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Vehicular Ad Hoc Networks

In the last decade, we witnessed an increasing interest in the transportation sector and the research community to improve road safety and supply commercial services by providing timely and accurate information to vehicular drivers and transport authorities. One way to achieve these goals is by sharing road traffic information through wireless and mobile networks with little or no infrastructure, known as Vehicular Ad hoc NETworks (VANETs). This chapter reviews an overview on VANETs, starting with a general VANET definition of VANET and its main characteristics which distinguish VANETs from the other wireless networks. This chapter also highlights VANET fundamental applications proposed to increase utilities of Intelligent Transportation Systems (ITS). Moreover, VANET architectures and mobility models are presented in this chapter, in addition to the most used vehicular network simulators applied to evaluated VANET performances. Finally, this chapter outlines the main VANET challenges and issues, like data routing, VANET scalability, routing robustness and self-organization, and security.

1.1. VANET definition, characteristics and applications

1.1.1. *Definition of vehicular* ad hoc *network*

VANETs are seen as a specific type of mobile ad hoc network (MANET), which provides data communication in vehicular areas using a wireless transmission. VANETs are conceived to enhance wireless communication initially provided by vehicular cellular networks either in urban or rural areas. Two kinds of VANET nodes exchange data messages in multi-hop mode, namely mobile nodes (i.e. vehicles) and stationary nodes known as roadside units (RSUs) which are installed on

roadsides. All nodes forward data messages from the first sender called the source node to the final receiver known as the destination node. As a result, several types of transportation applications are performed to the benefit of passengers or transport authorities such as Freeway Management, Crash Prevention and Safety, Road Weather Management, Collision Avoidance, Driver Assistance [RIT 14].

Several academic definitions of VANETs were proposed in the literature. We propose a general definition of VANET, taking into account all vehicular network functionalities and its largest infrastructure, as follows:

VANET can be defined as a set of mobile nodes consisting of vehicles, as well as fixed nodes known as RSUs deployed at critical locations such as slippery roads, service stations, authority buildings, dangerous intersections or places well known for hazardous weather conditions [BIT 11]. VANET provides digital data communication in wireless and multi-hop manner between vehicles through inter-vehicle communication (IVC), and between vehicles and RSUs through vehicle-to-roadside communication (VRC), as shown in Figure 1.1.

Vehicles are equipped with some sort of radio interface, called an On-Board Unit (OBU), that enables short-range wireless IVCs and/or VRCs along with a Global Positioning System (GPS) integrated into vehicles to facilitate location-based services.

Contrary to MANET nodes, VANET vehicles do not move around arbitrarily, due to their restricted range of motion in terms of directions and speeds. In fact, vehicles move according to an organized pattern, called a mobility model, based on predefined roads, buildings, junctions and other traffic entities, in an urban or a rural area.

1.1.2. *Characteristics of vehicular* ad hoc *networks*

VANETs are special mobile and wireless networks, characterized by a set of particular properties which make them very distinct, and call for more requirements to develop networking vehicular applications. This section reviews the main properties of vehicular networks and shows the influence of these properties on the vehicular applications.
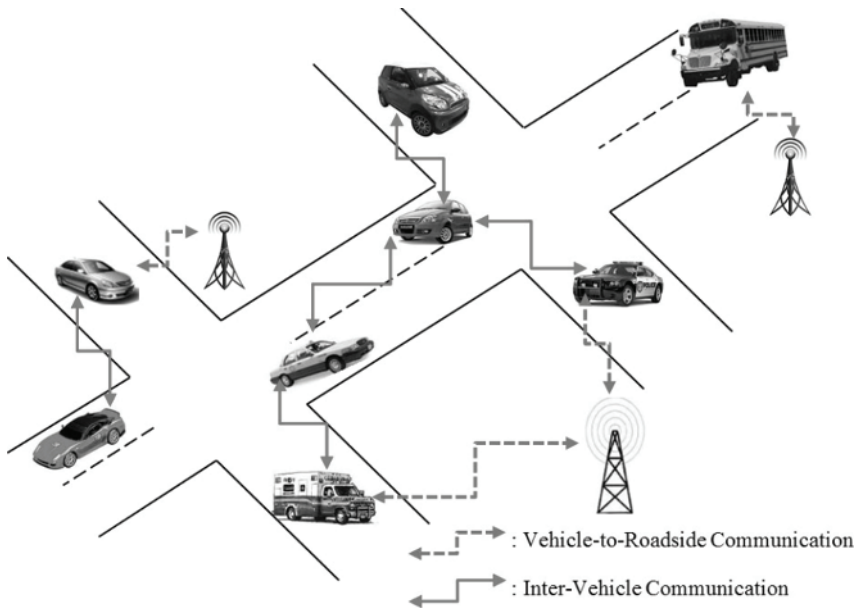
Figure 1.1. *Vehicular* ad hoc *network. For a color version of this figure, see www.iste.co.uk/bitam/bio-inspired.zip*

1.1.2.1. *Vehicle velocity*

In VANETs, vehicle velocity is the rate of change of the position of mobile node versus time. Vehicle velocity may range from zero when vehicles are stuck in traffic jam, to over 200 km/h on highways [SCH 08]. Vehicle velocity has an important potential on the vehicular network applications in the two extremes vehicle velocities. In the case of very high velocity, for example on highways, the period when transmitter and receiver are connected is very short (i.e. time of stable connection between transmitter and receiver). Therefore, the routing process should be frequently relaunched to find new routes and to ensure long period transmission. This frequent route discovery implies a considerable delay to transmit data packets, in addition to a significant packet loss due to the eventual use of expired routes. However, when vehicles move slowly, the network will be very dense in terms of nodes number. Consequently, high interference could occur, and then medium access solutions are required.

