applications that pertain to roadway safety (e.g. vehicle collision avoidance) and emergency services (e.g. those provided by police, re departments, ambulances and rescue vehicles) which impact in several ways: the data communications overall reliability and the extremely low latencies required. *Some critical applications require that the total time from rst signal detection to completion of multiple frames of data exchange must be completed within the order of 100 ms.* In this respect, WAVE adds the capability to simplify the operations and associated management in order to support fast access.
WAVE operations utilize a control channel and multiple service channels. Prioritized access in WAVE operations uses the EDCA[1] mechanism.
The extension of the PHY for WAVE builds on the OFDM system. The WAVE radio frequency system occupies a licensed ITS radio services band, as regulated in the United States by the Code of Federal Regulations. Other regions and countries may allocate other bands in the 56 GHz range. The OFDM system provides WAVE with data payload communication capabilities of 3, 4.5, 6, 9, 12, 18, 24, and 27 Mbps in 10 MHz channels. The support of transmitting and receiving at data rates of 3, 6 and 12 Mbps is mandatory. WAVE has the option to operate on 20 MHz channels. If using the optional 20 MHz channel implementation, data payload capabilities of 6, 9, 12, 18, 24, 36, 48 and 54 Mbps can be supported. The support of transmitting and receiving at data rates of 6, 12 and 24 Mbps is mandatory for the optional 20 MHz conguration. In the context of this standard, WAVE refers to operation within the ITS band and not to operation in other bands.
Stations operating in WAVE shall be capable of transferring messages between the roadside and vehicles travelling at speeds up to 140 km/h with a packet error rate (PER) of less than 10% for PSDU lengths of 1000 bytes and between the roadside and vehicles at speeds up to a minimum of 200 km/h with a PER of less than 10% for PSDU lengths of 64 bytes. For vehicle-to-vehicle communications stations shall be capable of transferring messages at closing speeds of up to a minimum of 283 km/h with a PER of less than 10% for PSDU lengths of 200 bytes. Multipath and the effects of motion are addressed.
These enabling standards hold significant promises for roadway operations and safety, thus capturing the interest of the automotive industry.

[1]The term EDCA (which stands for "Enhanced Distributed Channel Access") is used in wireless networks supporting the IEEE 802.11e Quality of Service standard. It supports differentiated and distributed access to the Wireless Medium using eight different user priority sub fields supporting four different Access Categories. These are Voice, Video, Best Effort and Background.

	GSM/3G	WiFi (Wi-Fi Alliance Version of 802.11n)	WiMax	DSRC
Standard/ Technology	Third generation cellular technology in 2001	New Wi-Fi technology with MIMO standard in 2009, 802.11n standard in 2009	Broadband technology in 2007	A short to medium range communications
Coverage	kilometers	500m	5 km	1000m
Bit Rate	2-3 Mbps	600Mbps using MIMO	75Mbps	6 to 27 Mbps
Applications	Between Vehicle and mobile phone communication	Roadside to vehicle and vehicle to vehicle communication	Internet access, Email, VoIP (Voice over IP)	Roadside to vehicle and vehicle to vehicle communication

Figure 2.11: Wireless Technologies for V2V and V2I communications. With the rapid development of information technologies, there are a number of wireless technologies which are potential for wireless InV, V2V and V2I communications.

2.5.6 Frequency and channel allocation

In Europe, ETSI (103) [1] has presented requirements for European-wide harmonization of spectrum to CEPT (European Conference of Postal and Telecommunications Administrations) and European telecommunication administrations for deployment of ITS within the 5.9 GHz band. The frequency band 5875 to 5925 MHz has been requested for deployment of safety-related ITS applications, which require protection against interference from other services and the frequency band. The frequency band 5855 to 5875 MHz has been requested for nonsafety-related ITS, which can be operated on a nonprotected/non-interference basis.

A recent paper provided a comprehensive overview of existing approaches for the usage of the 30 MHz frequency band dedicated for safety-related car-to-car and car-to-infrastructure communication (53). Advantages and disadvantages of these approaches were analyzed based on an extensive set of evaluation criteria. These criteria are summarized as follows:

[1] *The European Telecommunications Standards Institute (ETSI)* is an independent, non-profit, standardization organization in the telecommunications industry (equipment makers and network operators) officially created in 1988 in Europe, with worldwide projection. ETSI has been successful in standardizing the GSM cell phone system and the TETRA professional mobile radio system. ETSI is officially responsible for standardization of Information and Communication Technologies (ICT) within Europe. These technologies include telecommunications, broadcasting and related areas such as intelligent transportation and medical electronics. ETSI has 740 members from 62 countries/provinces inside and outside Europe, including manufacturers, network operators, administrations, service providers, research bodies and users in fact, all the key players in the ICT arena.

- *Usability*
  This represents the main requirement for safety-related car-to-car and car-to-infrastructure communication: low latency and high reliability for critical safety messages. The analysis focuses on latency, because network and/or applications should be responsible for reliability.

- *Robustness*
  The wireless links robustness can be evaluated in two aspects:

  1. it has to be robust in terms of bit errors (e.g., the bit error rate should be as low as possible);
  2. it has to be robust in terms of interference.

- *Cost*
  This criterion considers the material costs for mass production and deployment. Obviously, an inexpensive solution is preferred in order to re duce the market barrier.

- *Efficiency*
  This criterion evaluates the eff ectiveness of channel allocation in terms of bandwidth usage. Given the scarcity of available bandwidth allocated for car-to-car and car-to-infrastructure communication, this precious resource must be used eff ectively.

- *Scalability*
  This criterion evaluates the impact of channel allocation on the fl exibility of the overall car-to-car and car-to-infrastructure communication system in different scenarios such as highways, cities, and rural areas.

- *Development effort*
  This criterion considers development costs apart from material costs. A solution for channel allocation that allows a simple design and implementation of the car-to-car and car-to-infrastructure communication system is clearly preferred.

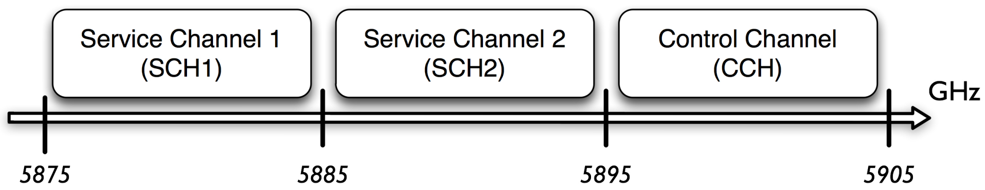

Figure 2.12: Frequency and channel allocation. 30 MHz frequency band dedicated for safety-related car-to-car and car-to-infrastructure communication where SCH1 is the first service channel, SCH2 is the secondary service channel, and CCH is the control channel.

