A Survey of Propagation Models used in Vehicular Ad hoc Network (VANET) Research

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***Abstract*— There is a lot of ongoing work in the area of VANET research. Because these systems often comprise several tens, hundreds or even thousands of nodes, a real-world test is a very costly and time consuming operation. Most VANET research is carried out using simulators, because it allows for fast and cheap evaluation of protocols and applications in a controllable and reproducible manner. A simulation study uses abstractions (i.e. models) in order to make a judgement on real-world viability. The model should reflect reality, hence accuracy is an important requirement.**

I. INTRODUCTION

INTELLIGENT TRANSPORTATION SYSTEM (ITS) applications are being defined with the aim to improve road traffic safety, efficiency and comfort. Many ITS applications rely on communication provided by Vehicular Ad hoc Networks (VANETs). In this case, Vehicle-to-Vehicle (V2V) communication takes place between vehicles which meet by chance. An important property is the absence of infrastructure; a VANET occurs as soon as two or more vehicles are within communication distance.

Because no infrastructure is involved, VANETs rely heavily on distributed measures to regulate access to the wireless channel. Protocols for random access, Time Division Multiple Access and flooding are implemented and evaluated in simulators. How well such a protocol will fare once deployed in a real-world testbed may differ greatly from the simulation results [1], as the simulator may be overly optimistic [2]. In some cases though, reality provides opportunities for two nodes to exchange information which would not have been possible in the simulator due to a simplistic propagation model [3].

The choice of radio propagation model also has a strong impact on the performance of a protocol [4] because the propagation model determines the number of nodes within one collision domain, an important input for contention and interference. This, in turn, has a direct effect on a node's ability to transmit a packet to another node. This can result in different figures for metrics such as throughput, dropped packets, medium load and latency.

The mobility often involved in VANETs causes nodes to move in and out of eachother's transmission range. Depending on the propagation model a node may share a collision domain with tens or hundreds of other nodes, or with only a handfull because the model accounts for buildings [5].

This paper provides a survey of propagation models used in VANET research, specifically in simulation studies. Several key issues are presented and some questions are raised, which could be looked into as future research. The work is structured as follows. Sec. II introduces the notion of network simulation in a vehicular environment. Sec. III delves into the propagation models used and Sec. IV provides a discussion on the findings. Finally, conclusions are provided in Sec. V.

II. SIMULATION

A wireless network simulator used in VANET research often provides a stack of protocols (reflecting the ISO OSI reference model) on top of which the protocol or application under test is implemented. A component managing (possible) connections between nodes often works in conjunction with the propagation model in order to evaluate which nodes are affected by a transmission. The results could be that a node correctly receives a message or receives garbled bits due to a collision.

A mobility model can be used to move the nodes around — as is generally the case in a VANET — either based on measured or generated traffic traces [6], an embedded mobility model [7], [8] or a coupling with traffic simulation software [9], [10].

A simulation can have two goals: a) Perform a statistical exploration to gain insight in how a system will work in a generic environment, or b) perform a site-specific evaluation of a system to gain insight in the operational properties in a specific environment. This is a method often used in site planning, which has its roots in cellular technology.

A. Mobility

VANETs are, in fact, a subset of Mobile Ad hoc Networks (MANETs) but with several important differences.

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Mobility is usually constrained, because the nodes follow roads according to some physical vehicle model. This results in predictable mobility patterns (within certain bounds). Speed is generally high in VANETs, but can differ greatly (e.g. communication between stopped vehicles or vehicles passing in opposite lanes). In contrast to MANETs, nodes in a VANET generally do not have strict weight, size and power consumption limits. The assumption that a mobile device is limited in resources, which is commonplace in MANETs, does not necessarily hold for VANET nodes. Furthermore, VANET nodes can safely be assumed to have access to certain peripherals such as positioning and navigation hardware.

Another important difference is more of a political nature, because a vehicle may easily travel outside an area covered by a certain legislature. Furthermore, vehicles from multiple vendors will need to be able to cooperate. As such standardisation is an important issue. This generally is not considered when evaluating a MANET application.