1.1.2.2. *VANET density*

VANET density is considered as a particular property which can make a basic distinction between vehicular network and other wireless networks. In fact, the

deployment area of VANET nodes can contain a very high number of nodes which can exceed 250 nodes in the transmission range of one node. This situation can occur if the vehicular traffic is very congested due to various reasons such as traffic jams and accidents, which is the case for the very high density. Consequently, many undesirable networking effects can occur, such as network fragmentation during the routing process, use of a long multi-hop path to transmit messages and high interference. However, a VANET can be considered low density if it contains a low number of nodes, scattered in vehicles' environment, particularly in rural areas or at off-peak traffic hours. In such cases, several forwarded messages can be dropped due to the absence of an intermediate node between the source node and the destination. Hence, several copies of messages should be stored and be present upon multiple times by the same transmitter causing an important delay of packet dissemination.

1.1.2.3. *Node heterogeneity*

The third key property of VANETs is the node heterogeneity which means a considerable diversity in the network nodes. Two aspects can be distinguished to explain node heterogeneity in such networks: the structural aspect and the functional aspect. The former concerns structure of VANET nodes, two major types of nodes can be cited: vehicles and RSUs. Vehicles are mobile nodes, with limited and different transmission range, equipped by OBUs as wireless transmission interfaces, as well as heterogeneous digital devices to perform computational applications, such as processor (CPU), memory. Also, vehicles can connect directly to other VANET nodes (vehicles or RSUs) through wireless waves that form a no-infrastructure subnetwork. This non-uniformity of vehicle devices requires more studies to ensure a continuous functionality of the entire network. The second component type of a VANET is RSU, defined as immobile nodes installed at a fixed location along the roadside aiming to help vehicles to connect to the global network or to the Internet as gateways. RSUs are in wired connection with other RSUs to form permanent infrastructure of VANETs. Due to its immobilities and wired links, RSUs' placement in vehicular area is a considerable issue.

From the point of view of VANET functions, vehicular network nodes can be categorized according to various types of vehicular applications, namely control applications installed on authority vehicles or on RSUs, fixed sensing applications ensured by RSUs, emergency and ad hoc applications performed by private and authority vehicles and warning and maintenance applications executed by emergency vehicles. Consequently, a certain level of distinction is required during

implementation and management of applications such as ensuring access control, privacy and priority.

1.1.2.4. *Mobility model*

Due to the vehicular environment, consisting of roads, buildings, junctions and traffic regulations, VANET vehicles move around in a regular and restricted mobility model [PLÖ 08]. This regularity of nodes' movement does not occur on the other kind of ad hoc networks. Hence, VANET studies should be based on strict and realistic mobility model to obtain more significant results and realistic conclusions.

Three main submodels of mobility can be mentioned: highway, rural and urban submodels. The highway is a mobility submodel located usually outside cities, and characterized by low density. It consists of two main roads in two different directions. Each road is formed by three or more lanes, in which vehicles can move with very high speed. However, the rural submodel consists of a set of more or less organized streets, where vehicles move with low speed. Vehicles in rural area form a low dense network. The third submodel is the urban submodel. It represents city road network which is very dense and consists of lots of small or big roads, many junctions usually equipped with traffic lights and signals, as well as buildings which limit wireless communication. In the urban network, vehicles can move with low speed, but on some roads they can move with relatively high speeds. Vehicles' movement in each of these submobility models is constrained by vehicle speeds, directions and densities that represent challenges to be taken up in VANET studies.

1.1.3. *Applications of vehicular ad hoc networks*

Different types of application can be supported by vehicular networks such as vehicle safety, automated toll payment, traffic management, enhanced navigation, location-based applications (e.g. finding the closest fuel station, restaurant or hotel), and infotainment applications through Internet-based services [BIT 13b]. In this section, the main applications provided by VANETs are outlined.

1.1.3.1. *Road safety applications*

It is widely accepted that road safety applications are the most sensitive services in VANETs because of the significant impact they can have on human lives. The main goal of safety applications relies on the aggregation and sharing of VANET information through safety messages, which are transmitted by each VANET node (i.e. vehicle and RSU). These safety messages gather vehicular information

including vehicle and traffic states. The carried information is vehicle location, velocity, acceleration, brake state, traffic lights states, pedestrian numbers, etc. On the basis of timely delivery and processing of safety vehicular information, vehicles drivers can react appropriately and avoid dangerous and undesirable situations such as accidents and collisions.

1.1.3.2. *Vehicular authority services*

Vehicular ad hoc networks are also designed to help and expedite traffic tasks of transport authorities such as police and emergency recovery units. More specifically, authority applications can contribute to road safety and traffic improvement by transmitting warning and emergency messages from authority vehicles to other vehicles in order to inform approaching emergency vehicles using virtual sirens, or to preempt vehicle priorities which help authority vehicles to reach their destination rapidly. This kind of service is known as "emergency response". Moreover, VANETs are also intended to support another kind of authority service called "traffic surveillance". In fact, nodes of VANET can sense and send information to authority centers using surveillance applications such as stolen vehicle tracking, vehicle safety inspection, electronic license plate verification and electronic drivers' license checking. It is worth noting that this type of application must not be abused by anyone, which clearly underlines security requirements and the need for a discussion of legal aspects of vehicular communication [SCH 08].

1.1.3.3. *Enhanced driving*

Enhancing driving is another category of applications supported by VANETs. This category improves driving by providing local traffic information as well as information concerning the global vehicular environment. Local traffic information is data sent by other vehicles or RSUs which helps drivers to improve their driving. For example, a climatic condition may be sensed by VANET nodes and disseminated in the local area to suggest some beneficial actions, such as running the vehicle air conditioner in a polluted or congested area, or lighting up headlights in the underground passage. However, global traffic information is data which concern the entire network and can be sent by distant nodes to all network nodes to indicate a network state or useful information that helps drivers to make the appropriate decision against a critical situation. We can mention the case of traffic congestion which could be reported in the entire network, so distant drivers can take another road which is much faster. Furthermore, there are also various comfort applications which improve drivers' and passengers' traveling and provide informative services

such as fuel station locations, global weather information and emergency and breakdown services.