Taking into account the basic channel usage scenarios from C2C-C Consortium[1], some scenarios are eliminated based on qualitative observations. First, currently available WLAN chipsets only support 10 and 20 MHz channels. Thus, a 30 MHz channel would require new hardware and incur significant development cost. For this reason, the usage of a 30 MHz channel is ruled out. Second, a measurement study for channel interference (78) indicates that the simultaneous usage of two adjacent channels caused significant packet loss and hence is unacceptable for ITS safety applications. Although measurements were conducted only for 10 MHz channels, similar effects are expected for simultaneous usage of 10 and 20 MHz channels. For this reason, it is not possible to divide the allocated spectrum into a 10 and 20 MHz channel. Further, because measurement results45 show that 20 MHz channels were more susceptible to bit error rates than 10 MHz channels, the usage of 20 MHz channels is not further considered.

Although the usage of adjacent channels is possible, certain mechanisms such as WAVE (101) channel switching have to be in place to prevent simultaneous transmissions on these channels. Although interference also occurs between non-adjacent channels, it is much lower than in the case of adjacent channels. However, it is expected that packet losses caused by interference between on adjacent channels can be recovered by reliability mechanisms at the network layer and/or applications. From recent measurement

[1]Car-to-Car Communication (C2C-C) Consortium is an industry consortium initiated by major European vehicle manufacturers in 2002. By 2008, the C2C-C Consortium had about 50 partners from industry and research. The main target is the creation of an open European industry standard for CAR-2-X communication based on wireless LAN technology, to support efforts to achieve interoperability, to push for harmonization of worldwide standards, and to develop deployment strategies. The major focus of the consortium is road safety and traffic efficiency applications. The C2C-C Consortium is open for car manufacturers, suppliers, research organizations, and other partners.

results (79) (91), the reasoning above and an extensive set of evaluation criteria (54), the channel allocation shown in Fig. 2.12 outperforms the best results in terms of channel allocation and interference robustness.

2.5.7 Cellular networks

Since initial analog technologies, such as the American AMPS [1] or the European TACS[2] cellular networks have been gradually improved in terms not only of availability all around the world, but also in the quality of service offered. As a result of applying digital communications to cellular networks, the GSM (Global System for Mobile communications) technology achieves the purpose of spreading mobile phones among normal population. Its wide adoption in Europe last years has led the expansion of GSM to other potential markets, like the Chinese one. Many people usually identify the GSM technology as the second generation (2G) of cellular networks, which substituted the first one, based on analog technologies.

Although the main concern of cellular networks, until some years ago, was focused on telephony purposes, data connections are becoming more and more popular these days. GPRS (General Packet Radio Service) appeared with the aim of providing higher data rates than the 9.6 Kbps offered by the standard GSM. GPRS provides a maximum of 177/118 Kbps in the downlink/uplink channels, and it is understood as the intermediate step between 2G and 3G, hence this is the reason why it is called 2.5G. Last years, the expansion of CDMA (Code Division Multiple Access) communication technologies

[1] The "Advanced Mobile Phone System" was an analog mobile phone system standard developed by Bell Labs, and officially introduced in the Americas in 1983 and Australia in 1987. It was the primary analog mobile phone system in North America (and other locales) through the 1980s and into the 2000s. As of February 18, 2008, carriers in the United States were no longer required to support AMPS and companies such as AT&T and Verizon have discontinued this service permanently. AMPS was discontinued in Australia in September 2000. (source www.wikipedia.org)

[2] "Total Access Communication System" (TACS) and ETACS (Enhanced) are mostly-obsolete variants of AMPS which were used in some European countries (including the UK & Ireland in 1983). TACS was also used in Japan under the name "Japanese Total Access Communication" (JTAC). It was also used in Hong Kong. ETACS was an extended version of TACS with more channels. Both TACS and ETACS are now obsolete in Europe, having been replaced by the GSM system. In the United Kingdom, the last ETACS service operated by Vodafone was discontinued on 31 May 2001, after sixteen years of service. ETACS is however still in use in a handful of countries elsewhere in the world. NMT is another analog cellular standard that was widely used in Europe, mainly in the Nordic countries, which has now been fully replaced by GSM except for limited use in rural areas due to its superior range. (source: www.wikipedia.org)

has lead to the appearance of the 3G cellular networks.
CDMA2000 and UMTS (Universal Mobile Telecommunications System), this one as the evolution of GSM 2G, are two of the most extended 3G technologies. UMTS offer 384/128 Kpbs, but the recent HSPA (High Speed Packet Access) improvements offer maximum data rates of 14.4/11.5 Mbps. The introduction of cellular networks in the vehicular domain comes from several years ago, when GSM or GPRS data connections started to be used in tracking and monitoring systems. The appearance of GPRS also made possible the usage of cellular networks for providing traffic information or emergency warnings (65). However, until the arrival of 3G technologies, low data rates had avoided the spread of cellular networks in ITS (11). The advantages of the UMTS communication medium in mobility environment is defended by some authors, which use the UMTS aerial interface for direct V2V communications. The usage of the UMTS operators infrastructure in bidirectional communications is present in the literature, as monitoring systems (38) for example, but its application for V2V communications is still a challenge, due to inherent delay problems. Another drawback of using data connections with cellular networks is the extra money which has to be paid for the usage of the operators infrastructure. Current trend is paying a fixed quote per month, with an extra cost if the transmission rates fall out of the contract, but it is expected that the adoption of UMTS among the population and the vehicular field decrease the price of the final bill, by means of special agreements with operators. Apart of this, some people think that a general communication technology for the ITS domain is still needed, and cellular networks could be the solution (48).

2.5.8 Radio Data System and Traffic Message Channel

The Radio Data System (or RDS) was developed to carry digital data using the common FM radio band. This allows to multiplex additional information with the audio emission, such as the name of the radio station or the current song, but also it can include a data flag which indicates the receiver it has to pay attention to the broadcasting information because it is being transmitted a traffic bulletin. RDS offers a data rate of 1187.5 bps, and the transmission range offered by FM can reach locations at 80 kilometers far way. The RDS version deployed in U.S. is called RBDS (Radio Broadcast Data System) and operates almost identically as RDS, however its usage is less common. A more suitable solution for traffic information dissemination is offered, however, by the Traffic Message Channel (TMC) system. With this system, information about traffic problems is broadcasted digitally, so an appropriate navigation device can warn the user and calculate an alternative route, for instance. The notifications reported by TMC include an event identifier and the location of the problem. TMC traffic is usually transmitted through RDS, and this is the reason why both technologies are usually put together.

2.5.9 Satellite

Satellite communication consists of three main entities: sender station, satellite system, and receiver devices. First of all, data is sent from the sender station to the satellite, which is in charge of forwarding the information to receiver devices. Satellite communications offer a very wide coverage and a great broadcast capabilities. It is suited to provide connectivity at remote places, such as mountain areas or islands, but also in developing countries. The data can be sent from an only sender to multiple receivers at the same time and using the same frequency. Thus, satellite communications are suitable for multimedia broadcasting, such as live video, movies and music.

