Chapter 7
Modeling of Intermittent Connectivity in Opportunistic Networks: The Case of Vehicular Ad hoc Networks

Anna Maria Vegni, Claudia Campolo, Antonella Molinaro and Thomas D. C. Little

Abstract This chapter analyses connectivity issues in a particular type of opportunistic networks: Vehicular Ad hoc NETworks (VANETs). The features of opportunistic networks well-fit VANETs, characterized by connectivity disruptions occurring due to quick network topology changes, high vehicle speed and variable vehicle densities. VANETs provide both intervehicle and vehicle-to-network-infrastructure communications. Vehicle-to-vehicle communications may not be the most appropriate interconnection scheme for data delivery in sparse or totally disconnected scenarios. Vehicle-to-infrastructure communications represent a viable solution to *bridge* the inherent network fragmentation that may exist in multi-hop networks formed over moving vehicles, but a ubiquitous roadside infrastructure can incur prohibitive deployment and maintenance costs. In this chapter, we present recent related work focusing on vehicular connectivity models and review hybrid and opportunistic vehicular communication paradigms designed to improve connectivity.

Keywords Opportunistic networking · Intermittent connectivity · VANETs

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7.1 Introduction

Opportunistic networks are one of the most interesting evolutions of mobile ad hoc networks (MANETs). In opportunistic networks, the assumption of a complete path between the source and the destination is relaxed: mobile nodes are enabled to communicate with each other even if a route connecting them may not exist or may break frequently [1]. Traditional routing protocols for the Internet and MANETs [2] assume that an *end-to-end* path exists, thus they fail in opportunistic networks.

Opportunistic networking techniques allow mobile nodes to exchange messages by taking advantage of mobility and leveraging the *store-carry-and-forward* approach. According to this technique, a message can be stored in a node and forwarded over a wireless link as soon as a connection *opportunity* arises with a neighbor node, which is opportunistically used as a nexthop toward the destination [1].

Messages that are cached in the network and wait for an end-to-end path to be available, can suffer from additional delays in delivery. This is why opportunistic networks are also considered as a special kind of *delay tolerant network* (DTN) [3], providing connectivity despite long link delays or frequent link breaks that can be caused by nodes moving out of range, environmental changes, interference from other objects, etc. [4].

Opportunistic networks include: mobile sensor networks [5], pocket-switched networks [6], and vehicular ad hoc networks (VANETs) [7]. A VANET is a special kind of MANET in which packets are exchanged between mobile nodes (vehicles) traveling on constrained paths, in case of vehicle-to-vehicle (V2V) communications, and between vehicles and road-side access points (APs) (*a.k.a.* road-side units, RSUs), in case of vehicle-to-infrastructure (V2I) communications [8].

There are several characteristics that differentiate VANETs from the MANETs. MANET applications are identical (or similar) to those enabled by the Internet. In contrast, although VANETs can support them, e.g., enhanced informative services, audio/video streaming, and generalized entertainment, they have been mainly designed to improve the quality of transportation through time-critical *safety* and *traffic management* applications [9]. Additionally, vehicular applications demand strict communications performance (e.g., timely and reliable message delivery) that are not always needed in conventional wireless networks.

Vehicles move with higher speeds as compared to MANET nodes: in MANETs speed ranges from 0 to 5 m/s, while in VANETs speed ranges from 0 to 40 m/s. Moreover, vehicular networks have to cope with variable network densities induced by traffic conditions and by mobility patterns: vehicles do not move independently of each other, but according to well-established traffic models where mobility is constrained by road topology, speed limits, and traffic lights.

All these unique features let VANETs well fit into the class of opportunistic networks. On the one hand, the highly *dynamic topologies* caused by different vehicle speeds and mobility patterns, e.g., vehicles traveling on the roadway in opposite directions, are characterized by frequent link breakages that strongly hinder stable and durable V2V communications. On the other hand, the *limited infrastructure* *coverage,* because of sparse RSUs settling, may cause *short-lived* and *intermittent* V2I connectivity.

In several research works, protocols and standards have been developed for supporting and improving short-range communications between vehicles and between vehicles and infrastructure. A special interest has been devoted to analyze *connectivity*, which has unique features in the vehicular environment and can be deeply influenced by factors such as vehicle density and speed, and radio communication range. Connectivity in VANETs has been studied through simulations [10–13, 23] and analytical evaluation [14–29].

The study of connectivity is not only important to evaluate the performance of VANETs and to understand packet exchange between vehicles and vehicles and RSUs, but its modeling and prediction are crucial in enabling network designers and providers to effectively improve network planning deployment and resource management, in order to meet applications' requirements.

The objective of this chapter is to provide a comprehensive understanding of connectivity in VANETs, one the most interesting instance of opportunistic networks. We provide an extended description of the main factors affecting connectivity and the models proposed in the literature to characterize it especially in intermittently connected vehicular networks, and we review hybrid communication paradigms designed to improve connectivity in challenging network conditions.

This chapter is organized as follows. In Sect. 7.2, we introduce vehicular networks, their envisioned set of applications and main features. In Sect. 7.3, we overview the main connectivity issues in VANETs. Recent models that analytically characterize V2V and V2I connectivity are surveyed in Sects. 7.4.1 and 7.4.2, respectively. In Sect. 7.5, we provide an overview of the main state-of-the-art representative solutions for improving connectivity performance in vehicular networks, particularly opportunistic approaches and hybrid V2I/V2V solutions. Finally, in Sect. 7.6 conclusive remarks will be summarized.

7.2 VANETs : An Overview

In the last few years, VANETs have interested several players, from automotive manufacturers and academia to governmental agencies and standardization bodies, mainly for the expected deep social and economical impact related to the wide variety of applications conceived for these environments. Vehicular applications are typically classified in (i) active road *safety* applications, (ii) *traffic efficiency* and *management* applications, and (iii) *comfort* and *infotainment* applications [9].

Active road safety-related applications are geared primarily toward avoiding the risk of car accidents and making safer driving by distributing information about hazards and obstacles. The basic idea is to broaden the range of perception of the driver beyond his/her field of vision and allowing him/her to react much quicker, thanks to alerts reception through wireless communications.

Transport efficiency and management applications focus on optimizing flows of vehicles by reducing travel time and avoiding traffic jam situations. These applications, such as enhanced route guidance/navigation, traffic light optimal scheduling, and lane merging assistance, while optimizing routes also allow reducing gas emissions and fuel consumption.

Although the primary purpose of VANETs is to enable safety applications, non-safety applications are expected to create commercial opportunities by increasing the number of vehicles equipped with *on-board* wireless devices, thus pushing *market penetration* of the technology and making it more cost-effective. Comfort and infotainment applications aim to provide the road traveller with information support and entertainment to make the journey more pleasant. They are so varied and range from traditional IP-based applications (e.g., media streaming, voice over IP, web browsing) to applications unique to the vehicular environment (e.g., point of interest advertisements, maps download, parking payments, automatic tolling services).

VANETs applications exhibit very heterogeneous requirements. The main concern for safety applications is finding reliable, low-latency, and efficient methods for disseminating safety messages. In contrast, non-safety applications have very different communication requirements, from no special real-time requirements of traveler information support applications, to guaranteed quality-of-service (QoS) needs of multimedia and interactive entertainment applications.

There are several wireless access technologies that may be used for vehicular communications: such as IEEE 802.11 and wireless wide area network (WWAN) technologies, like long-term evolution (LTE) and worldwide interoperability for microwave access (WiMAX) [9]. In recent years, there was a wide consensus on the use of IEEE 802.11, which is a mature, high-bandwidth and low-cost technology with the capability to well fit the multi-hop, distributed, unstable and ad hoc nature of vehicular environments. To this aim, the IEEE 802.11p standard [30] has been recently published as an amendment to IEEE 802.11; it is intended to operate with the IEEE 1609 protocol suite [31] to provide the wireless access in vehicular environments (WAVE) protocol stack.