1.1.3.4. *Business and entertainment services*

Vehicular networks can improve comfort of drivers and passengers by providing commercial services through the Internet or other private networks. These business services ensure delivering digital products to road consumers, such as parking payment and road usage payment. Note that vehicular businesses should warrant all conventional digital business requirements such as transaction security and privacy, and secured payment. Moreover, entertainment and interactive multimedia services are also delivered by VANETs, such as downloading movies and music, and playing online games.

1.2. VANET architectures

Following on from different types of communication devices and network infrastructures, VANETs can be organized within three categories of architecture: vehicular WLAN/cellular, pure ad hoc and hybrid architecture.
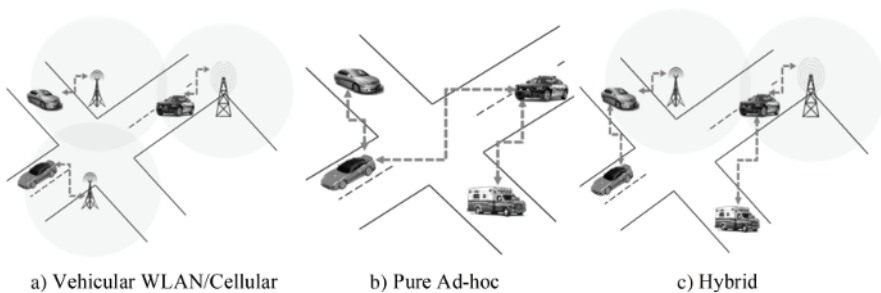

a) Vehicular WLAN/Cellular   b) Pure Ad-hoc   c) Hybrid

Figure 1.2. *Various VANET architectures; a) vehicular WLAN/cellular; b) pure ad hoc; c) hybrid. For a color version of this figure, see www.iste.co.uk/bitam/bio-inspired.zip*

1.2.1. *Vehicular WLAN/cellular architecture*

In this category, vehicular network consists of vehicles as wireless and moving nodes, as well as a fixed infrastructure used to link vehicles to a wider network such as the Internet, as shown in Figure 1.2(a). Two kinds of fixed infrastructure can be

cited: Vehicular Wireless Local Area Networks (V-WLAN) and Vehicular Cellular Network (VCN).

V-WLAN is formed by a set of access points fixed at traffic intersections and allows vehicles to move around within a local coverage area and still be able to benefit network connections and applications. However, VCN consists of a set of fixed cellular gateways supplying wireless connections over land areas known as cells. Each cell is equipped by at least one fixed transceiver called roadside base station or RSU. It is worth noting that the vehicular network can combine both V-WLAN and VCN, so that RSU ensures connection if vehicle is within cell coverage area, otherwise an access point is used if present.

It is easy to show that access points or roadside units are narrowly deployed due to high costs or geographic limitations such as rural areas, islands and mountains. This situation urges vehicles to engage in direct communication with each other, which gives birth to pure vehicular ad hoc network (pure VANET) architecture.

1.2.2. *Pure* ad hoc *architecture*

Contrary to vehicular WLAN/cellular architecture, there is another vehicular network where no fixed infrastructure is required to ensure vehicular communication. This kind of network architecture is called pure VANET. This category considers that the network architecture is identical to MANET architecture, where the network is formed by only a set of mobile nodes (vehicles) performing vehicle-to-vehicle communication (i.e. peer-to-peer communication), as shown in Figure 1.2(b). Moreover, vehicles transmit data packets in a multi-hop manner and the disseminated information is self-managed in a distributed fashion without any centralized control [SCH 09].

Despite the advantages of the peer-to-peer approach to transmit data in such architecture, such as reduced delay and low-cost transmission, this category suffers from several drawbacks, namely absence of authority control and assistance, required by many sensitive applications such as vehicular safety, area monitoring, driving help and entertainment [LEE 06]. Also, these types of applications could not be provided by ordinary vehicles; only fixed communicating units (i.e. RSUs) installed, managed and controlled by authorities in fixed centers (i.e. city halls, police stations, meteorology offices, etc.) might be able to provide such applications.

1.2.3. *Hybrid architecture*

After analyzing the above architectures, it was suggested to take advantage of both fixed infrastructure and vehicle-to-vehicle infrastructure to form a new general architecture of vehicular network called a hybrid vehicular network, which is more flexible and provides richer contents [LEE 10]. It is a vehicular network composed of two parts; an infrastructure part which is a set of RSUs (i.e. access points and/or cellular gateways), in addition to a set of mobile nodes (i.e. vehicles) represents a no infrastructure part, as shown in Figure 1.2(c).

In this architecture, vehicles engage themselves as routers and/or end-nodes, and can send and receive data packets to and from other vehicles in ad hoc and multi-hop fashions, and/or via RSUs as fixed nodes. Compared to the abovementioned architectures, a hybrid VANET is very flexible, less expensive and very appropriate to different vehicular scenarios such as highways, urban and rural areas. For simplicity, in the literature and in the remainder of this book, a hybrid vehicular network is called a VANET.

1.3. Mobility models

To study message dissemination in VANETs, it is very difficult, even impossible, to realize real experiments in vehicular areas due to high risks, dangers and elevated costs of these examinations. Therefore, a simulation study is suggested to validate new contributions in this domain. However, it is very important to consider, in simulations, realistic scenarios which describe accurate vehicle movements taking into account several key parameters including velocity, displacement, and node density. To achieve this, several movement models were proposed in the literature, known as mobility models.