Although sender stations and receiver devices are usually installed at fixed locations, the later ones can be mobile and equipped in vehicles. This kind of architecture is feasible for a unidirectional system providing an I2V service, however it must be taken into account the important delay which suffer data packets, due to the propagation distance to and from the satellites. The bandwidth obtained in a mobile terminal is between 300 and 500 kbps. A sender station is usually too big to be brought inside a vehicle, and it requires a precise orientation to the satellite used. The UniDirectional Link Routing (UDLR) (95) has been standardized to emulate bidirectional communications with a satellite unidirectional link, where mobile terminals receive data using the satellite channel and transmit using other access technologies.

2.6 Overview of Communication systems in VANETs

This section presents the CAR-2-X (with this term it is intended *car-to-car* and *car-to-infrastructure* communication) system architecture and details of Geocas protocolst[1]

[1]Geocast refers to the delivery of information to a group of destinations in a network identified by their geographical locations. It is a specialized form of multicast used by some routing protocols for

that serve as a basic building block for CAR-2-X communication in many European R&D projects. As shown in Figure 2.14, the CAR-2-X communication system consists of three domains: the *in-vehicle domain*, the *ad hoc domain*, and the *infrastructure domain*. The in-vehicle domain refers to a network logically composed of an *On-Board Unit* (OBU, which is responsible for CAR-2-X communication) and (potentially multiple) *Application Units* (AUs). It also provides communication services to AUs and forwards data on behalf of other OBUs in the ad hoc domain. An OBU is equipped with at least a single network device for short-range wireless communications based on IEEE 802.11p radio technology, and may also be equipped with more network devices, for example, for nonsafety communications, based on other radio technologies such as IEEE 802.11a/b/g/n (see 2.5.1 for details). An AU is typically a dedicated device that executes a single or a set of applications and uses the OBUs communication capabilities. An AU can be an integrated part of a vehicle and be permanently connected to an OBU. It can also be a portable device such as laptop, PDA, or game pad that can dynamically attach to (and detach from) an OBU. An AU and an OBU are usually connected with a wired connection, but the connection can also be wireless, using Bluetooth, WUSB, or UWB[1], for example. The distinction between AU and OBU is logical: they can also reside in a single physical unit.

The ad hoc domain, or vehicular ad hoc network (VANET), is composed of vehicles equipped with OBUs and stationary units along the road, termed road-side units (RSUs). OBUs form a mobile ad hoc network (MANET), which allows communications among nodes in a fully distributed manner without the need for centralized coordination. OBUs directly communicate if wireless connectivity exists among them.

mobile ad hoc networks. Geocast routing protocols are extremely important in vehicular networks.

[1]Wireless USB is a short-range, high-bandwidth wireless radio communication protocol created by the Wireless USB Promoter Group. Wireless USB is sometimes abbreviated as "WUSB", although the USB Implementers Forum discourages this practice and instead prefers to call the technology "Certified Wireless USB" to differentiate it from competitors. Wireless USB is based on the WiMedia Alliance's Ultra-WideBand (UWB) common radio platform, which is capable of sending 480 Mbit/s at distances up to 3 meters and 110 Mbit/s at up to 10 meters. It was designed to operate in the 3.1 to 10.6 GHz frequency range, although local regulatory policies may restrict the legal operating range for any given country.

Wireless USB is used in game controllers, printers, scanners, digital cameras, MP3 players, hard disks and flash drives. Kensington released a Wireless USB universal docking station in August, 2008. It is also suitable for transferring parallel video streams, while utilizing the Wireless USB over UWB bandwidth.

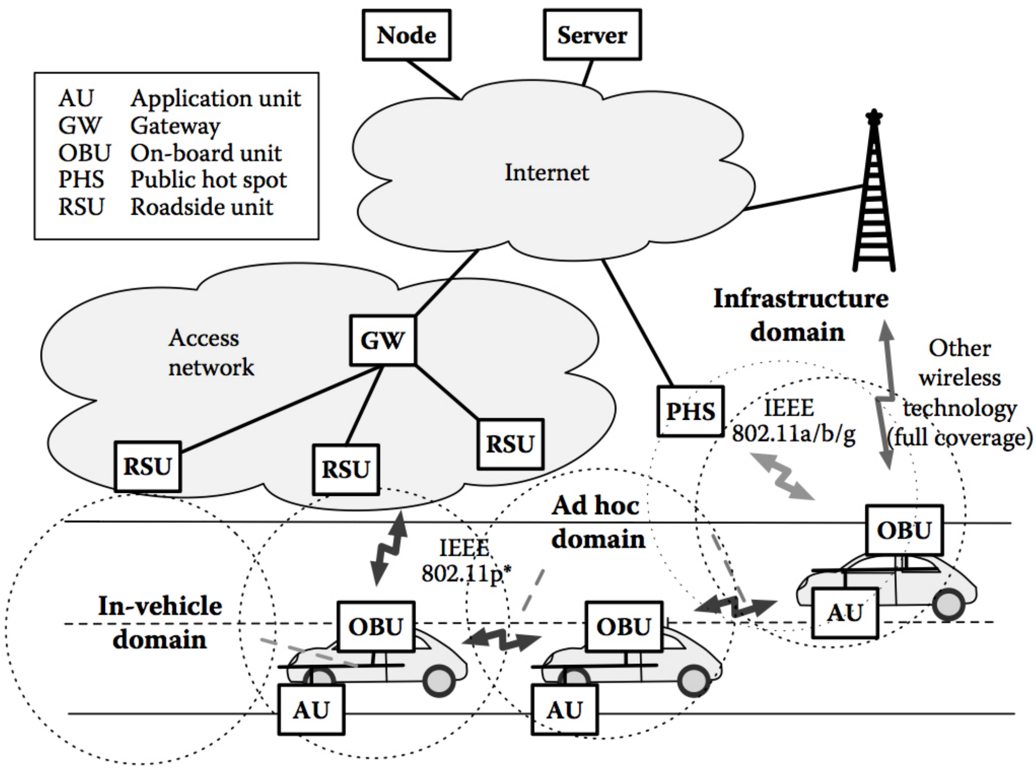

Figure 2.13: CAR-2-X communication scheme. Typical VANET scenario showing a CAR-2-X communication system and involved protocols of the IEEE 802 family. As shown in the figure, the CAR-2-X communication system consists of three domains: the *in-vehicle domain*, the *ad hoc domain*, and the *infrastructure domain*.

In the case of no direct connectivity, dedicated routing protocols allow multihop communications, where data are forwarded from one OBU to another, until they reach the destination. An RSU can be attached to an infrastructure network, which in turn can be connected to the Internet. As a result, RSUs may allow OBUs to access the infrastructure. In this way it is possible for AUs registered with an OBU to communicate with any host on the Internet, when at least one infrastructure-connected RSU is available.

