ANALYTICAL MODELING OF DELAY-TOLERANT DATA DISSEMINATION IN VEHICULAR NETWORKS

ASHISH AGARWAL

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ANALYTICAL MODELING OF DELAY-TOLERANT DATA DISSEMINATION IN VEHICULAR NETWORKS

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Logic will get you from A to B. Imagination will take you everywhere. Albert Einstein

If we knew what it was we were doing, it would not be called research, would it? Albert Einstein

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ABSTRACT

Vehicular networking is an emerging technology to support applications involving communications between vehicles, between vehicles and fixed access points, and between vehicles and the Internet cloud. The goal is to enable vehicles to exchange information for improved safety through situational awareness, enhanced convenience, and achieve increased levels of efficiency in time and energy consumption; all significant societal objectives. Safety messaging, real-time traffic and route updates, traffic monitoring, remote diagnostics, general purpose Internet access and in-car entertainment are examples of applications that are targeted by this technology.

This dissertation considers communication and networking among vehicles that are commonly constrained to navigable roadways. We propose a novel routing technique that incorporates attributed, or labeled, messaging; geographic routing; and delay tolerant networking techniques in a solution that operates in a network characterized by rapid mobility and time-varying partitioning (fragmentation). An analytical model is developed to demonstrate the performance of opportunistic data exchange in a delay tolerant network setting.

Contributions of the work include revelation of phase transition behavior due to vehicle density and transmission range. We are able to identify regimes of density where gains are achieved by exploiting the opportunistic contacts between vehicles traveling in opposing directions in a network characterized by time-varying partitioning. The results, supported by simulation, imply that delay tolerant networking architectures are most useful at traffic densities of 20 vehicles/km and higher. Also significant is the observation that increased mobility of nodes from 0 m/s to 10 m/s yields an order of magnitude increase in the performance of messaging from 0 m/s to 200 m/s. The proposed architecture is compared with existing mobile ad hoc networking schemes and performance gains achieved are provided in detail. It is demonstrated that large access point separations are possible in a hybrid environment with intermittently placed access points supported by multihop networking. The performance is dominated by vehicular traffic density. Under delay tolerant networking assumption, minimum delay and maximum propagation rates are achieved for low vehicular traffic densities of 20 vehicles/km, for given parameters. A path based messaging scheme would achieve similar performance at 40 vehicles/km.

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Chapter 1

Introduction

Today, vehicles leverage autonomous control in the form of a human operator. Traffic laws and driving conventions provide the common rule-sets guiding the system behavior. The drivers process the road conditions based on visual input, limited to periphery of vision, and make control decisions. Knowledge of behavior of other vehicles in the system is limited to visual (turning lamps, headlights) and sound (horns) signals. Traffic is ordered or chaotic based on the negotiation principles of vehicle controllers (drivers). When a controller fails to successfully negotiate, accidents occur.

We envision a future, not with flying cars, but with vehicles transiting the network of roadways and highways autonomously. The vehicles are able to drive themselves through computer control and negotiate roadways assisted by navigation devices. Such a system has benefits of efficiency, throughput and safety, especially in urban and dense populations. Roadways can be scheduled as a resource, permitting for high speed densely packed trains of vehicles (platoons) yielding higher utilization and throughput. The automated travel vision for future road travel is becoming technically feasible given recent developments in network technology and system design.

In the future, vehicles can be autonomous as a mirror of a human operator. Vehicles competing in the DARPA Grand Challenge use vision based techniques to detect the roadway and employ robotic arms to perform control actions such as steering and gear lever operation [Gro08]. Alternately, under a more centralized control, vehicles negotiate the use of roadway by sharing state information with vehicles in the vicinity and are guided by using data originating from a region beyond limits of human observation. The vehicles will be potentially driven by technologies such as self piloted steering and automatic braking. Automated control will rely on visual sensors for pathway information and positioning systems for routing information. More importantly, vehicles will share location and future actions for coordination with neighboring vehicles through wireless communication and negotiate the use of the shared resource, roadway. We envision a safe automated system using distributed sensing and control enabled by inter-vehicle networking. Fig. 1·1, illustrates the vision of vehicles traveling autonomously on the roadway, such that each vehicle has a safety zone around it. Vehicles maintain their safety by developing situational awareness through shared state information of the environment (roadway) and other vehicles in the system.

1.1 Vehicular Networking

The concept of vehicular networking has emerged with technological advancements in sensing, communication, computation and storage capabilities. Embedding communication capability enables a vehicle to share state information with its environment. Greater awareness of the roadway conditions and vehicles in close proximity improves the safety capabilities of a vehicle. The driver can receive early warning of dangerous conditions. Alternately, advance warnings can prepare a vehicle's safety systems, such as anti-brake lock systems, air bags and pre-tension safety belts, in the event of an impending collision. Information gleaned from traveling vehicles is useful for traffic management systems. Traffic information systems can react better to congestion in the system and offer alternate routes to destinations, thereby sav-

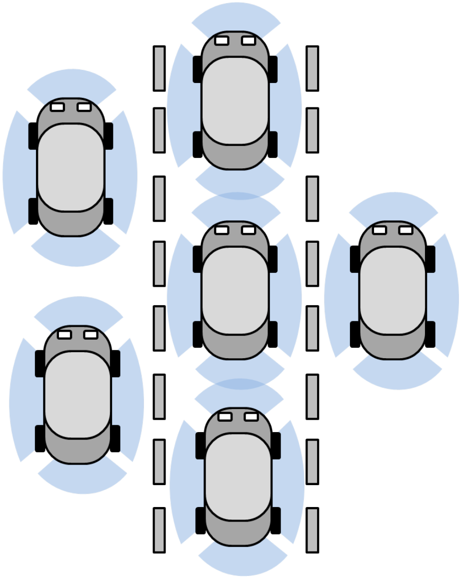


Figure 1·1: Illustration of autonomous vehicles traveling on the roadway, each surrounded by a safety zone that is likely maintained by sharing state information with other vehicles in the vicinity.

ing time and energy. Finally, connectivity to the backbone Internet enables access to social interaction and infotainment applications. There are several techniques to implement these applications. Communication and networking embedded in a vehicle's architecture enables advanced degree of control and better granularity of information available to the system that can be exploited simultaneously by multiple applications. Fig. 1·2 illustrates various applications and models of communication in a vehicular network.

IntelliDrive is a United States Department of Transport (USDOT) [USD10] initiative that aims to enable safe, interoperable networked wireless communication among vehicles. The goal is to leverage the potentially transformative capabilities of wireless technology to make road transportation safer and smarter. Models include communication between vehicles, between vehicles and infrastructure, and between vehicles and personal devices.

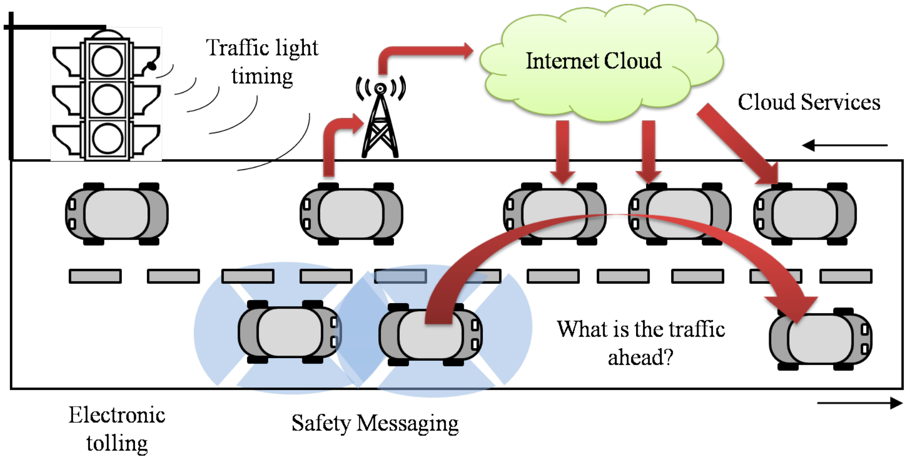


Figure 1·2: Illustration depicting various models of communication and applications in a vehicular network.

Similar initiatives are underway elsewhere in the world. Smartway in Japan aims to create a new platform for equipping roadways with infrastructure that facilitate communication and networking between vehicles and the environment [MAK06]. The goal is to enable new applications and enhance existing ones such as navigation, safety, electronic automated tolling, parking and vehicle diagnostics to cite a few. In Europe, Organizations such as E-ENOVA, Car-2-Car Communication Consortium, PREVENT, PATH and WATCH-OVER [EEN10, CAR10, Tut07, PAT07, WAT10] are bringing together all modes of transport into the information infrastructure to create an *Intelligent Transportation System* (ITS). Projects such as PROPEDES, ROCC, SEIS, [EEN10, CAR10, PAT07] cover diverse topics such as pedestrian safety, intersection safety, development of application specific hardware and use-case scenarios for the implementation of a transportation safety communication infrastructure.

1.2 Problem Specification

The goal of government organizations and industrial groups is to establish standards and goals for vehicular communication. At the same time, universities and research organizations are working on adapting existing technologies and developing new ones for the vehicular networking environment. There are several challenges to enabling vehicular communication. A network formed over moving vehicles has characteristics of topology and mobility that are similar to, yet distinct from traditional mobile ad hoc networks (MANET). In this section, challenges in the vehicular networking environment are identified that influence the design of vehicular networks and implementation of applications. The impact of these observations is discussed in the context of design requirements for a vehicular network.

1.2.1 Vehicular Networking Scenarios

There are two main models for real-world scenarios for navigable roads. These are described as the 'rural' or the 'highway' model, illustrated in Fig. 1·3 and the 'urban' or the 'grid' model, Fig. 1·4. The highway model is linear with bidirectional roadways. Vehicle mobility on the roadway is characterized by the *'Freeway'* mobility model [HKG$^+$01]. The density of vehicles on the roadway is typically sparse in rural areas. The mobility rate of vehicles is relatively high (20 m/s to 35 m/s, 72 kph to 126 kph, 45 mph to 78 mph), especially when compared to typical MANET scenarios.

In contrast, the 'urban' model is characterised with the *'Manhattan'* mobility model [HKG$^+$01]. The roadways typically form a grid and the vehicle density is considered dense consistent with the urban population. The mobility rate of vehicles is relatively lower (10 m/s to 20 m/s, 36 kph to 72 kph, 22 mph to 45 mph). Roadways are often unidirectional, i.e. vehicle traffic travels only in one direction.

These models are considered distinct from MANET models as the motion of a

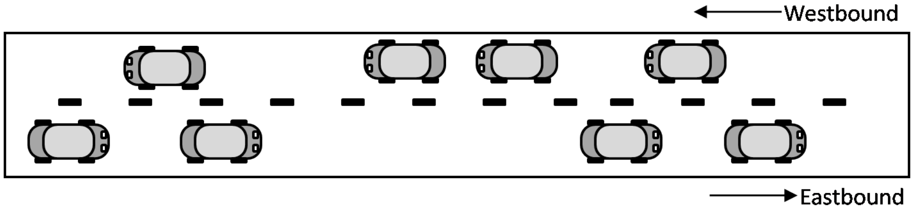


Figure 1·3: Rural vehicular network scenario, with mostly linear roadway and sparse vehicular traffic.

vehicle is relatively predictable and constrained. Vehicles are constrained in motion in that they travel along roadways, the knowledge of which is available through map-based information systems (GPS). Further, the density in the network varies between extremes of sparse and dense. This is a potential challenge in achieving connectivity in the network. Vehicles traveling on a bidirectional roadway come in intermittent contact with several unique vehicles on the roadway. There is potential to exploit the mobility and intermittent contacts to compliment the messaging goals. However, the contacts are short-lived and topology of the network changes frequently. Thus, the requirement is for a solution that adapts and operates in the various scenarios.

1.2.2 Application Requirements

There are three distinct classes of applications in vehicular networks; Safety Messaging, Traffic and Congestion Monitoring and general purpose Internet access. These are illustrated in Figure 1·5. While a detailed discussion of these applications is provided in Sec. 2.3.2, it is noted here that the requirements for each are significantly different.

Safety messaging applications involve sharing state information of a vehicle with other vehicles and the environment. The goal is to maintain safety in the system and avoid collisions. Such applications typically involve communication between vehicles within a short range of the order of 20 m to 120 m [NMSH06]. The nature of data

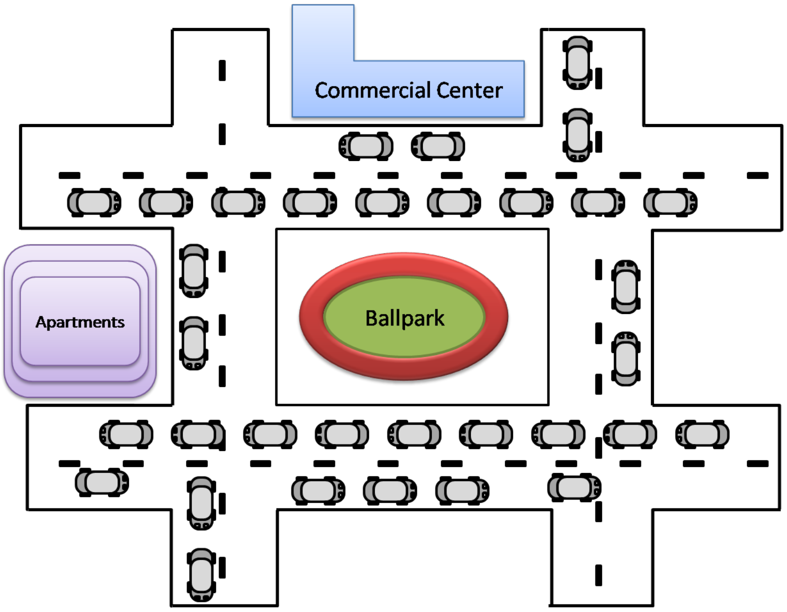


Figure 1·4: Urban scenario of a grid with several intersecting roadways and dense vehicular traffic.

exchange is of a small payload data exchanged with high frequency, depending upon proximity of vehicles. As the data are safety critical, the latency requirements are of minimum delay (< 400 ms) and high reliability [AST03].

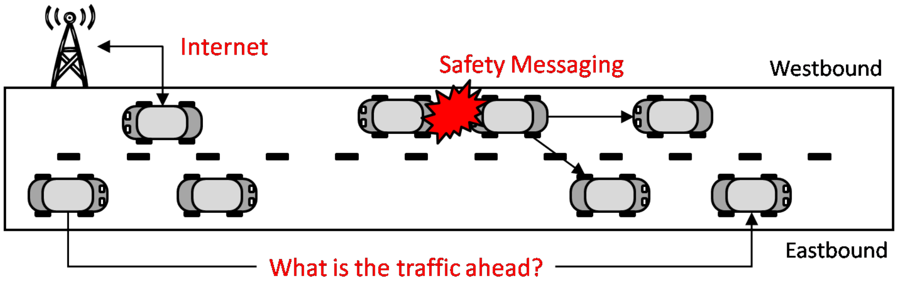


Figure 1·5: Different classes of applications in a vehicular network

Traffic and congestion monitoring applications require collecting information from vehicles that span multiple kilometers. Overall messaging in the network is potentially large as the requirement is to collect data from several vehicles in the network.

The lifetime of data are of the order of several minutes as typically the traffic conditions change slowly [NDLI04]. Thus, the latency requirements for data delivery are relatively relaxed. The data are not safety-critical and applications can support delays in data delivery.

Finally, connectivity to the Internet allows access to wide range of applications that are described as *'infotainment'*, serving the dual purpose of information and entertainment. Applications include information such as places of interest, current information that is dynamically updated in a vehicle's on-board unit (GPS). These applications require infrastructure such as access points (cellular towers) for connectivity to the backbone network. The models of communicating with Internet servers are well defined. An open problem in this context is the last-mile connectivity between vehicles and the infrastructure.

1.2.3 Network Connectivity

A vehicular network is characterized by mobile nodes that travel along roadways. The topology from a networking perspective is dynamic owing to bidirectional mobility, variable density depending upon locality (urban/rural) and time (day/night). Communication technologies for vehicular communication are in various stages of development. The DSRC (Dedicated Short Range Communication Spectrum) [XMSK04], based on the 802.11 protocol is under development and proposes a range of 200 m.

There are multiple models of communication; vehicle to vehicle (V2V) communication and vehicle to infrastructure (V2I) communication, as illustrated in Fig. 1·6. V2V communication is essential for safety type applications as the round-trip delay for communication through infrastructure are high and do not satisfy the constraints. Internet connectivity requires access to backbone network through infrastructure. However, given the large expanse of the road network, instrumenting the roadway with roadside access points is a challenging proposition.

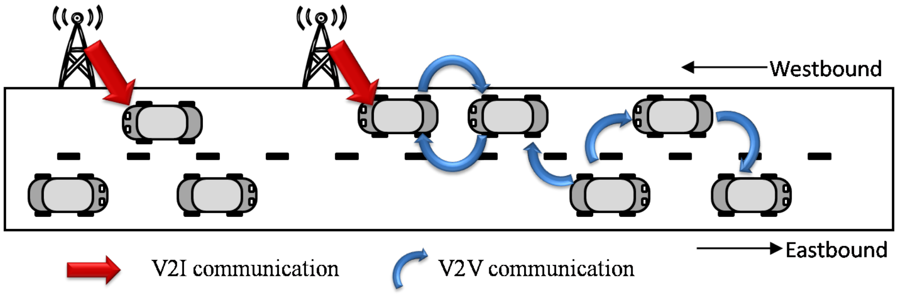


Figure 1·6: Illustration of vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) communication.

For a vehicle to vehicle (V2V) communication model, achieving end-to-end connectivity is difficult for a technology with limited communication range. There is often sparse density in the network. From a networking perspective, the network is divided into disconnected subnets that are partitioned from each other. At the other extreme, in high density scenarios, there is contention in the network due to a high density of vehicles communicating at the same time [MC08]. As a result of the contention, there are packet collisions and increased delays in data delivery with lower packet delivery probability.

Other communication technologies under consideration include short-range 60 GHz and optical communication based on LEDs (Light Emitting Diodes) [DH07, AMY$^+$07]. These technologies are favourable as they are directional in nature and are less affected by contention type problems faced in omni-directional technologies. Thus, connectivity is a significant challenge for the vehicular networking environment. The lack of connectivity impacts the design and performance of a routing protocol. Hence, it is essential that the routing be aware of the potential lack of connectivity in the network.

1.2.4 Synopsis

Applications in vehicular networking are diverse in their requirements. There are different models of communication, vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) that serve these requirements. A summary of the questions targeted in this dissertation include:

- What are the characteristics of connectivity in a vehicular network? Given a communication technology and corresponding parameter of radio range, how does connectivity vary in a vehicular network?
- How is data dissemination achieved in the dynamic environment of a vehicular network? What are the design features of an efficient routing protocol that enables data exchange in this dynamic environment?
- Is there an opportunity to exploit bidirectional mobility of vehicles to support data dissemination in a partitioned environment?
- How is delay tolerant networking (DTN) applied in a vehicular network?
- What is the performance of multihop messaging in a vehicular network? Can gains be achieved from delay tolerant networking?
- What is a good strategy to place access points in the network?

1.3 Dissertation Outline

1.3.1 Contributions

The main contribution of this work is to develop a model that analyzes data propagation in delay tolerant vehicular networks. The model provides a tool that eases analysis for several parameter sets and eliminates the need for lengthy simulations.

The model also demonstrates the conditions for phase transition in the behavior of message propagation, a quantity that cannot be measured accurately from simulations. Specific contributions include:

1. Identification of different models of communication in vehicular networks and requirements for applications that are supported by these models (Sec. 2.3.2).
2. A novel routing technique that incorporates elements of attributed messaging, geographic routing and delay tolerant messaging to enable message dissemination in a dynamic network (Sec. 4.1).
3. Analytical model that provides an upper bound and a lower bound to the performance of messaging in a delay tolerant network setting. An approximation model that closely follows the simulation results (Sec. 5).
4. Revelation of phase transition behavior performance of messaging with increasing vehicular traffic density. This observation is consistent with the percolation theory model for one-dimensional linear networks, however, is unique to a mobile delay tolerant network (Sec. 6.2.1).
5. Access point placement strategy that minimizes the placement of expensive infrastructure based on observed network parameters of vehicle density and performance constraints (Sec. 6.3).
6. Improved performance over existing MANET techniques. Results validate that a delay tolerant networking scheme performs better at lower vehicle densities when partitions are observed in the network (Sec. 6.4).

1.3.2 Organization

The remainder of this dissertation is structured as follows:

Chapter 2 describes the motivation for enabling networking among vehicles on the roadway. It introduces the concept of Intelligent Transportation Systems (ITS) and explains its importance and relevance. The use-case scenarios are discussed in the context of how communication plays a role in enabling several unique applications that improves safety and comfort in transportation.

Chapter 3 describes the related work in the research areas of *mobile ad hoc networks* (MANETs), *delay tolerant networks* (DTNs) and vehicular networks that this dissertation draws upon for reference and motivation.

Chapter 4 describes the concepts of the clustering of vehicles on the roadway, attributing (labeling) data to enable directional message propagation and finally the delay tolerant routing protocol that together form the foundation of this dissertation.

Chapter 5 demonstrates with the help of an analytical model the performance of messaging in the vehicular networking scenario.

Chapter 6 presents the results based on the proposed solution and the analytical model developed. The analytical model is compared with simulation results and evaluated for several parameters.

Chapter 7 concludes with a summary of contributions made in this dissertation, and overviews avenues for further research.

Chapter 2

Vehicular Networking

This chapter overviews the broad area of vehicular networking. We start with a description of Intelligent Transportation Systems (ITS) concept. We describe the concept of using vehicles as sensors and the opportunity to exploit vehicles' sensors in a distributed fashion. We explore the networking models and enabling technologies for communication. We overview some current and potential applications that can be instantiated over networked vehicles. We highlight some of the key features of these applications that are interesting to note as challenges to networking.

2.1 Intelligent Transportation Systems

Intelligent Transportation Systems (ITS) can be defined as the application of computing, communication and algorithmic techniques to enhance transportation methods [Cot09]. The goal is many-fold; increase safety, reliability, decrease congestion on the roadways, improve public transport services, increase comfort and efficiency, decrease environmental impact, etc. ITS potentially includes all modes of transportation – air, rail, road, subway, waterway, etc. In this dissertation, we concentrate on roadways as the mode of transportation, and focus on communication and networking between vehicles.

Apart from lowering costs (economic, social and environmental), there is a strong need for ITS. Urban cities throughout the world are increasingly getting congested. Yet, there is limited room to expand and build new modes of transportation. In the

United States, as the population grew 20% between 1982 and 2001, traffic congestion jumped 236%, [IBM10]. Traffic congestion causes several environmental, economic, and social problems. Carbon emissions from transportation constitute one-third of the U.S. carbon output, costing nearly $20 billion dollars. The fuel spent in traffic congestion is equivalent to 58 supertankers. Productivity lost due to congestion is equivalent to 3.7 billion hours. The cumulative losses are equivalent to 78 billion dollars [IBM10]. ITS are needed to improve capacities and alleviate the problems arising from congestion [IBM10].

The United States Department of Transportation's (USDOT) ITS program focuses on vehicles and infrastructure and methods to integrate the components through communication and networking. The goal is to improve safety, mobility and productivity. A notable initiative is the IntelliDrive program that seeks to develop a standardized communication platform for [UDO10, Int10].

2.2 Vehicular Sensors

Vehicles are increasingly being equipped with sensing and computing capabilities. Figure 2·1 illustrates a snapshot of the common sensors in a present day vehicle. Due to the large number of sensors, a controller area network has been designed to centralize the control and management of the on-board sensors. Examples of sensors include Tire Pressure Monitoring Systems (TPMS), Traction Control Systems (TCS), Electronic Stability Control Systems (ESC), Vehicle Speed Sensor (VSS), etc [Fea06]. These sensors are used to control actuators or warn drivers of potentially dangerous conditions that compromise the safety of a vehicle. There is potential to share this information with other vehicles in the system that may or may not be equipped with similar systems to enhance the total safety of the system.

To further augment the awareness of a vehicle about its environment, vehicles

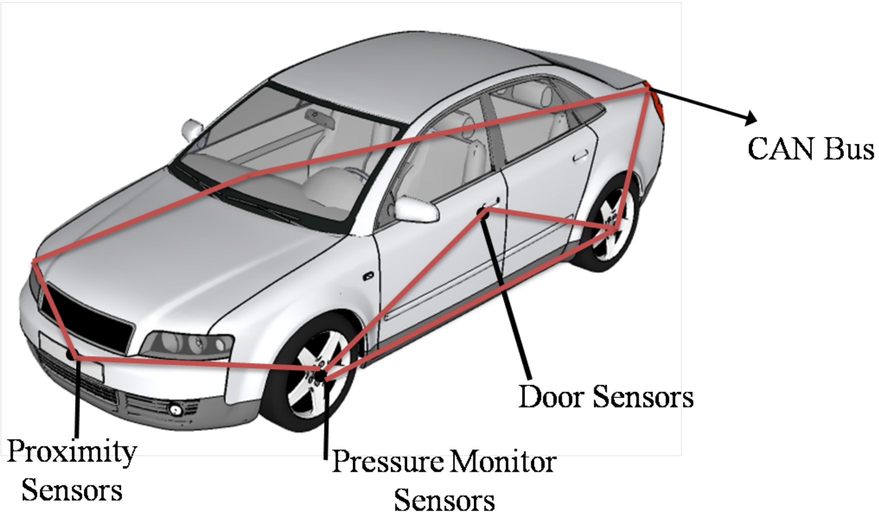


Figure 2·1: Image illustrating vehicle on-board sensors and controller area networks within a vehicle.

are being equipped with advanced cameras all around the vehicle. Rear-view cameras installed in a vehicle provide a view of blind-spots and difficult to view portions of the rear and assist the vehicle to reverse, especially in large cars like SUVs and trucks. Figure 2·2 illustrates the positioning of various cameras and sensors that assist in providing a complete view around the vehicle. Further advances in imaging technology are enabling cameras to recognise road signs and detect moving or stationary objects in the path of a vehicle such as bicycles and pedestrians [Lie09]. This is especially useful in urban and dense environments.