B. Propagation Environment

Generally, the wireless channel is a highly chaotic and unpredictable system [3]. On its way from transmitter to receiver a signal is being reflected, scattered and absorbed by objects in the propagation environment. As such its magnitude is altered, but due to multiple paths it can also interfere with itself or with signals sent in other frequency ranges.

With the context of VANETs comes also a typical radio wave propagation environment. Vehicles generally move on roads, but other scenery can vary from open farmlands to forests to large urban canyons and bridges. Another typical property of the VANET propagation environment is the presence of large metal objects which are continuously changing position in the environment, namely the vehicles themselves. As such the environment is highly dynamic.

Large-Scale effects on radio wave propagation are the following three phenomena:

1) Reflection: Reflection occurs when a wave encounters a large surface with certain optical properties. In models reflection is often translated to a pathloss exponent, such as the 2 in (2) and 4 in Eq. (3)

2) Diffraction: This phenomenon is explained by Huygens' Principle, which states that every point on a wavefront acts as the seed for a secondary wavefront. This enables waves to propagate around edges or through holes. This can be modeled with the *knife-edge* diffraction model [11], which can be used for site-specific modeling of propagation over mountains and large buildings.

3) Scattering: A radio wave scatters when it encounters an object which is small compared to the wavelength, spreading the waves in all directions. This can account for a received signal which is stronger than would have been predicted by relection and diffraction alone.

Small-scale effects on radio wave propagation are often referred to as *fading*. At the receiver multiple versions of the original signal arrive; they can be reflected and diffracted and arrive with time and phase difference. These *multipath waves* interfere with eachother, which can cause large fluctuations in signal quality with apparently small changes in time or receiver location. This relative motion causes frequency modulation because each multipath will have a different *Doppler Shift*, the resulting frequency change is derived as follows:

$$f_d = \frac{v}{\lambda}\cos\theta \tag{1}$$

Here v is the relative velocity, λ the wavelength and θ the angle between the signal path and the direction of movement.

C. Channel Parameters

A mobile channel can by characterised with channel parameters. The reception of multipath components can be seen as a sample which can be expressed by means of statistical quantities. *Delay Spread* is the standard deviation of the arrival times. *Doppler Spread* measures the spectral broadening caused by relative motion of transmitter and receiver.

D. Radio Technologies

Several communication technologies have been used in VANETs in the past, such as infrared [12] and short range radio. The short range radio technologies used is primarily Wi-Fi, although some research is has been done in the 900MHz band [13] and in the millimeter range (60-78GHz) [14]. Recently most VANET research converges to IEEE 802.11p [15], a Wi-Fi variety tailored for communication in the vehicular environment as part of the Wireless Access in Vehicular Environments (WAVE) standard [16], [17].

IEEE 802.11p builds upon the proven and mature 802.11 standards, hence providing relatively cheap but powerful and flexible communication devices. It provides low latency access to the medium – nodes do not first have to associate and authenticate with base stations – and is optimised for the ad hoc domain. IEEE 802.11p operates on 7 channels in the 5.8-5.9GHz band (as shown in Fig. 1) and is expected to have a maximum communication range in the order of 1km.

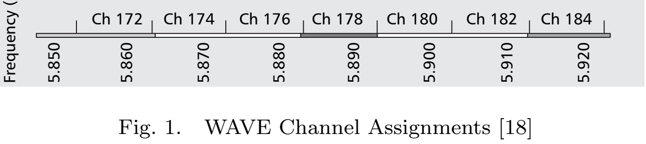

Fig. 1. WAVE Channel Assignments [18]

A node listens to the Control Channel (CCH) at least a certain amount of time. On the CCH announcements for services can be transmitted, these services can then be provided on the Service Channels (SCH). The WAVE

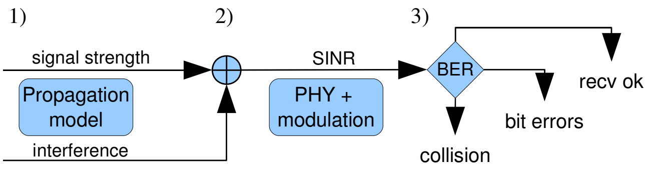

Fig. 2. Generic model to evaluate reception

standard does not define if one radio should listen to channels in time slots or if multiple radios can be used to observe several channels simultaneously. The channel access is defined in IEEE 1609.4 [19]. So far, most ITS-related VANET research focuses on applications operating on a single channel as if in isolation (i.e. the only application using the channel).