2.7 The importance of Geocast protocols in VANETs

Geocast is basically an ad hoc routing protocol using geographical positions for data transfer. Its basic principles were originally proposed as an alternative to pure topology-based internetworking (57) and in mobile ad hoc networks (47).

Geocast assumes that vehicles acquire information about their position (i.e., geodetic coordinates) via GPS or any other positioning system. Every vehicle periodically advertises this information to its neighbor vehicles and a vehicle is thus informed about all other vehicles located within its direct communication range. If a vehicle intends to send data to a known target geographic location, it chooses another vehicle as a message relay, which is located in the direction towards the target position. The same procedure is executed by every vehicle on the multihop path until the destination is reached. Th is approach does not require establishment and maintenance of routes. Instead, packets are forwarded on the fly based on the most recent geographic positions. In detail, Geocast assumes that every node knows its geographical position and maintains a location table containing other nodes and their geographical positions. Geocast supports point-to-point and point-to-multipoint communication. The latter case can be regarded as group communication, where the endpoints are inside a geographical region.

Core protocol components of Geocast are *beaconing*, a *location service*, and *forwarding*. With beaconing, nodes periodically broadcast short packets with their ID, current geographical position, speed, and heading. On reception of a beacon, a node stores the information in its location table. The location service resolves a nodes ID to its current position. When a node needs to know another nodes position that is currently not available in its location table, it issues a location query message with the sought node ID, sequence number, and hop limit. Neighboring nodes rebroadcast this message until it reaches the sought node (or the hop limit). If the request is not a duplicate, the sought node answers with a location reply message carrying its current position and a time stamp. On reception of the location reply, the originating node updates its location table. Forwarding basically means relaying a packet towards the destination.

The most innovative method for distribution of information enabled by geographical routing is to target data packets to certain geographical areas. In practice, a vehicle can

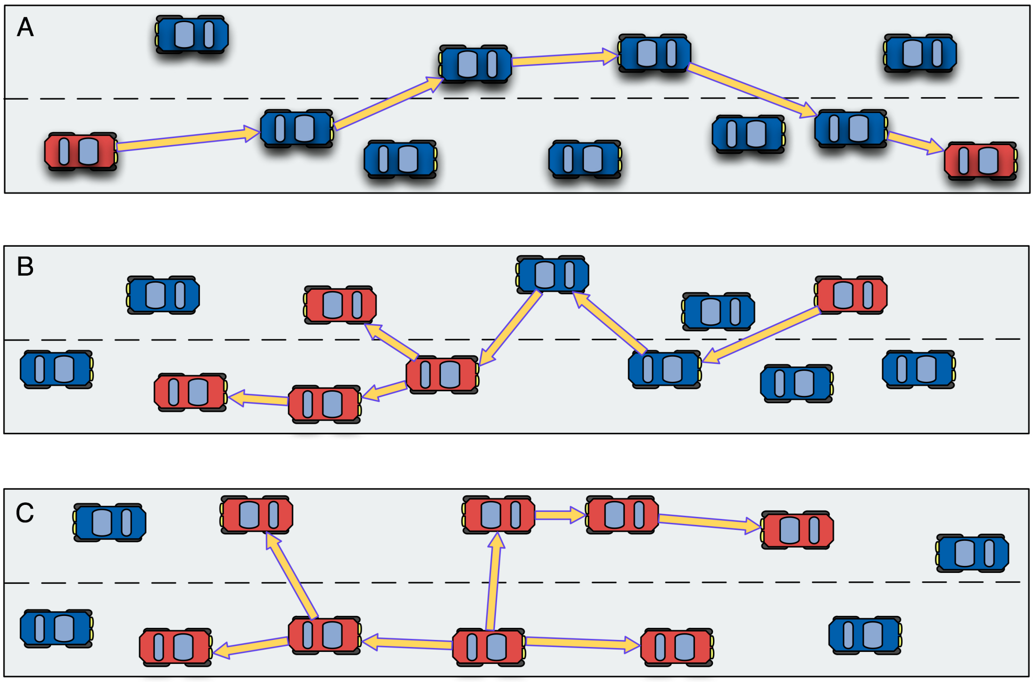

Figure 2.14: Geocasting forwarding schemes. Typical geocasting forwarding schemes: *unicast* (A), *broadcast* (B) and *topologically scoped broadcast* (C).

select and specify a well delimited geographic area to which the messages should be delivered. Once again, intermediate vehicles serve as message relays and only the vehicles located within the target area process the message and further send it to corresponding applications. In this way, only vehicles that are actually affected by a dangerous situation or a traffic notification are notified, whereas vehicles unaffected by the event are not targeted.

In summary, Geocast comprises the following forwarding schemes:

- *GeoUnicast*

  According to this scheme, when a node wishes to send a unicast packet, it first determines the destinations position (by location table look-up or the location service) and then forwards the data packet to the node towards the destination, which in turn reforwards the packet along the path until the packet reaches the destination.

- *GeoBroadcast*
  In this scheme, data packets are distributed by flooding where nodes rebroadcast the packets if they are located in the geographical region determined by the packets. This simple flooding scheme is enhanced with techniques based on packet numbering to alleviate the effects of so-called broadcast storms. Broadcast storms (a typical problem in wireless ad hoc networks) occur when multiple nodes simultaneously rebroadcast a data packet that they have just received. GeoAnycast is similar to GeoBroadcast but addresses a single node (i.e., any node) in a geographical area.

- *Topologically scoped broadcast (TSB)*
  According to this scheme, data packets are broadcasted from a source to all nodes in the n-hop neighborhood. Single-hop broadcast are a specific case of TSB and are used to send periodic messages (beacons or heartbeats).

Chapter 3

Mobility models in vehicular networks

Software development for vehicular scenarios is a very complex process because of the many factors that can impact on the overall result, ranging from the mobility of the nodes to the radio transmission and the end-to-end delay. In order to overcome or at least reduce the probability of failures in terms of application functionalities, simulation becomes a very important and mandatory step in software design before any implementation. Moreover, simulations are fast, cheap, repeatable and make it possible to investigate the influence of single parameter variations. A large number of network nodes can be simulated which is not feasible in real-world experiments. In case of new protocols' design, it is imperative to use a mobility model that accurately represents the mobile nodes (MNs) that will eventually utilize the given protocol. Only in this type of scenario it is possible to determine whether or not the proposed protocol will be useful once implemented. The faithfulness of the simulation results is proportional to the realism of the parameters and the accuracy of the models used in the simulation, in particular, the mobility model (MM) which defines the movements of the mobile nodes within the simulated area during the simulation. Obviously, the rules that describe the movements can vary according to model we want to simulate. The earlier mobility models used to simulate MANET(115) (93) assume the terrain with no obstacles and nodes to be able to move freely in the whole rectangular simulation area. This is realistic for some applications of pedestrians but inappropriate for VANET, where it is important to consider constrained routes and obstacles. Currently, there are two types of mobility models used in the simulation of networks: *traces* and *synthetic models*(60). Traces are those mobility patterns that are observed in real life systems and provide accurate information, especially when they involve a large number of participants and an appropriately long observation period. However, new network environments (e.g. ad hoc networks) are not easily modeled if traces have not yet been created. In this type of situation it is necessary to use synthetic models. Synthetic models, instead, attempt to realistically represent the behaviors of MNs without the use of traces.

