet forwarding route is forced to follow the road topology. Also, the received signal level variability introduced in model C increases the average distance between forwarding nodes and therefore reduces the number of forwarding nodes needed to route the information from source to destination.

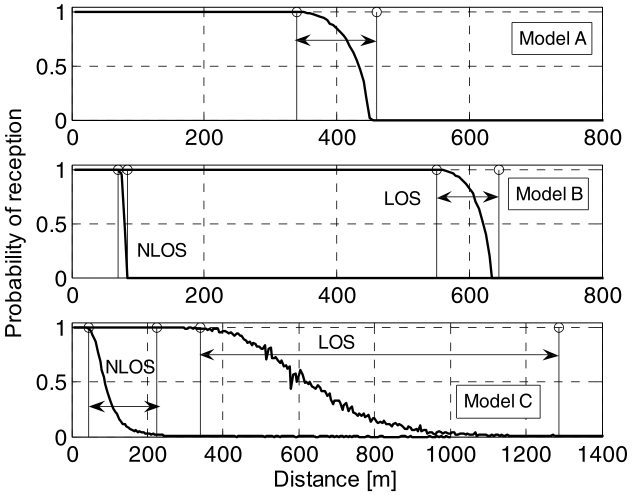

Fig. 22 Probability of packet reception for different propagation models

When analysing the operation of any routing protocol, it is interesting to identify the causes of packet reception errors at MAC level that provokes an increase in the number of retransmissions. Figure 21 classifies for the unicast[4] routing protocols the packets transmitted at MAC level depending on whether they were correctly received (RCV) or not. In the latter case, they could be dropped because of radio channel error (ERR), packet collision (COL), radio channel error and packet collision (ECO) or because they could not be detected due to low received signal level (NDET). Figure 21 shows that radio channel errors represent the most important packet dropping reason at MAC level. Radio channel errors are produced with unicast routing protocols because neighboring vehicles with low link reliability are selected to forward data packets. Depending on the channel model considered, the probability of having neighbors with low link reliability considerably differs. This effect can be observed in Fig. 22, which highlights with arrows the areas where unreliable links can be created, i.e. the areas with probability of packet reception lower than one. Moreover, based on the channel model employed, the geographic distribution of

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[4] It is important to note that MAC analysis for broadcast protocols such as CBF would be significantly different since many different nodes contribute to routing the message from source to destination. As a result, broadcast protocols can result in very high destination packet delivery ratios experiencing low average MAC system performance.

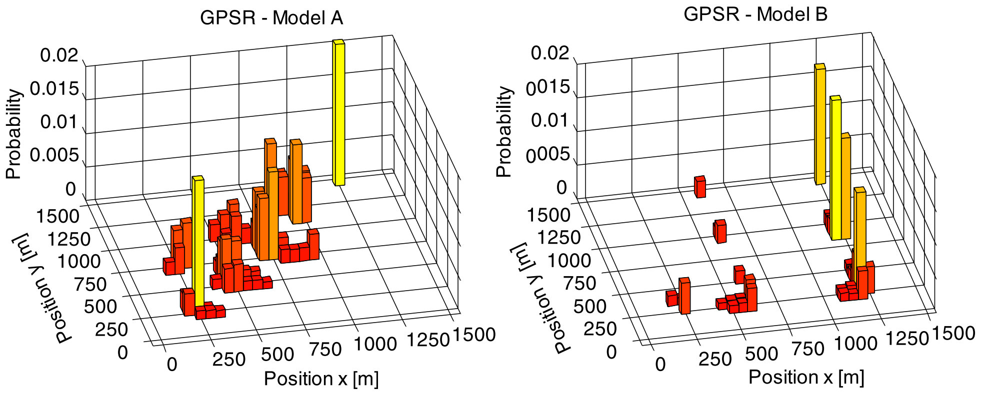

Fig. 23 Geographic distribution of packet losses caused by radio channel errors

packet losses due to radio channel errors can considerably vary. As shown in Fig. 23, when modelling buildings as obstacles, packet losses due to radio channel errors are mainly located near the intersections. However, with simpler channel models such as propagation model A, packet errors are distributed over a larger area.

Apart from the study of radio channel errors, it is also important to analyse the variance of packet collision probability across the different models shown in Fig. 21. The higher collision probability observed for the simpler propagation model is due to the higher detection of neighboring nodes (Fig. 16) observed with the model under the emulated environment, which results in a higher interference probability and packet collisions.

The results shown in this section have demonstrated the strong impact of the radio channel modelling not only on the performance of geographic-based VANET routing protocols, but most importantly on their operation. Adequately understanding and reflecting such operation in research studies is a crucial factor to design VANET routing protocols viable for future implementations in real VANET networks.

6 Conclusions

The radio channel propagation highly influences the performance and operation of wireless communication systems. The influence can be even more remarkable in vehicular communication networks given the low antenna heights, the highly dynamic network topology and the strict performance requirements established by traffic safety applications. Despite the expected impact of radio channel on the performance and operation of VANET systems, many VANET-related studies significantly simplify the radio channel modelling. In this context, this study has analysed, quantified and demonstrated the strong impact of the radio channel modelling on the performance, and most significantly, the operation of VANET networking and communication techniques. The conducted study has extensively proved that inaccurate, and under certain conditions even wrong, conclusions about the performance and operation of vehicular communication protocols can be obtained when not adequately modelling the radio propagation conditions. This is particularly the case when considering road safety applications with strong reliability and low latency instantaneous communication requirements. As a result, the conclusions of this paper encourage for further research in the VANET channel understanding and modelling.

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