Vehicles as Sensors

The mobile or cellular telephony industry has seen rapid growth recently with the advent of smart-phone and high speed data connectivity. With advancement in technologies and availability of sensory data such as GPS and accelerometers, several new applications have emerged that exploit locality to provide services. Applications running on smartphones provide the ability to publish location based information

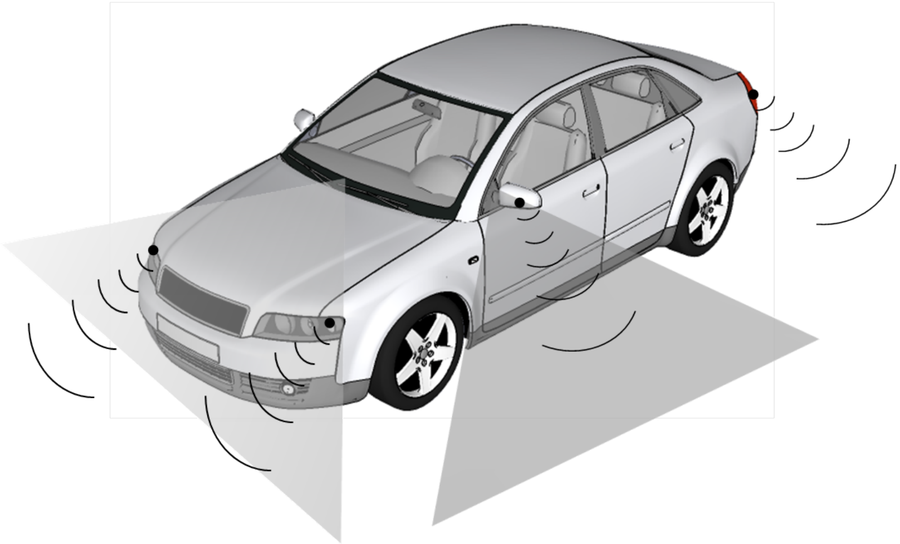


Figure 2·2: Image illustrating cameras and sensors around a vehicle, enabling all around view.

such as events that is shared with other users. In a similar manner, vehicles equipped with communication capability will likely enable sophisticated applications. Here, we highlight some unique applications that have emerged recently that use vehicles as sensor nodes.

One growing application of intelligent transportation is the usage of large numbers of vehicles as mobile sensors. Applications range from inferring traffic speeds in real time to the usage of GPS traces for updating digital road maps. Vehicles within such deployments must not only possess sensing equipment, but also have access to network connectivity in order to transfer the data to the cloud. Systems of this sort are known as *telematics*. One of the best known projects in this field is General Motors' OnStar service [OnS08], in which drivers can request directions, remote unlocking (in the event of lost keys), or there are situations in which there is autonomous contact with emergency services. Such services are the commercial force behind the deployment of sensors (such as GPS receivers) in vehicles. In turn, such sensors can be used for more complex ITS applications.

One example is the OPTIS project in Sweden [Kar02], where 220 cars were equipped to report their speeds over cellular GPRS modems in real-time. This enabled the city departments to collect data to validate data from existing camera/loop-detector systems at comparatively low cost. A similar study was carried out by Nokia in California [Rea08]. The study equipped 200 cars to report their speeds to a central server every 30 seconds, with the aggregated data then being transmitted back to the vehicles. Other examples of similar projects are StreetSmart [DJ07], TrafficView [NDLI04], SOTIS [WER$^+$03b]. Another advanced application of distributed sensors is to determine the content of salt required on the roadways in snow conditions. Based upon the collected feedback from stability control sensors of a vehicle, a city may choose the distribution of salt to avoid slippery conditions. Inrix and Dash are examples of two companies whose business models are based upon collecting data from vehicles on the roadway [Inr09, Das09]. Fleets of vehicles provide real-time data from the vast expanse of roadways to create a centralised map of traffic statistics on the roadways.

In MITs CarTel [HBZ$^+$06] project, several cars were equipped with embedded computers, on-board diagnostics units for reading engine parameters, GPS receivers, and 802.11b/g wireless transceivers. The units recorded details of the wireless networks they encountered, and attempted to connect to the Internet through them, providing insight into the availability of WiFi hotspots and the amount of data that can be transferred through them. The results showed that a median transfer of 216 KBytes per session was possible. Given that $32,000$ unique networks were recorded over the experiments duration [EBM08], this suggests that such connectivity has great utility. Separately, the project also used accelerometers to record locations where the vehicles experienced motion that could be due to a pot-hole in the road surface. Using further data processing techniques this enabled researchers to develop a map of pothole locations [EGH$^+$08].

2.3 Vehicular Networking

Vehicles equipped with wireless communication capability potentially exchange data autonomously to enable sophisticated applications. Thus, vehicles that are equipped, can be viewed as nodes of a network. Vehicles are equipped with sensors that detect dangerous conditions and warn drivers or enable actuators that prevent or mitigate a crash. With communication capability, vehicles can exchange safety messaging and state information that increase situational awareness of a vehicle beyond the line of sight and beyond the sensor capability of a vehicle. One technique to develop applications is to equip a vehicle with advanced sensors that function autonomously. Another approach is to enable cooperation among vehicles achieved through communication and networking.

2.3.1 Networking Architectures

There are three primary models for interconnecting vehicles (we do not consider a satellite-based model here). The three models are an infrastructure model where vehicles connect directly to infrastructure, an ad hoc model where vehicles connect multihop to vehicles in the vicinity and a hybrid model that includes intermittently placed access points supported by multihop communication over connected vehicles.

Infrastructure Model

One architecture is an infrastructure-based solution in which vehicles connect to a centralized server or a backbone network such as the Internet, with the help of road-side infrastructure such as cellphone towers, WiMax, or 802.11 access points, as illustrated in Fig. 2·3. The infrastructure is able to manage the network and provides connectivity to the backbone network (Internet). However, the round-trip delays for data are potentially high, of mixed reliability and therefore, unsuitable for safety applications [Cot09]. Connectivity in this model is subject to availability of infrastructure and often such solutions are cost intensive.

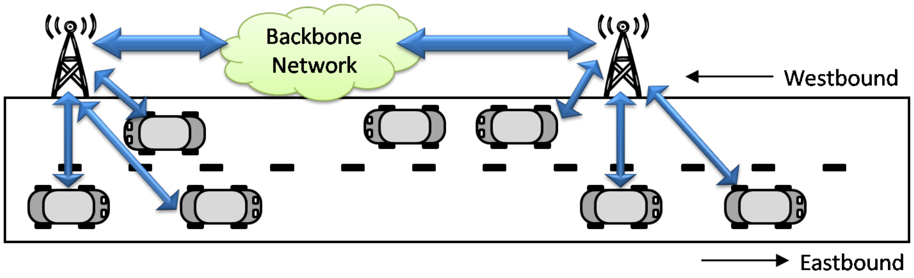


Figure 2·3: Illustration of an infrastructure model where vehicles communicate directly with infrastructure such as road-side access points.

Ad Hoc Model

Another solution proposes to exploit multihop connectivity via an ad hoc network formed over moving vehicles, illustrated in Fig. 2·4. Communication between vehicles that are in close proximity with one another is supported by this model. As the vehicles are potentially within communication range, the associated delays are minimal. Connectivity to vehicles that are outside the communication range can be supported by multihop connectivity. However, multihop connectivity to vehicles separated by large distances is subject to prevailing traffic conditions under the assumption of short-range radio communication, [WBMT07]. Daytime traffic is likely to be sufficiently dense while traffic at night is likely to be sparse. Furthermore, vehicular mobility can be difficult to predict. Individual vehicles can leave or join a highway at random. Thus, end-to-end connectivity is hard to achieve for low density and random departure scenarios, [WBMT07]. For short-range communication, the connectivity in this model is subject to prevailing traffic conditions [WBMT07]. Complex solutions are required to manage the network in the absence of a centralized authority.

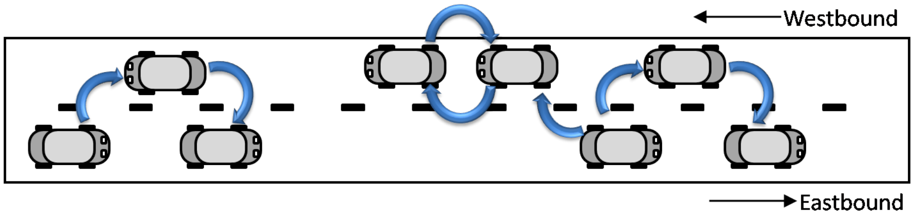


Figure 2·4: Illustration of an ad hoc model of communication in a vehicular network.

Hybrid Model

The third architectural solution is a hybrid network that proposes to use a combination of two schemes. Vehicles connect to roadside infrastructure directly when in range and exploit multihop connectivity otherwise. The infrastructure is assumed to be placed intermittently in the network such that vehicles are not always connected directly. However, the vehicles are able to exploit multihop communication and achieve connectivity. The infrastructure is assumed connected to the backbone network (Internet), thereby providing suitable connectivity for applications.

2.3.2 Applications

The development of vehicular networking is focused on several distinct applications. In this section, we describe the applications, the requirements that distinguish them and discuss some use-case scenarios. We broadly categorize the applications as Safety Messaging, Traffic and Congestion Monitoring and General Purpose Internet Access. These broad classifications are illustrated in Figure 2·6.

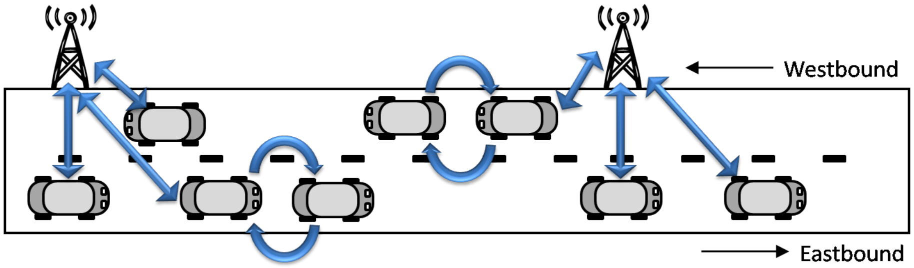


Figure 2·5: Hybrid model of vehicular network, communication with intermittently placed roadside infrastructure supported by multihop connectivity.

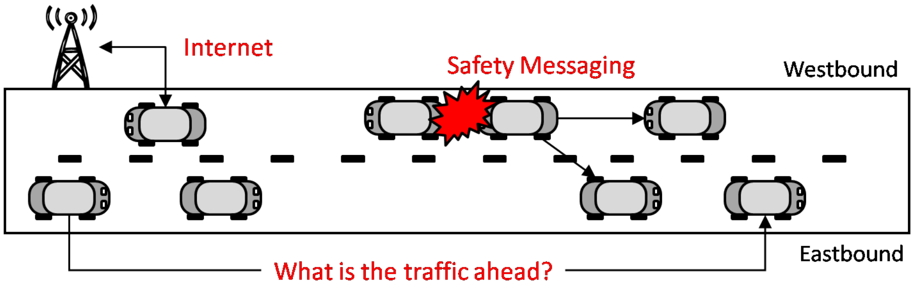


Figure 2·6: Different classes of applications in vehicular networks.

Safety Messaging

Improving safety in vehicles is an ongoing challenge for the automotive sector. As recently as February 2010, vehicle manufacturers are facing recalls due to safety concerns [Bun10]. While there has been advancement in vehicular safety technologies such as anti-lock brake systems (ABS), traction control systems (TCS) and electronic stability control (ESC) that prevent vehicles from crashing [Ash08]. These technologies can be further augmented by increasing awareness inside a vehicle about the environment around a vehicle. Currently, sensor technologies, such as cameras, LIDAR, RADAR, are being developed to increase awareness of the environment around a vehicle [Shi09]. Another technique is to share state information, such as speed, heading, acceleration, GPS position, etc. There is ongoing work in developing situational awareness around a vehicle by sharing state information among neighboring vehicles through wireless communication, [Ash08]. Illustrated in Fig. 2·7, each vehicle has a safety bubble around it, such that knowledge of the state of vehicles in or around the bubble is important. The state information of each vehicle is shared by vehicle-to-vehicle (V2V) communication. This enables each vehicle to develop situational awareness of the environment around it. Developing situational awareness is essential for a vehicle to determine its future actions that are feasible and yet maintain safety of the vehicle. The concept is an extension of motion planning using Partially Observable Markov Decision Processes (POMDP) in robotics [MHC09]. Here, robots future states are determined by decisions based on observed states (situational awareness) of other objects including robots in the vicinity. The decision making paradigm is enabled by POMDP.

Safety messaging is important as having state information of a vehicle's environment is a first step towards enabling autonomous vehicles. As seen in the field of robotics, coordination between autonomous mobile units can be achieved if there is knowledge about other units in the environment [Ram08, rob09]. Without going into further detail, we describe some of the current applications of safety messaging.

- **Adaptive Cruise Control (ACC)**

  ACC is a system that measures the distance to the vehicle in front and automatically adapts the speed of the vehicle to maintain a fixed distance between the two. This technology is available in some of the present day cars.

- **Lane Departure Warning System (LDWS)**

  Development of autonomous driving also calls for computer control of the lateral motion. Starting in 2000, several cars introduced technology that can warn the driver when the car threatened to leave the current lane without signaling. Newer systems apply several techniques that not only warn the driver,

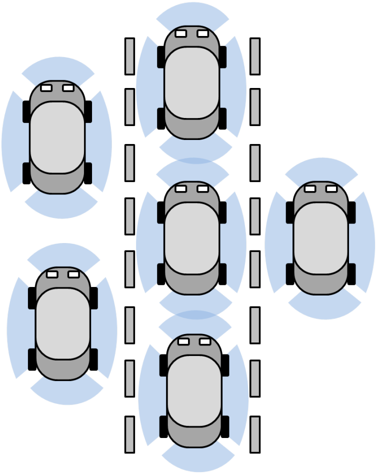


Figure 2·7: Illustration of safety zones around a vehicles, maintained by sharing state information enabled by wireless communication with several vehicles in the vicinity.

but actually keep the car in the appropriate lane. Lane Keep Assist System (LKAS), [PBW07], provides additional steering torque to keep the car in the right lane, while another system equips the vehicles stability control system to apply brake pressure to some of the wheels to adjust the vehicles course. Ford technology is based upon systems that were developed for fighter aircraft [Shi09].

- **Lane Change Assistance (LCA)**

  Fully autonomous driving would require automatic and safe lane changes, so a vehicle must detect other vehicles in the vicinity and their speeds. Volvo has developed the Blind Spot Information System (BLIS), which utilizes a camera to detect vehicles in the drivers blind spot and provides an audible and visible warning.

- **Traffic Sign Recognition (TSR)**

  Situational awareness of the environment includes knowledge of the roadway on which the vehicle is traveling. The vehicle needs to be aware of the traffic rules and regulations. One approach to implement this within the current infrastructure is to develop the ability to read traffic signs.

A number of these systems rely on expensive sensor technologies that can be suitably adapted to function with wireless communication capability. A communication enabled system has additional benefits of potentially higher degrees accuracy and control at high speeds within close proximity thereby achieving increased system throughput.

Traffic and Congestion Monitoring

Traffic related information is essential to compute travel time estimates. Efforts to provide traffic related information in recent times include web-cameras that help determine traffic situations on major highways or in urban areas. Magnetic loop installations have been used to determine the traffic rates and densities on roads [PAT07]. Traffic control centers monitor and control traffic with the help of web cameras. However, the systems described have an inherent delay, such that they do not relay active information to the traveler on the road. The data are collected in a central location, processed over time and distributed over media that are not always directly connected to vehicles on the roadway. As a result of the delayed information, vehicles are often unable to react sufficiently and avoid congestion on the roadway. A distributed automated system can be devised with networked vehicles and traffic lights that is more efficient and proactive than a centralized control system. With the help of inter-vehicle communication, active systems can potentially be developed to relay updated and accurate information on travel estimates. Coupled with GPS systems, the traveler can get information about traffic on specific routes, occurrence of accidents, tolls, road works, etc. Armed with this information, alternate routes can be planned thereby saving travel time. Savings can be further extrapolated to fuel and emissions saved in idling vehicles stuck in traffic. Highways often deploy large sign-boards to warn travelers of heavy traffic, but such information cannot be fully exploited unless an alternate route is proposed. Here map-based GPS systems can be employed to map alternate routes and determine travel time on those routes to save time. Often sections of roadways are under repair thereby increasing travel time. Additionally, detour paths can be guided by wireless beacons where map-based information is not available to the road user.

The vast distributed network of vehicles equipped with sensors provides real-time data for transportation research applications. Data collected from roadside observation can be an automated task that reveals traffic flow characteristics and road usage data. Lane charging or fee-based usage of special high-speed lanes on highways is a concept proposed to ease congestion and generate revenue to support highways. Toll collection and booth management are applications aimed at easing congestion on sections of the highways and ensuring smooth travel.

General Purpose Internet Access

Providing general Internet access to networked vehicle has several benefits. GPS systems already provide information about gas stations, ATMs, stores etc. However, the information provided is pre-stored and not updated regularly. With Internet access updated information including enhanced details such as timings, phone numbers and special offers from stores can be provided. This would allow stores to execute roadside marketing campaigns to promote business. An example is food outlets on highways can market special packages for off-peak hours, thereby attracting customer traffic. Internet access is also a very useful distraction for fellow passengers especially children. The ability to access Internet while on the move is very desirable for young netizens and the Internet offers several activities such as movies, social networking, music, chatting, etc.

2.4 Delay Tolerant Networking

The concept of Delay Tolerant Networking (DTN) emerged with a motivation to inter-connect networks operating in environments that lack continuous end-to-end connectivity or networks that are sporadically connected for short time-periods interspersed large periods of disconnection. The initial work around this concept was presented in Reference [Fal03]. At present, there is a Delay-Tolerant Networking Research Group (DTNRG) [MF09] working on the architectural and protocol design principles required for interconnecting such networks. A delay tolerant network is described by a network that is comprised of static or dynamic nodes such that the network graph is not fully connected at all times. The network connectivity graph changes by virtue of node mobility or sleep-wake scheduling or dynamic node density. As a result, there is lack of end-to-end connectivity between all node pairs in the network graph. This is illustrated in Figure 2·8(a). Importantly, messages are stored in a persistent buffer when there is lack of desired connectivity. With time as the network connectivity graph changes, desired connectivity is achieved, multihop or otherwise and the messages are forwarded from the persistent storage buffer.

Data Mules

Consider the scenario illustrated in Fig. 2·8, where nodes are `A`, `B`, `C` and `D` are nodes in a sparse network that is partitioned. At time instant t_1, there is no connectivity between nodes `A`, `B`, `C` and `D`. At time instant t_2, by virtue of mobility, nodes `A` and `B` move within communication range of each other. At time instant t_3 and t_4, the network graph changes, and nodes `B` and `C` and nodes `C` and `D` are connected,

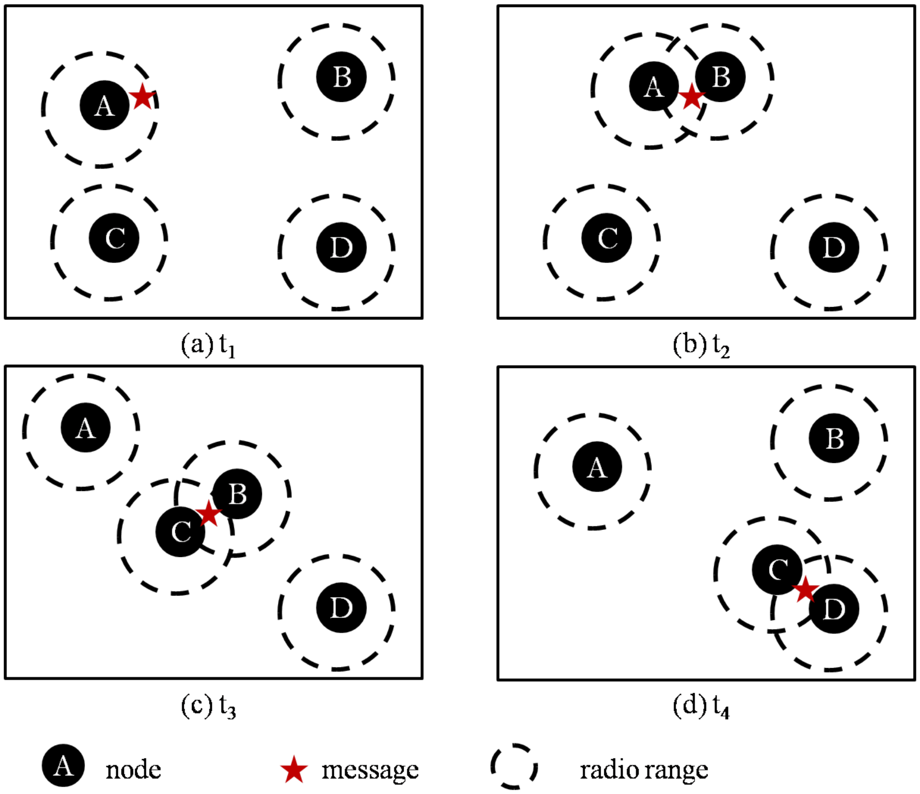


Figure 2·8: Message exchange in a delay tolerant network and the role of *data mules* in the network.

correspondingly. Thus, over the time instants, t_1, t_2, t_3 and t_4, a path between nodes `A` and `D` is formed. Data can be *cached* or stored in a persistent buffer that awaits connectivity between nodes. Thus, exploiting the changing network connectivity graph and the multihop message propagation, data are forwarded, originating at node A, to node D. This illustrates the concept of delay tolerant networks (DTN), where nodes *cache* data in the absence of connectivity and forward data opportunistically when intermittent connectivity is available. In this example, nodes `B` and `C` serve as *data mules* that *transport* data from nodes `A` to node `D`, similar to *mules* carrying goods. In this dissertation, we consider the role of vehicles on the roadway as data mules that have the capability of caching and forwarding data while moving along the roadway.

We envision vehicles as data mules that interact and sense the environment, other vehicles, collecting valuable information as they traverse the system of roadways. The data collected bear a strong spatial temporal correlation with nodes (vehicles) in the network. The opportunistic contacts with other vehicles and environment can be exploited to instantiate applications in environments that are otherwise constrained by lack of connectivity. We simply introduce the concept of DTNs and data mules here, for greater detail on DTN, we direct the reader to the references described in Chapter 3.

2.5 Summary

To summarize this chapter, we have highlighted the existing initiatives in Intelligent Transportation Systems (ITS) and their importance. We describe the ingredients of an intelligent road transportation system, sensors to detect the environment and wireless communication technologies to enable interaction and coordination. The targeted applications emphasize the need for networking methodologies to enable an intelligent transportation system.

Chapter 3

Related Work

This chapter is organized in subsections based upon topics in related research that are referred in this dissertation. An overview of related work in Mobile Ad Hoc Networks (MANETs) research is provided from where concepts of routing have been adapted in this dissertation. We provide a background of work in delay tolerant networking (DTN) research which form the basis of the proposed solution. The vehicular networking research community has worked on several issues such as communication technologies, routing issues and analytical models for data dissemination. Finally, we describe related work in percolation theory and capacity of networks that are referred in support of our results.

3.1 MANETs: Mobile Ad Hoc Networks

3.1.1 Routing

Routing protocols are classified based on their design, hierarchical, position based or flat routing protocols. Flat routing protocols are further classified as Reactive (On-Demand) or Proactive (Table-Driven). Analysis and simulation of routing protocols from mobile ad hoc networking (MANET) research is provided in Ref. [HXG02]. In this dissertation, we classify routing protocols on the basis of their path-formation strategies. Routing protocols such as AODV and DSR form a path from the *source* to *destination* prior to message dissemination. The route formed is typically embedded in the message. In scenarios of high mobility, these protocols perform poorly due to rapidly changing topologies in the network. While there are several different routing protocols, we refer the reader to the survey article for details.

In a vehicular network, characterized by rapidly changing topologies and varying densities, these routing techniques are likely to perform poorly due to increased overhead in path formation and path maintenance. The authors in reference [ST09] have explored the performance of routing protocols in the context of scalability and mobility. Reference [MWH01] provides a survey of the various position based routing protocols. These protocols are referred to as techniques to apply geographic routing principles to enable data dissemination in a vehicular network.

3.1.2 Connectivity and Phase Transition

Node connectivity in the context of ad hoc networks has been previously studied by researchers in [Bet02, Bet04]. Connectivity in vehicular networks is unique as it is restricted to relatively predictable paths (roadways). Nodes in MANETs have relatively higher degree of freedom, but at the same time a lower mobility rate. This dissertation considers a linear model with relatively high rate of vehicle mobility. Gupta and Kumar in reference [GK00, GK98] present rigorous results on the capacity of a network and the critical power requirements for connectivity in an ad hoc network. In [GT02], authors have shown that even one-dimensional mobility increases capacity of the network. An analytical model developed by the authors demonstrates that for one-dimensional and random mobility patterns the interference decreases and improved network capacity is observed brought about by node mobility. In a similar context, we demonstrate that under assumptions of vehicle density and physical radio, increased mobility aids in speeding-up message propagation. In this dissertation, the results presented confirm the conjectures of the authors, but we do not provide the same rigorous proofs.

Phase transition phenomenon in the context of ad hoc networks has been discussed in reference [KWB01]. The authors discuss a model of random placement of nodes in a unit disk and analyze probabilistically the properties of the connectivity graph in the context of increasing communication radius. In reference [CM08], authors study the availability of transient paths of short hop-length in a mobile network and observe that a phase transition occurs as time and hops are jointly increased according to the logarithm of the network size. In reference [SB03], the authors provide an upper bound and lower bound on the critical transmission range in a sparse ad hoc network. The work is extended to consider mobility and dense networks and discusses the trade-offs between communication capability and energy consumption.

Authors in [KY08] have studied information dissemination in a network with unreliable links. Several works have studied connectivity characteristics in a one-dimensional linear arrangement of nodes [GNE06], [FL04], [DTH02]. Our work is unique in that it considers a linear arrangement of nodes that are *mobile* in *opposing* directions as compared to existing models that consider static networks. Our transient connectivity and delay tolerance assumptions are unique and distinct from previous work.

3.1.3 Clustering

Clustering in mobile ad hoc networks is a concept to create logical groups of nodes to enable management, topology control and routing. Several models for clustering have been proposed in related work [YC05]. This dissertation refers to the model presented in [BKL01]. In the context of vehicular networks, clustering has been discussed as a means to achieve connectivity and enable data dissemination in [SES04]. The TrafficView system presented in [NDLI04] and SOTIS (Self Organizing Traffic Information System) [WER$^+$03b] rely on various models of clustering for vehicle data management and routing. The concept of cluster formation and cluster maintenance in the context of a vehicular network is beyond the scope of this dissertation. For details on techniques and methodologies, the reader is referred to related work. The concept of clustering is essential as it allows spatial reuse of resources to increase system capacity. In vehicular networks it is important to coordinate transmissions of messages and maintaining consistent data on the roadway in the event of random departures from clusters. Further it helps in reducing redundant transmissions in the network.