In VANETs, there are three primary models for interconnecting vehicles, based on (i) network infrastructure, (ii) inter-vehicle communications, and (iii) hybrid configuration:

1. The first architecture is an *infrastructure-based solution* in which vehicles connect to a centralized server or a backbone network such as the Internet, with the help of road-side infrastructure, e.g., cellular base stations, IEEE 802.11 APs, IEEE 802.11p RSUs. This approach is illustrated in Fig. 7.1. The infrastructure nodes have the role of managing the network and providing connectivity to the backbone, e.g., the Internet, or they could serve as gateways for vehicles to communicate with transportation authorities. In this configuration, the roundtrip delays for data dissemination are potentially high, which make such solution unsuitable for safety applications. Connectivity in this model is subject to availability of infrastructure and often such solutions are cost intensive. Although the deployment of a dedicated vehicular network infrastructure, e.g., relying on IEEE 802.11p road-side

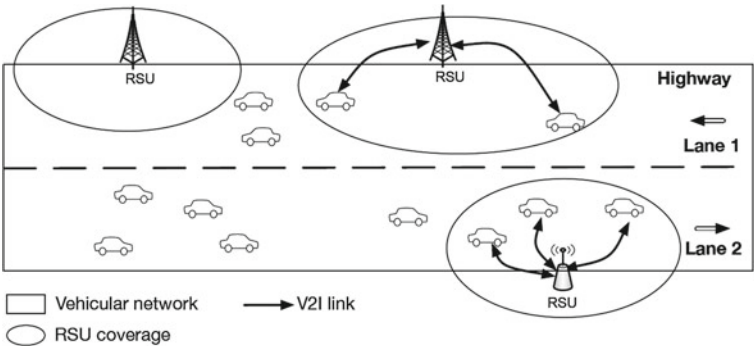


Fig. 7.1 An infrastructure-based solution for V2I communications. The RSU coverage is variable depending on the wireless technology

technology, cannot be considered as a short-term solution, IEEE 802.11 APs are widely available, especially in urban scenarios. Their low-cost, high-capacity, and low-coverage nature yields the opportunistic access to road-side communication infrastructures from traveling vehicles, known as *drive-through* [32];

2. The second solution exploits *direct ad hoc connectivity* among vehicles, as depicted in Fig. 7.2. Depending on the scope of the applications and on the network topology, packets may need to be forwarded at intermediate hops or not, therefore V2V can be either deployed as multi-hop or single-hop communications. For instance, multi-hop systems are useful for applications requiring long-range communications (e.g., traffic monitoring), while single-hop systems are indicated for applications requiring short-range communications (e.g., lane merging);
3. The third architectural solution is a *hybrid configuration* that proposes to use a combination of the two previous communication modes (i.e., V2V and V2I). Vehicles in range directly connect to the road-side infrastructure, assumed to be intermittently available, while they exploit multi-hop connectivity otherwise. The two communication protocols, V2V and V2I, have been developed as part of the *vehicle infrastructure integration (VII)* initiative [33], to be adopted in the vehicular environment. A conceptual VII system is shown in Fig. 7.3, where data information can be exchanged among vehicles, traffic management centres, as well as multimedia service providers for entertainment applications. Notice that the integration of V2V and V2I communications is in general called as inter-vehicle communication (IVC), that is, in an IVC system, vehicles and all road-side stations are assumed to have communication capabilities.

In summary, VANETs have some unique features, such as the constrained mobility pattern, the high vehicle mobility and the quickly changing network topology, ranging from sparse traffic densities to high car concentration in a small area, the multi-hop nature of V2V links, and the adverse effects of a hostile environment on the radio signal propagation. These unique features pose several issues to be addressed. Among them, modeling connectivity and designing solutions aiming at

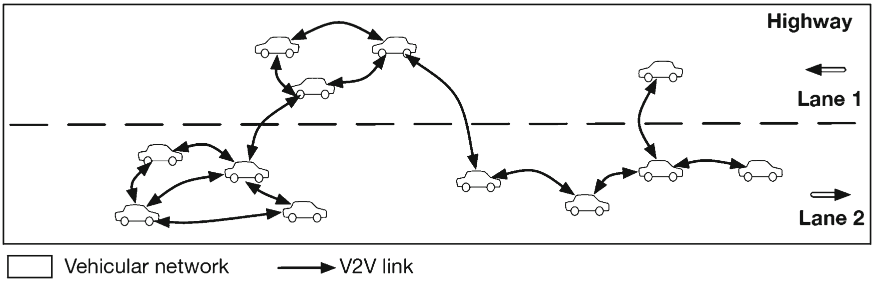


Fig. 7.2 Ad hoc connectivity via V2V

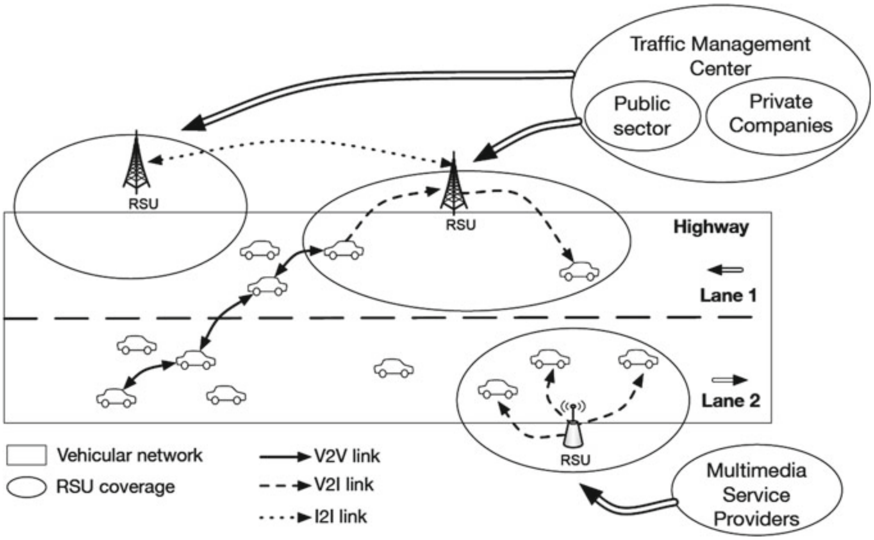


Fig. 7.3 Illustration of conceptual VII systems, as depicted in [29]

improving performance, by tolerating or reducing disruption when connectivity is sparse and by coping with congestion in crowded network conditions, represent the main challenging issues, as extensively discussed in next sections.

7.3 Connectivity in VANETs

Connectivity has a great impact on the performance of ad hoc networks, since it influences factors such as capacity, routing efficiency, and QoS of delivered applications, such as delay and reliability. This is why it has received a great interest from the research community.

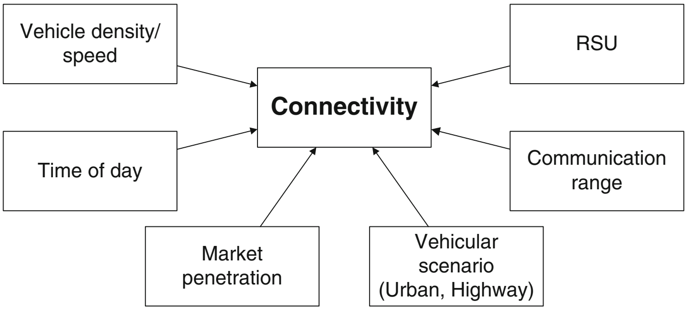


Fig. 7.4 Main factors affecting connectivity, as depicted in [14]

Although the connectivity analysis of VANETs is closely related to investigations on the connectivity of ad hoc and hybrid networks, many challenges and issues are peculiarities of the vehicular environment. Vehicles' connectivity is determined by a combination of several factors, as depicted in Fig. 7.4. Space and time dynamics of moving vehicles (i.e., vehicle density and speed), density of RSUs, and radio communication range strongly affect the connectivity in VANETs [14]. Most of these factors are mutually related.

Common mobility models for MANETs allow node mobility, determined by speed or pause time according to the random waypoint model (RWP) [34], to be considered independently of node density in performance evaluation. This is not the case for VANETs, where the average speed of vehicles is a function of vehicle density and vice versa (e.g., vehicles travel slower on congested roads). From the traffic theory [35] it is known that according to *macroscopic* vehicular traffic models, the behavior of each vehicle cannot be considered *separately*, as in *microscopic* models: all vehicles are aggregated into a flow which is described in terms of fundamental quantities including *vehicles density* (in vehicles per kilometer per lane), *flow* (in vehicles per hour per lane), and *speed* (in kilometers per hour). The values of these parameters are typically related by the so-called *fundamental traffic theory equation*, which is given in [35] by:

$$q = v \times k, \tag{7.1}$$

where q, v, and k are the traffic flow, average speed, and traffic density, respectively.

