ABSTRACT

RANGE MODULATION STRATEGY FOR MINIMIZING INTERFERENCE IN VEHICLE-TO-VEHICLE SAFETY COMMUNICATION

by Mason David Parrish

Vehicular communication networks hold promise to significantly improve road safety by giving vehicles improved awareness and advanced warning to emergencies. By their urgent nature, VANET applications regarding safety typically have strict performance requirements on delay and medium congestion. This has led to many different proposed approaches to improving the performance of safety message dissemination. Though these proposed solutions are able to improve the performance, they frequently make no mention of whether or not the improved performance is yet sufficient for the application. The proposed research will develop a scheme for modulating the transmission range of safety message broadcasts in order to satisfy the directly-measured delay requirements of each vehicle in the network. This method would guarantee that the message is delivered to each vehicle in due time whilst minimizing the interference in the network. The proposed research expands upon existing preliminary work by integrating more complete analysis of transmission delay and interference and implementing a more general system model. The theoretical analysis validates the proposed strategy, and simulations further characterize the behavior of the strategy under different conditions. Using the proposed strategy, vehicles on the road can adjust their communications to guarantee safety to every vehicle without overloading the network.

RANGE MODULATION STRATEGY FOR MINIMIZING INTERFERENCE IN VEHICLE-TO-VEHICLE SAFETY COMMUNICATION

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LIST OF ABBREVIATIONS

Abbr.	Description
VANET	Vehicular Ad hoc Network
V2V	Vehicle-to-Vehicle
RSU	Road-Side Unit
QoS	Quality of Service
ESM	Emergency Safety Message
CSMA/CA	Collision Sense Multiple Access / Collision Avoidance
AV	Autonomous Vehicle
HDV	Human-Driven Vehicle
RN	Relay Node

List of Major Variables

Symbol	Description
m	Index variable for the *m*th vehicle in the network
$x_m(t)$	Position of vehicle m at time t.
x_o	Position of the obstruction of the road
$x_{TX}(t)$	Position of the source vehicle at time t
$v_m(t)$	Velocity of vehicle m at time t
$x_{c,m}(t)$	Collision point of vehicle m
r_m	Reaction time of vehicle m
U_m	Delay tolerance of vehicle m
R_{TX}	Selected emergency safety message transmission range
N_m	Number of hops for a given transmission range to reach vehicle m.
T_m	Total transmission delay to vehicle m
S	Number of vehicles within a given range of a given vehicle
p_t	Probability of a vehicle transmitting a beacon message during time-frame t
ρ	Network density

Chapter 1 Introduction

This chapter introduces the concept of ad-hoc vehicular networks (VANETs), some of the applications they could provide, and the challenges in designing them. Furthermore, it summarizes the state of VANET research and briefly describes the novelty and motivation for the proposed research. The necessary components to complete the proposed work are described.

1.1 Background

Over the last three decades, advances in information and communication technology have had an enormous impact on society. Mobile communication networks enable individuals to connect to a host of persons or services at any time and any place, and internet access has become a basic home necessity. Presently, one of the least connected parts of everyday life takes place while driving, when interfacing with smartphones or other connected devices is unsafe. However, it is expected for vehicles to begin to adopt mobile communication capabilities in the coming years. If thoroughly adopted, this capability could enable services that provide improvements safety, driving efficiency, traffic capacity, infotainment, and more. Because of this, vehicular networks designed to enable vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications has been the subject of great interest from industry and academic research. These capabilities are often referred to as Intelligent Transportation Systems (ITS), and its goal is to make driving safer, more efficient, and more enjoyable [1]. This could involve alerts and information regarding road closures, traffic slowdowns, weather considerations, road hazards, lane changes, accidents, etc. as well as more efficiently routing vehicles through a city's grid to improve road capacity. To make driving more enjoyable, ITS could enable the vehicle to connect to the internet for social media, vehicle-to-vehicle chats, games, or more.

At the heart of ITS is the vehicular ad-hoc network (VANET). VANETs are a special case of the mobile ad-hoc network, which is characterized by a spontaneous network of highly mobile nodes that connect wirelessly without the need of existing infrastructure such as cellular towers or access points. As a speculative technology, there is research and development at each layer of implementation from physical to application. However, at all levels above physical, it often assumed that each vehicle in the network is equipped with an on-board unit capable of basic computing and short-range wireless communications as well as a suite of sensors, such as cameras, GPS, LIDAR, etc [2] [3].

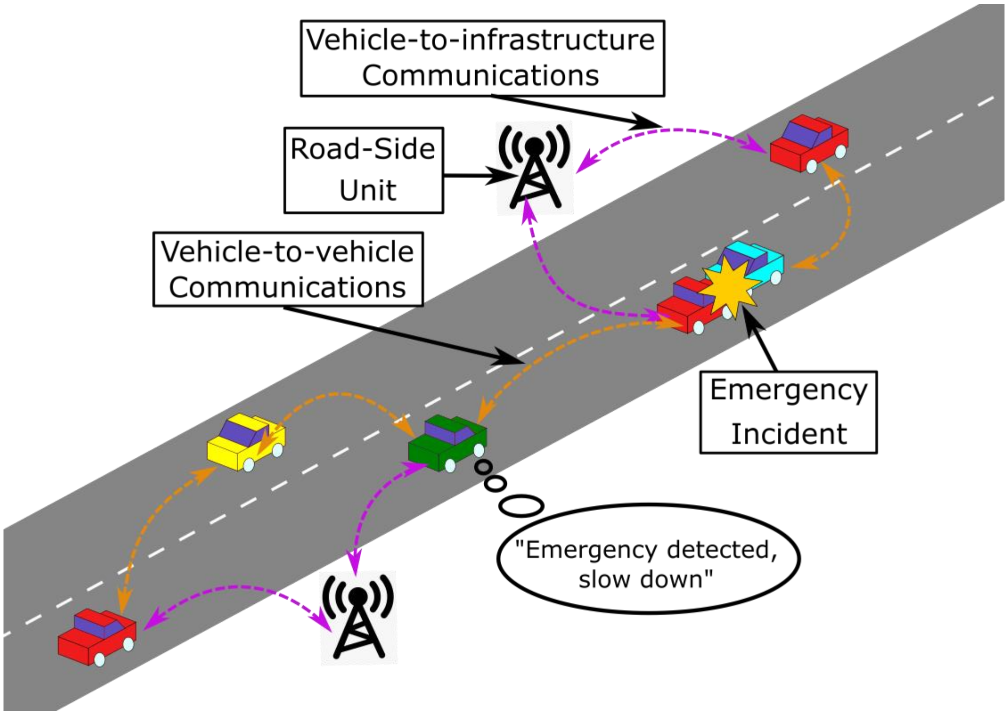

Figure 1: Illustration of a VANET

Cunha et al. provides a detailed overview of the main characteristics of VANETs, which is summarized here [2]. Firstly, they feature a highly dynamic topology. Vehicles can travel very quickly in relation to one another (especially if headed in different directions), so connections between vehicles are often temporary, resulting in frequent changes in the topology. Secondly, vehicles in VANETs are typically identified by their geographic location, not a static ID number. This is because it is usually not important which vehicle is in a particular location; the message is directed to whichever vehicle is in the relevant location. One of the advantages of VANETs is that the mobility of vehicles is constrained to the roads and the speed limits, meaning that the future positions of vehicles can more easily be predicted. Finally, depending on the application, the propagation model may vary. On highways, a free-space model is typically sufficient, but in cities, the presence of buildings and trees make a free-space model inadequate.

One of the biggest features of VANETs is the improvement to road safety. Routine communication of position, velocity, etc. among nearby vehicles can give drivers heightened awareness and emergency warning messages can give advanced warning of imminent accidents, which could prevent a great number of injuries and deaths worldwide. Before it can be adopted, however, it must first overcome certain challenges. VANETs are decentralized, wireless networks, which introduces challenges to mitigate cross-channel interference. Furthermore, depending on the circumstances, there may be strict delay requirements; after all, advanced warning is only helpful if it arrives before the driver would otherwise notice the danger.