3.2 Delay Tolerant Networking

Delay tolerant networks (DTNs) [Fal03], also known as Intermittently Connected Mobile Networks (ICMNs) or Opportunistic Networks, are characterized by periods of connectivity interspersed with periods where nodes are largely disconnected. Delay tolerant networking has found several applications in inter-planetary space communications, mobile ad hoc networks and sensor networks. Performance modeling in the context of ad hoc networks, particularly delay and throughput effects is of particular interest. An important observation is the absence of end-to-end connectivity in vehicular networks owing to the unique characteristics of vehicle mobility and time-varying vehicular density. While existing mobility models such as the “Freeway” and “Manhattan” model capture the mobility of vehicles along restricted pathways, they do not adequately reflect the fragmented connectivity. However, opportunistic connectivity allows us to employ a *store-carry-forward* mechanism, essentially a greedy approach.

3.3 Vehicular Networking

In this section, we discuss related work in vehicular networks in the context of communication technologies, routing protocols and analytical models.

3.3.1 Communication Technologies

Many different technologies have been considered to provide connectivity between vehicles (V2V) and between vehicles and infrastructure (V2I). During the course of this dissertation, these technologies are in different stages of development and standardisation. While these technologies are considered and referenced here, the parameters used in this dissertation are based on the IEEE 802.11b.

Satellite

One-way broadcast communication from satellites has been used to enable positioning technologies such as GPS and data dissemination via digital radio (XM Satellite Radio) [XM-10]. Related work on VSAT (Very Small Aperture Terminals) demonstrates achievable upload speeds between 64 Kbits/s and 128 Kbits/s, while download throughput are up to 438 Kbits/s [EWL$^+$05]. While satellite connectivity is ubiquitous, throughput available is low and latencies are high. The technology is feasible for certain aspects of vehicular communication but unlikely to serve requirements for vehicle to vehicle (V2V) communication.

GSM/GPRS

GSM (Global System for Mobile) and GPRS (General Packet Radio Service) are cellular network technologies that run in the 900 MHz and 1800 MHz frequency bands. Communication through these technologies requires connectivity to an access point (cellular tower) which is subject to deployment in the network. Applications that are developed using these technologies are typically low throughput (56 Kbit/s to 114 Kbit/s). The low frequency used by GSM enables long propagation ranges. Presently, *telematics* applications such as fleet monitoring and traffic data collection are developed using cellular technologies. High throughput and new generation technologies such as HSPA (High Speed Packet Access) over UMTS (Universal Mobile Telecommunications System) are currently in various stages of development and deployment [ZSGW09].

IEEE WAVE

WAVE (Wireless Access for Vehicular Environments) [Ber07] is the IEEE 802.11p draft under development to define standards and protocols to enable communication between vehicles (V2V) and between vehicles and infrastructure (V2I). The FCC has allotted 5.9 GHz frequency spectrum in the Dedicated Short-Range Communication (DSRC) spectrum to enable V2V and V2I communication [XMSK04]. The draft is a modification of the 802.11a standard that employs the use of DCF (Distributed Coordination Function). The implementation is a broadcast method to enable vehicles to share state information in a fast and efficient manner with minimal setup time.

Related work in reference [XMSK04] has considered safety communication between vehicles using the DSRC radio. However, it has been shown that contention is potentially a problem in the broadcast medium in dense vehicle density scenarios [TWP$^+$06]. Authors in [MCR09] provide an analytical model that determines the performance of DSRC protocols for safety messaging.

Short Range Technologies

Researchers are considering short range directional technologies for vehicle to vehicle (V2V) communication to serve the high data rate and reliability constraints for safety applications and counter the contention problem in broadcast technologies. Multiple GHz of internationally available, unlicensed spectrum surrounding the 60 GHz carrier frequency has the ability to accommodate high-throughput wireless communications [DH07]. The Visual Light Communication Consortium (VLCC) in Japan is developed applications for next generation LED (Light Emitting Diode) Systems. Researchers at Nagoya University in Japan have developed an LED based traffic light data dissemination system that modulates the LEDs at high rates to disseminate data vehicles that have receivers in the form of high speed cameras [AMY+07]. Intel [Gre09] has demonstrated an active-braking application using LED communication between vehicles.

3.3.2 Data Dissemination Models

Data dissemination models in vehicular networks are interesting due to the unique nature of communication and characteristics of the vehicular network. There is spatio-temporal correlation between vehicles and data in the network. Information in the network is often shared between all vehicles in a neighborhood. Thus, the models for communication are unique from conventional MANET models that often involve one-to-one communication. The dissemination models in vehicular networks are classified as: flooding or geocasting, request-reply, sharing and beaconing [HL10]. The various techniques are referenced here. This dissertation considers a variant of flooding and geocasting technique that incorporates a *store-carry-forward* approach to facilitate data dissemination.

Flooding or Geocasting

A broadcast is a single hop transmission of a packet to all nodes within radio range of the sender node. Flooding involves distributing the packet over a range spanning multiple wireless hops. Nodes within the broadcast transmission range of the sender are expected to rebroadcast the packets to deliver to nodes that are potentially several hops away from the source. Variants of this scheme are presented in [BK06, WBMT07]. Authors in [DJ07] apply 'gossip' and 'epidemic' dissemination techniques in their proposed scheme. Researchers in [WHF$^+$07] adapt their flooding techniques based on the density of nodes and 'age' of the information. Authors in reference [BSH00] propose to adapt the rebroadcast of messages based on the spatial location of nodes relative to the sender. The farther away from the sender, the more likely a node will rebroadcast the received information.

Reactive routing protocols such as AODV [HXG02] have been extended in vehicular networking scenarios by reference [KSA02]. The authors adapt the protocol to include geocasting functionality. However, the protocol is limited due to partitioning in the network and its ability to scale over large spatial separations between source-destination pairs. Various flooding approaches have been compared in reference [WC02].

Request-Reply

Information dissemination models in vehicular networking include scenarios of one-to-one communication. Reactive or on-demand algorithms for data dissemination have been considered. One technique is a request-reply method where a vehicle request for specific information from the neighborhood (cloud) and another vehicle possessing that information in its knowledge base is able to reply to the specific query [ZZC07]. Position based approach has been discussed to find empty parking spaces in dense urban areas [BKL01].

Sharing

Sharing techniques involve distributing data among a subset of nodes that are interested in the network. It is a publish-subscribe technique such that nodes publish information periodically and nodes that are interested subscribe to this information. One application of this technique is presented in [LM07]. The challenges include maintaining publishers and subscribers in the system and routing data from a publisher to a subscriber. A variant is presented in [STK$^+$06] which utilises public transport buses as 'message ferries' that store all information in the network. These 'oracles' do not drop any information received from publishers and are able to serve subscribers with information when publishers are absent. The density and predictable paths followed by buses is exploited for coverage in the network.

Beaconing

Beaconing techniques involve periodic sharing of information in the network. The challenge is to limit the number of broadcasts and yet maintain current information at all nodes in the network. Techniques involve adapting the beaconing rate or broadcast frequency based on node density and age of information [XB06]. Authors in [WFR04] adapt their beaconing algorithm based on arrivals and departures of vehicles from the roadway. In reference [WER$^+$03b], researchers compare current traffic situation with the received information to determine beacon update frequency. Adjusting the transmission power based on channel load to modulate beacon coverage is a technique discussed in [TMSH05].

3.3.3 Analytical Models for Data Dissemination

Several works have developed analytical models studying message propagation in VANETs. In reference [FM08], the authors study in detail the propagation of safety critical warning messages in a vehicular network. The authors develop an analytical model to compute the average delay in delivery of warning messages as a function of vehicular traffic density. Our work is unique in that we consider data propagation in the event of a partitioned network. However, our model is consistent with this work with respect to the network assumptions, e.g., exponential distribution of nodes in a one-dimensional highway setting. Another model proposed in [YAEAF08], assumes exponential distribution of nodes to study connectivity based on queueing theory. The authors describe the effect of system parameters such as speed distribution and traffic flow to analyze the impact on connectivity. However, the authors do not consider a scenario of dynamic network with bidirectional mobility.

In reference [UD08], the authors consider connectivity between vehicles on the roadway. The model is similar in that it assumes an exponential distribution of vehicles and characterizes bounds on connectivity between vehicles in a dynamic node mobility model. However, this dissertation considers similar connectivity characteristics in the context of delay tolerant messaging with non-variable vehicle mobility.

3.3.4 Delay Tolerant Networking in Vehicular Networks

In the context of vehicular networks, DTN messaging has been proposed in previous work in [WFR04, WBMT07]. In reference [WBMT07], the authors have evaluated vehicle traces on the highway and demonstrated that they closely follow exponential distribution of nodes. The work demonstrates network fragmentation and the impact of time varying vehicular traffic density on connectivity and hence, the performance of messaging.

The UMass DieselNET project explores the deployment of communication infrastructure over campus transportation network and records measurements on opportunistic networking [BGJL06]. Wu et al. have proposed an analytical model to represent a highway-vehicle scenario [WFR04]. In their approach, they investigate speed differential between vehicles traveling in the same direction to bridge partitioned network of vehicles. An important distinction in our work is that we consider bidirectional connectivity which is intuitively faster due to the speed differential in traffic moving in opposing directions. In our work, we demonstrate that the transient connectivity offered by opposing traffic can provide a substantial improvement in message propagation speed, beyond a certain critical threshold on traffic density.

MIT's CarTel [HBZ+06] project exploits open 802.11 access points, in the Boston-Cambridge area in Massachusetts, to disseminate collected information from equipped taxicabs in the vicinity. While not a true DTN deployment, the project is an example of the *store-carry-forward* approach of DTN networks that exploits transient connectivity. A similar project is BikeNet [EML+09], where a bicycle was fitted with a large number of sensors, including tilt, GPS position, speed, cyclists heart rate and galvanic skin response, and pollutant and allergen sensors. Sensor data was uploaded to WiFi access points that the bike encountered. The data was then used in order to rank particular routes in terms of how pleasurable they were to cycle on, or how polluted they were. The advantage of this scheme is that bicycles are able to access many areas that motorised vehicles are not, and hence a bike sensor network would provide data of interest to pedestrians too.

Delay tolerant approaches have been explored in [FKUH07] and [WBMT07] where the locomotion of a vehicle is exploited to bridge the partitioning in the network. The work presented in this dissertation provides details on techniques for message dissemination and an algorithm that handles acknowledgements for data delivery. Further, the analytical model confirms the ability to exploit traffic in opposing direction to bridge partitioning. And finally, the regimes of vehicle density where DTN techniques are applicable are unique to this work.

Chapter 4

Routing Solution

We consider a highway scenario (Fig. 4·1) where vehicles travel in either direction on a bidirectional roadway. We assume that vehicles are equipped with storage, computation and communication capabilities. The roadway is annotated as *eastbound* and *westbound* for convenience in the narrative. We assume that vehicles travel at fixed speed (v m/s) in both directions. A fixed radio range model is assumed such that vehicles within range are able to communicate with each other. As vehicles travel on the roadway, the topology of the network changes, nodes come in intermittent contact with vehicles traveling in *opposing* directions. These opportunistic contacts can be utilized to aid message propagation, as explained in subsequent text.

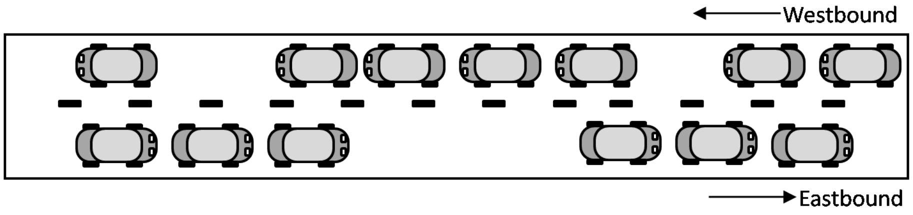


Figure 4·1: Illustration of the highway model.

4.1 Routing Model

We present a routing protocol to enable data dissemination in a vehicular network. We describe the different elements of the protocol, attributed or labeled messaging, clustering and delay tolerant networking.

4.1.1 Attributed Routing

The use of attributed (labeled) data emerged from routing in MANETs (mobile ad hoc networks). The idea is that information embedded in the data packet that is relevant to the data or routing of the packet can be interpreted independently by each node to make an intelligent routing decision, based on network conditions and parameters. We use the analogy of the postal system to describe this idea. An ordinary mail contains *Street, City, State and Country* as attributes of the destination. This is an example of a hierarchical attribute where the mail is routed based upon its origin and destination. The labels of the origin and destination at each level of hierarchy are matched, starting from the *Country*, to make a routing decision.

In the context of vehicular networks, there exists spatio-temporal correlation between data and nodes in the system. There are scenarios and applications where data are sourced from a location and destined for another location on the roadway. One example of such an application is traffic data. Traffic data from a roadway is collected by several vehicles on the roadway and is relevant to vehicles that are approaching the roadway, but at the instant are some distance away, say 5 miles. The traffic statistics or events such as congestion are typically updated in the order of minutes. Thus, the data are relevant to nodes in a specific space and for a certain time-frame. Moreover it is reasonable to assume that each vehicle is equipped with a GPS system that enables the vehicle to be aware of its location. The location coordinates are embedded in each packet such that each packet is attributed (labelled). Thus, a simplified geographic routing protocol can be implemented where each intermediate makes a routing decision based on the attributes embedded in the data packets and its own.

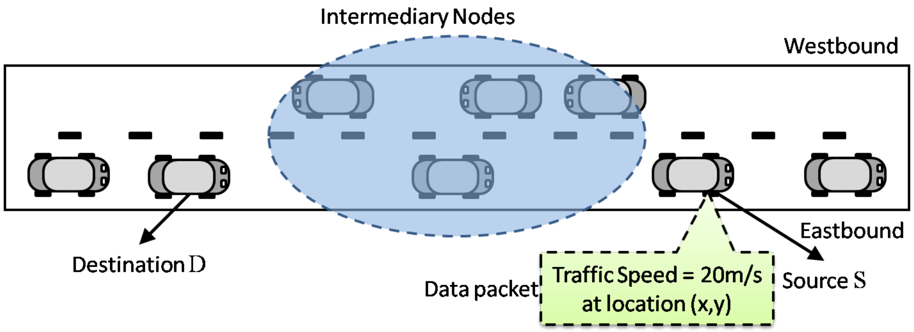


Figure 4·2: Illustration of attributed messaging using location attributes.

Fig. 4·2 illustrates a simplified version where the data originate at source S, destined for node D. Note here that the source and destination nodes, S and D are identified by location attributes. They do not have to be identified by unique IDs. The issue of naming is addressed elsewhere in text. By attributing source and destination locations in the data packet, the intermediate nodes are able to make routing decisions based on these attributes and their respective locations. Note that the attributes are not limited to location. The selection of attributes or labels are specific to the application and the design of the routing algorithm.

We propose the concept of `S-TTL`. In the Internet Protocol (IP), the Time-to-live (`TTL`) parameter defines the value for which the packet in the system is valid. If the value decreases to 0, the packet must be discarded [FHLL04]. In a similar context, we define `S-TTL` as a space-time-to-live parameter as a function of time and space. The data are valid for nodes that lie within a defined space within a certain time-frame. We use the `S-TTL` parameter to define the scope and lifetime of data in the network. The data maybe forwarded by nodes in the system as long as the `S-TTL` parameters are satisfied. The use of `S-TTL` allows us to limit the dissemination of data within a geographic region and at the same time, expire the data as it becomes old in the context of time. It is assumed that the value of `S-TTL` is defined by the application.

4.2 Clustering

We adopt the concept of clustering consistent with mobile ad hoc networking research [BKL01]. Due to the potentially large number of vehicles on a highway in dense traffic conditions, it is essential to implement a clustering scheme to localize and manage network collisions. By clustering vehicles, we can isolate classes of inter-cluster and intra-cluster traffic.

There are several techniques for cluster formation based on node ID and node mobility; we choose to adopt a technique relying on a distributed algorithm suited for the characteristics of our vehicular blocks [BKL01]. The creation and maintenance of a cluster is beyond the scope of this dissertation. For details, we refer to related work in utilising mobility based metrics for cluster formation and maintenance [BKL01].

For cluster stability, we require a threshold duration of connectivity before admitting a node to the cluster. We do not consider the effects of speed differentials within the cluster as the faster vehicles will leave one cluster and join another as the vehicle progresses on the road. Also, there are intersections on a highway where vehicles can join or leave the clusters. Once a cluster becomes very large we expect to split the cluster to better manage intra-cluster traffic. At the other extreme, when the traffic is sparse, the cardinality of a cluster can be 1.

The concept of a cluster of vehicles on the roadway is illustrated in Fig. 4·3. Each cluster has a `clusterhead` and a `clustertrail`, located at the front and rear of each cluster, entrusted with the task of communicating with other clusters. A node at the *head* or *tail* of the cluster will elect itself as the `clusterhead` or `clustertrail` for our protocol. (Node election is not covered here.) This allows us to limit congestion caused by the large number of participating nodes. The remaining nodes in the cluster, nodes which are not header or trailer, are described as intermediate nodes. Within a cluster, communicated messages are shared with all nodes to both facilitate

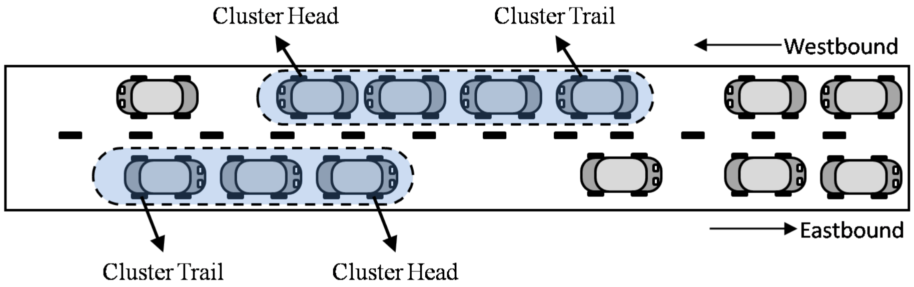


Figure 4·3: Figure depicting vehicles on the roadway, grouped in physical clusters. Vehicles that are `clusterhead` and `clustertrail` nodes are shown.

header/trailer replacement and general awareness of disseminated messages.

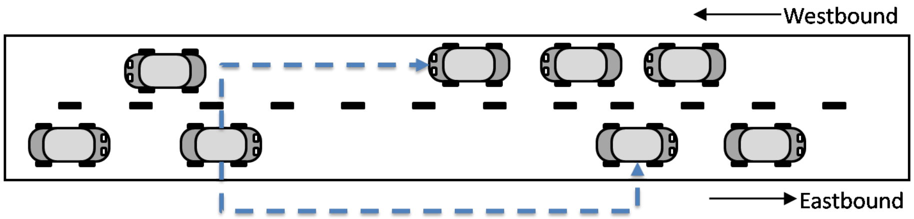
The concept of clustering is introduced to manage data traffic that are shared within a cluster and data that are shared with other clusters. The communication between nodes within a cluster is governed by the Inter-Cluster Communication Protocol, while data is shared with other clusters as per the Intra-Cluster Communication Protocol.

4.3 Application of Delay Tolerant Networking

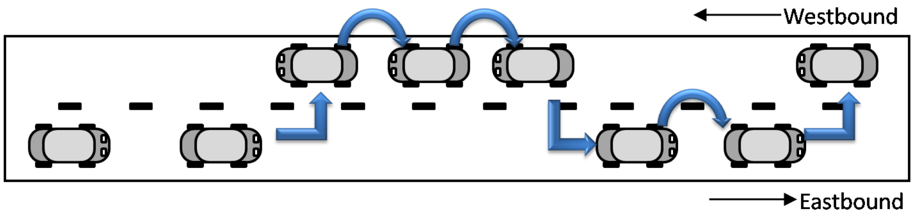
The concept of delay tolerant networking (DTN) has been introduced in Chapter 1 and described in detail in Chapter 3. In the context of vehicular networks, we have described the observation that vehicles tend to travel in blocks that are partitioned from each other in terms of network connectivity. Furthermore, some applications in vehicular networking are not as sensitive to delays in data delivery. These applications can be described as delay tolerant. Thus, we propose to use delay tolerant networking in enabling data dissemination.

The first observation is that the network is partitioned when considering one side of the roadway. However, roadways are typically bidirectional and there are vehicles traveling in the opposing direction. Thus, there is an opportunity to exploit nodes traveling in the opposing direction to bridge the partitions in the network. In Chapter 5, we demonstrate analytically that indeed this is true and evaluate the corresponding conditions of network parameters.

In essence, the network is characterized by disconnected subnets traveling on the roadway. MANET schemes that rely on path formation are an inefficient solution as end-to-end connectivity over large distances is seldom available. By virtue of orthogonal mobility, the subnets come in contact opportunistically. These opportunistic contacts are exploited to bridge partitions and greedily forward data. Thus, delay tolerant networking is used here as a *store-carry-forward* mechanism such that data are cached or buffered in a node's memory in the absence of connectivity and forwarded greedily whenever connectivity to the next hop is available.



(a) At $t = 0$, the network is partitioned and nodes are unable to communicate.



(b) At $t = \Delta t$, topology changes, connectivity is achieved and vehicles are able to communicate.

Figure 4·4: Illustration of delay tolerant network (DTN) messaging as the network connectivity changes with time.

Delay tolerant messaging is illustrated in Fig. 4·4, where at the time of reference $t = 0$, the network is partitioned and there is lack of instantaneous connectivity between nodes. At time instant $t = \Delta t$, the topology of the network changes by virtue of vehicle mobility and connectivity between previously partitioned nodes is available.

4.3.1 Custody Transfer Mechanism

In most message passing schemes, a message is buffered until an acknowledgment from the destination is received. However, due to network fragmentation and lack of connectivity, a question arises on handling acknowledgments. We propose the use of a custody transfer mechanism adopted from DTN techniques [FMH07]. With such a scheme, a message is buffered for retransmission from the originating cluster until it receives an acknowledgment from the next hop cluster. In the scenario under consideration, the goal is to propagate data in a single direction. The custody is implicitly transferred to another cluster that is in front along the direction of propagation and is logically the next hop in the message path. The traffic in opposing direction acts as a bridge but is not given custody of the message. The custody is not released until an acknowledgment is received from the cluster in front. Once the message reaches the next hop, the cluster has custody of the message and the responsibility for further relaying the message is vested with this cluster. The custody of the message may be accepted or denied by a cluster by virtue of it being unable to satisfy the requirements of the message. The rules for custody transfer, governed by the Custody Transfer Protocol (CTP), will be explored in future work.

The concept is illustrated in Figure 4·5. The figure shows clusters ($E1$ and $E2$) traveling in the *eastbound* and cluster $W1$ traveling in *westbound* direction of the roadway. The goal for data dissemination is the *eastbound* direction. The cluster $E1$ is partitioned from cluster $E2$. Thus, cluster $W1$ is used to bridge the partition. The data are forwarded from cluster $E1$ to cluster $E2$ over cluster $W1$. The acknowledg-

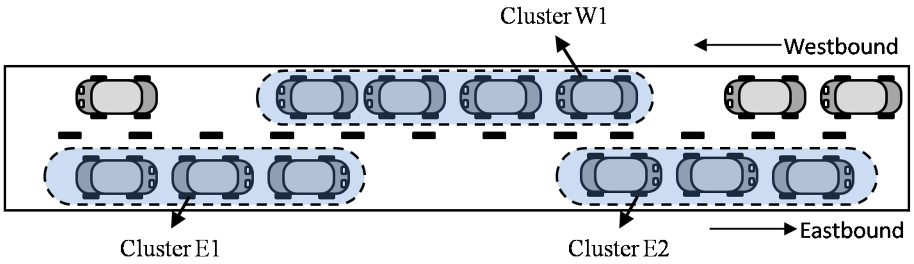


Figure 4·5: Illustration of custody transfer mechanism.

ment (`ACK`) of successful data delivery must be received from cluster $E2$ by cluster $E1$. Upon receipt of the acknowledgment, `ACK` message, the message can be purged as per application design. The custody of data forwarding for the message is now assumed to be with cluster $E2$, since cluster $E2$ is spatially in front of cluster $E1$. Since the data dissemination is intended in the *eastbound* direction and the cluster $W1$ is traveling in the *westbound* direction, the custody of the message cannot be given to cluster $W1$. An acknowledgment received from $W1$ does not qualify for successful data delivery because there are scenarios where the size/length of cluster $W1$ is insufficient to bridge the partition.

Thus, by using the custody transfer mechanism, we are able to ensure data dissemination and message handling within the constraints of a vehicular network. The data are forwarded greedily towards the destination when connectivity is available. Yet, at the same time we are able to purge data that have been successfully delivered to the next available hop in the network to manage the buffer or message queue. Further details of custody transfer mechanism are open to research and not within the scope of this dissertation. We rely on this mechanism as a means to enable data forwarding and message handling.

4.4 Directional Propagation Protocol (DPP)

The vehicles, assumed to be equipped with sensing equipment, generate data to be propagated along the highway. Data are attributed with parameters such as `S-TTL`, direction, class of recipients, etc. The routing structure identifies these attributes along with the location and heading of each vehicle. The propagation is called Reverse Propagation if the data are headed in a direction opposite to the direction of motion of vehicle and Forward Propagation if data are headed along the direction of motion of the vehicle. We will not discuss the reverse propagation scheme in detail here as it can be modeled as an extension of the forward propagation scheme.

Forward Propagation: In forward propagation, the vehicle is assumed to be traveling along the *eastbound* direction and the message propagation goal is also defined in the *eastbound* direction. The data can travel at a minimum rate of the speed of the vehicle since the data are traveling along the vehicle. The data are propagated to the `clusterhead`. The `clusterhead` now tries to propagate the data further along the *eastbound* direction, trying to communicate with other clusters located spatially ahead of this cluster. If the clusters are partitioned, the `clusterhead` attempts to use the clusters along the *westbound* direction which may overlap with other clusters along the *eastbound* direction to bridge this partition. Thus, the data are propagated to nodes traveling along *eastbound* direction which are otherwise partitioned from each other, by using clusters along the *westbound* direction. This temporary path occurs due to opportunistic contact with nodes in the overlapping clusters. Once the data are forwarded to the next hop and an acknowledgment (`ACK`) is received, the custody is transferred to that cluster. The entire process is repeated until the data reaches its required destination.

The routing at header nodes is described in the following algorithm:

```
Initialize $Node\_Direction$
for any $Message$ do
  if $Message$ is not in $Queue$ then
    Add $Message$ to $Queue$
    if $Message\_Direction = Node\_Direction$ then
      send ACK
      do $ForwardPropagation$
    else
      Route to $Trailer$
    end if
  else if $Message\_Direction = Node\_Direction$ then
    send ACK // Duplicate Message
  else
    if ACK for $Message$ exists then
      send ACK // re-transmission
    else
      do nothing // Duplicate Message
    end if
  end if
end for
```

4.5 Summary

In this chapter, a solution to enable routing and data dissemination in the constrained environments is presented. We describe the spatio-temporal correlation of data and nodes in the system and exploit attributed or labeled messaging to enable context driven data forwarding. We describe the occurrence of partitions in the network which hinder routing solutions that rely on path formation schemes. We adapt delay tolerant networking schemes to implement a *store-carry-forward* scheme to exploit opportunistic connectivity offered by nodes (vehicles) traveling in the orthogonal direction. We describe the operation of the protocol with an algorithm to describe the operation and decision making at each node. To model the performance of messaging, an analytical model is developed and presented in Chapter 5. The performance results based on the analytical model are compared with simulation results in Chapter 6.