This section classifies the proposed VANET mobility models into four categories according to the generated movement of vehicles as follows: random-based mobility model, prediction-based mobility model, group-based mobility model and time and spatial dependency mobility model. Moreover, some software tools used to simulate node mobility of VANETs are also explained. Figure 1.3 presents the proposed VANET mobility model classification.
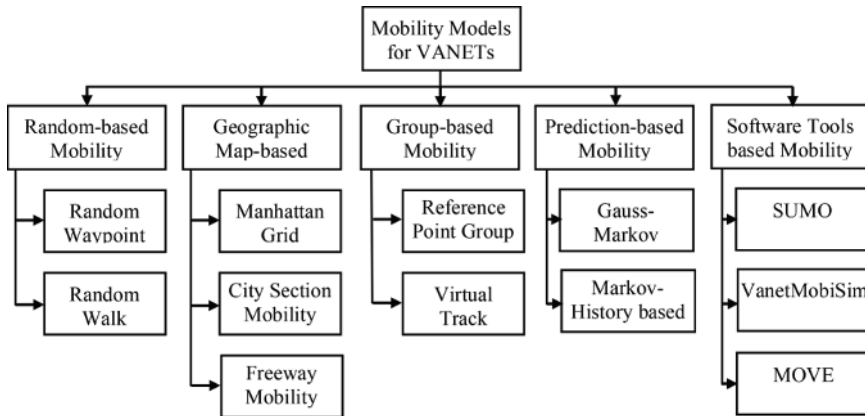
Figure 1.3. *Categories of VANET mobility models*

1.3.1. *Random-based mobility models*

In random-based mobility models, movement of vehicles progresses randomly over the time. In other words, vehicle location, velocity and acceleration change their values at random. For example, a vehicle chooses a random destination and a random speed between zero value and a maximum speed value. After that, the vehicle pauses for a fixed number of seconds. The following sections highlight principles of the main models of this category.

1.3.1.1. *Random waypoint mobility model*

For VANETs, the most widely and easily used mobility model is called random waypoint mobility, and was initially proposed for wireless ad hoc networks in [BRO 98] and applied to VANETs in [SAH 04]. This model considered that the mobile node (i.e. vehicle) moves periodically and then waits in its location during a certain period of time called pause time. After that, the vehicle randomly selects its direction from [0, 2π] which consists of all possible positions in neighborhood of the current position of the vehicle, as described in Figure 1.4. In addition, the following speed of the mobile node is randomly selected between two known values [minimum speed, maximum speed]. So, upon arrival, the mobile node pauses for a specified time period before starting the process again, and so on. It is worth mentioning that the vehicles can move either for a constant distance or for a constant time.

Despite its simplicity, the random waypoint mobility model is considered as a theoretical model, where it did not capture geographic restriction occurred in the simulated areas, such as buildings and roads. To surmount this limit, Choffnes *et al.* [CHO 05] enhanced this model and proposed the STreet RAndom Waypoint (STRAW) model for vehicular networks. STRAW constrains vehicle movement to streets defined by map data for real US cities and limits their mobility according to traffic congestion and traffic controls.
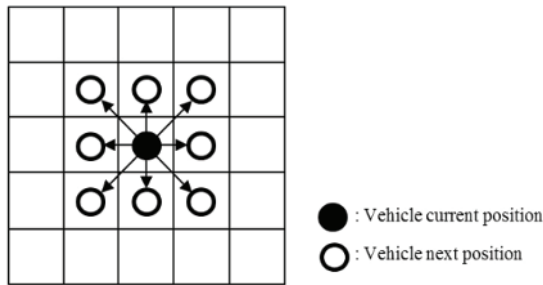

● : Vehicle current position

○ : Vehicle next position

Figure 1.4. *Random waypoint mobility model. For a color version of this figure, see www.iste.co.uk/bitam/bio-inspired.zip*

1.3.1.2. *Random walk mobility model*

Saleet *et al.* proposed in [SAL 10] a mobility model called random walk which is inspired by the movement of particles in nature. In this model, the vehicular area is represented as a grid of cells. Periodically, each vehicle moves to one of its four neighboring cells (i.e. north, south, east or west) with equal probability p fixed at 1/4, as shown in Figure 1.5.
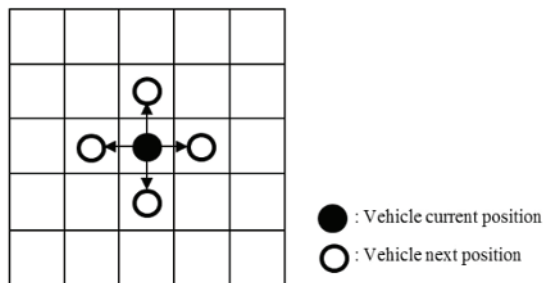

● : Vehicle current position

○ : Vehicle next position

Figure 1.5. *Random walk mobility model. For a color version of this figure, see www.iste.co.uk/bitam/bio-inspired.zip*

Furthermore, the vehicle chooses its new speed value according to a uniform distribution within the following interval [0, V_{max}], where V_{max} is the maximum value of vehicle speed. We note that the random walk model allows vehicles which meet the boundary of the simulation area to bounce off with same speed.

1.3.1.3. *Limitations of random-based mobility models*

Despite their simplicity, random-based mobility models are not applied to certain vehicular scenarios, especially in the occurrence of geographic restrictions and obstacles such as buildings, streets and curves. Moreover, some mobility characteristics can be omitted in this model, such as temporal or special dependencies in displacement, where the vehicle movement (direction and speed) is determined following temporary positions of the other vehicles in the neighborhood [BAI 04]. Also, the idea of moving vehicles with speeds determined at random is contradictory to the movement of vehicles in reality where the speed increases and decreases progressively over time.