Much of the research dedicated to VANETs seeks to optimize these two metrics: delay and throughput. In emergencies, messages can be sent to give early warning to drivers. These messages are infrequent and sent in small packets, meaning that throughput is not important. In contrast, the transmission delay is of utmost importance. Early warning for an emergency on the road can save lives and prevents injuries, but they are only as useful as they are early. Timely delivery of emergency safety warning is crucial to their function in VANETs.

In wireless transmissions (especially over short distances), the biggest cause of transmission delay in wireless networks is often the collision avoidance scheme. In wireless networks, the medium (the air) is inextricably shared between all nodes. If any two nodes transmit a message in the same time frame, a recipient in range of both messages will receive neither, as the messages collide and become unreadable. What's more, unlike wired networks, wireless networks have no way of sensing if a collision occurred or if the medium is going to be occupied. This means a medium access protocol must be utilized to decrease the probability of message collisions and verify that messages are received without collision. VANETs have been attributed the IEEE 802.11p protocol for wireless transmission, which means that, by default, this protocol is CSMA/CA (Carrier-Sense Multiple Access/Collision Avoidance). A diagram of how this protocol controls the timing of wireless transmissions is shown in Fig. 2 below.

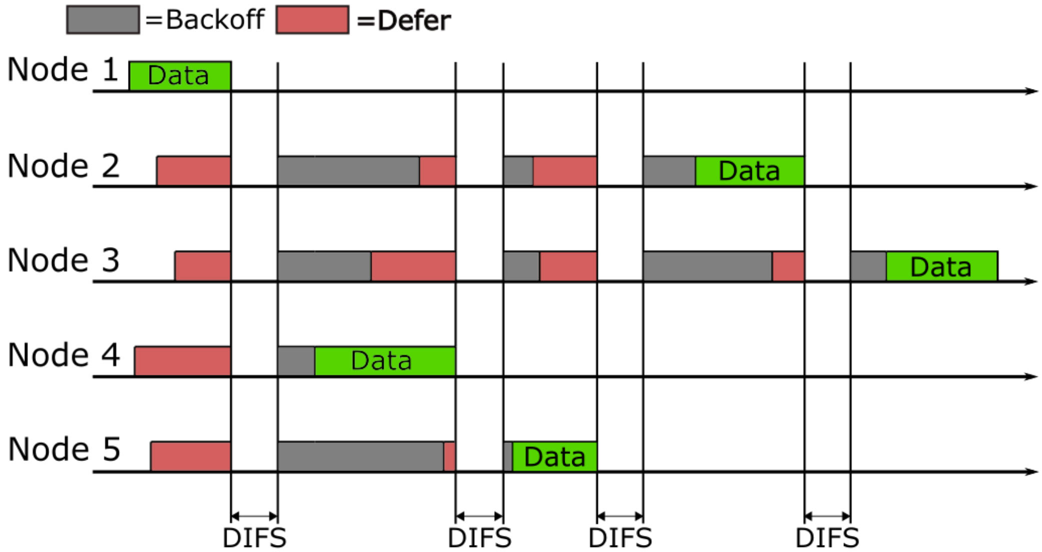

Figure 2: Timing Diagram of CSMA/CA MAC protocol for 802.11p wireless transmissions

CSMA/CA implements rules limiting when nodes are allowed to begin a transmission. In brief, nodes must wait a minimum of an inter-frame spacing (IFS) before transmitting. Once that time has passed and no transmissions are sensed, the node waits an additional, randomly chosen amount of time. If no transmission is still sensed, the node will transmit. The 'winning' transmitter exchanges data and acknowledgement with the receiver, spaced out by precisely an short inter-frame spacing (SIFS), ensuring no other nodes in the network attempt to transmit as well. This random waiting time during the contention window reduces the odds that two nodes try to transmit at the same time, but it's still possible. When this happens, each node doubles the range of times it randomly selects a waiting time from and waits until the next available window to attempt the transmission again, further decreasing the odds that two nodes transmit simultaneously. When the network is very dense, the delay caused by collisions can grow very large.

1.2 Research Overview

The development of a context-aware adaptive range modulation scheme for the dissemination of emergency safety messages (ESMs) in VANETs will be proposed. The scheme is novel in its approach to satisfying Quality of Service (QoS) requirements because it directly matches the observed requirements in real time as opposed to predetermined requirements. This scheme will rest on an optimization problem relating the range of a transmission, the current topology of the network and the state of the vehicles in it, and the predicted delay and interference.

Overall, the scheme will allow VANETs to prevent accidents when they are imminent and preserve network performance when they are not.

Though there are numerous schemes for reducing delay and interference in safety message disseminations, there are none that guarantee that such reductions are sufficient for the requirements of the safety message. In other words, it's unclear if the performance improvements other works feature would be enough to satisfy the application requirements. For example, the power control scheme presented in [4] is most effective at higher network densities, showing a delay of 60ms (a reduction of 150ms compared to other methods) in simulation. Within a vehicular network, each vehicle may have a different tolerance for delay. A driver with ample space before them could tolerate a high delay in the advanced warning message and a driver that is close to the vehicle in front has very little tolerance. If this scheme were deployed, it would succeed for any vehicles with more than 60ms of time to tolerate, but it would routinely fail to reach vehicles in more compromising positions, who are more likely to have needed advanced warning the most. Unless a 'blanket' strategy is able to achieve levels of performance significantly above the typical requirements, the only way to guarantee QoS for all vehicles is to adopt a strategy that adapts to the requirements of the present road scenario, not one that just achieves a flat improvement to performance. Other works have shown how transmission range can be adjusted to decrease delay [4]; the significant novel contributions of the proposed work include the real-time prediction of the delay requirement and the optimization for interference within this predicted bound.

The prediction of the delay requirement involves two steps. First is the prediction of each vehicle's tolerance, which depends on their position and velocity relative to the surrounding vehicles as well as the reaction time of the driver. This calculation is sufficiently covered by the preliminary work presented in Chapter 3. Second is converting this delay tolerance to a lower bound on the transmission range. In order to do this, there must be a mathematical relationship between the range of a transmission, the topology of a network, and the resulting transmission delay to each vehicle in the network. In Chapter 3, simplifying approximations are applied to obtain a proof-of-concept for the proposed transmission range modulation scheme. This approximation ignored a major component of VANET communications: interference and message collisions.

To further develop this, Chapter 4 presents an analysis of appropriate models for non-ideal wireless transmission delay. A balance must be struck between usability and accuracy, as the most accurate models may involve factors that cannot be reasonably measured or calculated in real time. Once a justified relationship is defined, the appropriate method of optimization will be developed and deployed in simulation, which will be adjusted to account for any additional relevant factors of the calculation. Predicting the delay requirement allows the system to guarantee that any range above the calculated minimum will arrive at each recipient in time for the necessary course of action to ensure safety. Among these ranges, the range that produces the minimum amount of interference should be chosen in order to minimize impact on the network performance. Therefore, a mathematical relationship between transmission range, the topology of a network, and the probability of a message collision can be used to inform the selection. As with the delay prediction, an analysis of appropriate probabilistic models of message collisions will be reviewed and applied. It is important to note that the safety message being broadcast is not being sent into silence; other vehicles are still sending and receiving routine beacon transmissions. In order to measure the interference of a safety message transmission, the strategy of beacon messages must be assumed and considered. Once an appropriate mathematical model is chosen, an analysis of the proposed system performance is carried out in simulated highway environments. The results of this analysis and simulation are shown in Chapter 4.

This work provides the following contributions to the work described in Chapter 3. Firstly, a more general model is considered for the network topology and transmissions therein. This will validate the conclusions of Chapter 3 and further support the efficacy of the proposed transmission range modulation strategy. Secondly, using a more complex model, the performance and behavior of the proposed strategy under different conditions is further characterized. Furthermore, the theoretical framework used to optimize the transmission range allocation is applied to provide an analysis of RSU deployment density.