Chapter 5

Analytical Model

In this chapter, we develop an analytical model to characterize the performance of the routing scheme described in Chapter 4. We have described a scheme that exploits locality of messages and opportunistic contacts between vehicles on the roadway to achieve greedy forwarding. The scheme is a *store-carry-forward mechanism* that caches/buffers data in the absence of connectivity and forward data when nodes are connected opportunistically. Our goal for developing an analytical model is to capture the time-varying connectivity in vehicular networks and characterize the delay tolerant messaging. For this purpose, we describe our simplified model of the roadway. We describe our assumptions and the explain parameters of interest.

Note that due to the unique nature of messaging and the dynamic network formed over vehicles on the roadway, it is hard to achieve an exact analysis of the performance of messaging. To simplify the analysis, we introduce certain assumptions and approximations. We first describe a model where one side of the roadway is a static distribution and consider a unidirectional model of varying node distribution on the other side of the roadway (Sec. 5.2). Subsequently, (Sec. 5.3), we relax the assumption to include dynamic node distribution on a bidirectional roadway. An exact analysis is hard to achieve; we develop *upper* bounds and *lower* bounds on performance of messaging. Finally, we describe an approximation (Sec. 5.3.3) based on our model that follows the simulation results closely. The models are evaluated and compared with simulation results presented in Chapter 6.

5.1 Networking Model and Assumptions

We describe elements of the vehicular network model that form the basis of our analytical models. The roadway model, physical radio model and the evaluation metrics are described here.

5.1.1 Roadway Model

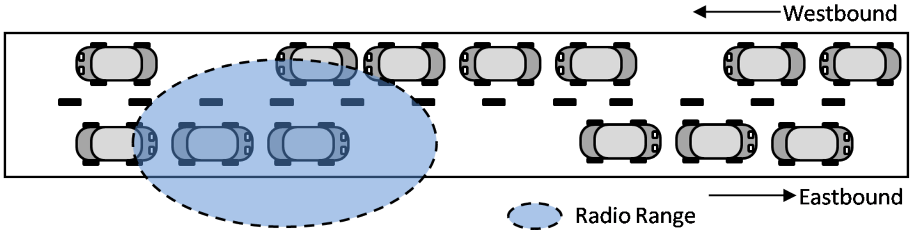


Figure 5·1: Illustration of the highway model.

The vehicular networking model is illustrated in Fig. 5·1. We consider the highway model of roadways where the roadway is modeled as largely rectilinear. The assumption is that packet radio is tolerant to local variations in directionality and curvature of the roadway. Furthermore, curvature and intersecting roadways can be solved by including location awareness derived from underlying positioning systems. Vehicles travel on a bidirectional roadway. We define each direction of the roadway as a directed pathway; and thus, each roadway has two opposing directed pathways. These directed pathways are referred to as the *eastbound* and *westbound* roadway henceforth in text. For simplicity, we consider a single-lane of the highway. Multiple lane models can be developed on the basis of our model and the extension is beyond the scope of this dissertation.

Vehicles are assumed to travel at a constant uniform velocity (v m/s). We do not consider speed differences between vehicles traveling in the same direction in this work. The argument in support of this assumption is that vehicles traveling in opposing directions have order of magnitude higher speed differences. Thus, the partitions occurring on the roadway are bridged faster by opposing traffic than by speed differential between nodes traveling in the same direction. This assumption is important as it implies that the partitions in the network are constant. To reconcile the size of partitions over time, we need to limit the vehicles to a constant speed.

We concentrate on information propagation on a roadway without infrastructure. Vehicles are assumed to be equipped with sensing, communication, computation and storage capabilities such that vehicles can form nodes of an infrastructure-less ad hoc network and can source information warning messages. Thus, we consider an ad hoc model of networking absent any infrastructure for developing our analytical model. For the sake of brevity, we consider a message propagation goal in the *eastbound* direction. The messaging performance in the *westbound* direction is a corollary of the *eastbound*, obtained by suitably replacing the parameters in the model.

5.1.2 Physical Radio

We define a radius of connectivity R. Thus, vehicles are assumed to be connected if the separation between vehicles is $\leq R$, irrespective of direction of travel. Physical radio propagation models that are dependent upon speed, interference or physical parameters are beyond the scope of this work. We consider our models to be technology agnostic of the physical layer connectivity. We concentrate on the ability to communicate and performance of networking for given radio technologies.

For the purpose of the analysis, we define a parameter called the *multihop radio propagation speed*, denoted by v_{radio}. The quantity is defined as the physical distance, equivalent to radio range (R), covered by a radio transmission in time (τ). The time (τ) includes latencies due to physical layer issues such as transmission and propagation. Thus, the multihop radio propagation speed is given by:

$$v_{radio} = \frac{R}{\tau} \tag{5.1}$$

This is a reasonable approximation and parametrized as a variable in our analysis. The variable can be adjusted as per the physical layer technology. It is typically order of magnitude larger than the vehicle speed, i.e., $v_{radio} >> v$. Wireless transmission speeds are often considered equivalent to the speed of light. However, these do not consider latencies due to physical layer and MAC layer characteristics. A typical value for multihop radio propagation speed is $v_{radio} = 1000$ m/s, as obtained from measurements in reference [WFR04].

5.1.3 Vehicle Density and Node Distribution

The network connectivity is a function of node distribution in the network. Thus, the performance of messaging is dependant upon vehicle distribution. We consider vehicles to be point objects such that the length of a vehicle is not factored. The distribution of vehicles on the roadway is illustrated in Figure 5·2, which shows vehicles as point objects. The inter-vehicle distance, or the distance between two consecutive vehicles on the roadway is denoted as X_i. Vehicles are considered to be connected if the inter-vehicle distance is less than the radio range, i.e., $X_i \leq R$. Correspondingly, vehicles are considered to be disconnected if the inter-vehicle distance is greater than the radio range, i.e., $X_i > R$.

For generating vehicular traffic, we use an exponential distribution to generate the inter-vehicle distances on the roadway. The exponential distribution has been shown to be in good agreement with real vehicular traces under uncongested traffic conditions, i.e., fewer than 1000 vehicles per hour [WBMT07]. Further, we can exploit the memoryless property of the exponential distribution [Ros04]. The mem-

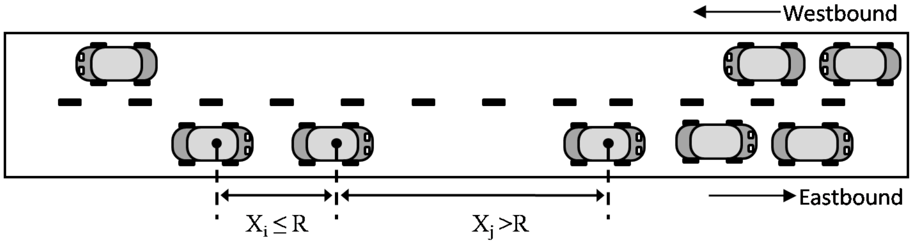


Figure 5·2: Illustration of distribution of vehicles on the roadway, inter-vehicle distance and corresponding connectivity.

oryless property implies that the inter-vehicle distances between nodes (vehicles) are independent of each other.

The distribution parameter for inter-vehicle distances is denoted as λ. For each direction of the roadway, eastbound and westbound, we assume the parameters to be independent of each other. The eastbound traffic distribution parameter is denoted as λ_e, while the westbound, it is denoted as λ_w

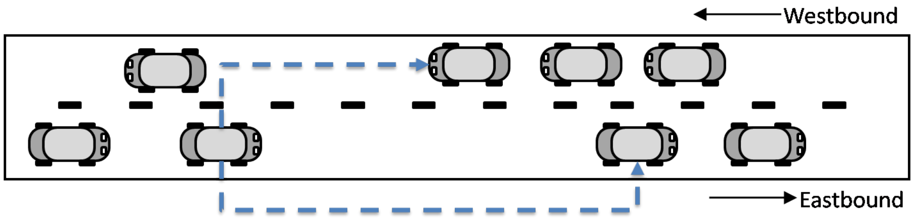
Finally, the exponential distribution allows us to compute the connectivity of two consecutive vehicles for given inter-vehicle distance. Two nodes are connected if the inter-vehicle distance is less than the radio range, i.e., $X_i \leq R$. The probability of connectivity is evaluated as:

$$P(X_i \leq R) = e^{-\lambda R} \leq 1, \tag{5.2}$$

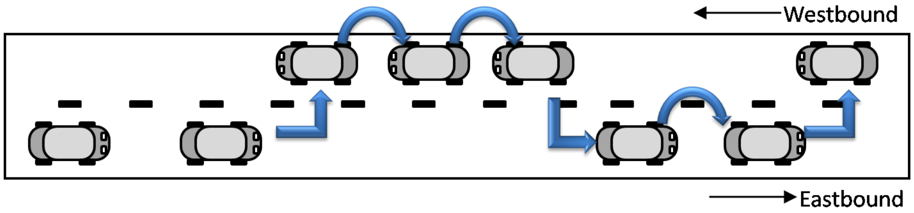
where, λ is the inter-vehicle distribution, R is the radio range. Note here that the probability of connectivity is always less than 1 for any value of traffic distribution (λ) and radio range (R). Thus, there is a non-zero probability that nodes are disconnected even in high traffic scenarios. This is consistent with our goal to study time-varying partitioning in the network.

5.1.4 Phases of Data Propagation

We have described the partitioning that exists in the network, such that vehicles form disconnected subnets. Further, we have described that there is an opportunity to exploit the opportunistic connectivity offered by vehicles traveling in orthogonal direction on a bidirectional roadway. For the delay tolerant assumption, data are buffered in a node's cache in the absence of connectivity and propagated multihop when the nodes are connected. As the vehicles traverse the roadway the connectivity changes and nodes are again disconnected. Thus, the messaging alternates between periods of connectivity and disconnection. As nodes are cached within a node, the node traverses at vehicle speed (v m/s). When messages propagate multihop, they cover the physical distance at multihop radio propagation speed (v_{radio} m/s).



(a) At $t = 0$, the network is partitioned and nodes are unable to communicate.



(b) At $t = \Delta t$, topology changes, connectivity is achieved and vehicles are able to communicate.

Figure 5·3: Illustration of delay tolerant network (DTN) messaging as the network connectivity changes with time.

We refer to the alternating periods of disconnection and (multihop) connectivity as *phase 1* and *phase 2*, respectively. The time-varying connectivity is described in Figure 5·3. At time instant $t = 0$, described as phase 1 of message propagation, the nodes are disconnected. Data are cached within a node and traverse the network at vehicle speed (v m/s), until connectivity becomes available. At time instant $t = \Delta t$, the topology changes, and messages are able to propagate multihop. The messages are said to be in phase 2 of message propagation, such that they traverse the physical distance at multihop radio propagation speed (v_{radio} m/s) until another partition is encountered. It is feasible to compute the distance and time for each scenario.

5.1.5 Evaluation Metrics

Our goal is to evaluate the performance of messaging in a dynamic network formed over moving vehicles. We described the spatial-temporal correlation of data and nodes in the system. Thus, it is reasonable to assume that the messaging goal can be characterized in terms of distance. Thus, we define the quantity *average message propagation speed* (v_{avg}) as the average speed with which data are able to propagate in a vehicular network. The messaging speed alternates between vehicle speed (v m/s) and multihop radio propagation speed (v_{radio} m/s) as the connectivity changes. The goal is to determine this quantity as a function of vehicle traffic density, eastbound and westbound (λ_e, λ_w), multihop radio speed (v_{radio} m/s), and vehicle speed (v m/s).

Denote by T_1^n and T_2^n the (random) amounts of time a message spends in the two phases, during the n-th cycle. The random vectors $(T_1^n, T_2^n), n \geq 1$ are i.i.d., due to the memoryless assumption on the inter-vehicular distances. Note, however, that T_1^n and T_2^n are not independent. For instance, suppose that, at cycle n, the distance between the current vehicle carrying the message and the next one traveling in the same direction is larger than average, then T_1^n and T_2^n are more likely to be large as well.

Based on our statistical assumptions, the system can be modeled as an *alternating renewal process* [Ros04], where message propagation cyclically alternates between phases 1 and 2. Denote $E[T_1] = E[T_1^n]$ the expected time spent in phase 1 and $E[T_2] = E[T_2^n]$ the expected time spent in phase 2. Then, the long-run fraction of time spent in each of these states is respectively [Ros04]:

$$p_1 = \frac{E[T_1]}{E[T_1] + E[T_2]}; \qquad p_2 = \frac{E[T_2]}{E[T_1] + E[T_2]}. \tag{5.3}$$

Given that the average time spent in phase 1 and phase 2 are $E[T_1]$ and $E[T_2]$ respectively, while the rate of propagation in each phase is v m/s and v_{radio} m/s respectively, we can compute the average message propagation speed v_{avg} as follows:

$$\begin{aligned} v_{avg} &= p_1 v + p_2 v_{radio} && (5.4) \\ &= \frac{E[T_1]v + E[T_2]v_{radio}}{E[T_1] + E[T_2]}. && (5.5) \end{aligned}$$

The primary goal of our analysis is to determine how $E[T_1]$ and $E[T_2]$ (and thereby the average message propagation speed v_{avg}) depend on the parameters λ_e, λ_w, R, v, and v_{radio}.

Table 5.1: Symbols and their meaning

Parameter	Abbreviation
Vehicle speed	v
Radio Range	R
Inter-vehicle distance	X_i
Multihop radio propagation speed	v_{radio}
Vehicle traffic distribution	λ
Vehicle traffic distribution *eastbound*	λ_e
Vehicle traffic distribution *westbound*	λ_w
Average message propagation speed	v_{avg}

5.1.6 Discretization

The analysis of the problem at hand is rendered difficult by its continuous nature. Specifically, if the distance between two nodes traveling in a given direction exceeds R, determining the probability that the nodes are connected through nodes traveling in the opposing direction is a difficult combinatorial problem. To circumvent this difficulty, we discretize the roadway into cells, each of size l. We consider a cell to be occupied if one or more vehicles are positioned within that cell. By virtue of the memoryless property of the exponential distribution, the probability p that a cell is occupied is $p = (1 - e^{-\lambda l})$, where l is the cell size and λ is the traffic density. For cells along the eastbound direction, the probability that a cell is occupied is $p_e = (1 - e^{-\lambda_e l})$, whereas for the westbound direction it is $p_w = (1 - e^{-\lambda_w l})$.

Thus, discretizing the roadway into cells renders the problem significantly tractable. However, an exact analysis is difficult to achieve given the orthogonal and high rate of mobility of vehicles. In order to characterize the messaging, we define bounds on the performance of messaging. We define an upper bound which we consider the best possible or optimistic view of connectivity. Correspondingly, there is a lower bound, which is a pessimistic view of the connectivity. Here, we discuss how to select appropriate values of l for the derivation of upper and lower bounds. The actual performance is expected to lie within these two bounds.

Upper Bound

To derive an upper bound on v_{avg}, we set $l = R$. Thus, we require each adjacent cell of length R to be occupied by at least one node as a condition to guarantee connectivity. This is an optimistic view of the system, since in reality, nodes located in adjacent cells may be separated by a distance greater than R, in fact as much as $2R$. Hence, requiring the presence of at least one node in each cell of size R is a necessary but insufficient condition, in general.

In addition, to simplify the analysis, we assume that all nodes located in a cell are located at the far-end extremity of that cell. Again, this provides an optimistic view, since the average distance computed that way between any two consecutive nodes traveling in the same direction is larger than what it is in reality. Note that, due to the cell discretization, it does not affect the probability that two consecutive nodes are connected. The inter-distance distribution between node is expressed with the following mixed probability distribution:

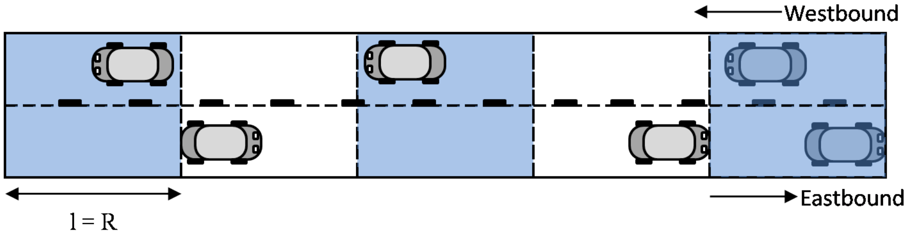
$$\begin{aligned} f_{X_u}(x) &= \lambda e^{-\lambda x}((u(x) - u(x-R)) \\ &\quad + \sum_{n=1}^{\infty}(e^{-\lambda nR} - e^{-\lambda(n+1)R})\delta(x-(n+1)R), \qquad \text{for } x \geq 0, \end{aligned} \tag{5.6}$$

where $u(x)$ is the unit step function and $\delta(x)$ is the Dirac delta function [Wei08]. The quantity X_u denotes a random variable distributed according to the upper bound distribution of the inter-vehicle distance.

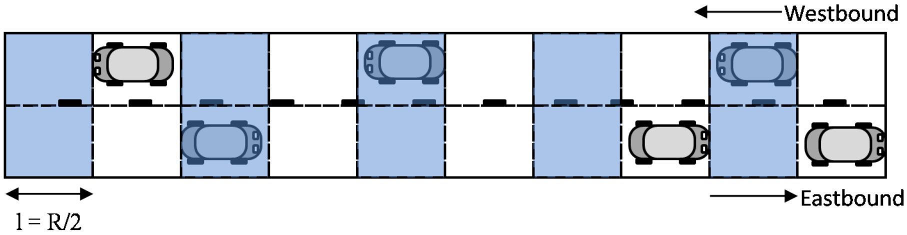
Thus, for the first cell, the inter-vehicle distance distribution between two nodes is exact and described by the original exponential distribution. However, when $x > R$ for each successive cell, we assume that nodes are located at the far-end extremity of the cell. With the nodes assumed to be placed at the end of each cell, the distance at each iteration becomes a fixed quantity and, hence, easier to compute. Thus, any node located in the second cell, i.e., at a distance between R and $2R$ from the preceding node, is assumed to be located at $2R$. The message propagation distance is then computed as $2R$, and so forth for the next cells.

Lower Bound

To derive a lower bound on v_{avg}, we set $l = R/2$. Indeed, when the cell size is $R/2$, nodes in adjacent cells are surely connected, irrespective of their location within



(a) Upper bound: With $l = R$, necessary but insufficient condition.



(b) Lower bound: With $l = R/2$, sufficient but not always necessary condition.

Figure 5·4: Illustration of discretized roadway with cells of size l, such that we model the upper and the lower bound on the performance of messaging.

their cells. Thus, even for nodes located at the two extremes of adjacent cells, the maximum distance between them is R, which is within communication range. Thus, for the lower bound, we set as a condition for connectivity that each adjacent cell of length $R/2$ be occupied by at least one node. Clearly, it is a sufficient condition, though not always necessary (i.e., two nodes may be connected even if the cell between them is empty).

Similar to Eq. (5.6), we assume that the distribution of nodes located at a distance smaller than R is the same as the original exponential distribution, while for each subsequent cell of size $R/2$, we assume that the nodes are placed at the near-end extremity of each cell. Thus, we arrive at the following conservative estimate on the probability distribution of the distance:

$$\begin{aligned} f_{X_l}(x) &= \lambda e^{-\lambda x}((u(x) - u(x-R)) \\ &\quad + \sum_{n=1}^{\infty}(e^{-\lambda(n+1)R/2} - e^{-\lambda(n+2)R/2})\delta(x-(n+1)R/2), \text{for } x \geq 0. \end{aligned} \tag{5.7}$$

Here, X_l is a random variable following the lower bound distribution of inter-vehicle distance. Fig. 5·4 illustrates the lower and upper bounds.

5.1.7 Relationship with Pattern Matching Problem

If the distance between two eastbound nodes is greater than R, then connectivity must be achieved using nodes along westbound direction. As per the discretization described above, the distance is equivalent to, say, N cells. The nodes along eastbound are connected if each of the N westbound cells in the gap is occupied by at least one node, an event which occurs with probability $(p_w)^N = (1 - e^{-\lambda_w R})^N$.

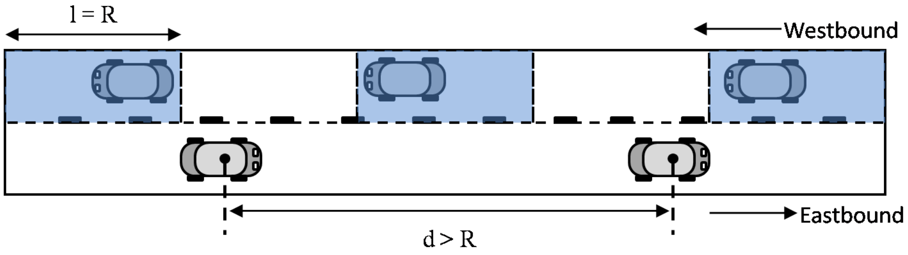
In the event that not all of the N cells in the westbound direction are occupied, the nodes along eastbound are deemed to be disconnected. A message is buffered in the node's cache until connectivity is achieved again. The node and, hence, the message traverse some distance (cells) until connectivity is achieved. The number of cells traversed until connectivity is achieved is analogous to the number of trials until a sequence is seen. This is described as *pattern matching* in classical probability theory [Ros04]. The pattern matching problem describes the task to compute the expected number of trials Y until N consecutive successes are obtained, which is given by the relation:

$$E[Y] = \frac{1 - p^N}{(1-p)p^N}, \tag{5.8}$$

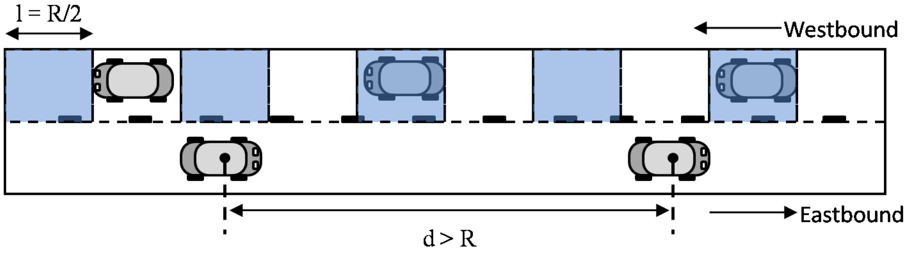
where p is the probability of success in a trial. This is analogous to our problem as we try to find the number of cells traversed by a node until N consecutive cells along *westbound* traffic are occupied by one or more nodes. We exploit this analogy for our analysis in the next section.

5.2 Unidirectional Model

We describe a scenario wherein the eastbound vehicles are partitioned such that vehicles are separated by a fixed distance $d > R$. While for the westbound roadway, the inter-vehicular distance is distributed as an exponentially random variable with parameter λ_w. Such an arrangement is chosen to specifically model the case in which vehicular traffic has partitions. Our objective is to characterize the behavior of time-varying connectivity. The length of the roadway for westbound traffic is divided into cells each of size l. We consider two bounds for the cell size; R, an upper bound, and $R/2$, a lower bound. The model is illustrated in Fig. 5·5



(a) Upper bound: With $l = R$, necessary but insufficient condition.



(b) Lower bound: With $l = R/2$, sufficient but not always necessary condition.

Figure 5·5: Illustration of the unidirectional model of vehicular network. Westbound roadway is divided into cells of size l to model upper and lower bound on the performance of messaging.

