Ad Hoc Networks 80 (2018) 158–171

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

Coverage and connectivity analysis of millimeter wave vehicular networks☆

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ARTICLE INFO

Article history:
Received 26 February 2018
Revised 6 August 2018
Accepted 11 August 2018
Available online 18 August 2018

Keywords:
Vehicular communication (V2X)
Millimeter wave (mmWave)
Stochastic geometry
Connectivity analysis
Mobility

ABSTRACT

The next generations of vehicles will require data transmission rates in the order of terabytes per driving hour, to support advanced automotive services. This unprecedented amount of data to be exchanged goes beyond the capabilities of existing communication technologies for vehicular communication and calls for new solutions. A possible answer to this growing demand for ultra-high transmission speeds can be found in the millimeter-wave (mmWave) bands which, however, are subject to high signal attenuation and challenging propagation characteristics. In particular, mmWave links are typically directional, to benefit from the resulting beamforming gain, and require precise alignment of the transmitter and the receiver beams, an operation which may increase the latency of the communication and lead to deafness due to beam misalignment. In this paper, we propose a stochastic model to characterize the beam coverage and connectivity probability in mmWave automotive networks. The purpose is to exemplify some of the complex and interesting tradeoffs that are to be considered when designing solutions for vehicular scenarios based on mmWave links. The results show that the performance of automotive nodes in highly mobile mmWave systems strictly depends on the specific environment in which the vehicles are deployed, and must account for several automotive-specific features such as the nodes speed, the beam alignment periodicity, the density of base stations and the antenna geometry.

1. Introduction

In recent years, vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications, which are collectively referred to as vehicle-to-everything (V2X) communications, have been investigated as a means to support emerging automotive applications ranging from safety services to infotainment [2]. The standard V2V communication protocol is the so-called dedicated short-range communication (DSRC) transmission service, which provides a nominal coverage range of about 1 km, with achievable data rates in the order of 2–6 Mbps [3]. V2I communication, instead, exploits the 4G-LTE connectivity below 6 GHz, enabling a data rate of up to 100 Mbps in high mobility scenarios [4]. However, the next generation of automotive systems will include advanced services based on sophisticated sensors to support enhanced automated driving applications and is expected to require very high data rates (in the order of terabytes per driving hour) that cannot be provided by current V2X technologies [5]. A possible answer to this growing demand for ultra-high transmission speeds can be found in next-generation radio technologies and interfaces, such as the millimeter-wave (mmWave) bands between 10 and 300 GHz [6].[1] Besides the extremely large bandwidths available at such frequencies, the small wavelength at mmWaves makes it possible to build complex antenna arrays and obtain high gains by beamforming (BF), thus further increasing the transmission rates. In addition, the inherent security of communication is also improved because of the relatively narrow beamwidth that can be achieved [7]. However, there are many concerns about the transmission characteristics at these frequencies. The path loss is indeed very large and the omnidirectional communication range is quite limited. Raindrops are roughly the same size as the radio wavelengths and cause severe scattering of the radio signal [8]. Moreover, mmWave signals do not pass through most solid materials, and movements of obstacles and reflectors cause the channel to rapidly appear and disappear [9]. Additionally, mmWave links are typically directional and require precise alignment of the transmit-

☆ A preliminary version of this paper was presented at the *6th International Conference on Modern Circuits and Systems Technologies (MOCAST)*, Thessaloniki, Greece, May 2017 [1].

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[1] Although strictly speaking mmWave bands include frequencies between 30 and 300 GHz, the industry has loosely defined it to include any frequency above 10 GHz.

https://doi.org/10.1016/j.adhoc.2018.08.007
1570-8705/

ter and receiver beams to maintain connectivity, an operation that resembles handover in cellular systems [10]. Those limitations pose new challenges for the design of vehicular protocols and exemplify how the connectivity performance of the automotive nodes operating at mmWaves is heavily influenced by the specific features of the environment in which the vehicles are deployed.

1.1. Related work

Given the simplicity of their topology and their high level of automation, highway scenarios have been heavily investigated in the literature to evaluate the connectivity performance of moving nodes in vehicular networks [11–13]. In particular, Khorashadi et al. [11] analyze the performance of multi-hop transport protocols in a multi-lane highway environment, with particular emphasis on the effects of the transmission power on throughput and latency. In [12], the authors conducted a realistic analysis of the vehicular ad hoc network topology by integrating realistic mobility traces and real database traffic demand with realistic channel models, taking into account the effect of blocking vehicles on the received signal power. The article in [13] provides a closed-form expression of the achievable throughput of infrastructure-based vehicular networks under a cooperative communication strategy, exploring the combined use of V2I and V2V communications to facilitate the data transmission. However, such analyses strictly deal with DSRC systems operating at 5.8 GHz, whose propagation characteristics are completely different from those of mmWave channels. Furthermore, in conventional vehicular systems, transmissions are mostly omnidirectional (though beamforming or other directional transmissions can be performed after a physical link between the nodes has been established). These solutions are therefore unsuitable for a mmWave scenario, which instead requires highly directional transmission schemes in all cases.