Supported by theoretical and empirical analysis, the proposed system offers a unique safety benefit to automotive environments. Compared to non-VANET collision-avoidance systems such as emergency automatic braking (wherein sensors in a vehicle can detect rapid imminent head-on collisions and apply the brakes automatically) [5], early warning distribution through the vehicular network has the distinct advantages of being viable in most highway environments and not requiring any automatic interference to prevent accidents. Such automatic systems, though most often a reliable safety feature, are subject to problems such as false detections and malware attacks. By taking the human reaction time into consideration for the selected transmission range, the proposed VANET ESM dissemination strategy can guarantee each driver is able to avoid collisions without any automatic intervention.

The motivation behind the proposed transmission range modulation strategy is to provide the safety benefits of a VANET-enabled early warning distribution system while minimizing the impact of this system on the larger VANET system as a whole. Due to the myriad of potential enhancements to automotive transport that VANETs could bring, it is a certainty that they will begin appearing in major volumes before long. With such a system in place, the proposed strategy provides a method of utilizing the unique capabilities of the VANET to improve traffic safety in a more intelligent manner.

1.3 Summary

The unique properties of VANETs and the services they will provide make them a challenge to implement. In particular, emergency safety warnings have strict performance requirements. When an ESM is being propagated through a network, it is imperative that the message is delivered promptly and without being lost to medium congestion. Many researchers have proposed schemes to address this, but we have seen few that have developed a scheme that predicts the quality-of-service (chiefly, transmission delay) requirements of the network given the road scenario before selecting the optimal parameters for transmission. To address this gap, further development of an adaptive range modulation scheme for ESM distribution in VANETs capable of making such optimizations is proposed. A system capable of this could both guarantee safety to all nearby vehicles as well as minimize the interference as much as possible.

The proposed strategy will be instated through the development of an optimization problem and its solution. The problem constrains the range selection to those values that will produce a predicted delay less than or equal to the predicted delay requirement and selects the transmission range within this bound that gives the minimum probability of a message collision. The computational solution to this optimization problem will be instated in a simulation of realistic road scenarios. The results will be compared to a different method of simulation to show the efficacy of the analytical solution.

The remainder of this thesis is organized as follows. Chapter 2 presents the design problem in detail, and gives a brief overview of the existing literature surrounding this problem. Chapter 3 presents the preliminary work accomplished as a proof-of-concept, and discusses the shortcomings of this work. Here, a detailed description of the proposed range modulation scheme is given, as well as simulated results of its performance. Chapter 4 describes a more complete model for VANETs and re-evaluate the performance of the proposed strategy under the context of non-ideal transmission. Finally, Chapter 5 concludes this thesis with a projected schedule of the proposed work.

Chapter 2 Related Works

This chapter describes the problem statement to be investigated in the proposed work and reviews the background literature regarding the subject. Several strategies for improving the performance of VANETs are presented. In each case, the insufficiencies that motivate the proposed work are discussed. The resulting gap in the literature is given and the benefit of the proposed work to VANETs is made clear.

Safety messages must be distributed throughout a vehicular network rapidly in order to give drivers the advance warning they may need. One way delay can be reduced is by increasing the range of each transmission along the link, reducing the number of hops to the recipients. With a larger range, however, multiple broadcasts and rebroadcasts can quickly saturate the medium, preventing the transmissions from being successfully received. The problem, then, is finding how to transmit a message promptly while minimizing the probability of a message collision. This problem must be addressed for VANETs to be useful, or else features such as advanced collision warning will be unable to fulfill their purpose.

2.1 Cloud-Assisted VANET Messaging Schemes

In the past decade, a significant amount of research on VANETs have proposed integration with cloud-computing in one form or another. Hussain et al. [6] define three types: Vehicular Cloud, Vehicles using Clouds, and Hybrid Vehicular Clouds. For the purposes of this work, we are only interested in a Vehicles-using-clouds architecture, as it describes a VANET utilizing cloud services to improve VANET functions. The advantages of cloud-connectivity are not difficult to see; it allows VANETS to make use of computationally intense processes without requiring the necessary computing power in each car, it allows vehicles to connect and communicate through a centralized service, and it allows networks to span much greater distances, to name a few. One of the major issues cloud-connectivity may help solve is the fast and reliable delivery of emergency safety messages. Though many different approaches have been proposed, we will discuss three here.

In [7], Ullah et al. discuss the strengths of FoG cloud computing in VANET applications. The presented structure involves connecting the vehicular network to dedicated resources at the edge of the cloud service, thereby reducing the latency of accessing and utilizing cloud services.

In this kind of structure, the core cloud service works ahead of time to prepare the necessary services at the edge for the vehicles to use instead of having every vehicle request flow through the series of connections to the core computing unit. In this work, however, the authors do not present any specific algorithm or scheme to improve VANET communications. This leaves the claims unsubstantiated without further research to present evidence in support of it.

A more in-depth approach to cloud-assisted VANETs is presented by [8]. Here, a hybrid approach is taken for information sharing: some basic information is still shared in a V2V fashion with broadcasted beacon messages, but other, more complex information or messages are relayed through the cloud network. The cloud network can then forward those messages to many different vehicles and the broadcast storm [9] [10] is avoided. In simulation, the authors report a 30% reduction in packet loss compared to standard V2V protocols. Though this is encouraging, the strategy involves passing emergency safety messages through the cloud service. However, as per [11] [12], emergency safety messages are typically limited to V2V communication due to the highly stringent delay constraint and the relatively low packet size.

Liu et al [13] proposed CMDS, or Cloud-assisted Message Downlink dissemination Scheme, as a means of optimizing the dissemination of safety messages. The goal of CMDS is to improve the efficiency and delay of the message compared to V2V strategies by first sending the message to the cloud, which then distributes the message smartly throughout the target areas. The strategy is intended for urban environments and works by utilizing buses as 'gateways' to the cloud, through which the message is sent to the cloud and to which the cloud delivers the message, to then be disseminated to nearby vehicles. The authors note that the strategy is reliant on the general observation that among same-bound traffic, the vehicular network is largely unchanging. For this reason, however, the strategy is limited to only urban environments densely populated with cellularly equipped buses. On a highway, there would not be such a network of gateway vehicles that could connect vehicles to the cloud. This is corroborated by the simulated results, which show that CMDS grants large improvements to message delay and message collision in grid-like streets, but marginal-at-best improvements on a highway-type road.

2.2 Digital-Twin plus VANET

A subset of recent research into Cloud-assisted VANETs involves utilization of digital-twin architectures, where a representation of the physical world is maintained in a digital space in the cloud. For instance, Liao et al. [14] have made use of this architecture to develop a system to assist drivers in merging onto highways from on-ramps. The proposed system is very complex, involving models of vehicle behavior, driver behavior, and real-time data integration, but it is nevertheless feasible because it utilizes cloud computational power to run it. Should the system work as designed, drivers on the on-ramp and nearby drivers on the highway will be instructed how to maneuver to enable smooth and safe merging. The authors showed the efficacy of the system by a real-life field test, in which three vehicles were equipped with the proposed system and an on-ramp merger was performed. Using speed variance as a metric for the safety of the drivers, they report a 67% increase in safety, proving the effectiveness of the system. This system is largely a V2I implementation, not involving any direct V2V communication, but the results demonstrate that an accurate digital twin for cloud-connected vehicles is possible. This is further supported by [15], who created an accurate real-time digital twin of highway vehicles inside the Unity game engine.

More recently, Zhao et al. have proposed an architecture for intelligent digital twin software-defined vehicular networks (IDT-SDVN) [16]. The authors claim that such a network architecture would allow VANETs benefits such as centralized network control and adaptive routing schemes. In essence, it would have vehicles send behavior data to the cloud service to allow a digital twin of the road to be constructed. With this, the digital twin can make adjustments to various network controls and, using machine learning to predict possible future states for the road, find the optimal choice. The authors demonstrate the effectiveness of the architecture through simulation in Python, which show performance that matches or improves upon software-defined vehicular networks, which is itself an improvement on basic VANET protocols [17] [18]. In their work, Zhao et al. laid out the significant design challenges that must be met for this architecture to be feasible. Included is the road traffic prediction, the high-speed fusion of such large amounts of data, the energy cost of such computing services, and cross-layer optimization. Nevertheless, the technology is promising.