5.2.1 Upper Bound

Consider the upper bound of connectivity in the network, each cell is of size $l = R$. The probability that a cell along the westbound roadway is occupied is given by:

$$p_u = (1 - e^{-\lambda_w R}) \tag{5.9}$$

The number of cells in the gap d are $N_u = \lfloor d/R \rfloor$. For eastbound vehicles to be connected, each cell in the gap d along westbound roadway must have at least one vehicle. In Phase 1, the nodes are disconnected, thus, at least one of the westbound roadway is empty, there is absence of multihop connectivity. Messages are cached until an event in which all N_u cells are occupied. This event is analogous to the *pattern matching* problem defined previously in text [Ros04]. Thus, the distance traversed until all N_u cells in the gap are occupied is given by Eq. 5.8:

$$\begin{aligned} E[D_1]_u &= \left[\frac{1 - p_u^{N_u}}{(1 - p_u)p_u^{N_u}} - \frac{d}{R}\right]\frac{R}{2} + d & (5.10) \\ &= \left[\frac{(1 - (1 - e^{-\lambda_w R})^{\lfloor d/R \rfloor})}{e^{-\lambda_w R}(1 - (1 - e^{-\lambda_w R})^{\lfloor d/R \rfloor})} - \frac{d}{R}\right]\frac{R}{2} + d & (5.11) \end{aligned}$$

Note that we subtract N_u cells from the computation as they are traversed at speed v_{radio} and are therefore, accounted in Phase 2. The pattern matching gives the number of cells unit after connectivity is achieved, while in Phase 1, the message propagation is at vehicle speed (v m/s) for the number of cells before the partition is bridged. Since vehicles in both directions are moving at the same speed, the distance covered until connectivity is adjusted by a factor of 1/2. Thus, the time spent in Phase 1 at vehicle speed (v m/s) is given by:

$$E[T_1]_u = E[D_1]_u / v \tag{5.12}$$

In Phase 2, nodes are considered connected by multihop connectivity, i.e., each cell in the gap d must have one vehicle. The probability of such an event is given by $p_u^{N_u}$, where p_u is the probability that a cell is occupied by a vehicle and N_u are the number of cells in the gap. The probability that a distance D_2 is covered is expressed as:

$$\Pr(D_2 = md) = (p_u^{N_u})^m(1 - p_u^{N_u}), \tag{5.13}$$

where m is a random variable for the number of connected components. We compute the expected distance covered in Phase 2 as:

$$\begin{aligned} E[D_2]_u &= \frac{dp_u^{N_u}}{1 - p_u^{N_u}} && (5.14) \\ &= \frac{d(1 - e^{-\lambda_w R})^{\lfloor d/R \rfloor}}{(1 - (1 - e^{-\lambda_w R})^{\lfloor d/R \rfloor})} && (5.15) \end{aligned}$$

Thus, the time spent in Phase 2 at multihop radio propagation speed (v_{radio} m/s) is given by:

$$E[T_2]_u = E[D_2]_u / v_{radio} \tag{5.16}$$

5.2.2 Lower Bound

Similar to the upper bound derivation, consider the lower bound of connectivity in the network, each cell is of size $l = R/2$. The probability that a cell along the westbound roadway is occupied is given by:

$$p_l = (1 - e^{-\lambda_w R/2}) \tag{5.17}$$

The number of cells in the gap d are $N_l = \lfloor 2d/R \rfloor$. For eastbound vehicles to be connected, each cell in the gap d along westbound roadway must have at least one vehicle. In Phase 1, the nodes are disconnected, thus, at least one of the westbound roadway is empty, there is absence of multihop connectivity. Messages are cached until an event in which all N_l cells are occupied. This event is analogous to the *pattern matching* problem defined previously in text [Ros04]. Thus, the distance traversed until all N_l cells in the gap are occupied is given by Eq. 5.8:

$$\begin{aligned} E[D_1]_l &= \left[\frac{1-p_l^{N_l}}{(1-p_l)p_l^{N_l}} - \frac{2d}{R}\right]\frac{R}{4} + d + \frac{d}{2} && (5.18) \\ &= \left[\frac{(1-(1-e^{-\lambda_w R})^{\lfloor 2d/R \rfloor})}{e^{-\lambda_w R}(1-(1-e^{-\lambda_w R})^{\lfloor 2d/R \rfloor})} - \frac{2d}{R}\right]\frac{R}{4} + d + \frac{d}{2} && (5.19) \end{aligned}$$

Note that we subtract N_l cells from the computation as they are traversed at speed v_{radio} and are therefore, accounted in Phase 2. The pattern matching gives the number of cells unit after connectivity is achieved, while in Phase 1 the message propagation is at vehicle speed (v m/s) for the number of cells before the partition is bridged. Since vehicles in both directions are moving at the same speed, the distance covered until connectivity is adjusted by a factor of 1/2. For the lower bound, we add an additional compensation of $d/2$, which is the distance, in the worst case, a message must cover when it alternates from Phase 1 to Phase 2. Thus, the time spent in Phase 1 at vehicle speed (v m/s) is given by:

$$E[T_1]_l = E[D_1]_l / v \tag{5.20}$$

In Phase 2, nodes are considered connected by multihop connectivity, i.e., each cell in the gap d must have one vehicle. The probability of such an event is given by $p_l^{N_l}$, where p_l is the probability that a cell is occupied by a vehicle and N_l are the number of cells in the gap. The probability that a distance D_2 is covered is expressed as:

$$\Pr(D_2 = md) = (p_l^{N_l})^m (1 - p_l^{N_l}), \tag{5.21}$$

where m is a random variable for the number of connected components. We compute the expected distance covered in Phase 2 as:

$$E[D_2]_l = \frac{dp_l^{N_l}}{1-p_l^{N_l}} \tag{5.22}$$

$$= \frac{d(1-e^{-\lambda_w R})^{\lfloor 2d/R \rfloor}}{(1-(1-e^{-\lambda_w R})^{\lfloor 2d/R \rfloor})} \tag{5.23}$$

Thus, the time spent in Phase 2 at multihop radio propagation speed (v_{radio} m/s) is given by:

$$E[T_2]_l = E[D_2]_l / v_{radio} \tag{5.24}$$

Theorem 5.2.1 *The average message propagation speed in the unidirectional model is as follows:*

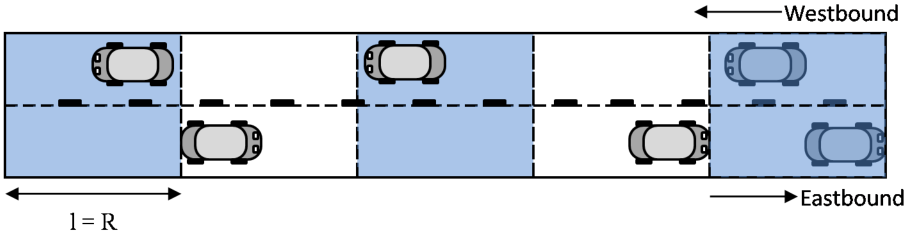
$$\frac{E[T_1]_l v + E[T_2]_l v_{radio}}{E[T_1]_l + E[T_2]_l} \leq v_{avg} \leq \frac{E[T_1]_u v + E[T_2]_u v_{radio}}{E[T_1]_u + E[T_2]_u} \tag{5.25}$$

5.3 Bidirectional Model

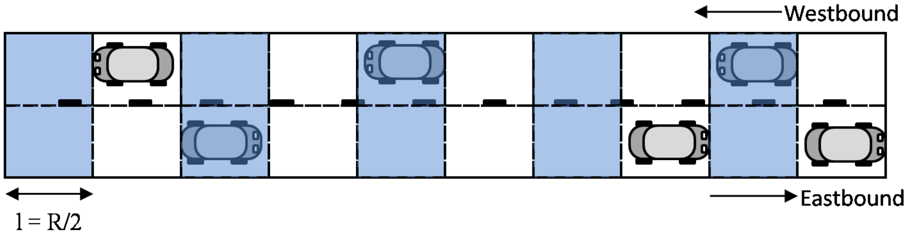
In the bidirectional model, we remove the constraint of partitioning imposed in the unidirectional model. Vehicles are exponentially distributed on both sides of the roadway, eastbound and westbound. Thus, now multihop connectivity is achieved on both sides of the roadway. The partitions are once again bridged using vehicles traveling on the westbound roadway. An illustration of the model is provided in Figure 5·6.

5.3.1 Upper Bound Analysis

In this section, we derive an upper bound on the average message propagation speed v_{avg}, based on the discretized system described in Section 5.1.6, i.e., assuming cells of size R and an inter-node distance distribution as given by Eq. (5.6). We denote by $E[T_1]_u$ and $E[T_2]_u$ the expected time spent by a message in Phase 1 and Phase 2 during each cycle. Once these quantities are computed, an upper bound on the



(a) Upper bound: With $l = R$, necessary but insufficient condition.



(b) Lower bound: With $l = R/2$, sufficient but not always necessary condition.

Figure 5·6: Illustration of discretization of the roadway into cells of size l, such that we model the upper and the lower bound on the performance of messaging for the bidirectional model.

average message propagation speed v_{avg} follows readily from Eq. (5.5).

The following Lemma provides an expression for $E[T_1]_u$.

Lemma 5.3.1 *The expectation of the time spent in Phase 1 in the upper bound system is:*

$$E[T_1]_u = \begin{cases} \frac{R(1-e^{\lambda_e R})}{2v\Pr(\bar{C}_u)} \Big[\frac{1}{e^{-\lambda_w R}} \Big\{ \frac{e^{-\lambda_e R}}{1-e^{-\lambda_w R}-e^{-\lambda_e R}} & \\ + \frac{(1-e^{-\lambda_w R})e^{-\lambda_e R}}{1-e^{-\lambda_e R}(1-e^{-\lambda_w R})} - \frac{2e^{-\lambda_e R}}{1-e^{-\lambda_e R}} \Big\} & \\ \Big\{ -\frac{e^{-\lambda_e R}}{(1-e^{-\lambda_e R})^2} - \frac{e^{-\lambda_e R}(1-e^{-\lambda_w R})}{(1-e^{-\lambda_e R}(1-e^{-\lambda_w R}))^2} \Big\} \Big] & \textit{if } e^{-\lambda_e R} + e^{-\lambda_w R} < 1 \\ \infty & \textit{otherwise,} \end{cases} \tag{5.26}$$

where $\Pr(\bar{C}_u)$ *is the probability that two consecutive eastbound nodes are disconnected, the expression of which is given by Eq.* (5.33).

Proof: In Phase 1, two consecutive eastbound nodes are disconnected from each other. Thus, there is a gap of $N \geq 1$ cells between the nodes, where N is discrete random variable. To bridge this gap, N cells along the westbound direction must each be occupied by at least one node. The data are cached in the first node's memory until connectivity is achieved. Owing to node mobility, a physical distance is covered in this time delay. The expected number of cells traversed until connectivity over westbound cells is achieved, is as given in Eq. (5.8). Note, however, that the last N cells are traversed at speed v_{radio}, and therefore, should be accounted as part of Phase 2 rather than Phase 1. Hence, we subtract them from the computation. Thus, for a given separation between eastbound nodes $N = n$, the expected distance traversed until connectivity is given by:

$$\begin{aligned} E[D_1|N=n]_u &= \frac{R}{2}\left[\frac{1-p_w^n}{(1-p_w)p_w^n} - n\right] &(5.27)\\ &= \frac{R}{2}\left[\frac{1-(1-e^{-\lambda_w R})^n}{e^{-\lambda_w R}(1-e^{-\lambda_w R})^n} - n\right] &(5.28)\end{aligned}$$

Note that a correction factor of 1/2 is applied as nodes in either direction, eastbound and westbound, are traveling at v m/s. Thus, the distance traversed until connectivity is effectively halved. Our next goal is to compute $E[D_1]_u$, i.e., the expected distance traversed in Phase 1 without conditioning on the gap size. Denote by $\bar{C}_u$, the event that two consecutive eastbound nodes are disconnected. Then,

$$E[D_1]_u = \sum_{n=1}^{\infty} E[D_1|N=n]_u \Pr(N=n|\bar{C}_u). \tag{5.29}$$

We compute $\Pr(N=n|\bar{C}_u)$ using Bayes' Law, i.e.:

$$\Pr(N=n|\bar{C}_u) = \frac{\Pr(\bar{C}_u|N=n)\Pr(N=n)}{\Pr(\bar{C}_u)}. \tag{5.30}$$

We have

$$\Pr(\bar{C}_u|N=n) = 1-(1-e^{-\lambda_w R})^n, \tag{5.31}$$

which is the probability that two consecutive nodes are disconnected given that the separation between them is n cells. This event occurs if the n cells along the westbound direction are not occupied. Next, we compute the probability that the separation between consecutive eastbound nodes is n cells. This quantity is given by the expression:

$$\Pr(N = n) = (e^{-\lambda_e nR} - e^{-\lambda_e (n+1)R}). \tag{5.32}$$

Finally, the probability that two nodes are disconnected can be computed as:

$$\begin{aligned}
\Pr(\bar{C}_u) &= \sum_{n=1}^{\infty} \Pr(\bar{C}_u | N = n) \Pr(N = n) \\
& \text{substituting from Eqs. (5.31), (5.32)} \\
&= \sum_{n=1}^{\infty} (1 - (1 - e^{-\lambda_w R})^n)(e^{-\lambda_e nR} - e^{-\lambda_e (n+1)R}) \\
&= (1 - e^{-\lambda_e R}) \left[\frac{e^{-\lambda_e R}}{1 - e^{-\lambda_e R}} - \frac{e^{-\lambda_e R}(1 - e^{-\lambda_w R})}{1 - e^{-\lambda_e R}(1 - e^{-\lambda_w R})} \right]. \qquad (5.33)
\end{aligned}$$

Using the above equations, we obtain:

$$\begin{aligned}
E[D_1]_u &= \sum_{n=1}^{\infty} E[D_1 | N = n]_u \Pr(N = n | \bar{C}_u) \\
&= \frac{R}{2\Pr(\bar{C}_u)} \sum_{n=1}^{\infty} \left[\frac{1 - (1 - e^{-\lambda_w R})^n}{(e^{-\lambda_w R})(1 - e^{-\lambda_w R})^n} - n \right] \\
& \left[(1 - (1 - e^{-\lambda_w R})^n)(e^{-\lambda_e nR} - e^{-\lambda_e (n+1)R}) \right] \\
&= \frac{R(1 - e^{\lambda_e R})}{2\Pr(\bar{C}_u)} \left[\frac{1}{e^{-\lambda_w R}} \left\{ \frac{e^{-\lambda_e R}}{1 - e^{-\lambda_w R} - e^{-\lambda_e R}} + \frac{e^{-\lambda_e R}(1 - e^{-\lambda_w R})}{1 - e^{-\lambda_e R}(1 - e^{-\lambda_w R})} \right. \right. \\
& \left. \left. - \frac{2e^{-\lambda_e R}}{1 - e^{-\lambda_e R}} \right\} \left\{ \frac{e^{-\lambda_e R}}{(1 - e^{-\lambda_e R})^2} - \frac{e^{-\lambda_e R}(1 - e^{-\lambda_w R})}{(1 - e^{-\lambda_e R}(1 - e^{-\lambda_w R}))^2} \right\} \right]. \qquad (5.34)
\end{aligned}$$

We note that the above expression holds only if $e^{-\lambda_e R} + e^{-\lambda_w R} < 1$, otherwise the series is divergent. The distance in Phase 1 is covered at the vehicle speed v. Thus, the expected time spent in this Phase 1 is $E[T_1]_u = E[D_1]_u / v$, leading to the expression provided by the Lemma.

Next, we provide an expression for $E[T_2]_u$.

Lemma 5.3.2 *The expectation of time spent in Phase 2 in the upper bound system* *is:* $E[T_2]_u$*. An upper bound on the expectation is described by:*

$$\begin{aligned}
E[T_2]_u &= \frac{R(1-e^{-\lambda_e R})}{v_{radio}\Pr(\bar{C}_u)}\left[\frac{e^{-\lambda_e R}}{(1-e^{-\lambda_e R})}+\frac{e^{-\lambda_e R}}{(1-e^{-\lambda_e R})^2}\right.\\
&- \left.\frac{e^{-\lambda_e R}(1-e^{-\lambda_w R})}{1-e^{-\lambda_e R}(1-e^{-\lambda_w R})}-\frac{e^{-\lambda_e R}(1-e^{-\lambda_w R})}{(1-e^{-\lambda_e R}(1-e^{-\lambda_w R}))^2}\right]\\
&+ \frac{1}{v_{radio}(1-\Pr(C_u))}\left[\frac{1}{\lambda_e}\left[1-e^{-\lambda_e R}(1+\lambda_e R)\right]\right.\\
&+ \left.R(1-e^{-\lambda_e R})\left[\frac{e^{-\lambda_e R}(1-e^{-\lambda_w R})}{1-e^{-\lambda_e R}(1-e^{-\lambda_w R})}+\frac{e^{-\lambda_e R}(1-e^{-\lambda_w R})}{(1-e^{-\lambda_e R}(1-e^{-\lambda_w R}))^2}\right]\right],
\end{aligned} \tag{5.35}$$

where $\Pr(C_u) = 1 - \Pr(\bar{C}_u)$ *is the probability that two consecutive eastbound nodes connected,* $\Pr(\bar{C}_u)$ *is derived in Eq.* (5.33)*.*

Proof: In Phase 2, nodes are connected and messages are able to propagate multihop. Phase 2 can effectively be divided in two parts. In the first part, the gap of N cells present during the previous Phase 1 is bridged. Therefore, the expected distance denoted $E[D_{2,1}]$ traversed during this part is given by:

$$E[D_{2,1}]_u = R\sum_{n=1}^{\infty}(n+1)\Pr(N=n|\bar{C}_u) \tag{5.36}$$

$$\begin{aligned}
&= \frac{R}{\Pr(\bar{C}_u)}\sum_{n=1}^{\infty}(n+1)\left[(1-(1-e^{-\lambda_w R})^n)(e^{-\lambda_e nR}-e^{-\lambda_e(n+1)R})\right]\\
&= \frac{R(1-e^{-\lambda_e R})}{\Pr(\bar{C}_u)}\left[\frac{e^{-\lambda_e R}}{(1-e^{-\lambda_e R})}+\frac{e^{-\lambda_e R}}{(1-e^{-\lambda_e R})^2}\right.\\
&\quad \left.-\frac{e^{-\lambda_e R}(1-e^{-\lambda_w R})}{1-e^{-\lambda_e R}(1-e^{-\lambda_w R})}-\frac{e^{-\lambda_e R}(1-e^{-\lambda_w R})}{(1-e^{-\lambda_e R}(1-e^{-\lambda_w R}))^2}\right],
\end{aligned} \tag{5.37}$$

where $\Pr(N=n|\bar{C}_u)$ is given by Eq. (5.30), and $\Pr(\bar{C}_u)$ is given by Eq. (5.33). Eq. (5.36) accounts for the fact that the next eastbound node is assumed to be located at the far-end extremity of the $(n+1)$th cell, as per our upper bound construction.

In the second part of Phase 2, consecutive eastbound nodes remain connected as long as the distance between them is less than R, or, if the distance is greater than

R, all *westbound* cells in the gap between the nodes are occupied. If the distance is greater than R, and not all westbound cells in the gap between the nodes are occupied, then the system re-enters Phase 1 and the message is carried at vehicle speed. We note that it is possible that the distance traversed during the second part of Phase 2 is zero.

Denote by C_u, the event that two consecutive nodes are connected and by $E[D'_{2,2}]_u$ the expected distance between two consecutive eastbound nodes, given that they are connected either directly or through westbound nodes. An expression for this quantity is the following:

$$E[D'_{2,2}]_u = \int_0^\infty x f_{X_u|C_u}(x) dx, \tag{5.38}$$

where $f_{X_u|C_u}(x)$ is the conditional distribution on the inter-vehicle distance based on the upper bound distribution, given that nodes are connected. This conditional distribution can be computed as follows:

$$f_{X_u|C_u}(x) = \frac{f_X(x)\Pr(C_u|X_u = x)}{\Pr(C_u)}, \tag{5.39}$$

where $\Pr(C_u|X_u = x)$ denotes the probability that two consecutive eastbound nodes are connected for a given value of x. Nodes are always connected if the next eastbound node is within radio range, i.e., $x \leq R$. If the inter-vehicle distance is greater than R, the nodes are connected if each of the corresponding n westbound cells are occupied, an event that occurs with probability $((1 - e^{-\lambda_w R})^n)$.

$$\Pr(C_u|X_u = x) = \begin{cases} 1 & \text{if } x \leq R \\ (1 - e^{-\lambda_w R})^n & \text{if } x = (n+1)R, \text{ for } n = 1, 2, 3, \ldots \\ 0 & \text{otherwise.} \end{cases} \tag{5.40}$$

Applying the upper bound distribution for inter-vehicle distance from Eq. (5.6):

$$\begin{aligned}
E[D'_{2,2}]_u &= \int_0^\infty \frac{x f_{X_u}(x)\Pr(C_u|X_u = x)}{\Pr(C_u)}dx \\
&= \frac{1}{\Pr(C_u)}\left(\int_0^\infty \lambda_e e^{-\lambda_e x}(u(x) - u(x-R))\right. \\
&\quad \left. + \sum_{n=1}^{\infty}(1-e^{-\lambda_w R})^n \delta(x-(n+1)R)\right) x dx \\
&= \frac{1}{\Pr(C_u)}\left[\int_0^R x\lambda_e e^{-\lambda_e x}dx\right. \\
&\quad \left. + \sum_{n=1}^{\infty}(n+1)R(1-e^{\lambda_w R})^n(e^{-\lambda_e nR} - e^{-\lambda_e(n+1)R})\right] \\
&= \frac{1}{\Pr(C_u)}\left[\frac{1}{\lambda_e}\left[1-e^{-\lambda_e R}(1+\lambda_e R)\right] + R(1-e^{-\lambda_e R})\right. \\
&\quad \left.\left[\frac{e^{-\lambda_e R}(1-e^{-\lambda_w R})}{1-e^{-\lambda_e R}(1-e^{-\lambda_w R})} + \frac{e^{-\lambda_e R}(1-e^{-\lambda_w R})}{(1-e^{-\lambda_e R}(1-e^{-\lambda_w R}))^2}\right]\right], \qquad (5.41)
\end{aligned}$$

where, from Eq. (5.33),

$$\begin{aligned}
\Pr(C_u) &= 1 - \Pr\left(\bar{C}_u\right) \\
&= \int_0^\infty \Pr(C_u|X_u = x) f_X(x)dx \\
&= \int_0^\infty (u(x) - u(x-R) + \sum_{n=1}^{\infty}\delta(x-(n+1)R)\Pr(C_u|X_u = x)dx \\
&= \int_0^R (1)\lambda_e e^{-\lambda_e x}dx + \sum_{n=1}^{\infty}(1-e^{-\lambda_w R})^n \Pr(N = n) \\
&= \int_0^R (1)\lambda_e e^{-\lambda_e x}dx + \sum_{n=1}^{\infty}(1-e^{-\lambda_w R})^n(e^{-\lambda_e nR} - e^{-\lambda_e(n+1)R}) \\
&= (1-e^{-\lambda_e R})\left[1 + \frac{e^{-\lambda_e R}(1-e^{-\lambda_w R})}{1-e^{-\lambda_e R}(1-e^{-\lambda_w R})}\right]. \qquad (5.42)
\end{aligned}$$

Thus, the expected distance covered given that two consecutive eastbound nodes are connected is given $E[D'_{2,2}]_u$. Once entering Phase 2, messages are able propagate as long as the connectivity is available, each time covering an expected distance of $E[D'_{2,2}]_u$ between two consecutive nodes. Hence, if connectivity is available for, say, j consecutive pairs of eastbound nodes, the distance covered is $jE[D'_{2,2}]_u$. Thus, the expected distance $E[D_{2,2}]$ covered during the second part of Phase 2 is:

$$\begin{aligned}
E[D_{2,2}]_u &= \sum_{j=1}^{\infty} jE[D'_{2,2}]\Pr(C_u)^j(1-\Pr(C_u)) \\
&= E[D'_{2,2}]_u(1-\Pr(C_u))\sum_{j=1}^{\infty} j\Pr(C_u)^j \\
&= E[D'_{2,2}]_u(1-\Pr(C_u))\frac{\Pr(C_u)}{(1-\Pr(C_u))^2} \\
&= E[D'_{2,2}]_u\frac{\Pr(C_u)}{(1-\Pr(C_u))}. \qquad (5.43)
\end{aligned}$$

We finally obtain $E[T_2]_u = (E[D_{2,1}]_u + E[D_{2,2}]_u)/v_{radio}$, leading to the expression given by the Lemma.

Based on the results of the previous Lemmas and Eq. (5.5), the next theorem provides an upper bound on v_{avg}.

Theorem 5.3.3 *The average message propagation speed is v if $(e^{-\lambda_e R}+e^{-\lambda_w R}) > 1$, as there are no gains achieved from the delay tolerant architecture. If $(e^{-\lambda_e R}+e^{-\lambda_w R}) < 1$, then the average propagation speed is upper bounded by:*

The average message propagation speed is upper bounded as follows:

$$v_{avg} \leq \begin{cases} \frac{E[T_1]_u v + E[T_2]_u v_{radio}}{E[T_1]_u + E[T_2]_u} & \textit{if } e^{-\lambda_e R} + e^{-\lambda_w R} < 1 \\ v & \textit{if } e^{-\lambda_e R} + e^{-\lambda_w R} \geq 1, \end{cases}$$

where $E[T_1]_u$ and $E[T_2]_u$ are the expressions given by Lemma 5.3.1 and 5.3.2.

5.3.2 Lower Bound Analysis

In this section, we derive a lower bound on the average message propagation speed v_{avg}, based on the discretized system described in Section 5.1.6, i.e., assuming cells of size $R/2$ and an inter-node distance distribution as given by Eq. (5.7). We denote by $E[T_1]_l$ and $E[T_2]_l$ the expected time spent by a message in Phase 1 and Phase 2 during each cycle. The derivations of these quantities follow the same lines as the upper bound analysis. Once these quantities are computed, a lower bound on the average message propagation speed v_{avg} follows from Eq. (5.5). The following Lemma provides an expression for $E[T_1]_l$.

Lemma 5.3.4 *The expectation of the time spent in Phase 1 in the lower bound system is:*

$$E[T_1]_l = \begin{cases} \frac{R(1-e^{\lambda_e \frac{R}{2}})e^{-\frac{\lambda_e R}{2}}}{4v\,\Pr(\bar{C}_l)e^{-\frac{\lambda_w R}{2}}} \left[\frac{e^{-\frac{\lambda_e R}{2}}}{1-e^{-\frac{\lambda_w R}{2}}-e^{-\frac{\lambda_e R}{2}}} \right. & \\ \left. +\frac{(1-e^{-\frac{\lambda_w R}{2}})e^{-\frac{\lambda_e R}{2}}}{1-e^{-\frac{\lambda_e R}{2}}(1-e^{-\frac{\lambda_w R}{2}})} - \frac{2e^{-\frac{\lambda_e R}{2}}}{1-e^{-\frac{\lambda_e R}{2}}} \right] & \textit{if } e^{-\frac{\lambda_e R}{2}} + e^{-\frac{\lambda_w R}{2}} < 1 \\ \infty & \textit{otherwise,} \end{cases} \tag{5.44}$$

where $\Pr(\bar{C}_l)$ *is the probability that nodes are disconnected, an expression for which is given by Eq.* (5.51).

Proof: The expected distance traversed between two consecutive eastbound nodes in Phase 1, given a gap of $N = n$ cells between them is is given by:

$$\begin{aligned} E[D_1|N=n]_l &= \frac{R}{4}\left[\frac{1-p_w^n}{(1-p_w)p_w^n} - n\right] \\ &= \frac{R}{4}\left[\frac{1-(1-e^{-\frac{\lambda_w R}{2}})^n}{e^{-\frac{\lambda_w R}{2}}(1-e^{-\frac{\lambda_w R}{2}})^n}\right]. \end{aligned} \tag{5.45}$$

Note that we did not subtract n within this equation. The reason is that, for the lower bound, we must account for the fact that one of the first n cells must be empty (otherwise, the nodes would have been connected). Hence, we conservatively add n cells to the distance traversed in Phase 1, which means that a message spends a relatively larger fraction of its time in Phase 1 traveling at vehicle speed v.