Over the years, many models have been proposed for speed–flow–density relationships [35, 36] but no single theory provides a complete picture of them.

Vehicle density varies significantly depending upon the time of the day and the location. Mornings and evenings are usually times of heavy traffic density—"rush hour"—and can suffer from congestion (*dense traffic condition*); while at off-peak times (e.g., night-time), roadways can be empty and intervehicle communications are not possible (*sparse traffic* and *totally-disconnected conditions*) [37]. Finally, urban areas yield high-density scenarios of slow moving traffic, while rural areas have relatively sparse population of vehicles. In urban environments, vehicle movements are restricted by the road topologies, buildings, etc., and affected by traffic density, which is determined by road capacity, traffic control, and driver behaviors. Traffic lights have also an important impact on connectivity: vehicles accumulate at red traffic lights in urban intersections by creating meeting points. However, as a drawback, a higher congestion can be experienced if the number of transmitting vehicles increases.

Vehicles traveling at different speeds are temporally able to communicate each other, and link disconnections can often occur. Things worsen if vehicles move in opposite directions, because the contact time interval gets shorter and limits the amount of data that vehicles can exchange.

Furthermore, the communication range has a direct impact on connectivity. Intuitively, a large transmission range must be chosen in order to keep the network connected, so that a vehicle can establish a link to any other vehicle in the network, either directly or over multiple hops. Typically, increasing the transmission range results in decreasing the number of hops between source and destination, leading to effectively increasing performance. A static transmission range cannot maintain the network connectivity due to the non-homogenous distribution of vehicles and the rapid traffic changes. However, in high-density conditions increasing the transmission range would cause severe degradation to the network performance because of high interference. Controlling the communication range by adjusting the transmission power can mitigate the adverse effects of high-density conditions, as proposed in [38].

It should be noticed that the actual transmission range depends on a number of factors, such as signal-to-interference-noise ratio (SINR) and receiver sensitivity. SINR on its turn depends on the transmission power, the interference, and the channel propagation features.

The *unit disk propagation* model [39] is largely used to describe channel propagation. It assumes that two mobile nodes are directly connected if and only if their Euclidean distance is less than or equal to the transmission range. Such a model is only suitable to model the radio environment on the highways, typically free of obstacles and buildings and characterized by line-of-sight (LOS) conditions [40] for short inter-vehicle distances. For larger distances, fading effects, mainly described by the Nakagami distribution [41], cannot be neglected causing serious additional and not deterministic attenuations. The log-normal shadowing model is used to model in a more realistic way signal propagation where the transmit power loss increases logarithmically with the Euclidean distance between two wireless nodes and varies log-normally due to the shadowing effect caused by surrounding environment [39].

Urban environments, conversely, are generally dominated by non-LOS (NLOS) communications, with multiple reflecting objects (e.g., buildings) that degrade the received signal quality and strength (*multipath effect*) [42, 43]. In both environments, due to the relatively low elevation of vehicle antennas, vehicles themselves (e.g. cars, trucks, buses) can act as obstacles to the signal propagation [44].

Intervehicle connectivity also depends on the *market penetration*; it is expected to be low at the initial phase of VANET deployment thus hindering V2V communications. Connectivity performance varies based on the penetration rate; unequipped vehicles physically occupy space and alter the spatial distribution of vehicles and their mobility [14]. Connectivity improves as the market penetration increases, since it directly translates in an increasing probability of finding a neighbor that forward messages. However, a higher number of equipped vehicles may increase the offered load to the network, thus increasing congestion.

Under quick topology network changes, mainly caused by vehicle speed, and in sparse (i.e., low density or low market penetration) or totally disconnected scenarios, vehicles are not always able to communicate, and V2V may not be the most appropriate interconnection scheme for some applications, especially non-safety critical ones [45, 46].

A solution for longer-range vehicular connectivity should consider pre-existing network infrastructure to enable V2I communications from vehicle to RSUs, and vice versa. A pervasive roadside infrastructure would be critical to encourage the adoption of IVC by individual drivers or car companies, since it is expected to take years before having a market penetration rate that can support efficient V2V communications.

However, the coverage of RSUs may not be complete due to the high costs for planning, deploying, and maintaining a ubiquitous road-side infrastructure. Candidate places for RSU installations could be service areas on a highway, or points of interests and crossroads in a city that leverage the already existing infrastructure (i.e., traffic lights, junction box, etc.). V2I connectivity also depends on the specific wireless technology for the RSUs (i.e., WiMAX, IEEE 802.11p, etc.) that influences the transmission range and radio coverage.

Most of VANET research has focused on analyzing VANETs as *well-connected networks*, e.g., often with the purpose of studying the *broadcast storm* problem caused by frequent contention and collisions due to redundant transmissions from neighboring vehicles in dense network topologies [47]. In contrast, especially at the early VANET deployment stages, as also argued in [48], we expect that the sparse RSU settling and the low market penetration rate, coupled with vehicle mobility and harsh radio propagation conditions, will result into intermittent, poor, and short-lived V2V and V2I connectivity. In this context, the design of reliable and efficient routing protocols that can support highly diverse and mainly intermittently connected network topologies is a challenging research topic, which may require the exploitation of opportunistic techniques.

7.4 Modeling Connectivity in VANETs: Literature Solutions

In this section, we explore recent related works coping with *how to model connectivity* in VANETs. Existing analytical models in the literature differ for the assumptions about vehicles distribution and mobility, the communication type, the number of communication hops, and the considered connectivity metrics. But, all of them share the same objective to provide important insights into how the network and road parameters, such as road topology, traffic density, vehicle speed and transmission range, affect the network connectivity behavior.

This section is organized in two subsections that, respectively, introduce the main related works addressing the connectivity issue in VANETs, on the basis of V2V and V2I communication modes.

7.4.1 Modeling V2V Connectivity

Vehicular connectivity represents an open issue since it is not always supported, and messages can be lost or never received.

Given the logistic challenges and the high costs of deploying and testing actual equipments in vehicles, simulations [10–13], and analytical models [14–23] are the only feasible and cost-efficient tools for analyzing the fundamental properties of V2V connectivity. However, due to their (potentially) higher computational efficiency compared to simulation-based approaches, analytical models are typically preferred. Moreover, they achieve more general findings compared to simulations that are, instead, always dependent on the simulation scenario.

The most of existing literature in VANET focuses on modeling the V2V *connectivity probability*. A largely common assumption in connectivity models is that a vehicular network is *partitioned* into a number of *clusters* [14, 15]: vehicles within a partition communicate either directly or through multiple hops, but no direct connection exists among partitions. Such an observation is also supported by simulations studies [13, 23].

Agarwal and Little [15] characterize a vehicular network by fast-paced vehicles traveling on constrained paths (roadways) with potentially short-lived connectivity. A *constant speed model* is assumed: vehicles exhibit different speed values (i.e., from 30 to 120 km/h) that do not change over time. The connectivity in the VANET is modeled through a graph of the network, which changes at a faster rate compared to MANET models. The *connectivity graph* is introduced as a graph, whose vertices correspond to vehicles equipped with an on-board vehicular communication unit and whose paths are defined by the short-range radio links; the connectivity over time can be then analyzed with snapshots of the graph. The graph may be adapted to a specific environment. Notably, the *Freeway* model restricts the vehicles' movement on several bi-directional multi-lane freeways (i.e., highways), while the *Manhattan* model restricts the movements to urban grids (i.e., roads with junctions) [8].

A time-varying traffic density implies a scenario in which there is lack of end-to-end connectivity between vehicles on the highway, and the network becomes *partitioned*. The connectivity graph formed by vehicles can be described as a partition yielding multiple disconnected subnets (*clusters*), as illustrated in Fig. 7.5.