1.3.2. *Geographic map-based mobility models*

To overcome limitations of random-based mobility models caused by geographic restrictions which form vehicular environments, several mobility models have been proposed in order to describe vehicle displacement over constrained and limited urban or rural maps. These vehicular maps consist of a set of roads, streets, obstacles, curves, buildings, etc. We present in the following sections main models of this category.

1.3.2.1. *Manhattan grid mobility model*

The Manhattan grid mobility model (MGMM) for VANETs was proposed by Naget and Eichler in [NAG 08]. MGMM was developed for urban areas where vehicles move on geographic map of a squared playground equally divided both horizontally and vertically into a grid of roads; each road has two lanes for the opposite direction, as shown in Figure 1.6. Once a vehicle reaches an intersection, a probabilistic selection is performed to choose the next direction. Concerning vehicle movement, two cases could be distinguished; the vehicle keeps moving in the same direction with probability equal to 1/2 or it turns left or right with probability fixed at 1/4 in each case. At a time slot, a vehicle's speed depends on its speed at the previous time slot and at the speed of the vehicle preceding it in the same lane.
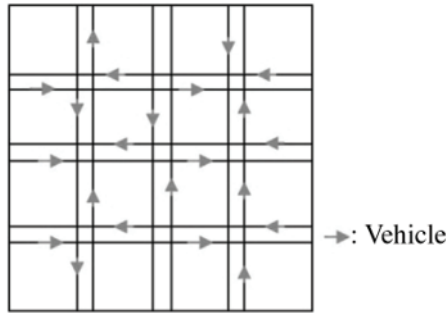
Figure 1.6. *Manhattan grid mobility model*

1.3.2.2. *City section mobility model*

Initially, the city section mobility model was proposed for ad hoc network in [DAV 00] and applied to vehicular networks in [HOS 09]. The city section mobility model describes vehicle movement on a street network consisting of a grid road topology in a city downtown area. Each road is considered bidirectional with a single line in each direction, as shown in Figure 1.7. A vehicle starts moving at a defined location on a road, and then a random selection of an intersection on the map is chosen as the vehicle's destination. As a result, the vehicle moves toward the selected destination with one horizontal and one vertical movement at most. The city section model considers the path with the shortest travel time between the start point and the destination and the vehicle's speed depends on the type of the traveled road such as a slow way, expressway, or others. While arriving at the destination, the vehicle pauses for a specific time, and then randomly chooses a new destination and repeats the process, and so on.
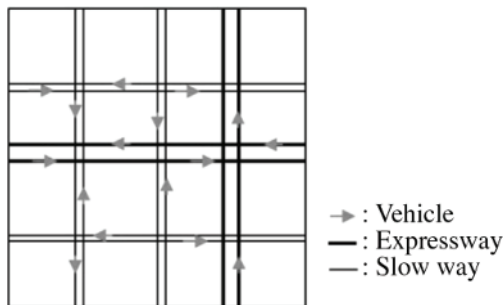

Figure 1.7. *City section mobility model*

1.3.2.3. *Freeway mobility model*

The freeway mobility model was proposed by Bai *et al.* in [BAI 03] to emulate the motion behavior of vehicles on a freeway, as shown in Figure 1.8. This pattern defines several freeways in a geographical map, in which each freeway is considered bidirectional with multilanes. Each vehicle of a lane moves strictly on the freeway with a velocity temporarily dependent on its previous velocity. It is worth noting that if two successive vehicles in the same lane are within the safety distance, the velocity of the following vehicle cannot exceed the velocity of the preceding vehicle.
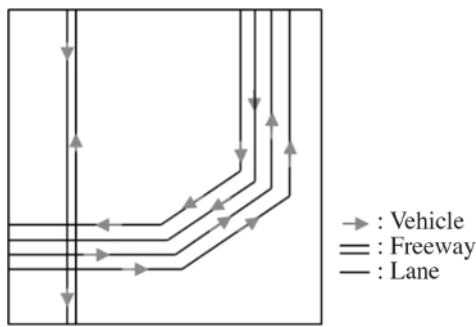

Figure 1.8. *Freeway mobility model*

1.3.2.4. *Limitations of geographic map-based mobility models*

This category of models is very simple to simulate and is more realistic due to the use of geographic restrictions; however, some traffic parameters may be considered to improve and predict vehicles' motion, such as network density making distinctions between vehicular scenarios in rush hours and off-peak hours.

1.3.3. *Group-based mobility*

The mobility models of this category focus upon using the collaboration among network nodes which have the same traffic goal, such as traveling to the same destination. Consequently, the network is divided into several groups of vehicles where each group possesses its own mobility behavior. This category lists the following models.