Denote by $\bar{C}_l$, the event that two consecutive eastbound nodes are disconnected. Then,

$$E[D_1]_l = \sum_{n=1}^{\infty} E[D_1|N=n]_l \Pr(N=n|\bar{C}_l). \tag{5.46}$$

We again compute $\Pr(N=n|\bar{C}_l)$ using Bayes' Law, i.e.:

$$\Pr(N=n|\bar{C}_l) = \frac{\Pr(\bar{C}_l|N=n)\Pr(N=n)}{\Pr(\bar{C}_l)}. \tag{5.47}$$

We have:

$$\Pr(\bar{C}_l|N=n) = 1-(1-e^{-\frac{\lambda_w R}{2}})^n; \tag{5.48}$$

$$\Pr(N=n) = (e^{-\lambda_e(n+1)\frac{R}{2}} - e^{-\lambda_e(n+2)\frac{R}{2}}); \tag{5.49}$$

$$\begin{aligned}
\Pr(\bar{C}_l) &= \sum_{n=1}^{\infty} \Pr(\bar{C}_l|N=n)\Pr(N=n) \\
& \text{substituting from Eqns. (5.48), (5.49)} \\
&= \sum_{n=1}^{\infty} (1-(1-e^{-\frac{\lambda_w R}{2}})^n)(e^{-\lambda_e(n+1)\frac{R}{2}} - e^{-\lambda_e(n+2)\frac{R}{2}}) \qquad (5.50) \\
&= e^{-\frac{\lambda_e R}{2}}(1-e^{-\frac{\lambda_e R}{2}})\left[\frac{e^{-\frac{\lambda_e R}{2}}}{1-e^{-\frac{\lambda_e R}{2}}} - \frac{e^{-\frac{\lambda_e R}{2}}(1-e^{-\frac{\lambda_w R}{2}})}{1-e^{-\frac{\lambda_e R}{2}}(1-e^{-\frac{\lambda_w R}{2}})}\right]. \qquad (5.51)
\end{aligned}$$

Using the above equations, we obtain:

$$\begin{aligned}
E[D_1]_l &= \sum_{n=1}^{\infty} E[D_1|N=n]_l \Pr(N=n|\bar{C}_l) \\
&= \frac{R(1-e^{\lambda_e\frac{R}{2}})e^{\lambda_e\frac{R}{2}}}{4\Pr(\bar{C}_l)e^{-\frac{\lambda_w R}{2}}}\left[\frac{e^{-\frac{\lambda_e R}{2}}}{1-e^{-\frac{\lambda_w R}{2}}-e^{-\frac{\lambda_e R}{2}}}\right. \\
&\quad \left. + \frac{e^{-\frac{\lambda_e R}{2}}(1-e^{-\frac{\lambda_w R}{2}})}{1-e^{-\frac{\lambda_e R}{2}}(1-e^{-\frac{\lambda_w R}{2}})} - \frac{2e^{-\frac{\lambda_e R}{2}}}{1-e^{-\frac{\lambda_e R}{2}}}\right]. \qquad (5.52)
\end{aligned}$$

We note that the above expression holds only if $e^{-\frac{\lambda_e R}{2}} + e^{-\frac{\lambda_w R}{2}} < 1$, otherwise the series is divergent. The distance in Phase 1 is covered at the vehicle speed v. Thus, the expected time spent in this Phase 1 is $E[T_1]_l = E[D_1]_l/v$, leading to the expression provided by the Lemma.

Next, we provide an expression for $E[T_2]_l$.

Lemma 5.3.5 *The expectation of time spent in Phase 2 in the lower bound system is:*

$$
\begin{aligned}
E[T_2]_l \;=\;& \frac{R(1-e^{-\frac{\lambda_e R}{2}})e^{-\frac{\lambda_e R}{2}}}{v_{radio}2\Pr(\bar{C}_l)}\left[\frac{e^{-\frac{\lambda_e R}{2}}}{(1-e^{-\frac{\lambda_e R}{2}})}+\frac{e^{-\frac{\lambda_e R}{2}}}{(1-e^{-\frac{\lambda_e R}{2}})^2}\right.\\
&\left.-\frac{e^{-\frac{\lambda_e R}{2}}(1-e^{-\frac{\lambda_w R}{2}})}{1-e^{-\frac{\lambda_e R}{2}}(1-e^{-\frac{\lambda_w R}{2}})}-\frac{e^{-\frac{\lambda_e R}{2}}(1-e^{-\frac{\lambda_w R}{2}})}{(1-e^{-\frac{\lambda_e R}{2}}(1-e^{-\frac{\lambda_w R}{2}}))^2}\right]\\
&+\frac{1}{v_{radio}(1-\Pr(C_l))}\left[\frac{1}{\lambda_e}\left[1-e^{-\lambda_e R}(1+\lambda_e R)\right]\right.\\
&+\frac{R}{2}(1-e^{-\frac{\lambda_e R}{2}})e^{-\frac{\lambda_e R}{2}}\left[\frac{e^{-\frac{\lambda_e R}{2}}(1-e^{-\frac{\lambda_w R}{2}})}{1-e^{-\frac{\lambda_e R}{2}}(1-e^{-\frac{\lambda_w R}{2}})}\right.\\
&\left.\left.+\frac{e^{-\frac{\lambda_e R}{2}}(1-e^{-\frac{\lambda_w R}{2}})}{(1-e^{-\frac{\lambda_e R}{2}}(1-e^{-\frac{\lambda_w R}{2}}))^2}\right]\right],
\end{aligned}
\tag{5.53}
$$

where $\Pr(C_l) = 1 - \Pr(\bar{C}_l)$ *and* $\Pr(\bar{C}_l)$ *is given by Eq.* (5.51)*.*

Proof: The expected distance denoted $E[D_{2,1}]$ traversed during the first part of Phase 2 is given by:

$$
\begin{aligned}
E[D_{2,1}]_l \;=\;& \frac{R}{2}\sum_{n=1}^{\infty}(n+1)\Pr(N=n|\bar{C}_l)\\
=\;& \frac{R(1-e^{-\frac{\lambda_e R}{2}})e^{-\frac{\lambda_e R}{2}}}{2\Pr(\bar{C}_l)}\left[\frac{e^{-\frac{\lambda_e R}{2}}}{(1-e^{-\frac{\lambda_e R}{2}})}+\frac{e^{-\frac{\lambda_e R}{2}}}{(1-e^{-\frac{\lambda_e R}{2}})^2}\right.\\
&\left.-\frac{e^{-\frac{\lambda_e R}{2}}(1-e^{-\frac{\lambda_w R}{2}})}{1-e^{-\frac{\lambda_e R}{2}}(1-e^{-\frac{\lambda_w R}{2}})}-\frac{e^{-\frac{\lambda_e R}{2}}(1-e^{-\frac{\lambda_w R}{2}})}{(1-e^{-\frac{\lambda_e R}{2}}(1-e^{-\frac{\lambda_w R}{2}}))^2}\right],
\end{aligned}
\tag{5.54}
$$

where $\Pr(N=n|\bar{C}_l)$ is given by Eq. (5.47), and $\Pr(\bar{C}_l)$ is given by Eq. (5.51). Denote by $E[D'_{2,2}]_l$ the expected distance between two consecutive eastbound nodes, given that they are connected either directly or through westbound nodes. An expression for this quantity is the following:

$$E[D'_{2,2}]_l = \; = \int_0^\infty x f_{X_l|C_l}(x) dx, \tag{5.55}$$

where $f_{X_l|C_l}(x)$ is the conditional distribution on the inter-vehicle distance, based on the lower bound distribution, given that nodes are connected. This distribution is computed as:

$$f_{X_l|C_l}(x) = \frac{f_X(x) \Pr(C_l|X_l = x)}{\Pr(C_l)}, \tag{5.56}$$

where $\Pr(C_l|X_l = x)$ denotes the probability the nodes are connected for a given value of x. We have

$$\Pr(C_l|X_l = x) = \begin{cases} 1 & \text{if } x \leq R \\ (1 - e^{-\lambda_w (n+1)\frac{R}{2}}) & \text{if } x = (n+1)R/2, \text{ for } n = 1, 2, 3, \ldots \\ 0 & \text{otherwise,} \end{cases} \tag{5.57}$$

Applying the upper bound distribution for inter-vehicle distance from Eq. (5.7):

$$\begin{aligned} E[D'_{2,2}]_l &= \int_0^\infty \frac{x f_{X_l}(x) \Pr(C_l|X_l = x)}{\Pr(C_l)} dx \\ &= \frac{1}{\Pr(C_l)} \left[\frac{1}{\lambda_e} \left[1 - e^{-\lambda_e R}(1 + \lambda_e R) \right] \right. \\ &\quad + \frac{R}{2}(1 - e^{-\frac{\lambda_e R}{2}}) e^{-\frac{\lambda_e R}{2}} \left[\frac{e^{-\frac{\lambda_e R}{2}}(1 - e^{-\frac{\lambda_w R}{2}})}{1 - e^{-\frac{\lambda_e R}{2}}(1 - e^{-\frac{\lambda_w R}{2}})} \right. \\ &\quad \left. \left. + \frac{e^{-\frac{\lambda_e R}{2}}(1 - e^{-\frac{\lambda_w R}{2}})}{(1 - e^{-\frac{\lambda_e R}{2}}(1 - e^{-\frac{\lambda_w R}{2}}))^2} \right] \right], \end{aligned} \tag{5.58}$$

where $\Pr(C_l) = 1 - \Pr(\bar{C}_l)$. In Phase 2, the distance $E[D'_{2,2}]_l$ is the expected distance covered between two consecutive nodes. Thus, the expected distance $E[D_{2,2}]$ covered during second part of Phase 2 is:

$$\begin{aligned} E[D_{2,2}]_l &= \sum_{j=1}^{\infty} j E[D'_{2,2}] \Pr(C_l)^j (1 - \Pr(C_l)) \\ &= E[D'_{2,2}]_l \frac{\Pr(C_l)}{(1 - \Pr(C_l))}. \end{aligned} \tag{5.59}$$

We finally obtain $E[T_2]_l = (E[D_{2,1}]_l + E[D_{2,2}]_l)/v_{radio}$, leading to the expression given by the Lemma.

Theorem 5.3.6 *The average message propagation speed is lower bounded as follows:*

$$v_{avg} \geq \begin{cases} \frac{E[T_1]_l v + E[T_2]_l v_{radio}}{E[T_1]_l + E[T_2]_l} & \textit{if } e^{-\frac{\lambda_e R}{2}} + e^{-\frac{\lambda_w R}{2}} < 1 \\ v & \textit{if } e^{-\frac{\lambda_e R}{2}} + e^{-\frac{\lambda_w R}{2}} > 1, \end{cases}$$

where $E[T_1]_u$ and $E[T_2]_u$ are the expressions obtained from Lemma 5.3.1 and 5.3.2.

5.3.3 Approximation

In this section, based on the derivations for the upper bound and lower bound, we develop an approximation model with the assumption that each cell is of size kR, where $0.5 < k < 1$. A reasonable value is $k = 0.75$. The analysis is exact based on the assumption that the expected number of cells from the pattern matching analogy are given by:

$$E[D_1 | N = n]_a = \frac{kR}{2} \left[\frac{1 - (1 - e^{-\lambda_w kR})^n}{e^{-\lambda_w kR}(1 - e^{-\lambda_w kR})^n} - n \right]. \tag{5.60}$$

The following summarize the approximation for the average time spent in Phase 1 and Phase 2, respectively. From these approximations, the average message propagation speed v_{avg} follows from Eq. (5.5).

Approximation 5.3.7 *An approximation of the expected time spent in Phase 1 is:*

$$E[T_1]_a = \begin{cases} \frac{kR(1-e^{\lambda_e kR})e^{-\lambda_e kR}}{2v\,\Pr(\bar{C}_a)} \left[\frac{1}{e^{-\lambda_w kR}} \left\{ \frac{e^{-\lambda_e kR}}{1-e^{-\lambda_w kR}-e^{-\lambda_e kR}} \right.\right. \\ \left. + \frac{e^{-\lambda_e kR}(1-e^{-\lambda_w kR})}{1-e^{-\lambda_e kR}(1-e^{-\lambda_w kR})} - \frac{2e^{-\lambda_e kR}}{1-e^{-\lambda_e kR}} \right\} \\ \left. - \left\{ \frac{e^{-\lambda_e kR}}{(1-e^{-\lambda_e kR})^2} - \frac{e^{-\lambda_e kR}(1-e^{-\lambda_w kR})}{(1-e^{-\lambda_e kR}(1-e^{-\lambda_w kR}))^2} \right\} \right] & \textit{if } e^{-\lambda_e kR} + e^{-\lambda_w kR} < 1 \\ \infty & \textit{otherwise}, \end{cases}$$

where $\Pr(\bar{C}_a)$ *is the probability that nodes are disconnected*

Proof: Denote by $\bar{C}_a$, the event that two consecutive eastbound nodes are disconnected. Then,

$$E[D_1]_a = \sum_{n=1}^{\infty} E[D_1|N=n]_a \Pr(N=n|\bar{C}_a); \tag{5.61}$$

$$\Pr(N=n|\bar{C}_a) = \frac{\Pr(\bar{C}_a|N=n)\Pr(N=n)}{\Pr(\bar{C}_a)}; \tag{5.62}$$

$$\Pr(\bar{C}_a|N=n) = 1-(1-e^{-\lambda_w kR})^n; \tag{5.63}$$

$$\Pr(N=n) = (e^{-\lambda_e (n+1)kR} - e^{-\lambda_e (n+2)kR}); \tag{5.64}$$

$$\begin{aligned} \Pr(\bar{C}_a) &= \sum_{n=1}^{\infty} \Pr(\bar{C}_a|N=n)\Pr(N=n) \\ & \quad \text{substituting from Eqns. (5.63), (5.64)} \\ &= (1-e^{-\lambda_e kR})e^{-\lambda_e kR} \left[\frac{e^{-\lambda_e kR}}{1-e^{-\lambda_e kR}} - \frac{e^{-\lambda_e kR}(1-e^{-\lambda_w kR})}{1-e^{-\lambda_e kR}(1-e^{-\lambda_w kR})} \right]. \end{aligned} \tag{5.65}$$

Using the above equations, we obtain

$$
\begin{aligned}
E[D_1]_a &= \sum_{n=1}^{\infty} E[D_1|N=n]_a \Pr(N=n|\bar{C}_a) \\
&= \frac{kR}{2\Pr(\bar{C}_a)} \sum_{n=1}^{\infty} \left[\frac{1-(1-e^{-\lambda_w kR})^n}{(e^{-\lambda_w kR})(1-e^{-\lambda_w kR})^n} - n \right] \\
&\quad \left[(1-(1-e^{-\lambda_w kR})^n)(e^{-\lambda_e (n+1)kR} - e^{-\lambda_e (n+2)kR}) \right] \\
&= \frac{kR(1-e^{\lambda_e kR})e^{-\lambda_e kR}}{2\Pr(\bar{C}_a)} \Bigg[\frac{1}{e^{-\lambda_w kR}} \Bigg\{ \frac{e^{-\lambda_e kR}}{1-e^{-\lambda_w kR}-e^{-\lambda_e kR}} \\
&\quad + \frac{e^{-\lambda_e kR}(1-e^{-\lambda_w kR})}{1-e^{-\lambda_e kR}(1-e^{-\lambda_w kR})} - \frac{2e^{-\lambda_e kR}}{1-e^{-\lambda_e kR}} \Bigg\} \\
&\quad - \Bigg\{ \frac{e^{-\lambda_e kR}}{(1-e^{-\lambda_e kR})^2} - \frac{e^{-\lambda_e kR}(1-e^{-\lambda_w kR})}{(1-e^{-\lambda_e kR}(1-e^{-\lambda_w kR}))^2} \Bigg\} \Bigg]. \qquad (5.66)
\end{aligned}
$$

We note that the above expression holds only if $e^{-\lambda_e kR} + e^{-\lambda_w kR} < 1$, otherwise the series is divergent. The distance in Phase 1 is covered at the vehicle speed v. Thus, the expected time spent in this Phase 1 is $E[T_1]_a = E[D_1]_a/v$, leading to the expression provided by the Approximation 5.3.7.

Approximation 5.3.8 *An approximation of time spent is Phase 2 is:*

$$
\begin{aligned}
E[T_2]_a &= \frac{kR(1-e^{-\lambda_e kR})}{v_{radio}\Pr(\bar{C}_a)} \Bigg[\frac{e^{-\lambda_e kR}}{(1-e^{-\lambda_e kR})} + \frac{e^{-\lambda_e kR}}{(1-e^{-\lambda_e kR})^2} \\
&- \frac{e^{-\lambda_e kR}(1-e^{-\lambda_w kR})}{1-e^{-\lambda_e kR}(1-e^{-\lambda_w kR})} - \frac{e^{-\lambda_e kR}(1-e^{-\lambda_w kR})}{(1-e^{-\lambda_e kR}(1-e^{-\lambda_w kR}))^2} \Bigg] \\
&\quad + \frac{1}{v_{radio}(1-\Pr(C_a))} \Bigg[\frac{1}{\lambda_e} \left[1-e^{-\lambda_e R}(1+\lambda_e kR)\right] + kR(1-e^{-\lambda_e kR}) \\
&\quad \Bigg[\frac{e^{-\lambda_e kR}(1-e^{-\lambda_w kR})}{1-e^{-\lambda_e kR}(1-e^{-\lambda_w kR})} + \frac{e^{-\lambda_e kR}(1-e^{-\lambda_w kR})}{(1-e^{-\lambda_e kR}(1-e^{-\lambda_w kR}))^2} \Bigg] \Bigg], \qquad (5.67)
\end{aligned}
$$

where $\Pr(\bar{C}_a)$ *is the probability that nodes are disconnected while* $\Pr(C_a)$ *is the probability that nodes are connected.*

Proof:

$$\begin{aligned}
E[D_{2,1}]_a &= kR\sum_{n=1}^{\infty}(n+1)\Pr(N=n|\bar{C}_a) \\
&= \frac{kR}{\Pr(\bar{C}_a)}\sum_{n=1}^{\infty}(n+1)\left[(1-(1-e^{-\lambda_w kR})^n)(e^{-\lambda_e(n+1)kR}-e^{-\lambda_e(n+2)kR})\right] \\
&= \frac{kR(1-e^{-\lambda_e kR})e^{-\lambda_e kR}}{\Pr(\bar{C}_a)}\left[\frac{e^{-\lambda_e kR}}{(1-e^{-\lambda_e kR})}+\frac{e^{-\lambda_e kR}}{(1-e^{-\lambda_e kR})^2}\right. \\
&\quad \left.-\frac{e^{-\lambda_e kR}(1-e^{-\lambda_w kR})}{1-e^{-\lambda_e kR}(1-e^{-\lambda_w kR})}-\frac{e^{-\lambda_e kR}(1-e^{-\lambda_w kR})}{(1-e^{-\lambda_e kR}(1-e^{-\lambda_w kR}))^2}\right], \qquad (5.68)
\end{aligned}$$

where $\Pr(N=n|\bar{C}_a)$ is given by Eq. (5.62), and $\Pr(\bar{C}_a)$ is given by Eq. (5.65).

$$E[D'_{2,2}|N=n]_a = x(u(x)-u(x-kR))+\sum_{n=1}^{\infty}(n+1)kR(\delta(x-(n+1)kR)). \qquad (5.69)$$

Denote by C_a, the event that two consecutive nodes are connected. Then,

$$E[D'_{2,2}]_a = \int_0^R x f_{X|C_a}(x)dx + \sum_{n=1}^{\infty}(n+1)kR\Pr(N=n|C_a). \qquad (5.70)$$

$$\Pr(N=n|C_a) = \frac{\Pr(C_a|N=n)\Pr(N=n)}{\Pr(C_a)}; \qquad (5.71)$$

$$\Pr(C_a|N=n) = (1-e^{-\lambda_w kR})^n; \qquad (5.72)$$

$$\begin{aligned}
\Pr(C_a) &= 1-\Pr(\bar{C}_a) \\
&= (1-e^{-\lambda_e R})+(1-e^{-\lambda_e kR})e^{-\lambda_e kR}\left[\frac{e^{-\lambda_e kR}(1-e^{-\lambda_w kR})}{1-e^{-\lambda_e kR}(1-e^{-\lambda_w kR})}\right]. \qquad (5.73)
\end{aligned}$$

Thus, substituting these values in Eq. (5.70), we have:

$$\begin{aligned} E[D'_{2,2}]_a &= \int_0^R x f_{X|C_a}(x)dx + \sum_{n=1}^{\infty}(n+1)kR\Pr(N=n|C_a) \\ &= \frac{1}{\Pr(C_a)}\left[\int_0^R x\Pr(C_a|X)f_X(x)dx \right. \\ &\quad \left. + \sum_{n=1}^{\infty}(n+1)kR\Pr(C_a|N=n)\Pr(N=n)\right] \\ &= \frac{1}{\Pr(C_a)}\left[\frac{1}{\lambda_e}\left[1-e^{-\lambda_e R}(1+\lambda_e R)\right] + kR(1-e^{-\lambda_e kR})e^{-\lambda_e kR} \right. \\ &\quad \left. \left[\frac{e^{-\lambda_e kR}(1-e^{-\lambda_w kR})}{1-e^{-\lambda_e kR}(1-e^{-\lambda_w kR})} + \frac{e^{-\lambda_e kR}(1-e^{-\lambda_w kR})}{(1-e^{-\lambda_e kR}(1-e^{-\lambda_w kR}))^2}\right]\right]. \end{aligned} \tag{5.74}$$

Finally, we obtain:

$$E[D_{2,2}]_a = \frac{E[D'_{2,2}]_a\Pr(C_a)}{1-\Pr(C_a)}. \tag{5.75}$$

We finally obtain $E[T_2]_u = (E[D_{2,1}]_a + E[D_{2,2}]_a)/v_{radio}$, leading to the expression given by the Approximation 5.3.8.

Approximation 5.3.9 *The average message propagation speed for the approximation is as follows:*

$$v_{avg} = \begin{cases} \frac{E[T_1]_a v + E[T_2]_a v_{radio}}{E[T_1]_a + E[T_2]_a} & \text{if } e^{-\lambda_e kR} + e^{-\lambda_w kR} < 1 \\ v & \text{if } e^{-\lambda_e kR} + e^{-\lambda_w kR} > 1, \end{cases}$$

where $E[T_1]_a$ and $E[T_2]_a$ are the expressions obtained from the Approximations 5.3.7 and 5.3.8 respectively.

Chapter 6

Performance Results

In this chapter, performance results obtained from the analytical model and simulation are presented. First, results from the unidirectional model described in Section 5.2. The results from the bidirectional model are subdivided into two subsections for symmetric and asymmetric vehicular traffic scenarios. Symmetric traffic density is the scenario where the average traffic density parameter is numerically equal on each side of the roadway. Asymmetric scenarios of numerically different parameters along the *eastbound* and *westbound* roadway are considered. An extension of these results considers a scenario of access point placement, supported by bidirectional traffic and multihop networking. Finally, the results obtained from the proposed scheme are compared with concepts and schemes from mobile ad hoc networking research.

The results presented in this text were generated using MATLAB [MAT10]. The analytical model described in Chapter 5 is parametrized for *eastbound* and *westbound* vehicular density (λ_e, λ_w vehicles/km), vehicle speed (v m/s) and multihop radio propagation speed (v_{radio} m/s). For vehicle density, we consider values ranging from 1 vehicle/km to 100 vehicles/km. The values cover typical conditions of sparse, medium and heavy traffic conditions on the roadway are described in related work [WBMT07]. Considering network connectivity, when the density is sparse, the network is disconnected in small subnets, cardinality is often 1, separated by partitions that are large in length. Under medium vehicle density conditions, the network is characterized by subnets that are frequently partitioned. In dense conditions, the network is largely connected such that the entire network is possibly one large subnet. However, there is a non-zero probability that a partition exists in the network.

For physical radio parameters, we refer to related work [WFR04]. The work considers an adaptation of the 802.11 wireless radio communication technology. An outdoor testbed has established a radio range (R) of 125 m. An estimated average delay over a single hop was computed and the resulting multihop radio message propagation speed (v_{radio} m/s) was established as 1000 m/s. It is useful to note that this dissertation is largely technology agnostic in that it can be used to model new and emerging connectivity technologies. The radio model is parametrized and can be adapted for different techniques. Recent work has considered short-range directional communication and free-space optical communication as connectivity technologies with distinct characteristics to support vehicular communication [DH07, AMY$^+$07].

The analytical results are compared with a simulation of the message dissemination scheme. Inter-vehicle distances are generated based upon vehicle density distribution. The simulation model is an exact model and does not consider discretization of the roadway. Based on the inter-vehicle distances, nodes are either connected or disconnected. Correspondingly, a message is disseminated multihop or cached until connectivity is achieved by vehicle mobility. The messaging speed alternates between multihop, when network is connected, and vehicle speed, when the network is disconnected. For the simulation compute the distance traveled and the time elapsed. For the sake of brevity, we consider directional data dissemination in the eastbound direction. As explained before, the performance characteristics in the westbound direction can be obtained by appropriately replacing the parameters.

There are two key inferences drawn from the results. The first is the observation of phase transition in the behavior of message propagation speed as the vehicle density increases. As vehicle density increases from sparse to dense network conditions, the network connectivity transitions from disconnected subnets to one large connected subnet. This observation has been established from fundamental research in percolation theory and more recently in mobile ad hoc networking research in references [KWB01, DTH02]. Notable in these results is the same observation for delay tolerant network settings which is unique to this dissertation. The second important observation from these results is the vehicle density relationship for eastbound and westbound roadway at which the phase transition occurs. This observation is only obtained from the analytical model and hard to achieve from simulation. The values of common parameters used throughout the results are summarized in Table 6.1.

Table 6.1: List of parameters, symbols, and corresponding values

Parameter	Abbreviation	Value
Vehicle speed	v	20 m/s
Radio range	R	125 m
Multihop radio speed	v_{radio}	1000 m/s
Vehicle distribution	λ	1 vehicle/km to 100 vehicles/km

6.1 Unidirectional Model

The unidirectional model describes a scenario where *eastbound* roadway is partitioned such that an instantaneous data path between nodes does not always exist. The goal of this model is to demonstrate that even with bidirectional mobility and changing topologies, vehicles along the *westbound* roadway can utilized to bridge the partitions and enable multihop data dissemination.

Figure 6·1, shows results from the analytical and simulation models. The *eastbound* roadway is partitioned such that inter-vehicle distance between consecutive nodes is fixed ($d = 300$ m). Considering a fixed radio range ($R = 125$ m) and constant vehicle speeds ($v = 20$ m/s), the network is partitioned. Multihop dissemination is achieved only when vehicles along *westbound* roadway bridge partitions. Thus, the results indicate that for vehicle density from 1 vehicle/km to 10 vehicles/km, the network is partitioned and data dissemination can only be achieved by physical vehicle mobility along the roadway, i.e., equivalent to vehicle speed (v = 20 m/s). As vehicle density increases, the partitions are bridged, multihop connectivity aids data dissemination. Thus, the average message propagation speed is between the maximum achievable speed and vehicle speed. When the density is approximately 100 vehicles/km, the network is largely connected by virtue of vehicle density on the westbound roadway. Thus, the data dissemination is mostly multihop propagation with infrequent partitions. The average message propagation speed is hence, equivalent to the maximum achievable – multihop radio speed ($v_{avg} = v_{radio} = 1000$ m/s).