E. Signal Parameters

It goes without saying that the frequency at which a radio technology operates greatly impacts its propagation properties. Besides its carrier frequency, other metrics are the transmitted power, the bandwidth and the symbol time, these are results of the modulation scheme used and out of the scope of this paper, but a combination of signal and channel parameters can lead to different kinds of fading. This fading is often characterised by a probability distribution and appropriate parametric assumptions [20], as discussed in Section III-B.

F. Implementation in simulators

Implementation of a propagation model in a simulator usually takes the following steps, illustrated in Fig. 2:

1) For every node n within a relevant distance, perform a calculation of the received signal strength. The received signal strength is calculated using a propagation model, as discussed in Section III.
2) For a transmission instance (e.g. the transmission of message x) all signal strengths from concurrent transmissions other than x received at node n are added as noise.
3) Based on the Signal-to-Interference and Noise Ratio (SINR) and Bit Error Rate (BER) a decision is made whether the message is correctly received or has bit errors. If the SINR is below a certain threshold it is impossible to detect the signal in the received noise, and a collision has occurred.

The thresholds for SINR and BER are hardware and modulation dependent and are out of the scope of this paper. Note that most propagation models in simulators consider nodes to be stationary for the duration of one transmission.

III. Propagation Models

The propagation environment in the simulator is used to judge the effects of propagation of electro-magnetic waves through the medium, usually this medium is air.

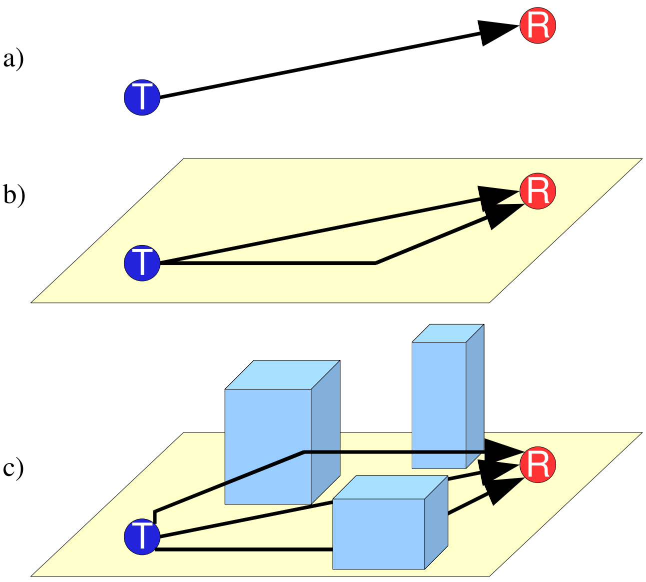

Fig. 3. Deterministic propagation: a) Free Space, b) Two-Ray Ground, c) Ray Tracing

In its most abstract form, this defines success or failure of reception of a message for a certain node.

Propagation models can be classified in large scale and fading or small-scale models. From an implementation point of view they can be either deterministic or probabilistic.

A. Deterministic Models

A deterministic model allows to compute the received signal strength, based on actual properties of the environment such as the distance between a transmitter T and a receiver R. These models range from simple (only account for distance between nodes) to very complex where they also account for multipath propagation in the environment modeled exactly as the area of deployment.

1) Free Space model: This model is sometimes also referred to as Friis model, after its inventor [21]. It models a single. unobstructed communication path [20].

The received power depends only on the transmitted power, the antenna gain and the distance between the sender and the receiver, as shown in Fig. 3.a). The idea is that, as a radio wave travels away from an (omni-directional) antenna, the power decreases with the square of the distance.

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

Where P_t is the transmitted power, G_t and G_r are the gains of the transmitter and receiver antenna gains and λ is the wavelength. α is the path loss exponent and is 2 in Free Space. L is the system loss. Often, G_t, G_r and L are set to 1 (matched antennas and no system loss).