Importantly, the work in [28] characterizes the performance of messaging in a fragmented network under the assumption of delay tolerant networking. Assuming exponentially distributed intervehicle distances, it is shown that vehicles, modeled as point objects whose length is not factored, traveling in the same direction are likely to be disconnected and the probability that two consecutive vehicles are disconnected is given in [15] as:

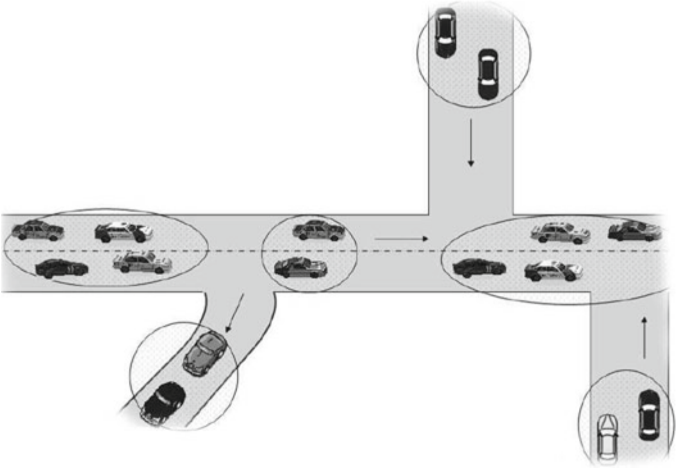


Fig. 7.5 Disconnected vehicle clusters, due to a gap among consecutive clusters, [16]

$$P\{X > R\} = e^{-\lambda R} \neq 0, \tag{7.2}$$

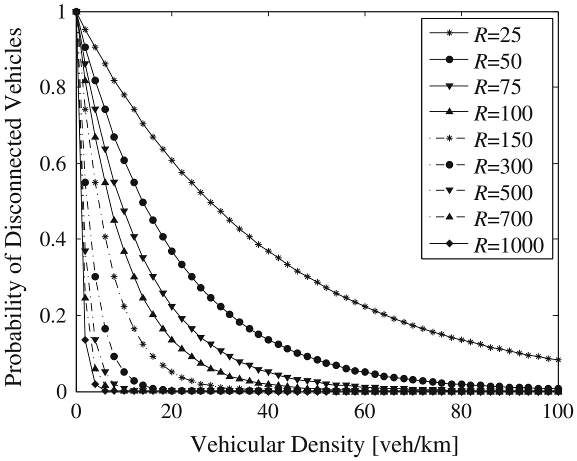
where X[m] is the intervehicle distance, λ [veh/m] is the distribution parameter for inter-vehicle distances, and R [m] is the radio range. Vehicles are considered to be connected if the intervehicle distance is less than the radio range, i.e., $X \leq R$. Correspondingly, vehicles are considered to be disconnected if the intervehicle distance is greater than the radio range, i.e., $X > R$.

The exponential distribution used to generate the intervehicle distances on the roadway has been shown to be in good agreement with real vehicular traces under uncongested traffic conditions [48]. The memoryless property of the exponential distribution [49] implies that the intervehicle distances are independent of each other. Figure 7.6 shows the connectivity trend as the density ranges from 0 to a 100 vehicles/km, for different values of the radio range parameter R [m]. We can notice that as the vehicle traffic density increases, the probability of disconnected vehicles decreases.

Similarly, for the same value of vehicle traffic, it is intuitive that vehicles are disconnected with increasing probability as the radio range decreases. It is significant to note that there is always a non-zero probability that vehicles are disconnected.

The work in [14] has analyzed the influence of a number of parameters on the V2V connectivity modeling, including (i) the vehicle density, (ii) the market penetration, and (iii) the radio communication range. The authors consider a hash-shaped grid of N vertical, and N horizontal roads; as in [28], they design the network through a *connectivity graph*. Two observed values are considered, i.e., (i) the fraction of vehicles not connected with any other vehicle, i.e., $\varphi(t)$, and (ii) the fraction of vehicles belonging to the largest connected component of the graph, i.e., $\theta(t)$. Vehicle clustering is addressed both analytically and through simulations. For scenarios with simple

Fig. 7.6 Disconnected vehicles probability versus the vehicle traffic density, for different communication range values



intersections, the authors show that accurate predictions of the network connectivity can be made using *percolation theory* [50], describing the behavior of connected clusters in a random graph.

In the stationary regime, the authors model the spatial distribution of vehicles with a *Poisson process*, and then compute an upper bound on the average fraction of vehicles that are connected to no other vehicles (i.e., $E[\varphi(t)]$). This represents the situation when the vehicular network is at a state that the rate of vehicles entering the network is the same as the rate of vehicle leaving it:

$$E[\varphi(t)] = e^{-2\lambda\rho R}, \tag{7.3}$$

where R [m] is the connectivity range enabling short-range intervehicle communications, and ρ [veh/m] is the vehicle density.

We remind that in one-dimensional networks, the knowledge of inter-node distances is necessary to analytically model connectivity in VANETs. Many authors rely on the assumption that the positions of the vehicles can be statistically modeled with a poisson point process (PPP), e.g., [14, 17, 18, 26, 27]. The PPP has two main properties, such as (i) the distance between two consecutive points is a random variable with an exponential distribution with parameter λ, and (ii) given $x \in \mathbb{R}^+$ the number of points falling in the finite interval $\mathcal{I} \overset{\Delta}{=} (0, x) \subset \mathbb{R}$ is a random variable with a Poisson distribution with parameter λx. Figure 7.7 shows an illustrative realization of a PPP with parameter λ. Denoting by n the number of Poisson points falling in, it is possible to define the n-dimensional positions vector as

$$\mathbb{R}^{(n)} = [R_1, R_2, \ldots, R_n], \tag{7.4}$$

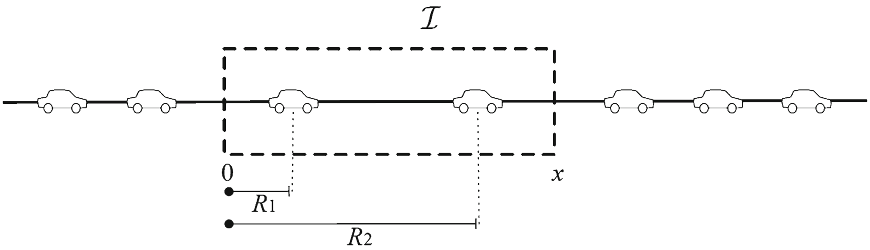


Fig. 7.7 An example of a vehicular linear network topology, where vehicles are placed following a Poisson process

where R_i, with $i \in \{1, 2, \ldots, n\}$, is the distance of the i-th point from the vehicle source placed in zero.

For what concerns the fraction of vehicles belonging to the largest connected component, i.e., $\theta(t)$, Kafsi et al. [14] consider the probability p that a road segment (i.e., the portion of road between two consecutive intersections) is covered by a sequence of connected vehicles. In this vision, the vehicular network is assumed as an *edge percolation model*, where each road segment is covered with probability p.

The use of percolation model allows addressing the case of a network with infinite size, with $N \to \infty$. According to [50] it is known that:

$$E[\theta(t)] = \begin{cases} 0 & \text{if } p < \frac{1}{2} \\ > 0 & \text{if } p < \frac{1}{2} \end{cases} \tag{7.5}$$

which is termed the *percolation phenomenon*. It means that there is a *critical density* above which a giant connected component appears (super-critical phase), while below this density, all connected components have a finite size. If the network is large but finite, its connectivity behavior is not much different. *Below* the critical density, all connected components are relatively small, and the largest of them may only contain a small fraction of the vehicles. On the contrary, *above* the threshold, a large connected component forms, containing typically more than half of the vehicles.

Therefore, a “soft” transition from below to above the critical density is expected, with the fraction of vehicles in the largest cluster suddenly shifts from low values to values close to one. Notice that these results are valid only if each road segment is covered independently with the probability p. It follows that the location of vehicles near intersections may influence the connectivity of adjacent segments. In addition, the authors show that traffic lights significantly influence the size of largest clusters, since the commonly observed accumulation of vehicles at red traffic lights can be beneficial for connectivity as it can sustain V2V communications. However, this clustering has the drawback of increasing the distance between equipped vehicles and its fluctuations. Thus, the largest cluster size remains low.

The presence of traffic lights is also considered in the analytical approach in [21]. The authors propose a stochastic traffic model, which relies on both the *fluid* model and *stochastic* model, in order to (i) characterize the general flow and the evolution of the traffic stream, and (ii) take into account the random behavior of individual vehicles. This method can be also utilized to characterize the connectivity dynamics inside the VANETs, modeled by stochastic traffic. With the knowledge of the vehicular density dynamics, the authors determine the probability that the network within an urban road segment is connected.