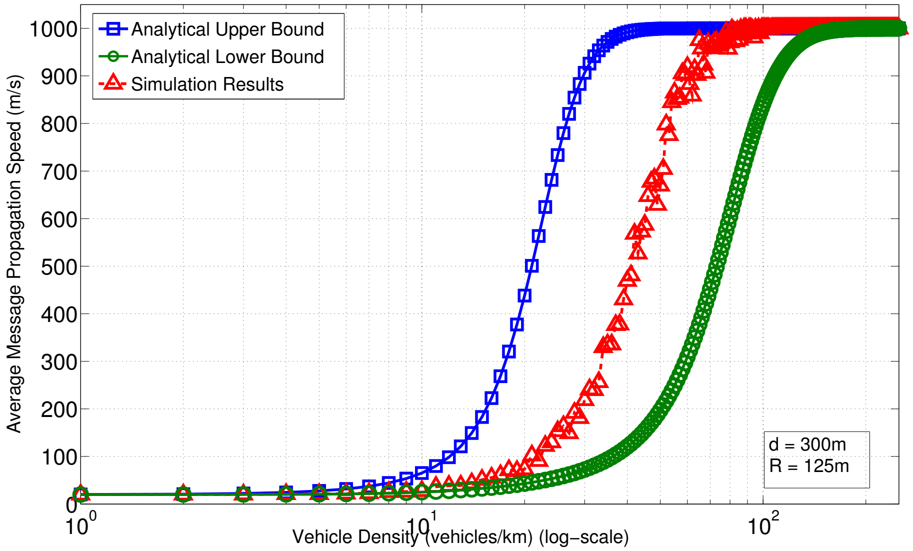


Figure 6·1: Average message propagation speed for increasing vehicle density for unidirectional model.

The upper bound is an optimistic view of the connectivity, thus, the maximum messaging speed is achievable at a density (40 vehicles/km) lower than the simulation results and the lower bound. The lower bound is a pessimistic view of the connectivity and thus, the performance lags the simulation results. The results indicate that indeed traffic moving in opposing direction can be utilised to bridge partitions between vehicles moving on the roadway.

6.2 Bidirectional Model

In the bidirectional model (Sec. 5.3), the assumption of a partitioned roadway is relaxed and exponential distribution of vehicles on both sides of the roadway, eastbound and westbound is considered. Thus, on each side of the roadway, there is potentially numerically different vehicle density. In Figure 6·2, the graph illustrates the performance of average message propagation speed with eastbound and westbound vehicle density, based on the approximation in Sec. 5.3.3. Message propagation in the eastbound direction is considered. From the graph, it is observable that the messaging performance is a function of the vehicle density and is asymmetric with respect to vehicle density on the roadway. Thus, to better understand the performance of messaging, two subsets of results are presented – symmetric and asymmetric vehicle density. In the symmetric case, numerically equivalent vehicle densities on either side of the roadway is considered while in the asymmetric case, the density distribution parameters are numerically different. The results are presented correspondingly in Sections 6.2.3 and 6.2.3.

6.2.1 Phase Transition

In Section 5, the analytical model revealed the relationship between the eastbound and westbound vehicle density. The result demonstrated that in order to bridge partitions along the eastbound direction, the average vehicle density in the westbound direction must be greater than a threshold quantity. Theorems 5.3.3 and 5.3.6 provide upper and lower bounds on the average message propagation speed v_{avg}. Specifically,

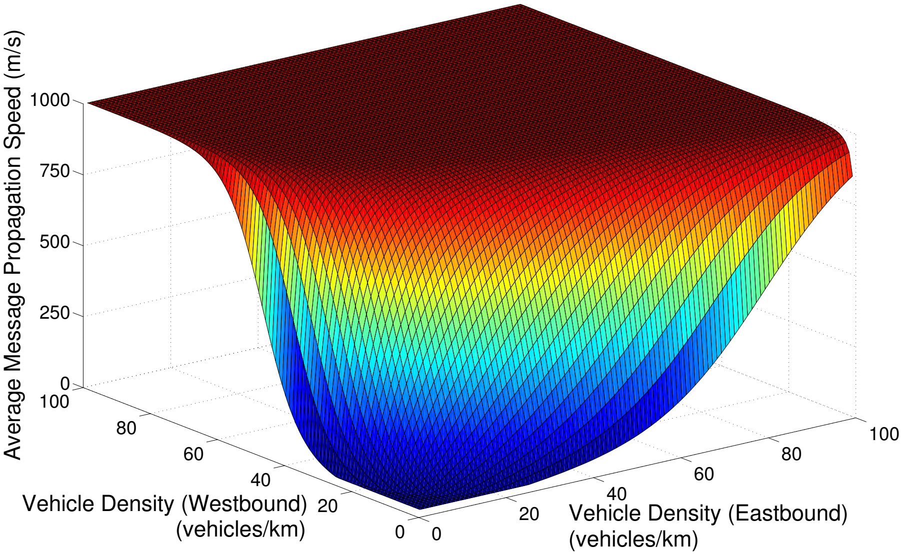


Figure 6·2: Average message propagation speed with vehicle density independently in the *eastbound* and *westbound* direction.

Theorem 5.3.3 reveals that if the combination of traffic densities in both directions is too low, i.e., $(e^{-\lambda_e R} + e^{-\lambda_w R}) > 1$, then v_{avg} does not exceed v, independently of the specific value of v and v_{radio}. On the other hand, Theorem 5.3.3 guarantees that if $(e^{-\frac{\lambda_e R}{2}} + e^{-\frac{\lambda_w R}{2}}) < 1$, then the value of v_{avg} is strictly larger than v and increases with λ_e, λ_w and v_{radio}.

The result is plotted in Figure 6·3. The figure illustrates the threshold for upper bound, lower bound and approximation curves. The graph is divided in 3 distinct regimes – Regime I, Regime II and Regime III. Regime I represents the region in the graph with low values of eastbound and westbound densities. The figure shows that for low traffic density in one direction (< 10 vehicles/km), a relatively high density of traffic in the other direction, $(10 - 25$ vehicles/km) is required. While this result may be intuitive, the mathematical relationship is only derived from the analytical model.

For these values of densities on the roadway depicted by Regime I, the partitioning in the network is such that vehicles on either side of the roadway are unable to exploit multihop connectivity. Due to lack of connectivity, the messaging speed is close to the minimum – vehicle speed. Regime III represents the region of relatively high eastbound and westbound densities. In this regime of densities, a small increase in the value of density is able to provide immediate gains in messaging performance. In this regime, multihop messaging is exploited to bridge partitions in the network. However, the same cannot be claimed for Regime II. The performance in this regime is uncertain as there are cases where multihop messaging can be applied, while others where partitioning dominates.

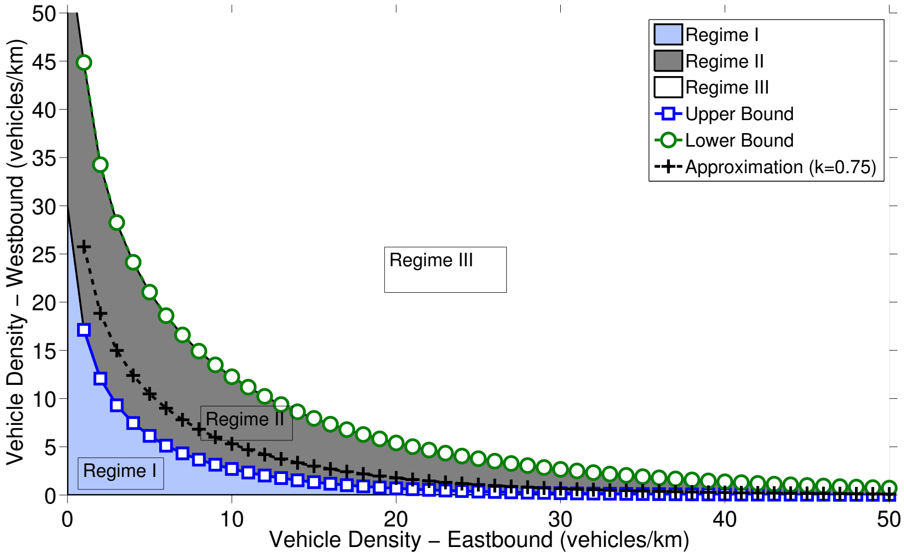


Figure 6·3: Three different regimes of message propagation speed. The phase transition between these two regimes takes place somewhere in `Regime II`, as given by the approximation curve.

The mathematical justification for the phase transition behavior is that, when the traffic density is too low, the expected time spent in Phase 1 is infinitely large. Looking back at Eq. (5.8) and the *pattern matching* problem analogy, it is observed that the expected number of cells needed to bridge a certain gap N grows at an exponential rate with N. On the other hand, the inter-vehicle distance probability distribution decays at an exponential rate with N. If the growth rate is larger than the decay rate, then the expected time spent in Phase 1 approaches infinity and the average propagation speed is the same as the vehicle speed. On the other hand, if the density on either side of the roadway is high enough, then the decrease rate is faster than the increase rate, and DTN architectures quickly become beneficial.

This result is important because it quantifies the density relationship between eastbound and westbound roadway. From results on percolation theory [KWB01], it is known that there is a critical density threshold for which the graph properties undergo a transition. The transition in these results is continuous in nature as opposed to a discrete transition. It is important to note that the critical density for transition cannot be claimed due to the continuous nature. Rather, the density relationship provides the scenarios where the densities are sufficient such that the delay tolerant assumption is exploited to bridge partitions occurring on the roadway.

6.2.2 Symmetric Traffic

In this section, results based on the assumption of numerically equivalent eastbound and westbound vehicle density distribution parameters are considered. The messaging goal is in the eastbound direction.

Average message propagation rate with vehicle traffic density

Figure 6·4 depicts the average message propagation speed for increasing vehicular traffic density. The traffic density is numerically equivalent in both eastbound and westbound direction. The *upper* bound, *lower* bound and *approximation* results are plotted. When the mean value of vehicle traffic density is below 10 vehicles/km, the network is essentially disconnected and the messages are buffered within vehicles. The data traverse physical distance at vehicle speed ($v = 20$ m/s). When the node density is high (> 50 vehicles/km), the network is largely connected. Thus, data are

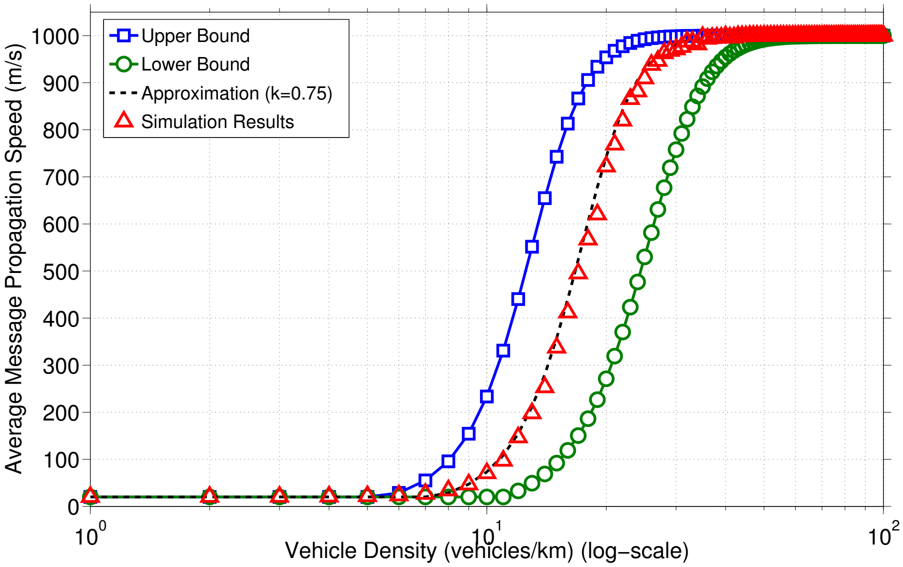


Figure 6·4: Comparison of simulation results and analytical bounds for message propagation speed as a function of vehicle density.

able to propagate multihop through the network at the maximum speed permitted by the radio ($v_{radio} = 1,000$ m/s). For medium vehicle density, the network is comprised of disconnected sub-nets. There is transient connectivity in the network as vehicular traffic moves in opposing directions. As a result of the delay tolerant networking assumption and opportunistic forwarding, the message propagation alternates in the two phases. The average rate, a function of the time spent in each phase, is between the two extremes of v m/s and v_{radio} m/s. Thus, the message propagation speed is a function of the connectivity in the network that is in turn determined by the vehicle density.

The simulation results are averaged over several iterations to account for the random node generation and the resulting topology. The simulation results lie well within the upper and the lower bounds. The approximation derived in Section 5.3.3 closely follows the simulation results. The approximation factor is chosen as a value of $k = 0.75$ as a good match with the simulation results. Thus, we are able to demonstrate that the analytical model captures the essence of messaging in the vehicular networking environment characterized by time varying connectivity and delay tolerant networking assumption.

Average delay with vehicle traffic density

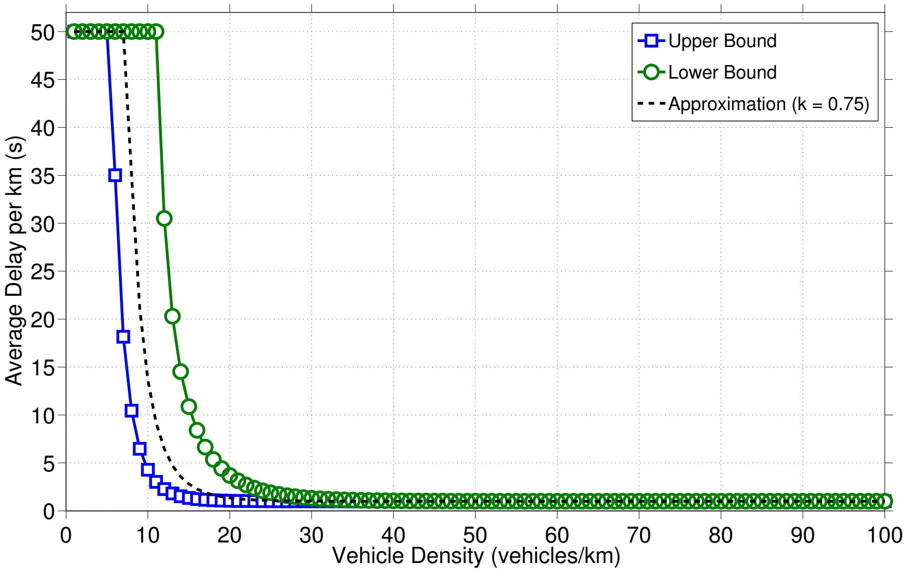


Figure 6·5: Average delay (per km) with vehicle density.

In Figure 6·5, the average delay for a message, originating at a source vehicle, in reaching a destination vehicle located 1 km away are plotted. The delay shown here is due to the delay tolerant assumption and is a function of the connectivity or lack of connectivity. The graph shows average delay per kilometer in message propagation as the vehicle traffic density increases. The delay is minimum when the network is connected and messages are able propagate multihop over connected vehicles. At lower densities, the network is disconnected, correspondingly, the delay is large. The delay, however, depends on the separation between source and destination nodes. Thus, if the separation is of the order of several kilometers, the delay is adjusted by a corresponding factor.

6.2.3 Asymmetric Traffic

In this section, the eastbound and westbound vehicle density distribution parameters are not equivalent. This results in asymmetric vehicle density on either side of the roadway. The goal is to study the performance of messaging under these conditions. This scenario is unique because in static networks that density is the dominating factor. In a dynamic network represented here, with the directionality of data and vehicle mobility, it is relevant to study the impact on messaging performance. The messaging goal, for subsequent results, is in the eastbound direction. For the sake of clarity, the results are plotted using the approximation model developed as it was found to be consistent with the simulation results.

Average Message Propagation Speed with Vehicle Density

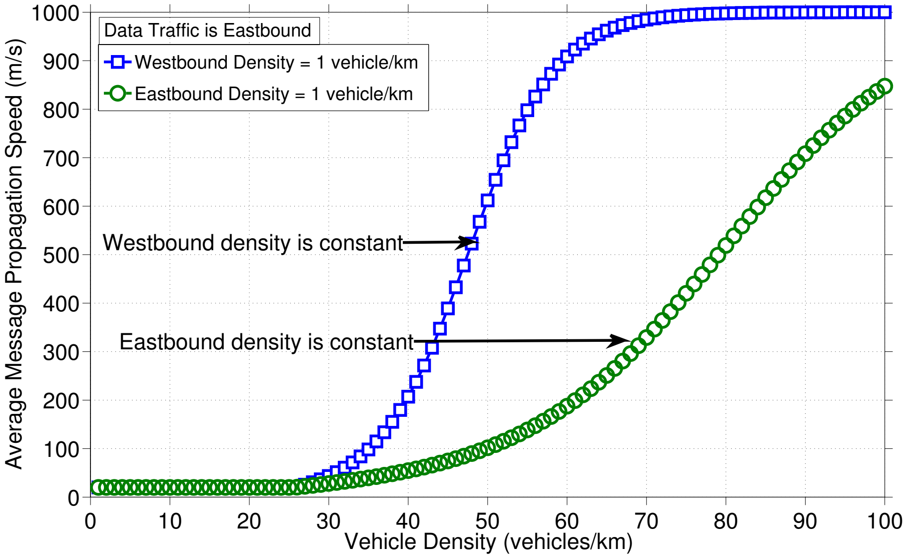


Figure 6·6: Average message propagation speed for fixed density on one side of the roadway (1 vehicle/km).

Figure 6·6, the results for average message propagation speed are presented in a scenario where the density on one side of the roadway is fixed while the other is a variable. For one curve, we fix the density on the eastbound direction at 1 vehicle/km, and compare the messaging performance for increasing westbound density. The other curve shows the performance for fixed density in the westbound direction and increasing eastbound traffic density. This results in asymmetric traffic densities on the roadway and correspondingly, the performance of messaging.

Comparing performance we see that for an average of 1 vehicle/km, in the eastbound direction, the network is partitioned. Thus, for low densities, the messaging performance is equivalent to the vehicle speed (v m/s). From previous analysis (Figure 6·3), there are no gains achieved from the delay tolerant assumption until the traffic density in the westbound direction is at least 27 vehicles/km, on average. As the westbound traffic density increases the messaging speed increases. However, the maximum performance is not achieved because of network partitioning and lack of end-to-end connectivity. When we consider the westbound density to be fixed at 1 vehicle/km and the eastbound density increases, the performance characterization is different. Here, we observe that as the eastbound density increases, the partitions are smaller in size, on average, and less frequent. Thus, even a sparse network density in the westbound direction is sufficient to bridge partitions and exploit multihop connectivity.

In Figure 6·7, the performance of messaging for a fixed traffic density of 15 vehicles/km are presented. Again, the performance is equivalent to vehicles speed (v m/s) until the minimum threshold density of $2-3$ vehicles/km is achieved in the other direction, which exploits the transient connectivity. For fixed traffic density in the *eastbound* direction, once the traffic density increases beyond the minimum threshold, the messaging performance increases rapidly with traffic density. However, since the partitions in the network still exist at the same rate, the messaging performance is dependant upon the *westbound* traffic for connectivity. In the inverse

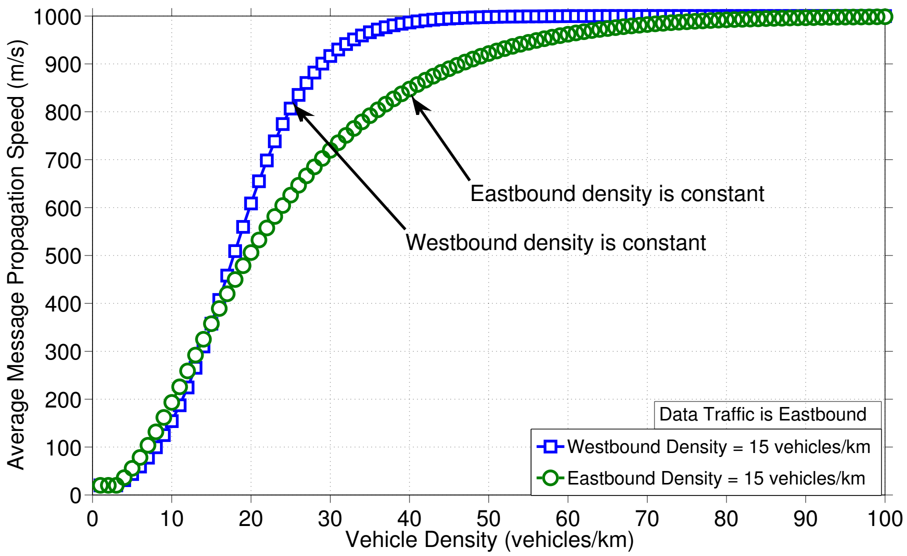


Figure 6·7: Average message propagation speed for fixed density on one side of the roadway (15 vehicles/km).

case, when the *westbound* density is fixed at 15 vehicles/km and the *eastbound* density is increased, the size of the partitions decreases and they become less frequent. Thus, the messaging performance is dominated by *eastbound* density. The two curves cross each other at 15 vehicles/km on the abscissa of the graph, which occurs when the value of *eastbound* density exceeds the fixed density of the other curve.

Figure 6·8 shows a comparison of performance at a fixed density of 35 vehicles/km. Here, as the densities are higher, the partitions are smaller and infrequent. The gains are rapidly achieved in messaging performance for increasing density. Thus, the curve increases rapidly and reaches the maximum performance value, as early as 20 vehicles/km for vehicle density in the opposing direction. In contrast to previous graphs, the fixed density of *eastbound* traffic of 35 vehicles/km is higher than the *westbound* density and dominates in the messaging performance.

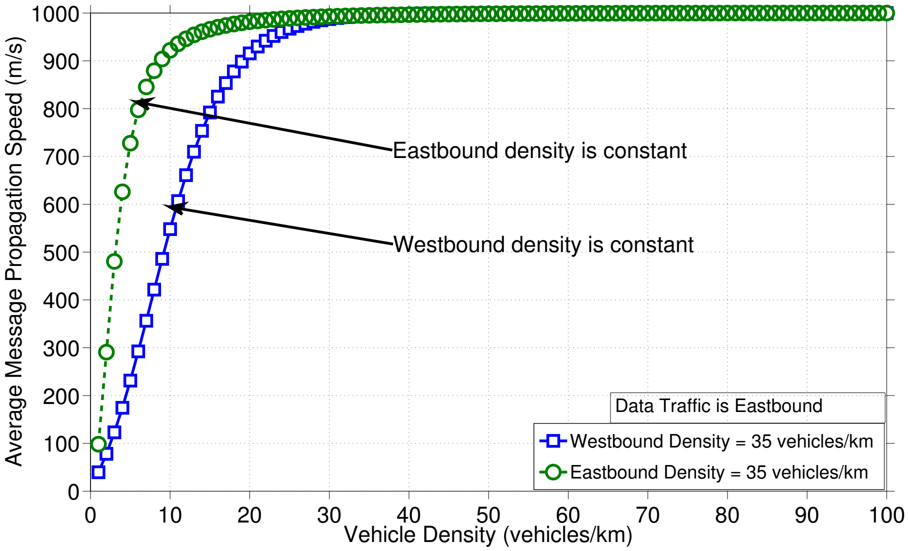


Figure 6·8: Average message propagation speed for fixed density on one side of the roadway (35 vehicles/km).

6.3 Access Point Placement

The model developed in Sec. 5 is extended to consider the placement of access points (fixed infrastructure) in the network. A scenario is considered such that access points are placed intermittently on the roadway to provide connectivity to the backbone network, supported by multihop communication. Access points are deployed at regular intervals (L m), such that they are not connected to each other, i.e., the separation is greater than the radio range ($L > R$). The characteristics of the access points is beyond the scope of this dissertation. We want to model the behavior of data propagation in the network.

The messaging goal is defined such that a message originates at a vehicle in the network and its destination is defined as the next access point up ahead on the roadway. For the sake of brevity, only symmetric scenarios of vehicle density on both sides of the roadway are considered. The goal is to develop insight on the achievable performance and ability to minimize the placement of infrastructure in the network.

Access point separations (L) of $5,000$ m, $7,500$ m and $15,000$ m are considered.

Average Message Propagation Speed with Vehicle Density

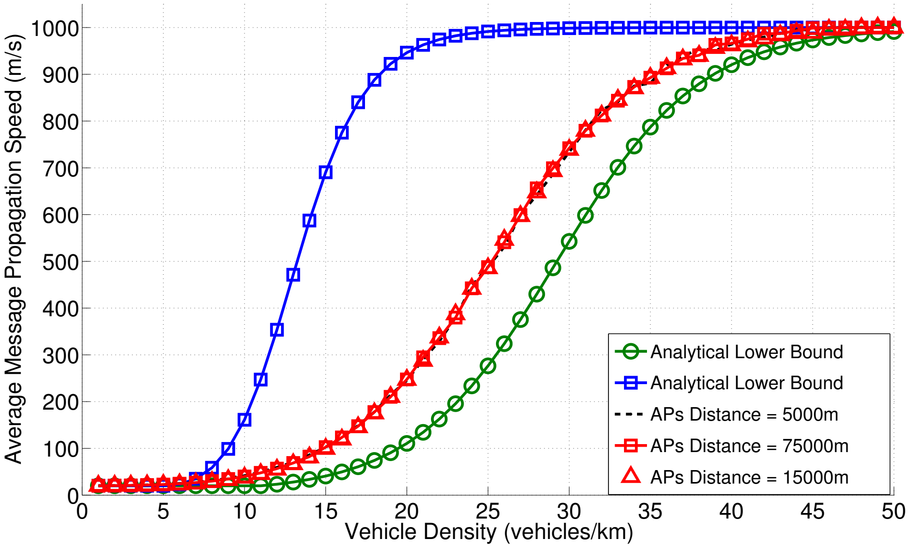


Figure 6·9: Average message propagation speed with vehicle density for various access point separations.

Figure 6·9 shows a comparison of the average propagation rates for different scenarios. The propagation rate is a long-run average of the physical distance covered by the message per unit time. As we described previously, the message alternates between multihop propagation rate and vehicle propagation rate, the average rate is the result of the proportion of time spent in each phase. The average propagation rate for different separations of access point placement is essentially the same. The simulation results are compared with analytical bounds for the network in the absence of infrastructure, Sec. 6.2.2. The results show that the propagation rate under the delay tolerant networking assumption is a function of vehicular traffic characteristics and the physical radio. Importantly, it is largely independent of the access point placement. Thus, the average message propagation speed for various access point separation remains the same.