2.3 Non-Cloud-Assisted VANET Emergency Messaging Schemes

In addition to utilizing cloud computing for message dissemination, researchers have also proposed methods for improving the reliability of emergency safety messages purely within the physical vehicle network. These strategies are often either decentralized strategies broadly applied to each vehicle in the network or forwarding strategies wherein the whole of the message path is determined by the source of the message. Either way, as with most of the other strategies discussed in this chapter, these schemes will be optimizing for lower delays or less medium congestion, or both. Three strategies will be discussed in this section.

Farooq et al develops two different techniques for message flooding in VANETS [19]. Traditional message flooding involves broadcasting a message to all connected nodes, and each node then rebroadcasting the message to all its connected nodes, on and on until every node has received the message. Under the authors' first strategy, called unidirectional forwarding, vehicles would only forward messages to vehicles behind them, eliminating the redundant rebroadcasts of messages. To cover situations in which a message ought to be passed forward, such as at an intersection, the lead vehicle passes the message through a nearby RSU. In their second strategy, vehicles select a vehicle in range to be the only vehicle to rebroadcast the message, further eliminating the medium congestion. These strategies showed improvement against ordinary message flooding, but the issue with message collisions was not solved entirely.

In [20], Arsalan and Rehman seek to mitigate a similar problem. Because the network is decentralized, VANETs are particularly prone to the broadcast storm problem, wherein multiple vehicles broadcast messages at a high rate, making communication unreliable due to the high medium congestion [10] [9]. Their avoidance scheme, called BSAM, has each vehicle in the network compare received messages against a short-term buffer to identify if the message has been received already. If it has, it can be discarded instead of being rebroadcast. This means a message can be flooded into a network and it will not be redundantly rebroadcast multiple times, mitigating the broadcast storm. Their simulations show an improvement against simpler VANET protocols, but the results are not compared to any benchmark for real-world need. To improve VANET communication to a sufficient level, it is likely that additional improvements are necessary.

Another improvement to message dissemination is presented in [21]. The authors propose an algorithm for reducing redundant rebroadcasts even further than Arsalan and Rehman. In the latter, the message counter would prevent a redundantly broadcasted message from being rebroadcast again, but vehicles had no way of knowing if a broadcast is unnecessary before sending it the first time. To address this, Shah et al. develop a scheme in which vehicles intentionally wait an amount of time before rebroadcasting a message. During this time, if they receive the message again, they cancel their broadcast. The time they choose to wait is dependent on the distance to the source of the message, with farther vehicles waiting less time. In practice, this means that the farthest along vehicle within a cluster will rebroadcast the message, and other vehicles will not. This result is very similar to the second method proposed by [19] above, with vehicles now adding an additional delay to their broadcasts. Similarly, the authors show in simulation that the proposed scheme improves both transmission delay and packet delivery ratio, but it is not shown that this improvement meets the real need of the network. Without such assurances, it would be unsafe to deploy this strategy to real-life road scenarios.

2.4 Transmission Range Modulation Schemes for VANETs

The primary control mechanism of our proposed strategy is the transmission range of vehicles as they distribute an emergency safety message. In brief, using a larger range will allow the message to reach more vehicles in fewer hops, but will also contribute to packet collisions. Conversely, using a shorter range improves the probability of message collisions, but the message may require more hops, and therefore more time, to reach every vehicle in the network. To identify a gap in the literature, we will discuss four other works that have utilized transmission range modulation to improve VANET communication.

VANETS use beacon messages to stay aware of the local network; more frequent broadcasts allow a higher level of awareness, but also introduce more message collisions. Willis et al. seeks to develop a strategy of broadcast power modulation that allows the network to maintain a certain sufficient level of awareness while minimizing message collisions [22]. The authors note that previous approaches to the problem have proposed reducing the rate at which packets are sent when high network density is detected. These approaches succeeded in limiting message collisions, but in doing so reduced the network awareness as well. The authors propose a scheme in which the transmission power is modulated, sending frequent beacon messages at a low range and an occasional beacon at a high range. This way, in high density scenarios, vehicles that need high awareness can receive frequent updates without creating collisions across the entire network. Their scheme is simulated in network and traffic simulators, and they report that a hybrid of rate-limiting and range-limiting is most effective at reducing message collisions.

Alternatively, Aygun et al. proposed an algorithm, called ECPR, for modifying the power and rate of transmissions in unity [23], meaning that the impact of power control is considered before deciding the degree of power control to use, and *vice versa*. This strategy would have the transmission range and rate change in response to an increase in vehicle density or network connectivity, or more specifically in response to a change in the overall network awareness. To this end, the authors define a method of integrating awareness as a metric in VANET calculations. Simulated results comparing this strategy to previous work show that ECPR reaches target awareness more stably than rate-only or power-only congestion control. In both works, however, the authors only consider the passive beaconing messages that allow a VANET to stay connected. The transmission and dissemination of an emergency safety message is highly urgent, spontaneous, and unpredictable. For such messages, awareness is not the metric to be optimizing, nor is transmission rate a meaningful concept.

Other works, however, have addressed emergency safety message delivery by utilizing range modulation. Due to the short-range nature of DSRC communication, multi-hop forwarding is necessary to propagate important safety messages throughout a vehicular network. However, this introduces some complications, such as increased delay, lower transmission reliability, and interference due to medium congestion. Bousbaa et al. notes that a balance must be struck between transmitting at a small enough range to minimize interference and transmitting at a large enough range to satisfy the delay requirement of the message [4]. To address this, the authors submit an algorithm called TRBIP for finding the transmission ranges for each vehicle in the network that minimizes transmission power while satisfying some delay constraint. The algorithm first constructs a transmission tree defining the optimal (least power) path for message forwarding in the network, and then alters that tree until the delay requirement is met. The resulting tree gives the optimal range for each node in the network to use when forwarding safety messages. The authors simulate this algorithm in NS-2 and find that TRBIP uses less power than previous algorithms while also allowing shorter delays, meaning the reliability and timeliness of safety messages are both improved. Promising as this may be, the algorithm involves computing and comparing $\sum_{i=1}^{N}\binom{i}{2}$ values, which must be repeated upon any change to the network. In a fast-changing network such as a VANET, this algorithm would be computationally intensive, and may create additional delay. Furthermore, the authors of TRBIP do not ground their work in real-world values. Both how a delay from one node to the next is calculated and what the maximum delay threshold could be are left unanswered. Due to this, the efficacy of this algorithm in practical VANET scenarios is unclear.

Proposed by Rezgui and Cherkaoui, PCS seeks to provide a similar service to TRBIP, altering transmission range to strike an optimal balance between transmission delay and medium congestion [24]. Instead of an algorithm to compute optimal transmission range, however, PCS solves an analytical expression for it. This equation relates the physical parameters of a network to the transmission delay and collision probability to a delay threshold based upon general delay requirements reported by the National Highway Traffic Safety Administration [25]. The power control scheme is implemented in conjunction with priority-aware deterministic access protocol to minimize the probability of message collision. In this way, it is more closely grounded in VANET applications than Bousbaa et al. In simulation, the proposed strategy successfully kept transmission delay below the acceptable threshold at all densities, though they report an inevitable drop in packet reception rate at high densities. It is also worth noting that previous strategies not implementing the proposed PCS also satisfied the delay constraint in most (but not all) network densities. Nevertheless, we identify one core shortcoming of this work: the delay tolerance is given as a fixed number. Though that number may be a good benchmark for the application of the safety message, in real applications there may be more or less time available for message dissemination. If there is less time than the NHTSA figure, then the proposed scheme would fail to deliver the message in time; if there is more time, then the transmission delay can be increased for the sake of decreasing the probability of packet loss due to message collisions. Therefore, an improved power control scheme would also include a method of determining the exact delay tolerance of the network for a specific safety message.