The use of percolation theory has been also used in [19] and [20]. Jin et al. in [19] give a theoretical analysis of the VANET connectivity in Manhattan grids by investigating the quantitative impact of (i) vehicle density, and (ii) transmission range on network connectivity. Jin et al. provide connectivity analysis in two different scenarios, featured with (i) small and (ii) large transmission ranges. Every road segment between two intersections can be regarded as a *bond* and the probability that a road segment is covered by a sequence of connected vehicles is denoted as p. A bond is said to be *open* with probability p, and then *closed* with probability $1 - p$. When the transmission range is small, it can be assumed that whether a bond is open or not is independent from other bonds, and the *bond percolation model* can be applied. This assumption does not hold for large transmission range scenarios for which the *Bollobás model* is better suited. In both cases, a network connectivity indicator *threshold* is derived, which determines whether the network connectivity is bad or not.

Given the vehicle density, the model allows calculating the minimum transmission range to achieve good network connectivity.

In [22] V2V connectivity is investigated in a highway scenario. Similar to some mentioned works, the authors assume the network can be partitioned and they focus on two metrics: (i) the platoon size (i.e., the number of vehicles in each connected cluster), and (ii) the connectivity distance (i.e., the length of a connected path from any vehicle). Unlike most of other related work that start from a given vehicle distribution on the road, by leaving unclear the effect of the vehicle's speed distribution and the road's traffic flow, the authors explicitly derive the distribution of the distances between cars. To more precisely study the effects of speed on connectivity, they provide bounds obtained by using stochastic ordering techniques, by following the work of Miorandi and Altman [51] for 1-D ad hoc networks, which transformed the problem of connectivity distance distribution into that of the distribution of the busy period of an equivalent infinite server queue. It was observed in [51] that the busy period of an infinite server queuing system has the same distribution as the connectivity distance. Moreover, the number of customers served during a busy period has the same distribution as the number of mobiles in a connected cluster in the ad hoc network.

The probability distribution and the expectations of the platoon size and the connectivity distance are both derived under different market penetration, number of lanes, transmission range, traffic flow, and speed scenarios. They found out that when the traffic's speed increases, the metrics of connectivity decrease. A further finding is that if the variance of the speed's distribution is increased, then, provided that the average speed remains fixed, the connectivity is improved.

Most of existing research studies focused on analyzing network connectivity in a simple highway scenario, modeled as 1D network topology, where vehicles travel in well-defined directions. Instead, a few studies exist that analyze connectivity in more complex two-dimensional urban scenario, [14, 21, 23]. The work in [23] provides a comprehensive framework for studying vehicular connectivity in urban VANETs by considering, in addition to [14, 21], the possible obstruction of signal propagation due to buildings. Besides extensive simulations based on their *Cellular Automata Model for Mobility* introduced in [52], the authors provide a statistical analysis of connectivity. The mobility model is designed to accurately describe traffic behavior in urban scenarios, with intersections, traffic lights, which exhibit great spatial diversity, making car distribution far from uniform.

Due to presence of intersections in urban scenarios, a link may be broken because of one or a combination of the following causes: (i) *non-intersection*, when two vehicles travel in directions away from each other causing the link to break when the distance increases beyond the transmission range; (ii) *light-indication*, when two vehicles traveling in the same direction sees red and green light, respectively; (iii) *turning-vehicle*, when the direction of vehicles change at the intersection. Closed form expressions of *link duration*, defined as the continuous time during which two vehicles are within transmission range of each other, are derived mainly through basic geometry, by assuming that: (i) vehicles move at *constant speed,* assumption supported by simulation results the authors achieved; (ii) vehicles have the *same transmission range;* and (iii) the *same probability* exists to *get a red or green light* upon arriving at intersections. The *re-healing* time, capturing the time duration in which there is no available paths between the two vehicles, is also derived starting from the assumption that it can be approximated by the time during which a vehicle is not in the largest connected cluster. Such an assumption is supported by simulation results showing that connectivity can be studied through cluster-based analysis, similarly to [14, 28], and that networks consist of one main cluster containing almost all of vehicles and other smaller clusters.

7.4.2 Modeling V2I Connectivity

Unlike V2V connectivity, difficult to be analyzed in large-scale test-beds, preliminary field-trials have been conducted to prove the *feasibility* of V2I communications to support Internet-based applications, e.g., [32, 53]. However, achieved performance are not promising: as a matter of fact, as vehicles move, their connectivity is both *fleeting*, usually lasting only a few seconds at urban speeds, and *intermittent*, with gaps between a connection and the subsequent one (i.e., vehicles could wait up to several minutes before obtaining again connectivity). The experimental study in [53] shows that the median vehicle-to-AP connection duration is around 13 s, while the mean duration between connections is around 75 s. Not negligible connectivity gaps between nearby Wi-Fi APs are also registered in experimental test-beds conducted in [24].

Only recently systematic approaches have been designed to model the (multi-hop) connectivity to infrastructure nodes [14, 24–29, 65]. In addition to the mobility and distribution patterns of vehicles, the market penetration rate of wireless technology in vehicles, and the transmission range, the distribution pattern of road-side stations would significantly affect the connectivity performance in V2I configurations.

Apart from addressing the connectivity in V2V communications, as previously described, Kafsi et al. in [14] study the influence of RSUs on vehicular connectivity. They assume that all RSUs are connected over wired or other fixed communication links, e.g., the Internet, in order to avoid intervehicle disconnections. The RSUs are placed at intersections, considering existing infrastructure at these locations (i.e., traffic lights, electricity, etc.), and have a distance of 400 m between each other.

The authors demonstrate that the differing vehicle placement conditions influence the overall connectivity and, most notably, the proportion of vehicles in the largest cluster. In contrast, RSUs do not significantly improve connectivity in all scenarios, e.g., RSUs at intersections do not reduce the proportion of isolated vehicles, which are more likely to be in the middle of the road, and then do not significantly increase the connectivity (i.e., the size of the largest cluster). As a consequence, RSU placements should be carefully planned and the authors suggest placing them in the middle of the road as a possible alternative. However, it should be noticed that results have been achieved with a *simplistic* channel model. Simulation results in [43] show, instead, that placing RSU at intersections can help to counteract corner propagation effects.

In [24] a Hidden Markov model (HMM) is proposed to model V2I connectivity. Single-hop V2I communications are considered, and vehicles experience connectivity *disruption* when they are not under AP coverage. In this context, the aim of the work is to model aggregate disruption in a particular drive. In fact, the HMM is based on experimental observations tracked through tests conducted by driving through existing domestic and commercial areas of a city where Wi-Fi connectivity is provided. Three states are considered in the HMM for modeling the connection state of vehicles: (i) *usable*, when a vehicle is connected to an AP and it is using its network services; (ii) *connected*, when a vehicle tries to get a connection with an AP; (iii) *disconnected*, when the vehicle is not under the coverage of an AP. Both open access APs (i.e., not requiring authentication) and closed access APs (i.e., requiring users to show proper credentials in order to access network services), are deployed in the considered scenario and accounted for in the proposed model. As a drawback, the main limitation of the work is that achieved results, e.g., in terms of the probability of encountering a given number of APs, are topology-specific and cannot generally represent all areas. However, this approach is valid for different areas, whenever the HMM state transition matrices are properly modified.

Understanding connectivity dynamics could have the additional benefit to help network designers and providers to effectively optimize the deployment of RSUs, that is a challenging task especially in case of disrupted V2I communications. In [25] it is introduced the notion of *intermittent coverage* for mobile users, called α-*coverage*, which provides the worst-case guarantees on the interconnection gap, while using significantly fewer RSUs. The *interconnection gap* is defined as the maximum distance, or expected travel time, between two consecutive vehicle-RSU contacts. Such a metric is chosen because the delay due to mobility and disconnection affects messages delivery more than channel congestion. As an analogy, the *crossing time* parameter defines the time a vehicle spends inside a wireless network, and represents a criterion for *handover* procedures in VANETs [54]. In [25] the authors rely on the *connectivity graph* concept, where RSUs are the vertex, and a weight is associated to each edge, i.e., a road segment that models the road length and the expected travel time. Informally, a deployment of RSUs provides α-*coverage*, if any simple path of length α in the network meets with at least one RSU. For a given deployment and a given budget on the number of RSUs, the proposed approach looks for an optimal RSU deployment providing α-*coverage* for a minimum possible α under the budget constraint. This problem is NP-hard, hence the authors propose efficient heuristics. The proposed framework can be used to decide how to place RSUs at roadside either from scratch or incrementally so that worst-case service guarantee can be given, e.g., for applications tolerating intermittent connectivity.