Average Delay with Vehicle Density

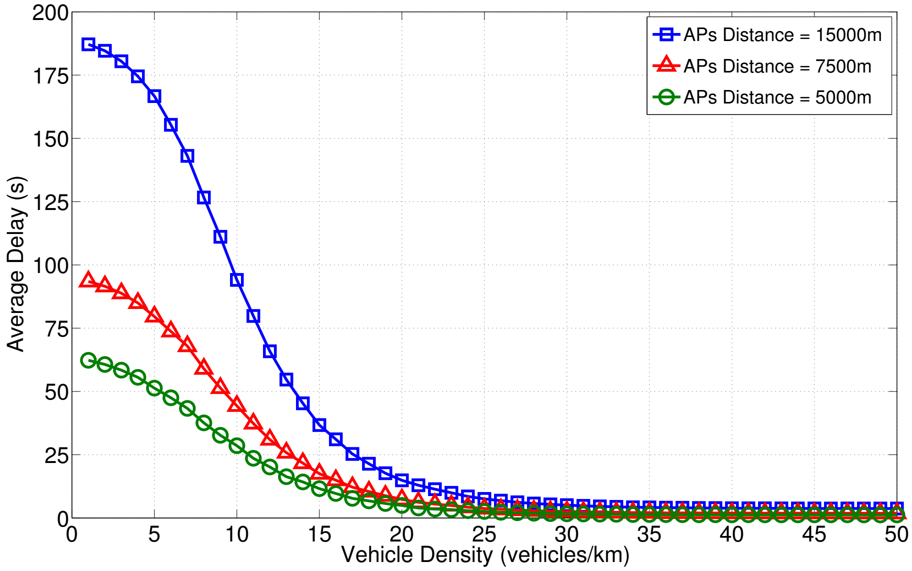


Figure 6·10: Average delay with vehicle density for various access point separations.

In Figure 6·10, a comparison of the average delays are presented. When the vehicle density is sparse, messages are unable to propagate multihop. The messages are stored and carried as the vehicle traverses the roadway, thus, the delay is of the order of time taken by vehicle to physically move to the access point. At the other extreme, when the network is dense, there is end-to-end connectivity between the vehicle and the access point and the delay is of the order of time taken for the message to propagate multihop to its destination. In the intermediate density case, messages propagate along vehicles in the absence of connectivity and multihop whenever opportunistic connectivity is available. For a separation of $5,000$ m, the average delay is 62.5 s as the vehicle travels at 20 m/s. Correspondingly, the delay for an access point separation of $15,000$ m, the average delay is 187.5 s. The contrast emphasizes the design choice for message delay as quality of service constraints demand limits over the delay.

In contrast, the average delay for various access point separations varies significantly when the traffic density is between 10 vehicles/km and 20 vehicles/km. Correspondingly, the average delay is less discernible for vehicular traffic density between 20 vehicles/km and 30 vehicles/km. Thus, given prior knowledge about the traffic on a roadway, the access points can be placed farther apart.

These results are significant as they demonstrate that for large access point separations, the average message propagation speed is independent of the access point separation. Trivially, the average delay, is a function of the access point separations. Importantly, the access point separations can be minimized with prior knowledge in the network. For example, for given constraints on quality of service and knowledge of vehicle density, access points are placed further apart or closer, such that the placement is minimized and constraints are satisfied.

6.4 Comparison with MANET techniques

In this section, the performance of the routing model are compared with schemes derived from mobile ad hoc networking research. Routing schemes such as AODV and DSR are based on the concept of end-to-end path formation. That is, a path from the source to destination must exist instantaneously for successful data routing. However, we have shown in a dynamic vehicular network, there are several partitions in the network and an end-to-end path between source-destination pairs is often difficult to establish. Considering varying vehicle densities, the performance of messaging in the proposed model is compared with MANET models.

Effect of Increased Mobility

In Fig. 6·11, the performance of the messaging scheme as the vehicular speed increases at fixed values of eastbound and westbound traffic density are observed.

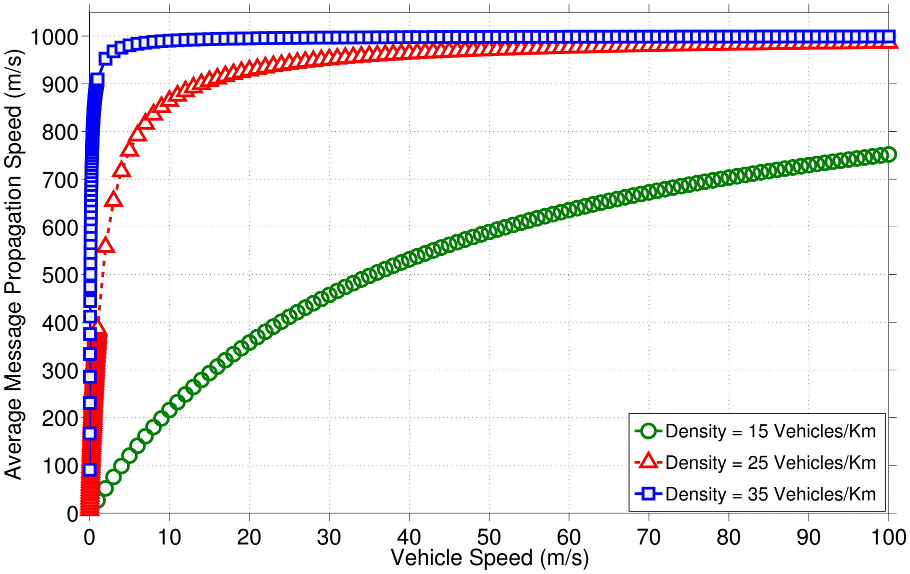


Figure 6·11: Impact of increasing vehicle speed on average propagation speed for various traffic densities, based on the approximation model.

The graph shows that the messaging performance, for the approximation model, increases by order of magnitude from 0 m/s to 200 m/s as vehicular mobility increases from 0 m/s to 10 m/s. This is counter intuitive to the observation in conventional MANET protocols that increased mobility decreases the messaging performance owing to short-lived paths. However, in this connection-less messaging paradigm, it is observed that messaging performance is aided by increased mobility. The partitions that occur in the network are bridged at a faster rate leading to increased messaging performance.

Average Message Propagation Speed with Vehicle Density

In Fig. 6·12, we compare the average propagation speeds achievable for the approximation model of the delay tolerant architecture with that of a MANET scheme such as AODV or DSR for a fixed source-destination separation of 12.5 km. The MANET schemes rely on path formation and require end-to-end connectivity be-

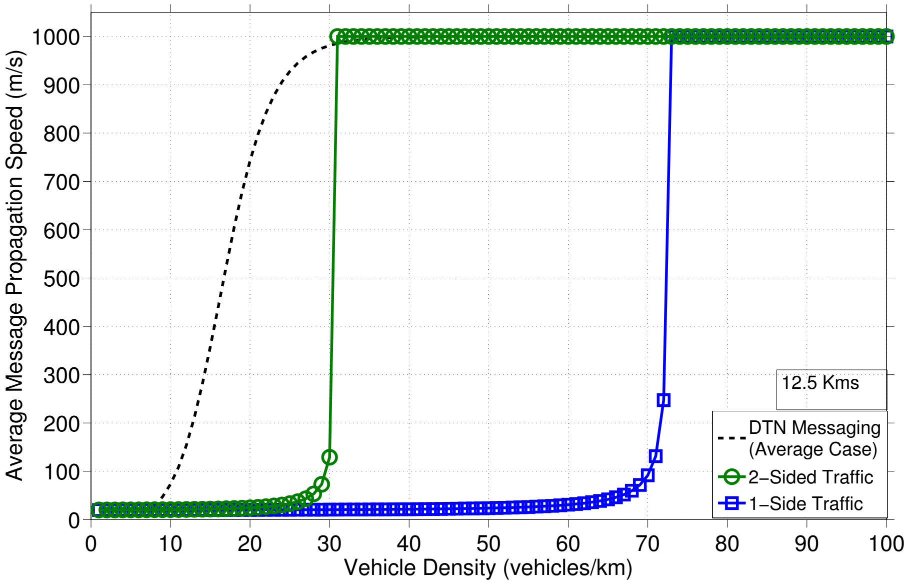


Figure 6·12: Comparison of DTN messaging strategy with a path formation based scheme utilizing 1-sided traffic or 2 sides of traffic for a distance of 12.5km.

tween the source-destination pairs. Thus, as a result, the scheme requires a high density of nodes for achieving end-to-end connectivity. It is evident that a scheme that utilizes only one direction of traffic for connectivity requires a density of nearly 70 vehicles/km, on average. However, if vehicular nodes traveling in either direction are used for path formation, maximum performance, on average, is achieved at about 30 vehicles/km. Whereas, for the DTN assumption, the messaging performance, is better for similar density values, is independent of the separation between the source-destination pairs, and is primarily a function of the vehicle density.

Access Point Placement

Fig.6·13 shows a comparison of the average delays for delay tolerant networking and a strategy involving end-to-end connectivity. In a strategy involving end-to-end connectivity, the network is considered disconnected unless there is an instantaneous end-to-end path between the access point and the vehicle. For low density scenarios,

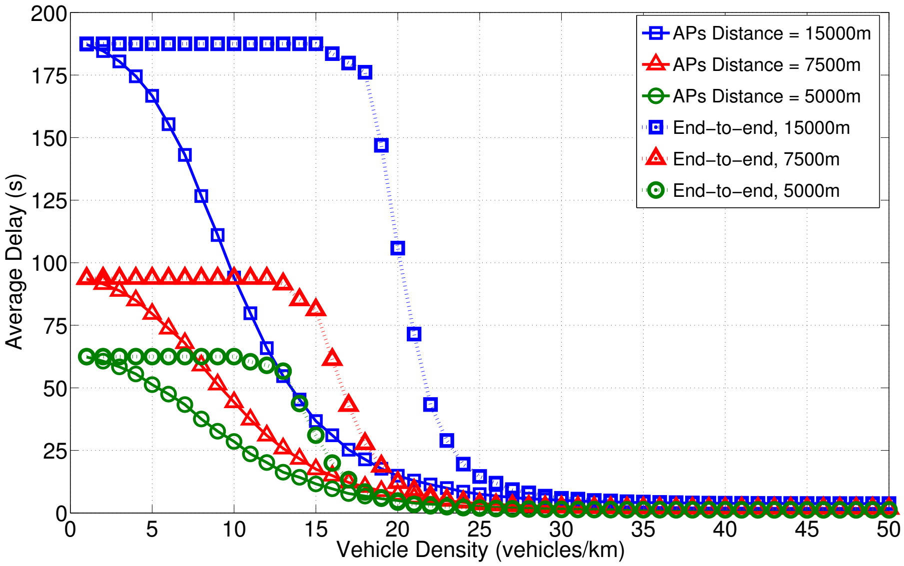


Figure 6·13: Comparison of MANET and DTN strategies, average delay with vehicle density for various access point separations.

the network is mostly disconnected, the delay associated is a function of the vehicle speed and access point separation. As the network is sparse, multihop connectivity is not available, the data are propagated as the vehicle travels the distance to the access point. As density increases, the network is likely fully connected, the delay is equivalent to the multihop propagation delay. When averaged over several iterations and varying densities, we observe that as the access point separation increases, the density required to obtain end-to-end connectivity, on average, increases. For example, for an access point separation of 5000 m the network is likely to be fully connected at 20 vehicles/km, while for 15000 m, the network is not likely to be fully connected until there are 30 vehicles/km on either side of the roadway. In contrast in the delay tolerant networking paradigm, there are gains achieved in the absence of end-to-end connectivity and the corresponding density requirements are significantly lower. This is to support our argument for the application of delay tolerant networking when considering access points in the network.

6.5 Summary

The results presented in this chapter provide several key insights about data dissemination in vehicular networks. The network connectivity is a function of the vehicle density. In sparse density scenarios, the network is characterized by frequently occurring partitions. It is demonstrated that vehicle traffic in the opposing direction can be utilized to bridge the partitioning, even if the connectivity is short-lived. A phase transition phenomenon in the network is demonstrated in the vehicle density relationship between the eastbound and westbound roadway. The results demonstrate density regimes where the delay tolerant assumption can be exploited to enable multihop dissemination and others where no gains are achievable.

The results demonstrate that the message propagation speed is a function of vehicle density on the eastbound and westbound roadway as well as the transmission range and physical radio characteristics. An upper bound, lower bound and approximation that matches with simulation results are presented. Further, the dependence of messaging on directionality of traffic is demonstrated through asymmetric density scenarios.

An extension of the model considers a hybrid scenario with intermittently placed access points. The results demonstrate that the average message propagation speed is independent of access point separations while the delay is a function of separation. The access point separations in a hybrid network can be minimized with prior knowledge of the network. For example, for given constraints on quality of service and knowledge of vehicle density, access points are placed further apart or closer, such that the placement is minimized and constraints are satisfied.

Significantly, we demonstrate that the proposed model is independent of the source-destination separation. The routing technique is able to exploit transient connectivity in the network offered by traffic moving in opposing directions. A scheme based on end-to-end path formation strategy requires, on average, a high density of nodes in the network to achieve a performance similar to the proposed DTN scheme. This strengthens our case for a connection-less messaging paradigm where maximum achievable speed is achievable, on average, at a density lower than MANET schemes. Finally, it is observed that contrary to MANET observations, increasing mobility in the network aids message propagation.

Chapter 7

Conclusion

7.1 Summary

We consider the problem of networking among vehicles traveling on navigable roadways. Vehicle traffic density on the roadway varies between the extremes of sparse and dense traffic, depending upon the roadway (urban/rural) and time of the day (day/night). From a network connectivity standpoint, the network is partitioned when the density is sparse, and likely connected in dense situations. Our focus is to develop a mechanism that enables data propagation in a network formed over moving vehicles characterized by vehicles as nodes. A significant challenge is the phenomenon of time-varying partitioning (fragmentation) in the network. As vehicles move at relatively fast rate, the topology of the network changes as vehicles come in intermittent contact with other vehicles on the roadway.

A novel routing technique is proposed that incorporates elements of mobile ad hoc networks such as attributed, or labeled messaging; geographic routing and delay tolerant networking to build a solution that operates in a network characterized by rapid mobility and time-varying partitioning (Sec. 4). To demonstrate the applicability of this solution, as a first model, one side of the roadway is considered partitioned, while vehicles traveling in the opposing direction of the roadway are randomly distributed (Sec. 5.2). We show that under the assumption of delay tolerance, vehicles traveling in opposing direction can indeed be exploited to bridge partitions in the network (Sec. 6).

The preliminary model is extended to include exponential node distribution on either side of the roadway. The analytical model is developed to determine the performance of messaging in the network (Sec. 5.3). The model is parametrized for network variables that allows us to study the behavior for various scenarios and settings. A key observation in these results is the occurrence of phase transition phenomenon in properties of the network with respect to increasing node density in the network. This observation is consistent with previous work in mobile ad hoc network research with respect to behavior of connectivity in a static network with increasing node density. Significant in this dissertation is the demonstration that the density relationship at which gains from the delay tolerant assumption are achieved. These parameters are not easily determined by simulations that are lengthy and time consuming.

Finally, the performance of messaging in a hybrid environment comprising of intermittently placed fixed access points (infrastructure) is considered (Sec. 6.3). Analysis of behavior of message propagation in the network suggests an optimization on the placement of access points for given network parameters. For given vehicle density scenarios and quality of service constraints such as delay in data delivery, access points can be placed farther apart (or closer) to minimize the placement of costly infrastructure and at the same time satisfy the constraints.

7.2 Research Contributions

The significant contributions in this dissertation are summarized below:

1. **Routing Protocol**

   A novel routing protocol based on attributed or labelled messaging, geographic routing and delay tolerant networking is proposed. The concept of `S-TTL`, (`Space-Time-to-Live`), is introduced to control the dissemination of messages in both space and time, exploiting the spatio-temporal correlation of data and nodes in the network.

2. **Analytical Model**

   The analytical model developed in this dissertation presents upper and lower bounds for performance in a dynamic network. The model is unique in that it captures delay tolerant messaging in a network with time-varying partitions (fragmentation). The approximation developed closely follows the simulation results, obviating the need for lengthy and time consuming simulations for determining performance. The model is adaptive as it is parametrized for vehicle density, vehicle mobility and physical radio characteristics.

3. **Phase Transition**

   The phenomenon of phase transition in the performance of the network is revealed in this dissertation. The *eastbound-westbound* density relationship is determined such that multihop connectivity is exploited to bridge partitions occurring in the network. The relationship is only revealed by the analytical model and hard to determine from simulation.

4. **Improved Performance**

   The routing protocol presented performs superior to MANET schemes based on path formation strategies. The gains in performance are achieved by exploiting transient connectivity to enable message propagation, while MANET schemes potentially fail due to absence of end-to-end connectivity. The performance results demonstrate better performance, especially at lower densities.

   Contrary to expectations, it is demonstrated that a connectionless messaging paradigm, such as one presented in this dissertation, performs better in scenarios of increased mobility. MANET schemes perform poorly in scenarios of increased mobility due to increased overheads in path maintenance due to frequently changing topology. An increase in vehicle speed from 0 m/s to 10 m/s achieves a corresponding increase from 0 m/s to 200 m/s at certain vehicle densities. In the proposed scheme, with increased mobility, partitions are bridged at a fast rate resulting in improved performance.

5. **Access Point Placement**

   Strategies for placement of access points in the network are investigated. It is possible to place access points farther apart by exploiting multihop connectivity over moving vehicles. Importantly, it is demonstrated that knowledge of network parameters such as vehicle density and quality of service constraints can be exploited to minimize placement while satisfying the constraints. Under the delay tolerant assumption, at a low density of 20 vehicles/km, messaging performance rates achieved are similar to those achieved by MANET schemes at higher densities of 40 vehicles/km.

7.3 Future Work

The following section summarizes some of the open problems are related to the work in this dissertation. They are organized as extensions of work presented in this dissertation.

1. **Clustering**

   The concept of clustering has been discussed briefly. Clustering is exploited among vehicles traveling in the same direction to create logical groups that coordinate and maintain information flow in the network. At one extreme, when the density of vehicles on the roadway is low, the size of a cluster is one (single vehicle). While at the other extreme, when the density is high, the cluster can potentially encapsulate the entire network in the form of a single connected component. The creation and maintenance of a cluster is an open issue in this work and we refer to related work in MANET research [BKL01].

2. **Attributed routing – `S-TTL` Parameter**

   The concept of `S-TTL` is presented to exploit the spatio-temporal correlation of data and nodes in the network. However, the determination of exact value of this parameter is application specific. Applications such as traffic monitoring involve collecting data over several kilometers while others such as tolling maybe short-lived. The determination of this parameter is open question and left for future work.

3. **Comparison with real vehicle traces**

   The analytical model and simulation traces rely on vehicle density generated based upon exponential distribution. While the exponential distribution has been shown to be in good agreement with real vehicle traces, the performance of the network with real vehicle traces is left unsolved. The nature of performance is expected to be similar while a more accurate approximation factor can be developed using real vehicle traces.

4. **Vehicle speed distribution**

   The analytical model assumes constant vehicle speed such that the partitions in the network remain constant. Considering a variable speed distribution will represent dynamic partition lengths that will require complex modifications to this model. While this has been considered in related work [WFR04], the gains expected are significantly lower than those achieved by exploiting bidirectional mobility.

5. Two-dimensional model

In this dissertation, a linear model of the roadway is considered. An interesting extension is to determine the performance in a two-dimensional network. While the results presented can be extended to the two-dimensional model, the problem reduces to one of finding an optimal path. This was deemed beyond the scope of this dissertation.

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CURRICULUM VITAE

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Education

- **PhD**, Electrical and Computer Engineering, Boston University, May 2010
  Dissertation Title: GPA 4.0/4.0
  Analytical Modeling of Data Dissemination in Vehicular Networks
  Vehicular networks are targeted to interconnect vehicles on the roadway to enable safety and *telematics* applications. We develop innovative techniques for data dissemination and demonstrate gains over traditional MANET techniques. Critical density threshold conditions are demonstrated based on percolation theory. The model is adapted to suit hybrid environments with fixed access point infrastructure and created the ability to select design parameters for optimal placement.
- **M.S.**, Computer Systems Engineering, Boston University 2007
- **B.E.**, Computer Engineering,
  Netaji Subhas Institute of Technology (NSIT), New Delhi 2003

Professional Experience

- **Research Assistant**, Multimedia Communications Lab, Boston University
  - Research on *directional communications in vehicular networks* 2009-2010
    Developed models for nearest neighbor communication using Free-Space Optical (FSO) communication. Prepared a feasibility and use-case analysis.
  - Research on *delay tolerant communication in vehicular networks* 2006-2009
    Developed analytical model for delay tolerant message propagation in vehicular networks. Results demonstrate critical density of phase transition based on percolation theory.
  - Research on *sensor networks* 2005-2006
    Programmed and networked `Intel PXA-255` based embedded Linux system to interact with sensor motes. Led a team project to study environments such as bat habitat and soil moisture due to cloud occlusion for inter-disciplinary NSF grant.
- **National Priority Setting NSF Workshops**, Participated in
  - NITRD Workshop on High Confidence Automotive Cyberphysical Systems April 2008

  - NITRD Workshop on High Confidence Transportation Cyberphysical Systems Nov. 2008

- **Presenter and Reviewer** 2005-Present
  Chaired panel discussions and reviewed papers for international conferences and journals.
- **Technology Support**, Boston University School of Law, Boston, MA 2003-2004
  Managed, configured and installed computer and audio-visual systems.
- **Summer Intern**, Engineering Support, Hughes Electronics, New Delhi, India 2002
  Provided engineering support for Interactive Distance Education Program using VSAT
- **Summer Intern**, Software Engg., Tata Infotech (now TCS), New Delhi, India 2001
  Provided support for software projects in Java and Microsoft Foundation Classes.

Refereed Publications

- **A. Agarwal** and T.D.C. Little, "Role of Directional Wireless Communication in Vehicular Networks," in *Proc. Intelligent Vehicles Symposium (IV '10)*, San Diego, CA, June 2010. *(under submission)*

- **A. Agarwal** and T.D.C. Little, "Impact of Asymmetric Traffic Densities on Delay Tolerant Vehicular Networks," *Proc. 1st IEEE Vehicular Networking Conference (VNC '09)*, Tokyo, Japan, October 2009.

- **A. Agarwal**, "PhD Forum: Routing Protocol and Performance Modeling in Delay Tolerant Vehicular Networks, " *Proc. 17th IEEE Intl. Conf. on Networking Protocols (ICNP '09)*, Princeton, NJ, Oct. 2009.

- **A. Agarwal** and T.D.C. Little, "Access Point Placement in Vehicular Networking," in *Proc. IEEE Wireless Access for Vehicular Environments (WAVE '08)*, Troy, Michigan, December 2008.

- **A. Agarwal**, D. Starobinski, T.D.C. Little, "Analytical Model for Message Propagation in Vehicular Ad Hoc Networks," *Proc. IEEE Vehicular Technology Conf. (VTC-Spring '08)*, Singapore, May 2008.

- T.D.C. Little and **A. Agarwal**, "Connecting Vehicles to 'The Grid'," in *Proc. National Workshop on High Confidence Automotive Cyber-Physical Systems*, Detroit, MI, April 2008.

- **A. Agarwal**, D. Starobinski, T.D.C. Little, "Exploiting Downstream Mobility to Achieve Fast Upstream Message Propagation in Vehicular Ad Hoc Networks," in *Proc. Mobile Networking for Vehicular Environments 2007, (INFOCOM '07)*, Anchorage, AK, May 2007.

- **A. Agarwal** and T.D.C. Little, "Prospects of Networked Vehicles of the Future," (*Position Paper*) in *Real Time Embedded Systems & Applications Conference (RTAS '07)*, Bellevue, WA, April 2007.

- T.D.C. Little and **A. Agarwal**, "An Information Propagation Scheme for Vehicular Networks," in *Proc. of IEEE Intelligent Transportation Systems Conference (ITSC '05)*, Vienna, Austria, September 2005.

Book Chapter

- **A. Agarwal** and T.D.C. Little, "Opportunistic Networking in Delay Tolerant Vehicular Ad Hoc Networks," in *M. Watfa (Ed.) Advances in Vehicular Ad Hoc Networks: Developments and Challenges*, IGI Global, 2010.

Journal Publications

- **A. Agarwal** and T.D.C. Little, "Access Point Placement in Vehicular Networking," in *International Journal of Ultra Wide Band Communications*, March, 2010. (*under submission*)

- **A. Agarwal**, D. Starobinski and T.D.C. Little. "Phase Transition Behavior of Message Propagation Speed in Delay Tolerant Vehicular Networks," in *Special Issue of IEEE Transactions on Intelligent Transportation Systems: Exploiting Wireless Communication Technologies in Vehicular Transportation*, July 2009. (*under submission*)

Other Publications

- **A. Agarwal** and T.D.C. Little, "Evaluation of Nearest Neighbor Communication Using Free Space Optics," (Poster and Abstract) in *NSF Seminar on Smart Lighting - Lighting Innovation for a Smarter Tomorrow*, Boston, MA, February 2010.

- **A. Agarwal** and T.D.C. Little, "Exploiting Locality in Vehicular Networking: A Case for VLC," (Poster and Abstract) in *NSF Seminar on Smart Lighting - Lighting Innovation for a Smarter Lighting Communication*, Troy, NY, June 2009.

- T.D.C. Little, **A. Agarwal**, J. Tang, "Prototype Wireless Sensor Network for Ecological Study: REU Report," *MCL Technical Report TR-12-31-2005*, September 2005.

- T.D.C. Little and **A. Agarwal**, "A New Information Propagation Scheme for Vehicular Networks," (Abstract and Poster) in *Proc. 3rd Intl. Conf. on Mobile Systems, Applications and Services (Mobisys '05)*, Seattle, WA, June 2005.

Honors and Awards

• Semi-finalist ICE (Ignite Clean-Energy Competition)	2009
• Winner (2nd position) at the Entrepreneur Design Contest (EDC)	2009
• Graduate Teaching Fellowship, College of Engineering, Boston University.	2008
• Research Assistantship, Multimedia Communications Lab, Boston University.	2005
• Travel grant from College of Engineering, USENIX.	2005
• Graduate Teaching Fellowship, College of Engineering, Boston University.	2004
• All India Certificate of Merit in Mathematics (top 0.1% candidates).	1997
• Junior Science Talent Search Scholarship.	1996
• "Most Innovative Design of a Recycled Product" Award	1995

Professional Activities

- Technical Program Committee (TPC) WEIA '09
- Reviewer for Journal of Selected Areas in Communications-Special Issue-Vehicular Communication Networks (JSAC '10), Transactions on Intelligent Transportation Systems (ITS), Vehicular Technology Conference (VTC '10), (VTC '09), (VTC '08), Wireless Access in Vehicular Environments (WAVE '09), (WAVE '08).
- Volunteer with American India Foundation (AIF - New England Young Professionals Chapter)
- Track Chair, BU Technology Entrepreneurship Night '08
- Sponsorship Committee, BU Technology Entrepreneurship Night ('08, '09), raised $2000
- Events Organization Committee, TiE, Boston Chapter (The Indus Entrepreneurs)

Technical Competence

- Operating Systems - Proficient in operating Windows, Linux and Mac OS X
- Programming Languages - Python, Java, C, C++, C#, .Net
- Packages - MATLAB, LaTeX, TinyOS, MySQL
- Spoken Languages - English, Hindi, German

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