2.5 Summary

The decades of research into VANETs collectively show that the concept has many difficulties that must be overcome. Its highly mobile and decentralized nature make it difficult to apply existing network optimization strategies, and the limitation to wireless communication introduces further complications in delay and medium congestion. Furthermore, in the case of ESMs, the performance requirements are strict; the message must be delivered quickly, and it must arrive reliably. A failure in either two may be the difference between life and death. Therefore, on the topic of emergency messages, the problem is how to ensure the message is delivered in the required time with as high of a probability of successful delivery as possible.

Several different researchers have proposed strategies and protocols aimed at making an improvement to transmission delay, packet delivery ratio, or both, but there remains a gap in the literature. Commonly, these researchers justify their proposed scheme by showing a direct improvement to one of those metrics in a simulated environment, but it is not always mentioned if the performance meets the needs of the vehicles in the network. Among those strategies that involved modulating the transmission range of vehicles forwarding an emergency message, one author did bound their strategy by a maximum delay threshold [24]. However, this threshold is taken as a fixed number, selected per the application of the message. This number may be roughly accurate in most scenarios, but it is unlikely to be exactly correct. This is important because the inaccuracy is at best missed potential (because the delay could have been increased slightly to improve message collision odds) or at worst fatal (because the assumed threshold was higher than the real threshold, and the algorithm did not deliver the message in time).

Therefore, the gap we seek to fill is creating an emergency message dissemination strategy that finds the optimal parameters for the specific situation at hand. This involves firstly developing a method for predicting the exact delay threshold given the road conditions, and secondly employing a strategy that will maximize the packet delivery probability subject to that delay threshold. To do this, an in-depth analysis of the transmission delay and packet delivery probability of emergency messages in VANETs is required.

Chapter 3 Range Modulation Strategy for Vehicle-to-Vehicle Safety Messaging Considering Human Reaction Time

This chapter describes the preliminary work of this thesis. This work serves as the foundation for the work presented in Chapter 4. Section 3.1 discusses similar works and explains the novelty of the proposed adaptive strategy. Sections 3.2 and 3.3 describe the system model and define the problem explicitly, and section 3.4 discusses the simulation configuration and the simulation results. Section 3.5 concludes the chapter and discusses the strengths and shortcomings of the work presented in this chapter.

3.1 Introduction

Though there have been countless effective advancements in automotive safety, accidents still account for nearly 40,000 deaths and 4.5 million injuries each year in the United States alone [26]. This motivates much of the extensive work in developing real-time vehicular communication and computation systems. With the advancements of such vehicular networks, drivers can both stay more aware and react quicker to avoid potential accidents [13] [4] [27]. Additionally, the continuing evolution of automated technology can deliver greater safety benefits and automated driving systems, bringing up an undeniable growing trend of increase in the number automated vehicles (AVs) in use each year [28]. It is foreseeable that AVs will coexist with human-driving vehicles (HDVs) for a long time to come, and their impact on transportation systems is the topic of much research [29] [30] [31]. Thus, the coordination between these two types of vehicles will be critical in improving road safety for all.

The distinct differences in the nature of these two types of vehicles, however, makes a mixed system more complicated than a homogeneous one. AVs are divergent from HDVs in the way they behave as well as in the way they interface with a vehicular network. Firstly, it has long been known that the reaction time of drivers is a significant factor in their safe driving and in the overall traffic flow [32]. AV's, on the other hand, are driven by computers that can react with negligible delay to stimuli. Secondly, AV's can interface more directly with the network than HDVs can, both communicating more information and potentially making use of more of the shared information. In contrast, for HDVs, information from the network must be synthesized into notifications that are useful and understandable to the human drivers. To suit the needs of both types of vehicles, a novel system for improving accident avoidance would make vehicles aware of the speeds, positions, and reaction time of other vehicles in the network. This way, each vehicle is more aware of the traffic flow and safe driving requirements. In fact, with this information, it is possible to make accurate predictions of how each vehicle would individually behave in the case of an emergency. Furthermore, these predictions will allow vehicles to determine whether an emergency broadcast will reach others fast enough to allow them to come to a safe stop. However, in traditional vehicular ad hoc network (VANET) protocol, it is not reasonable for vehicles to be able to know the reaction times of other vehicles.

In order to ensure that every vehicle is aware of neighboring vehicles' complete information, in this work, we will propose a digital twin-based cloud-centric network architecture that will allow vehicles to share more information and enable adaptive modulation of the transmission range of the vehicle-to-vehicle communications. Digital twin is a digital representation of mobile vehicles in the virtual cyberspace and is located at the edge cloud. The individual agents in digital twin (as the representative of the physical vehicle) will use information about all neighboring vehicles to determine whether a broadcasted safety message of a given range will reach every vehicle in time to prevent a collision. By using real-time data of neighboring vehicles, the system can significantly improve safety in the event of unsafe driving conditions such as tailgating or icy roads by tailoring safety message broadcast range specifically to the present needs of the nearby vehicles.

The basic premise of the proposed strategy is as follows. Increasing the transmission range of the vehicle-to-vehicle safety message will decrease the transmission delay by reducing the number of hops the message takes. By predicting the delay tolerance of each vehicle in the network, we can predict the minimum necessary transmission range for the safety message such that each vehicle receives the message in time to avoid a collision. Though the lowest transmission delay could be achieved by broadcasting at the largest possible transmission range regardless of the delay tolerance of the affected vehicles, this approach will significantly degrade the reliability of the safety messages. As Bousbaa et al. observes, “inter-vehicular transmission interference is a critical problem for VANETs, which can be reduced by minimizing the total transmission power” [4]. The loss in signal integrity when broadcasting at such high ranges would more than counteract the benefit of a shorter delay. The proposed strategy will guarantee the safety of the affected vehicles while minimizing the risk of the safety message being lost to interference by finding the minimum transmission range that meets the delay tolerance of nearby vehicles.

The concept of modulating the transmission range of vehicle-to-vehicle communications has been proposed to reduce delay by minimizing medium congestion in [22] [27]. Aygun et al. developed a scheme for modulating transmission range to maintain a required level of passive awareness in the vehicular network [23]. However, few existing works have dealt with the range modulation problem considering the coexistence of AVs and HDVs or directly integrated human reaction time into the strategy design.

To exploit the coordination with AVs and HDVs coexisting for minimizing transmission range while simultaneously improving safety, in this chapter, a strategy to adaptively modulate the transmission range of the vehicle-to-vehicle communications in digital twin-based cloud-centric vehicular network will be developed. The main contributions of this chapter are as follows. Firstly, a hierarchical architecture integrating the vehicular network with a digital based cloud network for a digital twin-based framework for real-time, individual reaction time predictions and range determination is proposed. Secondly, based on the proposed architecture, human reaction time is considered as a crucial parameter to design a novel range modulation protocol for vehicular network safety messaging. Finally, simulations in different scenarios are conducted to demonstrate the efficacy of the proposed strategy.

The remainder of the chapter is organized as follows: Section 3.2 provides an overview of the network architecture. In Section 3.3, the proposed range modulation strategy is presented. Section

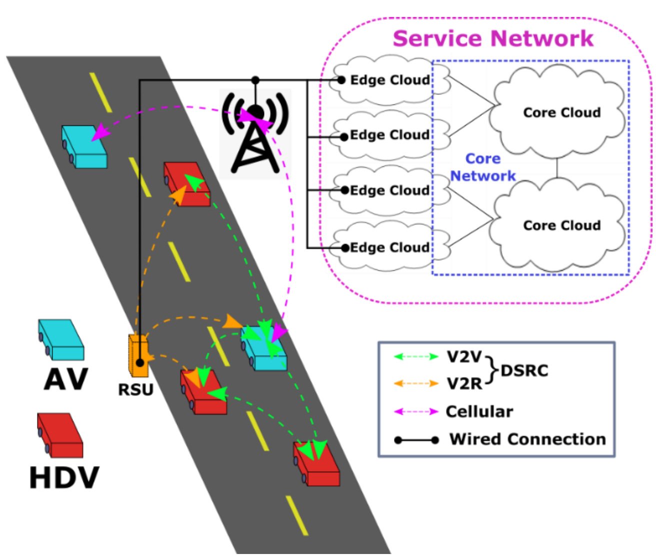

Figure 3: Illustration of the proposed network architecture

3.4 demonstrates the performance of the proposed strategy by simulations. Section 3.5 concludes this chapter.