3.1 MANET'S MOBILITY MODELS

3.1.1 Entity models

In this type of models, the movement of each node is defined separately and independently from the others. Each node moves by itself, following its own parameters.
The first model of this category was described by Albert Einstein in 1926(60) in order to mimic the erratic movement that many entities show in nature by moving in extremely unpredictable ways and it is called *Random Walk Mobility Model (RWMM)*. In this mobility model, that is widely used and sometimes referred to as *brownian motion*, a MN moves from its current location to a new location by randomly choosing a direction and speed in which to travel. The new speed and direction are both chosen from predefined ranges, $[speedmin, speedmax]$ and $[0, 2\pi]$ respectively. Each movement in the Random Walk Mobility Model occurs in either a constant time interval t or a constant distance traveled d , at the end of which a new direction and speed are calculated. If a MN, which moves according to this model, reaches a simulation boundary, it bounces off the simulation border with an angle determined by the incoming direction. The MN then continues along this new path. Many derivatives of the Random Walk Mobility Model have been developed including the 1-D, 2-D, 3-D, and d-D walks. In 1921, Polya proved that a random walk on a one or two-dimensional surface returns to the origin with complete certainty, i.e., a probability of 1.0(116). This characteristic ensures that the random walk represents a mobility model that tests the movements of entities around their starting points, without worry of the entities wandering away never to return. One of the main issues of RWMM is that it is a memoryless mobility pattern because it retains no knowledge concerning its past locations and speed values, thus generating unrealistic movements such as sudden stops and sharp turns.

The most popular random mobility model is the *Random Waypoint (RWP)*(44), largely used for simulating ad hoc networks and avaliable in many simulators like *ns2*(3), *GloMoSim*(2) and *Qualnet*(4). According to this model, a MN stays in a location and waits for a certain amount of time (i.e. *pause time*). Once this time expires, the MN chooses a new random location whithin the simulation area and than travels towards it at a selected speed, uniformly distributed in a predefined interval. Usually, MNs are initially distributed randomly and uniformly in the simulation area but it is important to realize that this is not representative of the manner in which nodes distribute themselves when moving. One of the most important parameter in RWP simulations is the average MN neighbor percentage, given as the cumulative percentage of a total MNs that are a given MN's neighbor. In fig. 3.4 50 MNs move accordingly to RWP for roughly half an hour; it is easy to realize that there is high variability during the first 500 seconds and this effect should be considered in short simulations, as they can seriously affect the performance results. Another problem that usually affecs RWP is the so called *"density waves"*, where a density wave is the clustering of nodes in a particular region of the simulated area (in RWP this occurs frequently in the center of the map). To overcome this problem and promote a semi-constant number of neighbors throughout the simulation, the *Random Direction Mobility Model (RDMM)* was developed. In this model, MNs choose a random direction and then travel to the border of the simulation area in that direction; once the area boundary is reached, like the RWP model, MNs pause for a specified time, choose a direction - in the range between 0 and 180 degrees - and continue the process. A slight modification to RDMM is the *Modified Direction Mobility Model (MDMM)*, where MNs can change direction without reaching the boundary of the simulation area.
Although the Random Waypoint based mobility models are widely accepted for their simplicity of implementation and analysis, there are some problems related to:

- *temporal depdendency:* due to physical contraints of the mobile entity itself, the velocity of mobile node will change continuously and gently instead of abruptly, i.e. the current velocity is dependent on the previous velocity. However, the velocities at two different time slots are independent in the RWP based models;
- *spatial dependency:* the movement pattern of a mobile node may be influenced by and correlated with nodes in its neighborhood. In RWP based models, instead,

each mobile node moves independently of others;

- *geographic restrictions:* in many cases, the movement of a mobile node may be restricted along the street or a freeway. A geographic map may define these boundaries.

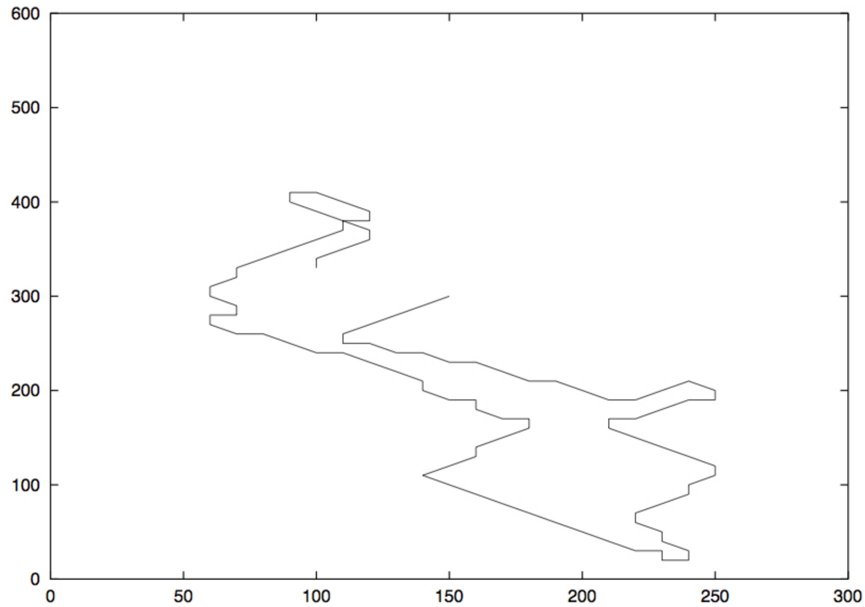

Figure 3.1: Random Walk Mobility model. Traveling pattern of a MN using a probabilistic version of RWM.