The potential of mmWave technology as a means to enable future Intelligent Transportation System (ITS) communications has been first acknowledged in [14], which makes the case that the mmWave band is the only viable approach to handle the massive data rates that can be generated in next-generation vehicles. A non-exhaustive list of relevant works regarding V2X communication systems operating at mmWaves includes articles [1,5,15,16]. However, the presented results were not analytically investigated nor validated, and suffer from scalability issues.

In this context, stochastic geometry has emerged as a tractable approach to model and analyze the performance of wireless systems via spatial processes, such as the Poisson Point Process (PPP) [17,18]. In [19–21], the authors exploit stochastic geometry and queuing theory to develop tractable and accurate modeling frameworks to characterize and analyze the performance of traditional vehicular networks in a multi-lane highway setup. However, it is not possible to directly apply those results to mmWave automotive scenarios due to the specific features of this type of communication. In this respect, several literature works, including [22–24], provide general schemes to stochastically evaluate the coverage and rate performance in mmWave 2-D cellular networks. However, it is not easy to translate such studies into the context of mmWave systems for automotive scenarios, due to the more challenging propagation characteristics of highly mobile vehicular nodes (VNs). Finally, to the best of our knowledge, paper [25] is the only available contribution that models a highway communication network operating at mmWave frequencies and characterizes its fundamental metrics. However, it does not consider some important automotive-specific features, e.g., the vehicle's speed or the beam alignment probability, and adopts an approximated path loss model in which the Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) probabilities are independent of the distance and distribution of the nodes. Furthermore, it does not investigate the connectivity performance of the vehicular nodes when modeling a dynamic environment.

1.2. Contributions of this paper

The above discussion makes it apparent that next-generation mmWave automotive networks should support a mechanism by which the vehicles and the infrastructure can quickly determine the best directions in which to establish the mmWave link, an operation which may increase the latency and the overhead of the communication and may have a substantial impact on the connectivity of vehicular nodes. With this in mind, as an extension of our work [1], in this paper we provide the first analytical model to evaluate the coverage, connectivity and throughput performance of a dynamic V2X network operating at mmWaves. We therefore consider a typical one-dimensional multi-lane highway setup based on a V2I communication scenario, in which cars exchange data with mmWave Base Stations (BSs) deployed on both sides of the road. The original contributions of this paper can be summarized as follows:

- We develop a novel tractable framework based on stochastic geometry to evaluate both the coverage and the connectivity performance of an automotive node in a dynamic mmWave vehicular environment, based on a realistic measurement-based distance-dependent path loss model. In particular, this is the first contribution in which an analytical expression for the beam alignment probability and connection stability (i.e., the probability that the vehicle does not disconnect from its serving infrastructure over time) is evaluated considering a dynamic scenario.
- We validate our theoretical model through realistic Monte Carlo simulations. This approach has the benefit to include many more details than would be possible via analytical evaluations and allows to estimate the coverage and connectivity performance of the vehicular nodes accounting for realistic channel behaviors and propagation. Moreover, it makes the proposed model tractable and scalable with the number of nodes.[2] We prove that the performance of the vehicles in highly mobile mmWave systems strictly depends on the specific environment in which the nodes are deployed, i.e., on the nodes speed, the beam alignment periodicity, the density of base stations and the antenna geometry.
- We show that an optimal value of throughput can be associated with a threshold for the density of base stations, above which the deployment of more BSs results in a considerable increase of the system complexity while actually leading to worse communication performance.
- We evaluate and compare the connectivity capabilities of the V2X network adopting both a *rural* path loss model, in which the communication between the endpoints is impaired by large vehicles acting as blockages, and a distance-dependent *urban* path loss implementation, based on real-world measurements, in which environmental obstructions (i.e., urban buildings) can occlude the path between the transceivers. The results prove that, although the two models are of a remarkably different nature, they yield comparable results in terms of connectivity performance.

Overall, the purpose is to exemplify some of the complex and interesting tradeoffs to be considered when designing solutions for next-generation automotive scenarios operating at mmWaves.

[2] Although our simulator currently guarantees a high level of accuracy and generalizability, a validation of the proposed theoretical framework with experimental results will be part of our future investigations.