3.2 System Model

As shown in Fig. 3, roads are taken to be one-dimensional and bidirectional, representing a standard two-lane road. We consider two sets of vehicles in along the roads, e.g., AVs and HDVs. Each vehicle will be connected to cloud servers, which will carry out heavier computations as well as model the driver's behaviors, i.e., the driver's reaction time. For autonomous vehicles, this connection is maintained constantly through the cellular network that services the vehicle's autonomous driving [33] [34] [35]. Human drivers connect through Roadside Units (RSUs), which we assume to be deployed densely [36] [37]. During this connection, they will send the server the collected driving data and receive the model's updated reaction time prediction so that the HDV may share this information with other vehicles in the network.

Facilitated by the connection, a digital twin-based cloud-centric network architecture for AV system will be developed. Fig. 3 shows the digital twin-based architecture, in which there are four key components, i.e., Core Cloud, Edge Cloud, digital twin and the Ends. Core Cloud is fully connected with each other to build the core networks through high-speed optical links. These core clouds in the proposed architecture provide computing, caching, and communications resources for the ends as a network infrastructure service. Edge Cloud resides between the core cloud and the ends. It can help the core clouds to provide a very high quality of network services. Digital twin is a digital representation of mobile vehicles in the virtual cyberspace and is located at the edge cloud. It provides a new digital twin-based communication model to replace the traditional end-to-end communication model. The Ends refer to human driving vehicles and AVs in the network. They are consumers of the network services and are connected to the network via various access methods. The ends acquire services from network via digital twin. Vehicles access this service network through RSUs that may be installed along the road. Put in another way, each vehicle will provide the digital agent with its position and speed, and the digital agents of all vehicles in the network will share this information. The digital agents will then send their corresponding vehicles the information of all vehicles. This method of sharing vehicle information is preferred to direct vehicle-to-vehicle communication because the digital agents can communicate in a high-speed, defined network as opposed to an ad-hoc network, which is prone to message collisions and medium congestion. This architecture benefits the system in two ways. Firstly, by using cloud resources to execute more complex computations, the system does not require individual vehicles to be equipped with unnecessary computing power, making the system more easily implemented. Secondly, by having the network information shared between digital agents in the cloud network, vehicles don't need to rely on frequent and unreliable beacon broadcasts to know the relative position and speeds of others in the network.

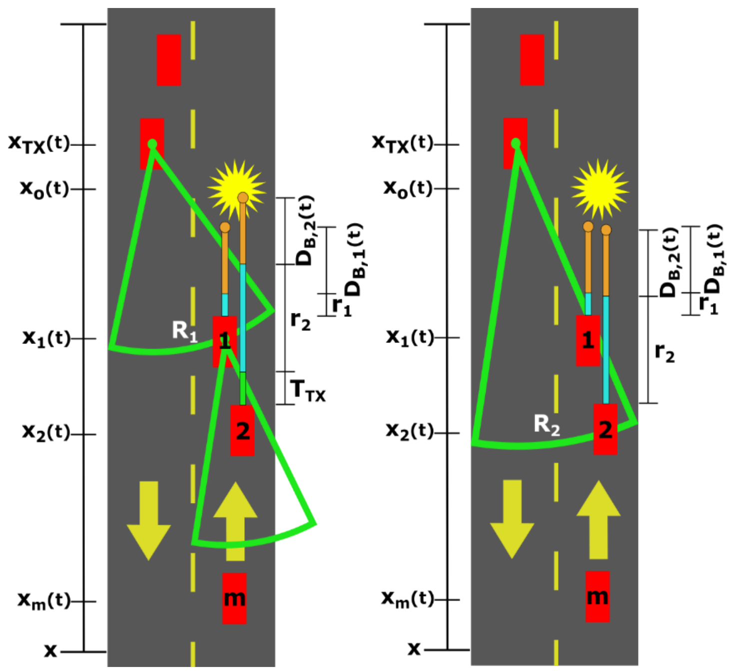

Figure 4a: Depiction of problem scenario with static range r_1

Figure 4b: Illustration with adaptively chosen range r_2

Figure 4: Comparison of two scenarios using different transmission ranges to deliver a safety message

For emergency safety messaging, an RSU would be able to assist in propagating any safety message farther along the road to other vehicles. However, even when in range of an RSU, emergency safety messages (ESMs) are typically propagated locally via vehicle-to-vehicle broadcasts because of the relatively small packet size and highly time-sensitive nature of the message [11] [12]. For the purposes of this chapter, safety transmissions to or from RSUs are not considered.

In this chapter, a mathematical relationship between driver reaction time, traffic flow parameters, transmission parameters, and the ideal transmission range is developed. Firstly, the reaction times of each driver are determined by a random number generated on a normal distribution based on the findings presented in [38]. An autonomous vehicle is represented by having a reaction time of zero seconds, since an AV is driving in an automated manner. The positions of each vehicle along the road are determined by generating time headways from the Pearson Type-III distribution shown in [39]. The parameters for the distribution are altered to match measured data from six different vehicle densities.

As an example (shown in Fig. 4), a set of vehicles move along the road at time period t, defined as $M(t)$. The m^{th} vehicle is located at position $x_m(t)$ in time period t, for each m $\{0, 1, 2, ..., M(t)\}$. The m^{th} vehicle move at speed $v_m(t)$, in time period t. The braking distance of the m^{th} vehicle at time period t is denoted by $D_{B,m}(t)$. Additionally, the driver in m^{th} vehicle has a reaction time $r_m(t)$. In Figures 4a and 4b, the distance vehicles 1 and 2 travel during these times (reacting and applying the brakes) is marked in blue and orange bars, respectively. For instance, along the road, an obstruction is placed at position x_o. The first vehicle to detect the road obstruction is taken to be the lead vehicle and their position on the road is denoted as $x_{TX}(t)$. Other vehicles will be placed along this line with varying densities, given in terms of vehicles per minute. Each vehicle will be placed according to the distribution of time headways presented in [39]. Though vehicle density on a highway can change with time, we will analyze the model in small windows of time such that the density is practically fixed. For each traffic density, the traffic flow may move at different speeds. The speed of traffic $V(t)$ and density $\rho(t)$ determine the position of each vehicle along the road $x_m(t)$. The average distance between vehicles will be defined as $D_{avg}(t)$. Each vehicle will make other vehicles in the network aware of its predicted reaction time r_m, so all connected vehicles know the reaction time of all other connected vehicles. Given a vehicle detecting some kind of obstruction or danger, the proper setting of transmission range $R(t)$ is crucial to deliver a safety message to all affected vehicles in time such that no vehicle is unable to react in time to avoid collision.

In this example scenario, we show the vehicle nearest to the obstruction at position $x_o(t)$ transmitting a safety message to all nearby vehicles (transmission is only shown as an arc for illustration purposes; in reality the message is broadcast in all directions). In Figure 4a, the transmitting vehicle sends the message using a static range, typically about 200 meters [37]. This allows vehicle 1, who is able to react quickly, to come to a stop before collision. This range does not reach vehicle 2, however, so vehicle 1 rebroadcasts the safety message after a small delay T_{TX}. The distance covered by vehicle 2 during this delay is shown as a green bar below the reaction distance and braking distance. We can see that, in this example, this small delay cannot be tolerated if an accident is to be avoided. In Figure 4b, the transmitting vehicle at $x_{TX}(t)$ transmits the message at a higher range, reaching both vehicles 1 and 2 in 1 hop, eliminating the transmission delay T_{TX}. This allows vehicle 2 to come to a full stop in time and avoid a collision.