From a topology point-of-view, this model regards the nodes as floating in free space.

2) Two-ray Ground model: The two-ray ground model also accounts for a reflection via the ground, given the dielectric properties of the earth in addition to the direct line of sight (LOS). As a result, nodes are positioned on a plane as depicted in Fig. 3.b). This model gives more accurate predictions at longer range than the Free Space model [11] and is given as follows:

$$P_r(d) = \frac{P_t G_t G_r h_t^2 h_r^2}{d^4 L} \tag{3}$$

Where h_t and h_r are the heights (in meters) of the transmit and receive antennas respectively. Eq. (3) shows a faster power loss than (2), but does not give good results for short distances because of oscillation caused by the constructive and destructive combination of the two separate paths. To cope with this, either (2) or (3) is used based on the magnitude of d, the T-R separation.

3) Ray Tracing model: Ray tracing is a technique often used to predict propagation for cellular systems. Modeling the propagation environment plays a critical role in the development, planning and deployment of, for instance, UMTS/IMT2000 cellular systems [22]. Because for these systems not only coverage but also bandwidth is an important issue, carefull siteplanning is in order. Ray tracing models can take into account the exact position, orientation and electrical properties of individual buildings in the environment in which the system is to function. Using the rules for reflection, diffraction and scattering all rays emanating from the source traveling towards a receiver can be modelled, as shown in Fig. 3.c). As a result, a complex impulse response $h(t)$ can be calculated as the sum of all contributions [23]:

$$h(t) = \sum_{n=1}^{N} A_n \delta(t - \tau_n) \exp(-j\vartheta_n). \tag{4}$$

The received signal $h(t)$ has N time-delayed impulses (rays), each of which is an attenuated and phase-shifted version of the original transmitted signal. Amplitude A_n, arrival time τ_n and phase ϑ_n are calculated for each ray using Snell's laws, the uniform geometrical theory of diffraction (UTD) and Maxwell's equations.

In order for such a model to work, all objects in the environment need to be modeled with characteristics such as permittivity, conductivity and thickness. This method also allows to use antenna radiation patterns.

Basically, ray tracing models are computed using 3-D vector mathematics. Evaluating every ray individually for a fixed antenna position is feasible, as it is used in cell planning. In the area of VANET research multiple transmitters and multiple receivers are moving in a continuously changing environment and $h(t)$ will need to be recomputed upon a change in the environment. Henceforth, ray tracing propagation models are not often used in VANET research, although some research is ongoing [24].

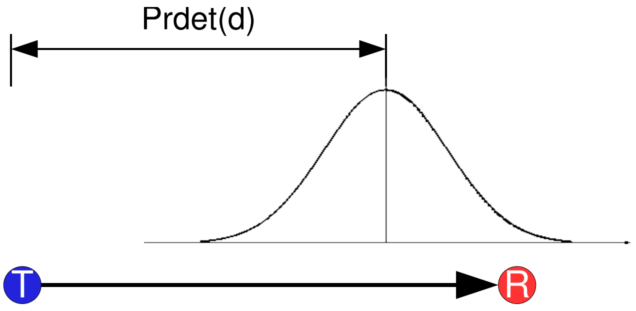

Fig. 4. Probabilistic Propagation

B. Probabilistic Models

Probabilistic models allow a more realistic modeling of radio wave propagation [3]. A probabilistic model takes a deterministic model as one as its input parameters in order to get a mean transmission range. For every individual transmission the received power is then drawn from a distribution, as shown in Fig. 4. The result is a more diverse distribution of successful receptions. It can happen with a certain probability that two nodes close to eachother cannot communicate, although it can also happen with a certain probability that two nodes beyond the deterministic transmission range can communicate. The distribution of these effects depends on the probabilistic model and its parameters.