In [26] an analytical model is derived to fully characterize the connectivity in a vehicular network considering both one-hop (direct access) and two-hop (via a relay vehicle) communications between a vehicle and the infrastructure. Closed-form equations have been derived for calculating (i) the *access probability*, i.e., the probability that *any arbitrary vehicle* can access its nearby RSUs within two hops, for user satisfaction analysis, and (ii) the *connectivity probability*, i.e., the probability that *all vehicles* can access at least one RSU within two hops, by investigating a sub-network bounded by two adjacent base stations, for service coverage analysis.

RSUs are uniformly deployed along a road, while vehicles are distributed on the road randomly according to a Poisson distribution. Equations are derived for a generic radio channel model and specified for the unit disk and log-normal shadowing models. The impact of the following system parameters has been considered: inter-RSU distance, vehicle density, and transmission range. Achieved results show that (i) when the vehicle density is low, a vehicle is either directly connected to an RSU or disconnected, i.e., cannot reach any RSU in at most two hops, while (ii) with an increase in vehicle density the *access probability* increases, since the probability for vehicles in the gap of the RSU transmission ranges to find a neighbor within the transmission range of an RSU, acting as a relay node, increases. These results can be useful for a network operator to design a network with a given level of access guarantee. However, the main weakness of this approach is that it neglects mobility aspects, expected to significantly affect performance.

Adbrabou and Zhuang in [27] propose an analytical model, which is useful to approximately estimate the minimum number of RSUs, required for covering a road segment. The focus is on *low-density* vehicular networks, where V2I communications can be extended through vehicles relaying packets. Instead of modeling connectivity-related parameters, the framework targets the impact of several parameters (including the vehicle speed) on *packet delay* performance, in case of disrupted connectivity.

As in most of the existing literature, the model assumes that vehicles are distributed as Poisson points. The authors introduce a new vehicle mobility model that is characterized by two random variables, (i) the vehicle speed (i.e., V [m/s], in the range $[v_L, v_H]$), and (ii) the time period (i.e., T[s]) during which a vehicle moves

Table 7.1 List of the main common assumptions in connectivity models for VANETs

Assumption	Assumption type	Study
Vehicle distribution	Poisson	[14, 15, 17, 18, 21, 26–28, 59]
Topology	1D w/o traffic lights/intersections	[15, 18, 22, 24–29, 59]
Underlying model	Connectivity graph	[14, 15, 19, 20, 25, 28, 65]
Propagation model	Unit disk model	[14, 15, 19, 21, 26, 28, 59, 65]
Distribution of RSUs	Uniform	[26, 28, 59]

with a constant speed and is exponentially distributed to model the driving behavior. Independent mobility assumption is valid since it is jointly considered with vehicles bypassing each other. Unlike results in [26], in [27] multi-hop connections are considered and then packet delivery delay is not influenced by variations in the vehicle density or transmission range, as long as these variations keep the vehicular network sparse.

Similarly in [28], the authors consider the problem of access point placement. Under the assumption of delay tolerant messaging, they consider varying vehicular traffic densities and various RSU separations, to achieve connectivity. Different design choices can be taken as a function of vehicular traffic density, physical radio characteristics, and vehicle speed. The authors have shown that a large RSU separation is possible in a hybrid vehicular networking environment, comprised of multi-hop communication over moving vehicles, supported by RSUs.

To summarize the main contributions of this section, the following Table 7.1 is reported. It enlists the main common assumptions to the connectivity models analyzed in Sects. 7.4.1 and 7.4.2.

7.5 Solutions Improving VANET Connectivity

The connectivity models surveyed in the previous section show that (i) V2V communications can be effectively established only for dense traffic scenarios, but they are very limited in low-density neighborhoods, and (ii) short-lived connectivity and disruptions can be experienced in V2I communications.

In order to extend vehicular connectivity support, several solutions have been proposed in the literature, mainly leveraging *opportunistic* approaches. As a matter, the opportunistic contacts in vehicular networks, both among vehicles and from vehicles to available RSUs, can be very well used to instantiate and sustain both safety and non-safety applications. In this section, we present different solutions improving connectivity in VANETs, based on multi-hop V2V and V2I opportunistic links. Moreover, a brief description of opportunistic networking via satellite communications will be also investigated.

Opportunistic forwarding is the main technique adopted in DTN [55], and also extended in VANETs to achieve connectivity between vehicles via V2V and to disseminate information [22, 28, 56]. In particular in [28], when assuming a bidirectional road, the clusters formed in one direction of the highway come in *intermittent* contact with clusters of vehicles traveling in the opposite direction. Such contacts can be opportunistically exploited as a *bridging* technique, linking the partitioning that exists between clusters traveling in the same direction of the roadway.

On the other hand, the exploitation of RSUs together with inter-vehicle communications represents a viable solution to extend connectivity support in those scenarios where vehicles are not able to directly communicate, particularly in some applications, to *bridge* the inherent network fragmentation that exists in any multi-hop network through expensive connectivity infrastructure [29, 53, 57–59]. The use of a vehicular grid together with an opportunistic infrastructure placed on the roads can be a good solution to guarantee *seamless connectivity* in dynamic vehicular scenarios [59–61], and *hybrid communication paradigms* for vehicular networking are used to limit intermittent connectivity. In such approaches, connectivity can be provided by both existing network infrastructure (e.g., APs, and RSUs) through a V2I protocol, and traditional V2V networking [59, 62–66]. This combination is commonly referred to as V2X.

The cooperation and coexistence of these two different methods (i.e., V2V and V2I) can assure a good connectivity in VANETs. In [62], the authors propose a Cooperative Infrastructure Delivery Protocol, which allows vehicles to gather information about encountered RSUs through direct communication with the network infrastructure, and subsequent exchange messages with neighboring vehicles via V2V. The authors show the effectiveness of their approach, although it is limited to the message exchange about the infrastructure discovery. In [63], Wedel et al. use V2X communications for an enhanced navigation system, which intelligently helps drivers to circumnavigate congested roads and avoid traffic roadblocks. Their contribution highlights advantages of V2X communication protocols for numerous safety applications. In [64] Jeongwook et al. analyze the performance of a general hybrid communication protocol, based on the IEEE 802.11p WAVE system. Finally, in [65] a hybrid communication paradigm achieving seamless connectivity in VANETs is presented. Moreover, in [66] to satisfy QoS requirements, QoSHVCP technique is presented, based on QoS priorization. Through the use of a load-balancing mechanism, the failure of achieving QoS requirements is considered, so that the message propagation delay of high priority packets decreases regardless of the network overload. Simulation results have indicated how a hybrid approach provides lower delays, while maintaining the level of user's performance.

Among many performance metrics of an IVC system is the multi-hop connectivity between two communication nodes: the connectivity between two equipped vehicles or RSUs is defined as the probability that a *multi-hop communication path* exists between them at a time instant [57, 59]. In [59], the authors have designed a hybrid communication protocol, simply named as *vehicle-to-X* (V2X), working in heterogeneous vehicular network scenarios, where overlapping wireless networks partially cover the vehicular grid. This approach relies on the concept of *multi-hop communication path*.

V2X takes origin from the main limitations of V2V and V2I communications, causing seamless vehicular connectivity management to be a challenge for VANETs. V2X leverages the advantages of both protocols, so that vehicles can *opportunistically* exploit the network infrastructure whenever inter-vehicle communications are not available. As a result, a vehicle in V2X can switch from V2V to V2I, and vice versa, on the basis of a decision algorithm that is executed in a distributed fashion by each vehicle, based on a cost function using path alternatives. It follows that V2X allows vehicles to "handover" from V2V to V2I, and vice versa. Each vehicle is assumed staying in a connectivity state whenever is connected via V2V or V2I. The handover from a serving communication protocol to the other one is initiated by each vehicle on the basis of a decision policy, namely *optimal path selection technique*, that chooses the optimal vehicular communication protocol between two end nodes (i.e., V2V or V2I).

This approach considers a *total cost function*, i.e., a linear combination of two physical parameters: (i) the radio resource utilization time, and (ii) the time interval needed to transmit a message over a *path*. An *optimal path* connecting the i-th vehicle to the k-th RSU via multi-hop is selected on the basis of a minimization process of the total cost function.