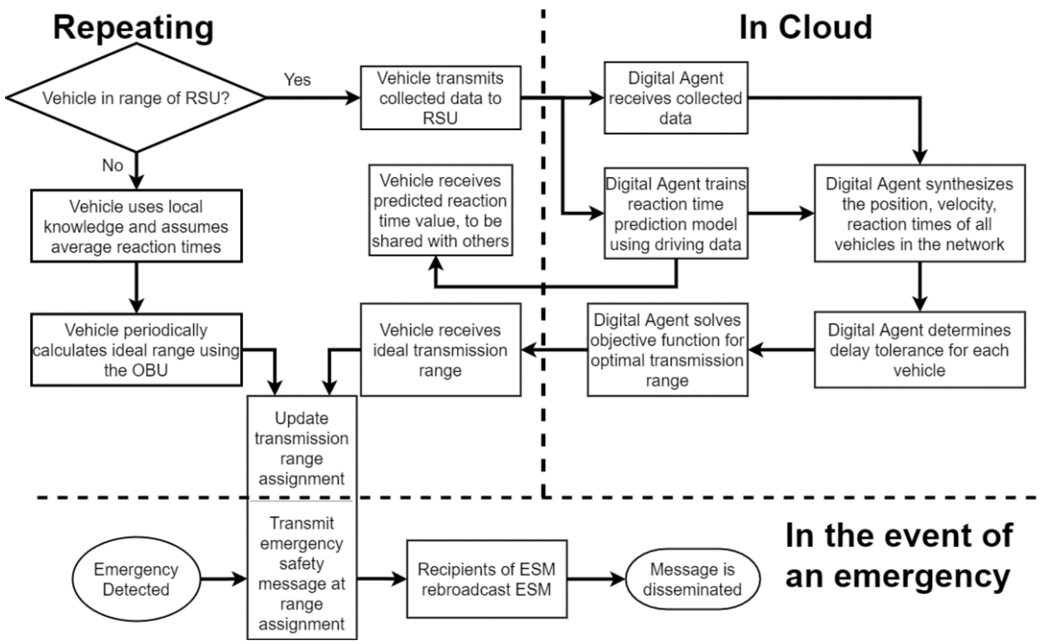

Figure 5: Framework for the transmission range modulation scheme presented in this chapter

Figure 5 shows the framework for the proposed transmission range modulation strategy. Vehicles in the network periodically communicate with their digital agents through RSUs, receiving updated real-time range assignments for use in the event of an emergency. The rate that this process is repeated is subject to how rapidly the network topology changes. For example, highway segments near large interchanges will have vehicles entering, exiting, and changing lanes rapidly. In this case, vehicles must frequently prompt their digital agents for updated transmission range assignments. Each time a vehicle communicates with its digital agent, it also sends recorded driving behavior data, which the digital agent uses to train a model predicting the reaction time of the driver. This prediction is updated as more training data is given, and the predicted value is sent back to the vehicle to be shared in beacon messages to other vehicles in the network. This method of pre-calculating the ideal transmission range assignment for the given highway scenario allows for zero delay in the event of an emergency, and poses a low computing overhead cost on the cloud computing service.

3.3 Problem Formulation

In the following section, the formulation of the range-optimization problem is given. The objective function and its constraints depend on a variety of different parameters, which we will categorize into two groups. Firstly, the transmission range R is the single parameter being optimized, so it is distinct from the other parameters involved. Secondly, the various parameters of the immediate road environment (such as the number of vehicles, their positions, the reaction times of drivers, the dryness of roads) all factor into the optimization. These parameters, however, are both uncontrollable and, within small time-frames, relatively unchanging. The collection of these road parameters is given in a vector $\hat{C}$:

$$\hat{C} = [r_m, \quad x_m(t), \quad x_o, \quad x_{TX}(t), \quad v_m(t), \quad \rho(t), \quad a, \quad M(t), \quad D_{AVG}(t)]. \qquad (1)$$

Table 1: Description of parameters

Symbol	Description
r_m	Reaction time of vehicle *m*
$x_m(t)$	Position of vehicle *m* at time *t*
x_o	Position of the obstruction of the road
$x_{TX}(t)$	Position of the source vehicle at time *t*
$v_m(t)$	Velocity of vehicle *m* at time *t*
$\rho(t)$	Density of the traffic at time *t*
a	Deceleration constant
$M(t)$	Number of vehicles in the affected network at time *t*
$D_{AVG}(t)$	Average distance between vehicles at time *t*

In predicting the urgency of a message to any particular vehicle, it is imperative to know the length of time that it will take for a vehicle to take the necessary actions to avoid collision. Depending on the circumstances, this maneuver could be to swerve out of the way, slow down, or perhaps even speed up. The slowest of these measures is to come to a complete stop. In our analysis, we will consider this maneuver to be taken to ensure that the safety message arrives soon enough for any possible maneuver can be taken. To be precise, the vehicle must come to a full stop before it reaches the point along the road that the preceding vehicle would reach, were it to begin braking immediately. This will ensure that no vehicle crashes into the vehicle in front of it. This point is defined in Eq 3. To find the braking time, the braking distance is calculated as the following.

$$D_{B,m}(t) = \frac{v_m(t)^2}{2a}, \tag{2}$$

$$x_{c,m}(t) = x_m(t) - x_{m-1}(t) + \frac{(v_m(t))^2}{2a} + r_{m-1} \cdot v_{m-1}(t), \tag{3}$$

where $v_m(t)$ is the velocity of vehicle m, r_m is the reaction time of vehicle m, and a is the rate of deceleration during braking. The deceleration constant a was defined to be 7.35 meters per second per second by [40]. Knowing this distance, we can find the time that can be afforded to deliver the safety message in time to this vehicle

$$U_m(\hat{C}, t) = \frac{x_{c,m}(t)}{v_m(t)} - \frac{D_{B,m}(t)}{v_m(t)} - r_m. \tag{4}$$

This tolerance metric can be compared to $T_m(t)$, the total delay of a message to vehicle m, shown below. Referring to Fig. 4a, $U_m(t)$ can be thought of as the maximum length of the green bar that is tolerable before vehicle m collides with the obstruction,

$$T_m(t) = N_m(t) \cdot T_{TX}. \tag{5}$$

where T_{TX} is the transmission delay of the safety message in seconds, and $N_m(t)$ represents the number of hops in the transmission link. The transmission delay is a function of ρ, the network density. The precise relationship, which can be found in [41], is not necessary for the analysis in this chapter. Instead, an approximate average delay is used in the calculations. This is justified because we strictly consider intermediate vehicle densities. In chapter 4 of this thesis, this assumption is relaxed. The number of hops in a transmission link could vary greatly depending on which communication protocol is used and the distance to the recipient. For instance, a two-hop routing protocol limits the number of hops to a maximum of two, requiring the recipient or forwarding vehicle to move into the range of the transmitter to receive the message if they are not already in range. This routing strategy significantly reduces network medium congestion, but is not greatly time-sensitive, making it ill-suited for emergency message delivery [42]. In the proposed system, messages will be limited to three broadcasted hops, with the broadcast range shrinking or growing to ensure that every vehicle in the network can be reached without relying on the movement of the nodes [36].