1) Log-Normal Shadowing: The Log-Normal Shadowing model uses a normal distribution with variance σ to distribute reception power in the logarithmic domain:

$$P_r(d;\sigma^2) \sim LN(P_{r_{det}}(d), \sigma^2) \tag{5}$$

Where $P_{r_{det}}$ is a deterministic model such as Eq. (2) or (3). As such the received power is given as:

$$P_r(d) = P_t - \overline{PL}(d_o) + 10\alpha\log\left(\frac{d}{d_0}\right) + X_\sigma \tag{6}$$

Here α is a pathloss exponent like the 2 in Eq. (2) and the 4 in Eq. (3). $\overline{PL}(d_0)$ is a reference pathloss measured close to the transmitter. Eq. (6) can be rewritten as:

$$P_r = P_{r_{det}}(d_0) \times 10^{PL(d)} \tag{7}$$

Which gives a received power by multiplying the deterministic received power with a Power Loss scale factor in dB:

$$PL(d) = -10\alpha\log10\left(\frac{d}{d_0}\right) + X_\sigma \tag{8}$$

2) Rayleigh: The Rayleigh propagation model [11] models the situation when there is no LOS, and only multipath components exist. This model incorporates intensive variations in received signal power because multiple paths can either combine constructively or destructively. The amplitude, delay and phase shift of these components greatly depends on the environment.

Environment	**Pathloss exponent α**
Free Space	2
Urban area, LOS	2.7–5
Urban area, no LOS	3–5
Indoor, LOS	1.6–1.8
Indoor, no LOS	4–6

TABLE I

Typical values for pathloss exponent α

Environment	**Shadowing deviation σ**
Outdoor	4–12
Office, hard partition	7
Office, soft partition	9.6
Factory, LOS	3–6
Factory, no LOS	6.8

TABLE II

Typical values for shadowing deviation σ

Like the Log-Normal shadowing model in Eq. (5), the Rayleigh model also depends on a deterministic model to which a certain variation is applied:

$$P_{r_{Rayleigh}}(d) \sim \text{Rayleigh}(P_{r_{det}}(d)) \tag{9}$$

This can be rewritten to read:

$$P_r(d) = P_{r_{det}}(d_0) \times 10^{PL(d)} \times \log(1 - \text{unif}(0,1)) \tag{10}$$

where the Power Loss factor is defined by:

$$PL(d) = -\alpha \text{log10}\left(\frac{d}{d_0}\right) \tag{11}$$

3) Longley-Rice: The Longley-Rice model (or Rice model) [3] models the reception powers following the Rayleigh distribution but additionally takes into account the positive effects of a LOS path with a certain scale factor k [25]:

$$\begin{aligned} P_r(d) &= P_{r_{det}}(d_0) \times 10^{PL(d)} & (12)\\ P_{r_{Rice}}(d) &= P_r(d) \times \mathcal{F}(d). & (13)\end{aligned}$$

With $PL(d)$ as given in Eq. (11) and $\mathcal{F}(d)$ defined as a Ricean PDF with a normal distribution:

$$\mathcal{F}(d) = c(\mathcal{N}(\sqrt{P_r(d)}, 1) + \sqrt{2k})^2 + \mathcal{N}(\sqrt{P_r(d)}, 1)^2 \tag{14}$$

With c defined as $\frac{1}{2(k+1)}$.

4) Nakagami: The Nakagami model is highly generic. Reception power follows a gamma distribution:

$$P_r(d; m) \sim Gamma\left(m, \frac{P_{r_{det}}(d)}{m}\right) \tag{15}$$

The parameter m specifies the intensity of fading effects. Nakagami includes other models, such as:

$$\begin{aligned} &\sim \text{Rayleigh} \quad for \quad m = 1\\ &\sim \text{Free Space} \quad for \quad \lim_{m\to\infty}, \end{aligned}$$

yet it is probabilistic. This model has been proven to reflect certain environmental conditions and the consequences on reception power well [26].

IV. Discussion

We observe that a VANET is mostly modeled as a cluster of nodes on a flat surface in a simulator. This abstracts from obstacles in the environment (such as buildings) which could influence the propagation. This can be accounted for by simply using a pathloss exponent $\alpha \neq 2$ in the Free Space or Two-ray Ground model, depending on the environment as indicated in Table I and by changing other parameters such as the deviation σ (see Table II) when using a probabilistic model. When using the Nakagami or Rice model, the strength of a LOS component can be set with the m-parameter or the k-factor respectively.