The hybrid vehicular scenario considered in [59] is depicted in Fig. 7.3, where (i) vehicles are traveling forward (reverse) in opposite directions, and (ii) several RSUs of different wireless technologies partially cover a given area. A vehicle is said to be disconnected from the forward (reverse) network if it is not connected to any forward (reverse) neighbors in the network, assuming that the vehicle moves forward (reverse). Moreover, since it is a bi-dimensional vehicular grid, and the *bridging approach* occurs, a vehicle is said to be disconnected from the forward (reverse) network if it is not connected to any forward (reverse) neighbors driving in the opposite direction. In other words, the network is disconnected if the separation between any two adjacent and opposite nodes is greater than a connectivity bond. However, this definition is valid for a whole network, while for a portion of network, it is said to be connected if, for every pair of end-vehicles, there exists a *path* between them; otherwise, it is disconnected.

Simulation results in [59] have shown that both in sparse and dense traffic scenarios, the optimum path can guarantee minimum total cost functions for vehicles connected via V2V, while high values are obtained with V2I in a dense traffic scenario, and with V2V in a sparse traffic scenario for increasing number of hops. The authors found out that V2V is most suitable in dense scenarios, and in sparse traffic neighborhoods for path with a limited number of hops; while V2I could be the most appropriate protocol in sparse scenarios when the number of hops linking a source to a destination is increasing. By alternating V2V and V2I opportunistically, seamless vehicular connectivity can be guaranteed. The potentiality of hybrid communication protocols benefits not only connectivity in disconnected scenarios, but also improves the message dissemination in VANETs. In [65] and [66] the authors rely on V2X approach and consider the *vehicular partitioning*, such as the vehicular network is

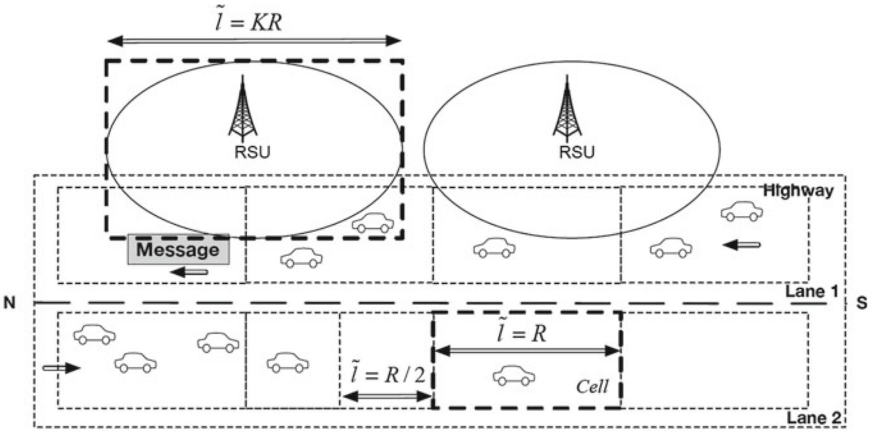


Fig. 7.8 Vehicular grid comprised of wireless RSU and V2V cells, [66]

comprised of different connectivity phases. The overall system can be modeled as an *alternating renewal process* where the vehicular connectivity structure alternates between three phases as follows:

1. Phase 1 (*No connectivity*): A vehicle is traveling alone in the vehicular grid. It represents a typical totally-disconnected traffic scenario where neither V2V nor V2I connectivity is available. The vehicles are completely disconnected;
2. Phase 2 (*Short-range connectivity*): A vehicle is traveling in the vehicular grid and forming a cluster with other vehicles. Only V2V connectivity is available within the transmission range of the sender/forwarder. No V2I connectivity is assumed to be available;
3. Phase 3 (*Long-range connectivity*): A vehicle is traveling in the vehicular grid with available neighboring RSUs. The vehicles enter the RSU coverage and are forced to connect via V2I to the Internet with accessible network infrastructure. No V2V connectivity is assumed to be available.

The probability that a vehicle lays in one of the three phases can be expressed as the probability that a vehicle is not connected, connected with neighbors, and with RSUs, respectively. In order to determine such a probability, it is useful to assume that a vehicular grid is discretized in terms of a number of cells, that is, the gap between two vehicles is equivalent to N cells. Figure 7.8 depicts the vehicular grid as composed of virtual RSUs and wireless V2V cells, with a variable size (i.e., $\tilde{l}$ [m]).

A cell is occupied if one or more vehicles are positioned within that cell. For a vehicle traveling alone on the southbound, i.e., S, (northbound, i.e., N), the probability that it will be connected in Phase 1 via multi-hop with a next vehicle on the southbound (northbound) depends on whether each of the N southbound (northbound) cells within the gap is occupied by at least one vehicle, given in [66] as

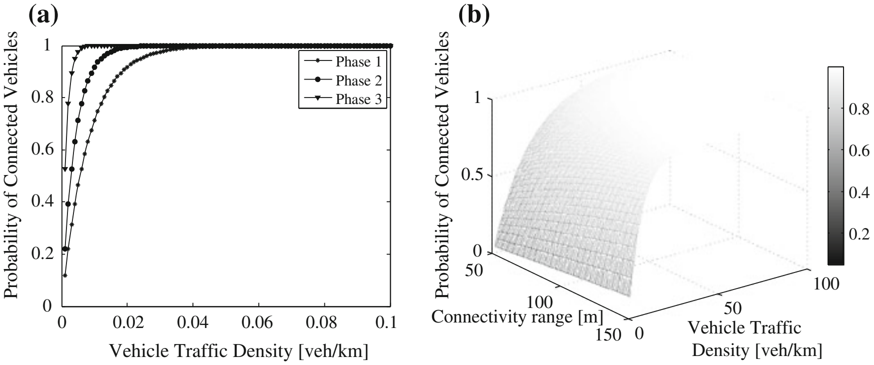


Fig. 7.9 Probability of connected vehicles (**a**) versus the vehicle traffic density (Phases 1–3), and (**b**) versus the vehicle traffic density and the connectivity range (Phase 1)

$$(p_{s,n})^N = (1 - \exp(-\lambda_{s,n} R))^N, \tag{7.6}$$

where $\lambda_{s,n}$ [veh/km] is the traffic density distribution on southbound and northbound, respectively. In this case, the number of cell is $N = 1$ since the gap equals the minimum intervehicle distance, i.e., $G = R$ [m].

In Phase 2, the vehicles along southbound (northbound) are connected via V2V if each of the N northbound (southbound) cells in the gap is occupied by at least one vehicle. This event occurs with probability $(p_{s,n})^N$, with $\lfloor N = G/R \rfloor$. In the event that not all of the N cells in the northbound direction are occupied, the vehicles along southbound are deemed to be disconnected.

Finally, in Phase 3, the probability that a vehicle traveling in the northbound (southbound) will be connected via V2I with a northbound (southbound) next vehicle depends on if each of the N northbound (southbound) cells in the gap is occupied by at least one RSU. In this case, $N = \lfloor G/(KR) \rfloor$ since the RSU cells are assumed to have a cell size $\tilde{l} = KR$ [m], with $K > 0$.

Figure 7.9a shows the analytical trend of the probability of connected vehicles for three different connectivity phases. The probability has been evaluated for R= 125 m; in Phase 2 vehicles are assumed to be separated for G = 150 m, while in Phase 3 the RSU wireless cells are greater than V2V cells for K = 1.5, and vehicles are separated for G = 1 km. Finally, in Fig. 7.9b the probability of connected vehicles in Phase 1 is shown. As expected, it depends on the availability of opportunistic links: the higher the vehicular density, as well as the connectivity range, the higher the probability of connected vehicles. The same trend can be obtained for connectivity in Phases 2 and 3.

In [67] the authors suggest to exploit RSUs to route packets between any source and destination in the VANET. RSUs, typically connected through a fixed infrastructure, act as a backbone and can communicate among each other to connect far vehicles. More in detail, when a vehicle has to send a packet to a remote vehicle it can send it to the nearest RSU, which in turn, forwards the packet to the nearest RSU to the destination. The benefit of such a solution is that it copes with the issue of finding, keeping, and updating a routing path to a specific destination, which could be difficult, if not impossible, in some vehicular environments because of fast topological changes and network fragmentation.

In previously surveyed works, we described how V2I communications can be opportunistically exploited to improve V2V connectivity, but solutions have been also proposed that leverage V2V support as a complement to possible intermittent connectivity with the road infrastructure, as mentioned in Sect. 7.4.2. The use of relay-based techniques have been proposed in [68–70], they lengthen the connection time with an AP and result in an increase in throughput.