Two other interesting mobility models (which however are outside of the scope of this work) are the *Boundless Simulation Area*, where MNs that reach one side of the simulation area continue traveling and reappear on the opposite side of the simulation area, and the *Gauss-Markov model*, designed to adapt to different levels of randomness using one tuning parameter. As a conclusion to the Entity Models, we can say that RWMM, by producing a Brownian motion, evaluates a static network when used to a performance investigation. With a large input parameter - that can be distance or time - is similar to the RWP model without pause times. The main difference between these two mobility models is the density wave in the center of the simulation area observed in RWP. On the other side, RWP model is used in many prominent simulation studies of ad hoc network protocols because it is flexible and it appears to create "quite" realistic

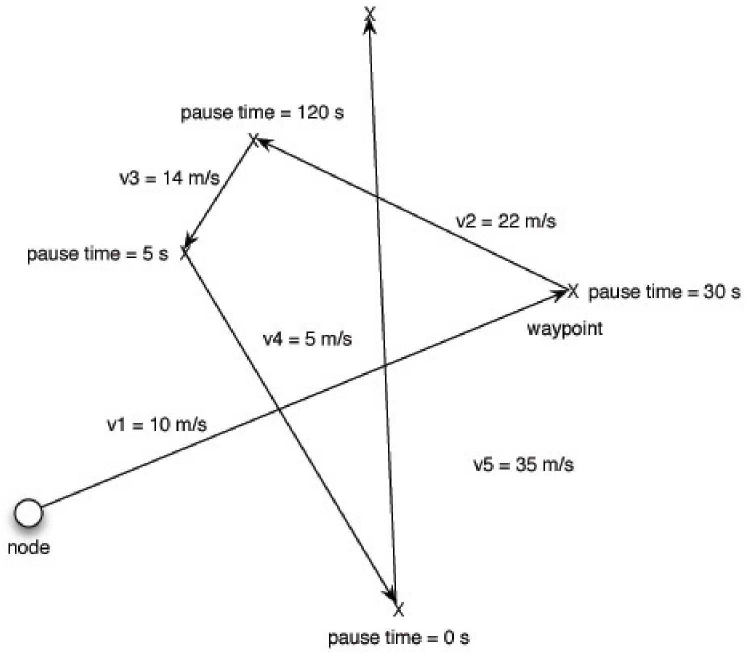

Figure 3.2: Random-Wapoint model In RWP, mobile nodes choose randomly a destination and move towards it with a constant velocity.

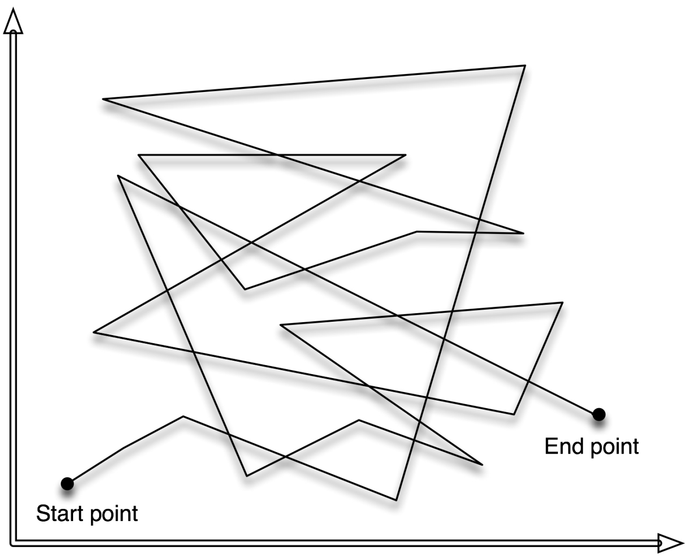

Figure 3.3: Random-Wapoint trace. Typical RWP's motion trace in a 500x500 area.

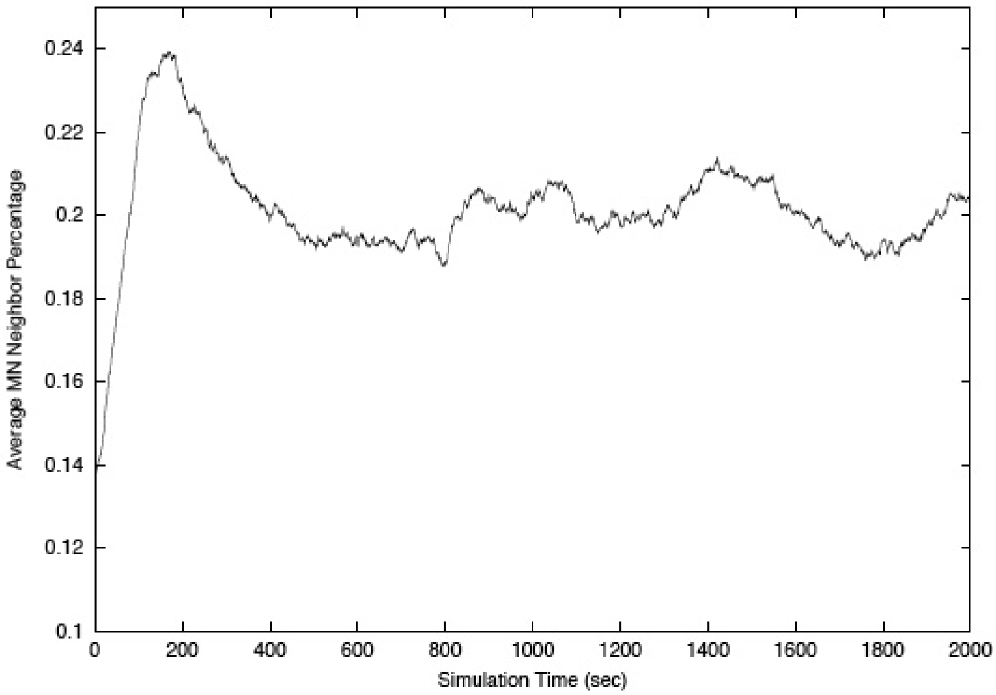

Figure 3.4: Random-Waypoint neighbors percentage. Average neighbors percentage vs. time.

mobility patterns for the way people might move in, for example, a conference setting or a museum. One concern with this model is the straight movement pattern followed by the MNs to reach the chosen destination. We will see, later on, that this model is not suitable to simulate VANET scenarios. Regarding to RDMM, we can say this model is realistic because it is unlikely that people would spread themselves evenly throughout an area (a building or a city). In addition, it is also unlikely that people will only pause at the edge of a given area. The MDMM, instead, allows MNs to pause and change directions before reaching the simulation boundary but it is somehow similar to the RWMM. The Boundless Simulation Area mobility model provides movements that can be expected in the real world and this is the only model that allows MNs to travel unobstructed in the simulation area, thus removing any simulation edge effects from the performance evaluation. One concern, however, is the undesired side effects that would occur when MNs can become neighbors again and again during the simulation time. This problem has to be taken into consideration when you want to simulate and evaluate performances of data dissemination protocols. As it concerns the Gauss-Markov mobility model, we can say that it provides movement patterns that one might expect in a real world (if appropriate parameter are chosen) but it prevents MNs to go close to the simulation area's edges.