1.3.3.1. *Reference point group mobility model*

The reference point group mobility (RPGM) model was proposed in [HON 99] by Hong *et al.* for ad hoc networks. This model is based on the idea of forming several groups of vehicles which have the same target. Each group has a logical center point which leads the entire group's motion behavior, including location, speed, direction, acceleration, etc. Therefore, the group trajectory is determined by providing a path for the center. In RPGM, vehicles are assumed to be uniformly distributed within the geographic scope of a group, where each vehicle is assigned a reference point used to follow the group movement. Thus, a vehicle randomly displaces in the neighborhood of its reference point at each step. In this model, a group motion vector $\overrightarrow{GM}$ is defined to represent motion behavior of each group. More specifically, at time τ, RPGM proposed that the reference point of a vehicle moves from a reference point RP(τ) to a next reference point RP(τ + 1) at time τ + 1 with vector $\overrightarrow{GM}$. Furthermore, a group vehicle moves to its new position by adding a random motion vector $\overrightarrow{RM}$ to the new reference point RP(τ + 1). We note that direction of $\overrightarrow{GM}$ is uniformly distributed between 0 to 2π degrees and its length is uniformly distributed within a certain radius centered RP (τ + 1), as shown in Figure 1.9.
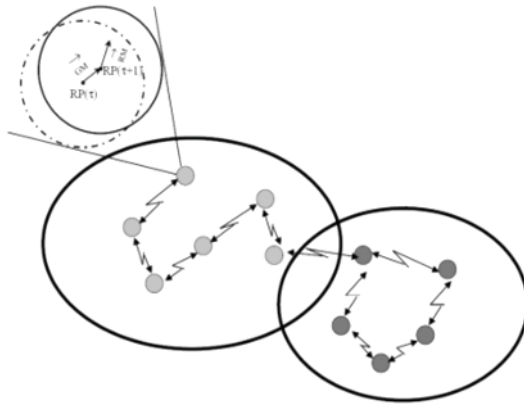

Figure 1.9. *Reference point group mobility. For a color version of this figure, see www.iste.co.uk/bitam/bio-inspired.zip*

1.3.3.2. *Virtual track mobility model*

A group-based mobility model called the virtual track (VT)-based group mobility model was proposed by Zhou *et al.* in [ZHO 04]. This model closely

approximates the mobility patterns in military MANET scenarios. VT describes dynamics of a group mobility starting with some switch stations deployed in the vehicular area at random. These switch stations are then connected through VTs with a given track width. VT considers that within the group, each vehicle moves along the same track toward the next switch station, in addition to an internal random movement of the vehicle within the scope of its group. Concerning the mobility speeds of each group, the VT model randomly selected a speed value between two values (minimum and maximum values).

Once group nodes reach a switch station, the group can be split into multiple smaller groups where some groups may even be merged into a bigger group, as shown in Figure 1.10. In this model, multiple classes of mobile nodes can be distinguished such as pedestrians, cars and trucks, where each class has its own traffic parameters such as velocity and movement pattern. On the basis of these common parameters, VT groups can be defined. Moreover, individual nodes can be modeled in VT as static nodes which do not belong to any group. These non-grouped nodes move randomly in the vehicular area without any restriction imposed by switch stations or VTs.
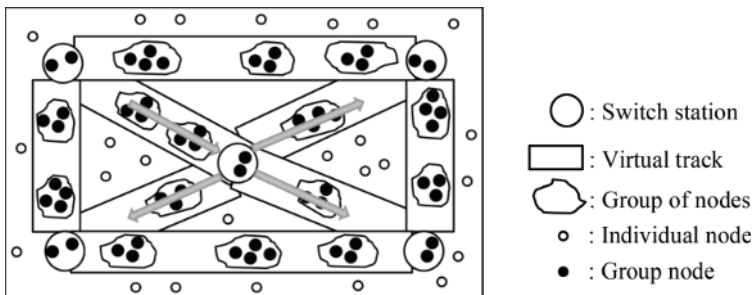
Figure 1.10. *Virtual track mobility model*

1.3.3.3. *Limitations of group-based mobility model*

Despite the good expected outcomes of this model's category such as the reduced routing overhead, there are some limitations concerning the reality of the group-based models, where it is not always right that nodes in the same geographic group move in the same directions. Moreover, assumption about the network density was not considered in this category.

1.3.4. *Prediction-based mobility models*

The prediction was considered in a new mobility category called prediction-based mobility models. To achieve this, each vehicle memorizes its previous speeds and locations in a correlation fashion aiming to predict the vehicle future movement. Therefore, the change in speed and direction of vehicles is smoother and more realistic. Moreover, network density may be determined using prediction rules according to vehicular traffic flow. We review in the following subsections, the most important mobility models of this category.

1.3.4.1. *Gauss–Markov based mobility model*

In this category, a Gauss–Markov mobility model was initially proposed in [LIA 99] and applied to vehicular networks in [MEG 10]. Based on the information gathered from prior velocities and locations of a vehicle, the Gauss–Markov model can predict future vehicle velocity as well as its future location. Formally, the vehicle velocities and locations are assumed to be correlated in time and modeled as a Gauss–Markov stochastic process as follows:

In continuous-time, a stationary Gauss–Markov process is described by the autocorrelation function:

$$R_v(\tau) = E[v(t)v(t+\tau)] = \sigma^2 e^{-\beta|\tau|} \qquad [1.1]$$

where σ^2 is the variance and β determines the degree of memory in the mobility model. In discrete cases, the mobile velocity is defined as follows:

$$v_n = v(n\Delta t) \qquad [1.2]$$

where Δt is the clock-tick period.

Then, the discrete representation of [1.1] is:

$$v_n = \alpha\, v_{n-1} + (1-\alpha)\mu + \sqrt{(1-\alpha^2)}x_{n-1} \qquad [1.3]$$

where

$$\alpha = e^{-\beta\Delta t}$$

where $(0 \leq \alpha \leq 1)$ is used to incorporate the degree of randomness while calculating the speed and direction of movement for a time period. The degree of randomness decreases as we increase the value of α from 0 to 1.

μ is the asymptotic mean of v_n when n approaches infinity, and x_n is an independent, uncorrelated and stationary Gaussian process, with mean $\mu_x = 0$ and standard deviation $\sigma_x = \sigma$, where σ is the asymptotic standard deviation of v_n when n approaches infinity.

However, displacement of a mobile node at time n, can be calculated by formula [1.4] as follows:

$$s_n = \sum_{i=0}^{i=n-1} v_i \qquad\qquad [1.4]$$

Note that by definition, $s_0 = 0$.