In [68] a relay-based solution is proposed to extend the service range of roadside APs. As a vehicle moves towards an AP, its signal quality with the AP may be poor. A vehicle interested in uploading data towards the AP selects both a vehicle geographically ahead of it to serve as a relay, as well as a vehicle behind it to serve as a relay when it leaves the AP coverage area. Similarly, Yoo et al. in [69] leverage V2V relay support as a complement to possible intermittent connectivity with the road infrastructure, for downlink applications. More in detail, if an AP has a data frame destined to a vehicle that is not within its range, it sends the frame to another vehicle closer to the destination vehicle, acting as a *relay*. The relay then will deliver this frame to the destination vehicle. A solution improving V2I connectivity through vehicular relay is also proposed in [70]. Unlike previous works, relying on *drive-thru* connectivity offered by already existing Wi-Fi networks, the proposal has been designed to be compliant with upcoming IEEE 802.11*p* WAVE standards.

All previous approaches rely on V2V and V2I paradigms, for short- and long-range communications, respectively. However, in totally disconnected scenarios neither V2V nor V2I approaches are available. In this situation, when safety-critical messages need to be transferred, vehicular connectivity could be achieved *only* by satellite communication links, as investigated in [71]. Satellite radio is one of a complementary set of network connectivity technologies in future vehicles equipped with *on-board* computers. Main strength points of satellite links are a global coverage and the availability of broadcast and multicast services; however, link budget analysis is challenging, as well as the size and form factor of *on-board* antennas, in some cases, are unacceptable compared to terrestrial solutions.

Satellite connectivity has been largely used in VANETs for outdoor navigation and positioning services, while search-and-rescue (SAR) applications are used mainly in emergency scenarios to provide search for and aid to people in distress [8]. The scheme proposed in [71], as depicted in Fig. 7.10, shows how the satellite connectivity can solve the problem of seamless and ubiquitous connectivity, when a vehicle is driving alone in an area that is devoid of network infrastructure (e.g., a rural area during night hours), or it is in a disaster and emergency situation. Such vehicle is sometimes called as *isolated vehicle* (or vehicle in distress) in a totally-disconnected area. Satellite connectivity, adopted in VANET as an opportunistic link, is intended to augment short and medium-range communications to *bridge* isolated vehicles or clusters of vehicles when no other mechanism is available. Particularly, an isolated vehicle needs to alert about an accident occurred; it is not able to communicate to any

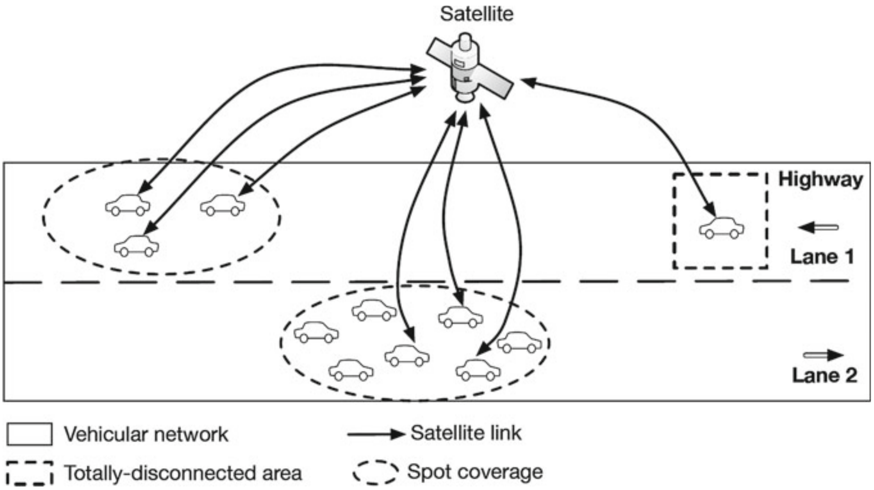


Fig. 7.10 An opportunistic networking scheme in a VANET scenario with satellite connectivity for safety applications. The satellite bridges an isolated vehicle, [71]

neighboring vehicles neither by V2V or V2I, but it can only send an SOS message via satellite links. An SOS message stores the vehicle's position. When the satellite receives the message, it will forward to the ground by *spot coverage* to clusters of vehicles in proximity. In the return link an acknowledgment is sent to the satellite in visibility, which forwards it to the isolated vehicle. The satellite works as a *bridge*, in order to connect the vehicle to the closest cluster of vehicles.

In [71] a dedicated low earth orbit (LEO)/medium earth orbit (MEO) Ka-band link analysis has been carried out, in order to evaluate (i) the minimum distance among cluster of vehicles and isolated user versus satellite orbit (i.e., LEO/MEO trade-off), (ii) the service availability along a selected time window, (iii) the LEO/MEO satellites visibility from uplink and downlink coverage, (iv) link feasibility and availability. The exploitation of satellite links in VANETs may provide a reduction of terrestrial network infrastructure, as well as multi-hop V2V communications, and a service coverage extension with respect to terrestrial infrastructure. Although promising, such a solution could be too expensive and requires further investigations.

7.6 Conclusions and Discussion

In this chapter, we have investigated connectivity issues in VANETs, i.e., a particular class of *opportunistic networks* in which, due to the dynamic behavior of vehicles and sparse RSUs settling, V2V and V2I connectivity links are short-lived and intermittent and have to be opportunistically exploited in order to transmit/forward messages.

We have described the main network and road parameters, such as road topology, traffic density, vehicle speed, market penetration of the VANET technology, and transmission range, which strongly affect the network connectivity behavior.

Existing analytical models in the literature have been investigated; each of them differs into the underlying assumptions and the considered connectivity metrics. However, some common assumptions have been noticed, as summarized in Table 7.1. For instance, most of the approaches rely on the Poisson model to describe vehicle distribution. Notice that, although the model is commonly used and widely accepted also in transportation engineering [35, 72], it does not capture the realistic interaction between vehicles, as outlined in [18]. First, positions of vehicles are not independent since drivers have to observe car-following or lane-changing rules. Second, the density of vehicles can vary significantly along a roadway due to both driving behavior and restrictions of network geometry.

Mobility dynamics are often completely neglected in existing studies thus hindering the possibility to effectively evaluate the performance of session-based applications. Studies evaluating connectivity metrics but neglecting connectivity dynamics, i.e., how connectivity between two vehicles changes with respect to time, are meaningful only when considering the dissemination of safety messages, which typically foresees the transmission of a single packet. However, session-based applications, like non-safety applications, may require the exchange of several packets, and in this case connectivity dynamics should be carefully considered.

With respect to connectivity metrics, besides the straightforward probability of connected (or disconnected) vehicles, other helpful metrics have been found in the literature. Link duration and crossing time, respectively, accounting for the connection duration among vehicles and between vehicles and infrastructure nodes, can determine whether a particular application can be supported in such an environment, e.g., Internet-based applications may not be feasible if contact times are below a given value. From a protocol designer's perspective, metrics like the infrastructure interconnection gap and the re-healing time may be used, respectively, to plan RSU placements and to indicate the size of a message buffer in case of *store-carry-and-forward* approaches carried out in V2V configurations.

It should be further noticed that, although not properly considered in several existing work, potential resource contention among several vehicles, concurrently accessing the medium to exchange data with nearby vehicles or RSUs, may significantly affect the quality and time duration of contacts.

Several works rely on the simplistic unit disk model to characterize channel phenomena, while realistic propagation models, accounting for shadowing effects and obstacles in urban scenarios, are considered only in a few works. Finally, another assumption simplifying the analytical treatment considers traditional 1D network topologies. It is the authors' convincement that since analytical models are expected to play an important role in performance evaluation of VANETs, they need to be significantly improved in terms of accurateness and realism.

Different solutions improving connectivity in VANETs have been presented. Some solutions exploit the presence of infrastructure nodes either to facilitate routing between distant vehicles or to bridge fragmented networks. Other approaches leverage handover mechanisms between traditional multi-hop V2V and V2I paradigms. Opportunistic networking via satellite communications is proposed to bridge isolated vehicles when no other mechanism is available. On the other hand, V2V relay-based techniques appear as a promising solution to "virtually" extend the infrastructure coverage and reduce connectivity disruptions. Further efforts are then required to design solutions enabling V2V and V2I connectivity in different network conditions to sustain both safety and non-safety applications.

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