Even when a sophisticated propagation model is used, it still needs to be parameterised correctly. In [27] the Log Normal Shadowing model was parameterised with $\alpha = 2.56$ and $\sigma = 4$ were used, based on real-world measurement data. In [26] a realistic set of parameters is provided for the Nakagami model. Measurements performed at 900MHz [13] provided input for a set of parameters for the Rice model [28].

Eventhough a model can be parameterised correctly, these parameters are averages of real-world data–mixing measurements of a highway through farmlands and urban area can generate just about any value from Tables I and II, so a real-world calibration really depends on which situation the model is calibrated to. Choosing a set of parameters creates a homogenous propagation environment inside the simulator.

As far as the author is aware, there is no VANET simulator which allows for sectorised propagation models, e.g. a piece of urban highway has a different set of parameters than an highway through farmland or a tunnel. Of course, these scenarios could be simulated separately, but boundaries and transitions from one area to another may be of interest.

Deterministic models (like Free Space, Two-ray Ground) are often used in VANET research. They can greatly increase the runtime performance of a simulation but it is reasoned they describe real conditions insufficiently [3]. A probabilistic model could better account for the variance in real world situations, which enables vastly different communication between two nodes having the same T-R separation.

Another observation is that in VANET simulation, nodes themselves are often dimensionless. The vehicles have no influence on radio propagation. It seems reason-able though, that in practice the large metal bodies of vehicles provide a wide range of effects on propagation:

- Vehicles often block Light-of-Sight (LOS) between two communicating vehicles, making multipath components dominant.
- Vehicles can function as waveguides or as reflectors, thereby increasing the transmission range beyond what could be expected based on Free Space propagation.

There is not a lot of research which takes this into account, if any. We reason this has several reasons:

1) The main focus of ITS research is on protocols, so an abstraction is provided for propagation. This is usually accomplished by using a unit disc graph model which defines a circle around the transmitter. Anything inside the circle receives the transmission.
2) Propagation environments are very diverse in VANETs, ranging from large, multi-lane roads in dense urban areas to highways through wide open farmland. A very detailed model for Dutch highways may not reflect the propagation environment of Japanese highways, making the effort spent in deriving the model questionable. It seems better to settle for an "average" model (i.e. stochastic with certain mean and standard deviation). This agrees with the scope of a VANET: it operates under a wide variety of propagation environments and not one which deterministically reflects one environment, as is the case when performing simulations for siteplanning cellular systems.
3) There are three different time scales at work, which makes proper simulation hard or very time consuming:
    a) Traffic operates in the order of seconds or minutes, it evolves rather slowly compared to radio communication. Before an interesting phenomenon in traffic has occurred, hundreds of communication instances could have happened.
    b) Protocols operate in the order of ms (e.g. DIFS, contention windows etc.).
    c) Radio propagation models may operate on an entirely different scale.

    Especially in a VANET simulation item c) becomes dominant as the number of nodes increases. Assuming n nodes in the network and every node is within interference range of all other nodes, the number of links between nodes is $\frac{n(n+1)}{2}$ (assuming bidirectional links). As can be seen, this does not readily scale, especially if we would like to recompute a ray tracing propagation model every time a node changes position.

In order to keep simulations scalable and still be able to simulate long periods in time (e.g. formation and dissipation of a traffic jam) the radio propagatin model is the first thing to optimise, abstract and simplify, and then a stochastic model provides a good solution.

V. CONCLUSIONS

The propagation model used in a VANET simulation has large influence on the results. It impacts which nodes are able to communicate and the probability of correct reception. As a result, it can influence the speed at which messages propagate through the network, directly influencing end-to-end delay in a multi-hop scenario. The probability distribution of correct reception also influences the overhead with respect to collisions and medium utilisation.

The real-world implementation could behave different from the simulation, so care must be taken when mapping model and parameters to the target environment. Because deterministic site-specific propagation modeling, like in siteplanning of cellular systems, is not viable in VANET simulations due to the varying nature of the environment and the mobility involved, the propagation environment is usually modeled stochastically. A certain mean transmission range or received power-to-position relation $P_r(d)$ is augmented with a random variate drawn from a certain distribution.

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