3.1.2 Group models

This class of mobility models represents movements of groups of nodes whose actions are completely independent of each other and describes very well many scenarios such as in tourist trips, where groups of tourists move together to visit particular monuments or in battlefields, where group of soldiers in a military scenario may be assigned the task of searching a particular plot of land in order to destroy land mines, capture enemy attackers, or simply work together in a cooperative manner to accomplish a common goal. Moreover, group models can easily and effective depict scenarios such as avalanche rescue, where the responding team consisting of human and canine members work cooperatively. The human guides tend to set a general path for the dogs to follow, since they usually know the approximate location of victims. The dogs each create their own random paths around the general area chosen by their human counterparts. Another example that can be represented by this model is a visit of a group of students to a museum. The museum guide who moves in the different parts of the museum

represents the reference point: the students follow him during the visit, and may make some movements individually around him.
The most general model of this group is the *Reference Point Group Mobility Model (RPGM)*(39), which represents a random motion of a group of nodes as well as a random motion of each individual within the group. Group movements are based upon the path traveled by a logical center for the group, which is used to calculate group motion via a group motion vector, $\vec{GM}$ (see figure 3.5). The motion of the group center completely characterizes the movement of its corresponding group of MNs, including their direction and speed. Individual MNs randomly move about their own predefined reference points, whose movements depend on the group movement. As the individual reference points move from time t to $t+1$, their locations are updated according to the groups logical center. Once the updated reference points, $RP(t+1)$, are calculated, they are combined with a random motion vector, $\vec{RM}$, to represent the random motion of each MN about its individual reference point. Figure 3.5 gives an illustration of three MNs moving with the RPGM model. The gure illustrates that, at time t, three black dots exist to represent the reference points, $RP(t)$, for the three MNs. As shown, the RPGM model uses a group motion vector $\vec{GM}$ to calculate each MNs new reference point, $RP(t+1)$, at time $t+1$; as stated, $\vec{GM}$ may be randomly chosen or predened. The new position for each MN is then calculated by summing a random motion vector, $\vec{RM}$, with the new reference point. The length of $\vec{RM}$ is uniformly distributed within a specied radius centered at $RP(t+1)$ and its direction is uniformly distributed between 0 and 2π. Movement patterns using the RPGM model are shown in figure 3.6. Figure 3.7 is an illustration of ve groups moving, such that each group has a different number of MNs. Both the movement of the logical center for each group, and the random motion of each individual MN within the group, are implemented via the Random Waypoint Mobility Model. One difference, however, is that individual MNs do not use pause times while the group is moving. Pause times are only used when the group reference point reaches a destination and all group nodes pause for the same period of time.

3.2 VANET'S MOBILITY MODELS

This section gives an overview of the models that are specifically proposed for simulating VANETs, or used in the general MANET context but still valid in VANET. Basically,

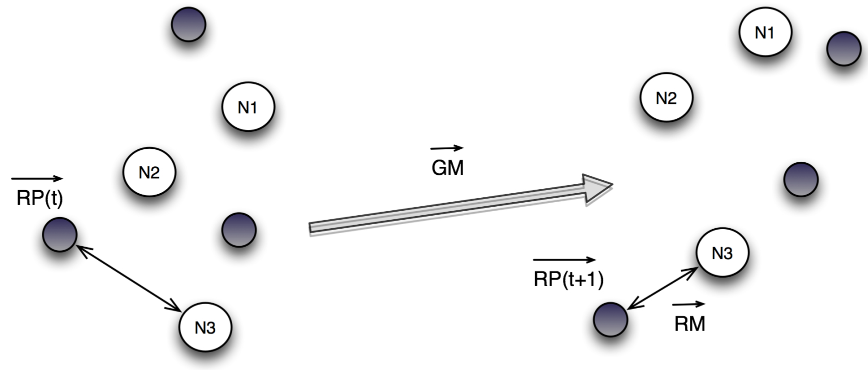

Figure 3.5: RPGM model Movements of three nodes according to the RPGM mobility model.

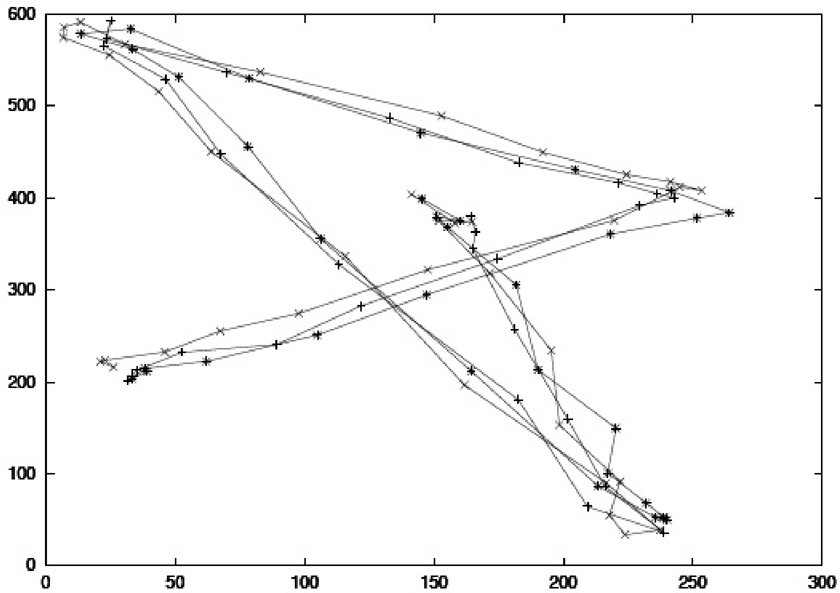

Figure 3.6: RPGM group pattern. Traveling group pattern of three nodes using the RPGM mobility model.

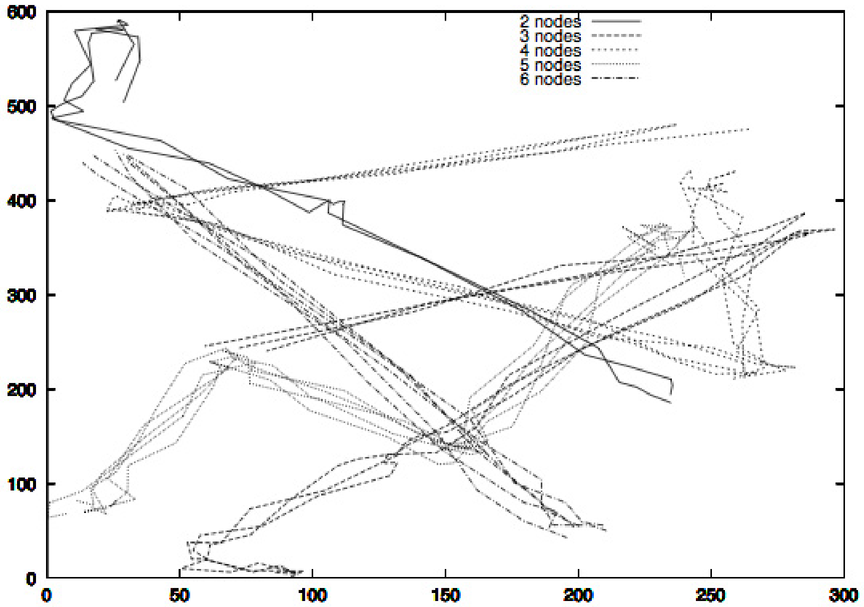

Figure 3.7: RPGM group pattern (5 mobile nodes). Traveling group pattern of five nodes using the RPGM mobility model.