Gauss–Markov mobility model is very realistic and aims to anticipate vehicle movement (direction and velocity) in a probabilistic manner. However, some other mobility parameters can be considered to enhance realistic aspects of this model, such as network density. However, some geographic details on the studied maps should be considered, such as lanes and curves.

1.3.4.2. *Markov-History based mobility model*

To cope with more realistic details of the VANET mobility model such as vehicle movements, speeds and network densities, a new Markov-history based mobility model for VANETs was proposed by Bitam and Mellouk in [BIT 13a]. First of all, a geographic area digitization is performed to prepare a digital map, which will be further used as a simulation area of a vehicular network consisting of all VANET entities (i.e. vehicles, roads, highways, turns, traffic lights, whole surface and other landmarks). This digital map could be reached using Geographic Information Systems (GISs) or vehicle tracking systems such as GPS or GLObal navigation Satellite Systems (GLONASS). We note that there are other sources of digital plans which can be used as data files such as TIGER data files [TIG 13] often provided freely by administrative authorities like the US Census Bureau.

The second phase of the Markov-history based mobility model is the initialization of vehicle positions. To achieve this, a node's number is calculated according to the traffic density, then nodes are assigned to the generated geographic area according to a discrete uniform distribution. This discrete uniform distribution is based on the studied geographic area surface, and the day period in which traffic is performed (i.e. rush hour, semi-rush hour or off-peak traffic times). These time intervals are obtained after a statistical study that is a specific to each studied region.

Furthermore, a prediction of vehicle displacements is ensured using a *Markov chain*. In this phase, the mobility of a node can be seen as a discrete event system

where, one mobile node which is in its current state (x_i) moves to a new state (x_{i+1}). Following the transition matrix of the direction prediction (D), each vehicle can continue traveling in straight direction, turning right or left or stopping. The transition matrix (D) was found after a statistical study [BIT 13a].

$$D = \begin{bmatrix} 1/2 & 3/16 & 3/16 & 1/8 \\ 3/4 & 0 & 0 & 1/4 \\ 3/4 & 0 & 0 & 1/4 \\ 1/2 & 0 & 0 & 1/2 \end{bmatrix}$$

A predicting submodel of vehicle velocity called a history-based submodel has also been proposed. After a statistical study, this phase gathers different histories of vehicle velocities in the studied area. Then, the most repeated history will be further considered to predict all vehicles' velocities.

Concerning the network density, the authors presented three density cases: high, medium and low network density according to rush hour, half-rush hour, and off-peak traffic times, respectively. Specifically, at each sampling time, the network density f area is updated using the appropriate formulas [1.5], [1.6] or [1.7]:

$$\text{in rush hour: } f(L, W, S) = \begin{cases} \left(\frac{L \times W}{S^2}\right), & L \geq S \text{ or } W \geq S \\ 1, & otherwise \end{cases} \tag{[1.5]}$$

$$\text{in semi-rush hour: } f(L, W, S) = \begin{cases} \left(\frac{L \times W}{2 \times S^2}\right), & L \geq S \text{ or } W \geq S \\ 1, & otherwise \end{cases} \tag{[1.6]}$$

$$\text{in the off-peak hour: } f(L, W, S) = \begin{cases} \left(\frac{L \times W}{2^2 \times S^2}\right), & L \geq S \text{ or } W \geq S \\ 1, & otherwise \end{cases} \tag{[1.7]}$$

where "*L*" and "*W*" are considered as the length and width of the geographic area, respectively, and "*S*" is considered as the surface devoted to one vehicle measured in meters.

1.3.4.3. *Discussion of prediction-based mobility models*

Prediction-based mobility models were considered as more realistic models compared to the other models (e.g. the random-based mobility model and group-based mobility model), when modeling mobile nodes' movement and network density, nevertheless, this category of models hide some VANET topology details such as obstacles and traffic lights, which cannot be omitted.

1.3.5. *Software-tools-based mobility models*

In this category, mobility models are generated upon using software tools. There are several examples; we mention in this chapter the most important examples namely Simulation of Urban MObility (SUMO), VanetMobiSim and MOVE.

1.3.5.1. *SUMO framework*

To simulate vehicle mobility, an open source framework called SUMO has been proposed in [KRA 02]. Within a traffic road network the size of a city, SUMO was designed to simulate movement of multiple entities including cars, public transport systems (bus and trains), motorized vehicles and pedestrians. In every time step which is fixed at one (1) second, each SUMO mobile entity has a certain place and speed. These values are updated in a way that yields to a collision-free system behavior, depending on the vehicle ahead and the street network the vehicle is moving in. Moreover, SUMO junctions are managed by right-of-way rules, however, some junctions may be equipped with traffic lights.

1.3.5.2. *VanetMobiSim framework*

In [HAR 06], VanetMobiSim was introduced as a generator of realistic vehicular movement, traces for telecommunication networks simulators. This software considers the road topology, the road structure (unidirectional or bidirectional, single or multilane), the road characteristics (speed limits, vehicle classes restrictions) and the presence of traffic signs (stop signs, traffic lights). To provide road topology, VanetMobiSim uses either the TIGER map extracted from the TIGER database [TIG 13] or the Voronoi diagram [AUR 91] which creates fast and configurable random graphs, reflecting the non-uniform distribution of obstacles in an urban area. We note that the Voronoi diagram is a space which is divided into a number of regions represented by a point each. In addition, VanetMobiSim proposed two mobility models aiming to manage intersections using traffic signs and lane changers of roads, respectively.

1.3.5.3. *MOVE framework*

Karnadi *et al.* [KAR 07] proposed a new framework called MOVE that allows users to generate rapidly realistic mobility models for VANET simulations. This software provides, as a result, a trace file of a realistic mobility model which can be immediately used by frequent network simulators, such as ns-2 [NS 13] and qualnet [QUA 13]. Two main entities that composed MOVE are the map editor and the vehicle movement editor. The Map Editor allows the road topology design which can be manually created by users, or introduced using real world map databases such as TIGER [TIG 13] or by Google Earth [GOO 13].

However, the vehicle movement editor helps the user to specify trips of vehicles and routes that each vehicle will take for one particular trip. To do so, three different approaches could be followed: the first approach allows the user to create the vehicle movement in a manual manner, in the second approach the vehicle movement is specified based on a bus timetable to simulate the movements of public transportation, where the third approach ensures the generation of vehicle movement automatically. This last method requires definition of a vehicle flow which describes a fleet of vehicles that moves from the starting road towards the same direction. The number of vehicles, starting and ending time, and the interdeparture time of the vehicle originating from the starting road are also needed. At each junction, MOVE defines the probability of turning towards a new direction, where this probability is considered as tuning parameter, which should be explicity defined by the user.

1.3.5.4. *Discussion of software-tools-based mobility models*

These frameworks proposed practical solutions to simulate mobility models of vehicular networks. However, most of these tools require an explicit introduction of vehicles' parameters and their movement schemes. Moreover, an integration of prediction movement schemes may improve the realistic aspect of this kind of mobility model.

1.4. VANET challenges and issues

Despite the important number of VANET research studies; there are still quite a number of problems that should be examined. In this section, we discuss that VANET-related research challenges and issues still require further investigations that enable VANET communications and services, and guarantee a certain level of quality and security, with low cost.

1.4.1. *VANET routing*

Routing is considered as one of the most important processes in VANET research that allows VANET applications and provides their communication services. It is defined as a process of selecting the best paths between the sender (the source node) and receiver (the designation node) through a set of VANET nodes. In order to improve vehicular safety, routing should forward a data packet with certain constraints, such as a reduced end-to-end delay and decreased dropped packets. However, due to the high-speed mobility of vehicles that implies frequent changing in network topology, found paths could rapidly change and then cause a delayed transfer of data, as well as a data packet loss. This problem has prompted researchers

to find robust routing protocols that discover efficient and long lifetime paths which guarantee quality of routing in terms of end-to-end delay, bandwidth, packet delivery ratio and normalized routing overhead.

1.4.2. *Vehicular network scalability*

Scalability is the ability of a network to efficiently handle a large number of nodes. In such situations, a large-scale network is characterized by a high density. In the VANET context, a vehicular network can be composed of hundreds of nodes especially in urban areas. For example, a bidirectional highway which consists of four lanes in each direction may be very dense in rush hours or if an accident occurred. As a result, disseminating messages between vehicles would be very congested, leading to an important rate of packet loss, in addition to an increase of the transmission latency which affects the performance of the network. Scalability is quite well supported by traditional networking methods if the network density is low (i.e. small number of nodes). However, these traditional methods are less efficient for large-scale networks [OVC 12]. This consequently results in thinking of new solutions that deal with a large number of nodes in VANETs.

1.4.3. *Computational complexity in VANET networking*

The heterogeneous nature of VANET nodes in terms of infrastructure and capacities are the basic reasons for increasing execution time devoted to disseminating data in VANETs. In other words, before sending data packets, there is a discovery process to be performed in order to find routes which could be more or less optimal. Therefore, improving computational operations required to find routes in VANET communication is known as the study of computational complexity. Such optimization improves network performance and helps us to provide the best configuration to find the best paths further used in transmission data. For example, to help car drivers make the appropriate decision in a critical situation (i.e. accident or congestion) aiming to surround vehicular traffic, it is mandatory to find the optimal path between sender and receiver in terms of Euclidian distance (i.e. shortest distance), which is more promising for forwarding and receiving safety packets in a reduced time, then the best decision can be made by car drivers. Traditional VANET networking solutions that work reasonably well for small-scale networks suffer from high complexity especially, for heterogeneous networks [DRE 10]. However, novel approaches yield optimal solutions with low complexity can be attempted.

1.4.4. *Routing robustness and self-organization in vehicular networks*

VANET robustness is the network ability to maintain an acceptable performance in cases of network disruptions. Robustness ensures a resilient network against link/node failures or removal of nodes or targeted attacks [SCE 13]. However, lacking a central control, VANET should ensure self-organized routing where the network finds solutions only using its own nodes. Robustness and self-organization become critical issues which should be addressed, since frequent and rapid mobility of decentralized vehicles lead to non-robust or reliable paths used to route data packets. Actually, conventional VANET routing techniques are inappropriate for VANETs either because these techniques are a projection of routing techniques designed for MANETs that are totally different in their hypothesis concerning the behavior of nodes (speed, direction, pause time, etc.), or because they did not consider VANET dynamics such as the complex collaborative routing process between network nodes which emerges as a robust global routing. Consequently, it is more promising to deal with a new realistic inspiration source to find robust and self-organizing solutions which can help researchers to conceive routing protocols that discover robust paths and/or alternative routes without any central management. As a result, found routes can ensure stable enough connection in the face of network dynamics and frequent traffic disruption which leads to network disconnection or partitioning.

1.4.5. *Vehicular network security*

VANET security consists of the policies used to control network access and prevent and monitor unauthorized access, misuse modification or denial of vehicular network resources. VANET security involves addressing several challenges such as authenticity policies which are able to verify the validity of the identity of a network user and protect vehicular nodes from different attacks penetrating the network using a falsified identity. Another security issue is the confidentiality of the network where a set of rules that limits access or places restrictions on certain types of information are defined. Here, a certain degree of confidence regarding the identity of the user, granting privileges, is established for that identity. Moreover, an encryption process should be defined to enhance VANET security where encoding messages are protected from being read by hackers.

1.5. Bibliography

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