these models simulate movements in routes, contrary to the previous ones that assume an open area. As we will see, the considered parameters differ from a model to another. For instance, some models use traffic control mechanisms (stop signs or traffic lights) at route intersections, and others just assume continuous movement at these points. Some assume routes to be single-lane, some others support multi-lanes routes. Some define the security distance, while others just ignore this parameter. Whereas it is crucial to test and evaluate protocol implementations in real testbeds environments, loogistics difficulties, economic issues and technology limitations make simulation the mean of choice in the validation of networking protocols for VANETs and widely adpted a first step in development of real world technologies. A critical aspect in a simulation study of VANETs is the need for a mobility model which reflects, as close as possible, the real behavior of vehicular traffic.

When dealing with vehicular mobility modeling, it is worth to introduce two concepts: *macro-mobility* and *micro-mobility*. With the former, we mean all the macroscopic aspects which influence vehicular traffic, such as: road topology, constraining car movements, per-road speed limits, number of lanes, overtaking, safety rules, traffic signs

establishing the intersections' crossing rules. The latter, instead, refers to the driver's individual behavior when interacts with other drivers or road infrastructure (traveling speed in different traffic conditions, acceleration, deceleration and overtaking criteria, driver's attitude, generally related to sex, age and/or mood).
Obviously, it would be desirable for a trustworthy vanet simulation that both micro and macro mobility descriptions be jointly considered. However, many mobility models employed for VANETs ignore these guidelines, thus failing in reproducing peculiar aspects of vehicular motion such as car acceleration and deceleration in presence of nearby vehicles, queuing at road intersections clustering caused by semaphores, vehicular congestion and traffic jams.

3.2.1 Factors affecting mobility in VANETs

As said just before, mobility pattern of nodes in a VANET can significantly influence route discovery, maintenance, reconstruction, consistency and caching mechanism and this can obviously affect data dissemination protocols.[1] For example, static or slow moving vehicles tend to hold the topology configuration, as they can be assimilated to "semi-static" and reliable relaying nodes; on the contrary, fast moving vehicles can cause highly changeble topolgy, demanding frequent route reorganization nad packet losses. In detail, the following factors can be considered in modeling VANETs' mobility:

- *block size:* if the block (that is the smallest area surrounded by streets) is extended, it causes few intersections and, then, in turn, the frequency of which the vehicles stop decreases;
- *streets layout:* streets force nodes to confine their movements to well-defined paths, determining the spatial distribution of nodes and their connectivity. Moreover, streets can have either single or multiple lanes and can allow one-way or two-way traffic;
- *average speed:* vehicle's speed determines how quickly its position changes, which in turn determines the rate of network topology change. The speed limit of each

[1] In (61), authors proved that some aspects of mobility (such as multiple lanes and synchronization at traffic signals) can be ignored as they have only a marginal impact on the overall ad-hoc routing performances. On the contrary, performance indexes like *delivery ratio* and *packet delay* are more sensitive to the clustering effect of vehicles waiting at intersections and/or acceleration/deceleration.

road, as well as acceleration and deceleration, also directly affects the average speed of vehicles and how often the existing routes are broken or new routes are established;

- *interdependent vehicular motion:* in sophisticated mobility models, the movement of each vehicle is influenced by the movement pattern of its surrounding vehicles (minimum safety distance, lane changing, overtaking);

- *traffic control mechanism:* stop signs and traffic lights affect the mobility and can result in the formation of clusters and queues. Furthermore, reduced mobility implies more static nodes and then, slower rates of route changes in the network. On the contrary, vehicles' clusters can affect network performance due to channel contention and longer network partitions.

3.2.2 Freeway

This model was introduced in(25) to emulate the movement pattern of mobile nodes on streets defined by maps and includes in the simulation area many freeways, each side of which is composed of many lanes. No urban routes, thus no intersections are considered in this model and the map is composed of a number of horizontal and vertical streets which are made up, in turn, of two lanes for each direction.
At the beginning of the simulation, the mobile nodes are randomly placed in the lanes and move using history-based speeds. The speed of each vehicle follows the following formula:

$$V(t+1) = V(t) + random() \times a(t)$$

Where $V(t)$ is the vehicle's speed at time t, $random()$ returns a random value in the interval $[-1, 1]$ and $a(t)$ is the acceleration of the vehicle at time t. A security distance should be mantained between two subsequent vehicles in a lane, so if the distance between two vehicles is less than this required minimal distance, the second one decelerates ($a(t)$ is forced to be < 0) and let the forward vehicle moves away. The change of lanes is not allowed in this model thus the vehicle moves in the lane it is placed in until it reaches the simulation area limit, then it is placed randomly in another position and repeats the process. This scenario is definitely unrealistic.

3.2.3 Manhattan

Like the freeway model, this is a generated-map-based model introduced in(25) to simulate a urban environment. The simulation area is represented by a map (generated before the simulation start) containing vertical and horizontal roads made up of two lanes, allowing the motion in the two directions (north-south for the vertical roads and east-west for the horizontal ones). Before starting the simulation, vehicles are randomly placed on the roads and then start moving continously according to history-based speeds following the same formula used in the freeway model. When reaching a crossroads, the vehicle randomly chooses a direction to follow that is continuing straightforward, turning left or turning right according to a triplet of probabilities. Contrary to the the freeway model, a vehicle can change a lane when it passes a crossroads with absolutely no control mechanism, thus continuing their movements without stopping. This makes this model unrealistic.

3.2.4 City Section Mobility

In *City Section Mobility Model*(15), the simulation area is a street network that represents a section of a city where the ad hoc network exists. The streets and speed limits are based on the type of city being simulated. For example, the streets may form a grid in the downtown area of the city with a high-speed highway near the border of the simulation area to represent a loop around the city. Each MN begins the simulation at a defined point on some street and then, randomly choose a destination, also represented by a point on some street. The movement algorithm from the current destination to the new destination locates a path corresponding to the shortest travel time between the two points; in addition, safe driving characteristics such as a speed limit and a minimum distance allowed between any two MNs exists. Upon reaching the destination, the MN pauses for a specified time and then randomly chooses another destination (i.e., a point on some street) and repeats the process.
This model can be seen as a hybrid model between RWP and Manhattan, as it introduces the principle of RWP like the pause-time and random selection destination, within a generated-map-based area. Anyway, contrary to RWP, the application domain (the union of the segments defined by the edges of the space graph) is unconvex.