The number of hops in a transmission link will be dependent on the position of the vehicles and the transmission range. However, because of the near infinite ways *m* vehicles can be arranged, it is impossible to represent this parameter in a single generalized equation. For the purposes of the optimization, vehicles are considered to be evenly distributed a distance $D_{avg}(t)$ apart. Under this consideration, the following expression for $N_m(t)$ can be given as

$$N_m(t) = \frac{x_{TX}(t) - x_m(t)}{R_{TX}(t)}. \qquad (6)$$

It is important to note that this assumption is used for the calculations, and that vehicles are distributed differently in simulation (see section IV). Because the vehicles are arranged in this way, the only sensible ranges to consider are positive integer multiples of $D_{avg}(t)$. Any range in between non-integer multiples of this distance will only be expending more power to reach the same nodes. Because of this, the decision variable of the optimization problem can be shifted to the strictly integer-valued variable i, where $i \in \mathbb{Z}^+$,

$$R_{TX}(t) = i \cdot D_{avg}(t), \text{ } i \text{ is integer-valued.} \qquad (7)$$

Though the purpose of this adaptive-range method is to occasionally increase the transmission range to prevent accidents, it is still pertinent to be as conservative as possible. Using an unnecessarily large transmission range is redundant and risks packet loss due to high medium congestion. Under the constraints enumerated above, the range used for the transmission link will be minimized. This objective function is given below in Equation 8.

$$\min Z = \sum_t i \cdot D_{avg}(t)$$
$$\text{s.t} \begin{cases} T_m(t) < U_m(t), m = 0, 1, \ldots M; \\ i \text{ is integer valued.} \end{cases} \qquad (8)$$

This calculation, from Equation 2 to Equation 8, is carried out by the digital agent within the digital twin framework. This leaves the vehicle's OBU free from making any computation, making it available for other applications. The calculations are done periodically so that, in the event of an emergency, the ideal transmission range can be utilized immediately.

3.4 Simulation Results

In this section, the simulation built to verify the above theoretical analysis and analyze the performance of the proposed transmission range modulation strategy is described. A model of the highway described in section 3.2 above is generated randomly and the proposed strategy is applied. The details of the simulation configuration are given in section 3.4.1, and the results are discussed in section 3.4.2.

3.4.1 Simulation Configuration

To simulate the proposed power allocation strategy, a realistic simulation of the problem as defined in section 3.2 will be created. In particular, the many road parameters that may be measured or learned by communication in a real-world application will be defined explicitly. As a case study, we consider the number of vehicles in the system to be 10. As mentioned in Section 3.2, the driver reaction times and headway distances are defined by random distributions based on [38] and [39], respectively. For the reaction time, a normal distribution with a mean on 1336 ms and a standard deviation of 333 ms was used. For headway distances, a Pearson Type III distribution for 10, 15, 20, 25, 30, and 37 vehicles per minute was used. These densities were chosen so that all densities are well-described as "intermediate traffic flow" (less than 56 vehicles/km) per [39]. The probability distributions for 10 through 25 vehicle/min flows were tabulated in Appendix A of [39]. For 30 and 37 vehicle/min, Type III distribution functions were made based on measured time headways in [43]. Finally, traffic speeds investigated were 40, 55, and 70 miles per hour.

Because the optimization problem defined by Equation 8 is a single-variable function, solving it does not require any methods such as mixed-integer linear programming. The solution is found in the simulation by first finding the boundary of the feasible region as defined by the constraints. Once both constraints are satisfied, the smallest possible range will necessarily correspond to the minimum tolerable power allocation because the objective function is strictly increasing over the domain. Because the positions and reaction times for each vehicle are determined by random distributions, the simulation is run 1000 times and the average result is taken.

To illustrate the strengths and drawbacks of the proposed strategy, different variations of the simulation were carried out for comparison. To demonstrate the importance of considering the driver reaction times, the strategy was applied to the scenario in which the reaction time of all vehicles is not considered. In other words, Equation 4 was carried out assuming $r_m = 0$. The maximum transmission delay is compared for each vehicle density at 55 miles per hour in Fig. 6. To observe how the system is affected by the presence of AVs in the network, another variation of the simulation was carried out. As the penetration rate increased, a higher proportion of the 10 vehicles in the system were (randomly) chosen to be AV's, represented by having a reaction time of zero seconds. The maximum transmission delay and corresponding power allocated at different penetration rates is shown in Fig. 7.

Finally, the improvement to safety is shown by comparing the strategy to one that uses a fixed range for all vehicle-to-vehicle communications. This comparison was drawn by counting the total number of instances across the 1000 iterations in which the first constraint in Eq. 8 is not met when the transmission range is set to 200 meters. This total is compared to the number of instances in which the proposed system also fails to meet this constraint (due to the range maximum). The results of this comparison are shown in Table 1. These counts could be thought of as collisions, but it is important to note the assumptions outlines in section 3.3. The only maneuver considered is braking to a full stop, and for each vehicle it is assumed that the vehicle ahead is immediately aware of the obstruction and begins braking immediately. These assumptions were made because they represent the worst-case-scenario and thereby force the system to work in any scenario, but the incidental effect is that there are many more "collisions" than is realistic.

3.4.2 Simulation Results

The primary purpose of the proposed power allocation strategy is to improve the safety of drivers on a highway. In this regard, the results in Table 1 show that modulating the transmission power in accordance with the urgency of vehicles along the road can reduce potential accidents by an average of 36%. It is more effective at slower speeds, and most effective at an intermediate traffic density. This is likely because these conditions leave vehicles close enough to one another to present the danger of an accident while not being so close that standard 200m communications are largely sufficient to reach the relevant vehicles. Even so, the proposed strategy reduced accidents by a significant amount in every scenario.

Table 2: Potential accidents avoided using proposed strategy

	Vehicle Density (veh/min)								
	10			25			37		
Speed	T	M	P(%)	T	M	P(%)	T	M	P(%)
40 mph	266	58	21.8	467	374	80.1	514	302	58.8
55 mph	293	49	16.7	502	232	46.2	550	181	32.9
77 mph	313	60	19.2	522	144	27.6	567	117	20.6

T = Total, M = Mitigated, P = Percent Mitigated

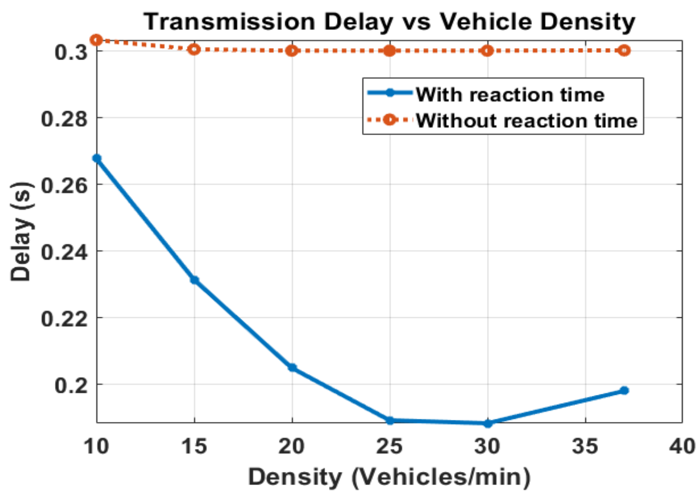

Figure 6: Comparison of transmission delay versus vehicle density for a system that considers the driver reaction time and a system that does not.

Figure 6 shows the average transmission delay of vehicles at different network densities. The blue solid line marks the average transmission delay that results from the proposed strategy when the system takes into account the reaction time of the drivers in the network. The red dashed line shows the resultant transmission delay of the same strategy applied without consideration for reaction times.

The pattern exhibited by the proposed strategy as shown in blue illustrates that the average transmission delay of vehicles is lowest at the density of 25 vehicles per minute. This corroborates the result given by Table II; at intermediate densities (e.g., 25 vehicle/min), the average transmission delay is decreased due to the larger transmission range of the transmitter enabling more connections among vehicles, compared to the lower density case (e.g., 10 vehicle/min). While the density continued increasing (e.g., 37 vehicle/min), the average distance between vehicles becomes smaller and a smaller transmission range within the feasible region would be selected based on the proposed strategy, which will lead to the increased average transmission delay.

When reaction time is not considered as shown in red line, however, the performance is not sensitive to changes in the network density. Even though the average delay tolerance is changing over the range of densities, the chosen transmission delay is constant. This is because, when reaction time is not considered, the perceived tolerance of each vehicle is significantly greater than the maximum delay allowed by the three-hop limit. Therefore, no matter the distribution of vehicles, once the system has ensured the three-hop limit is met, the system sees no

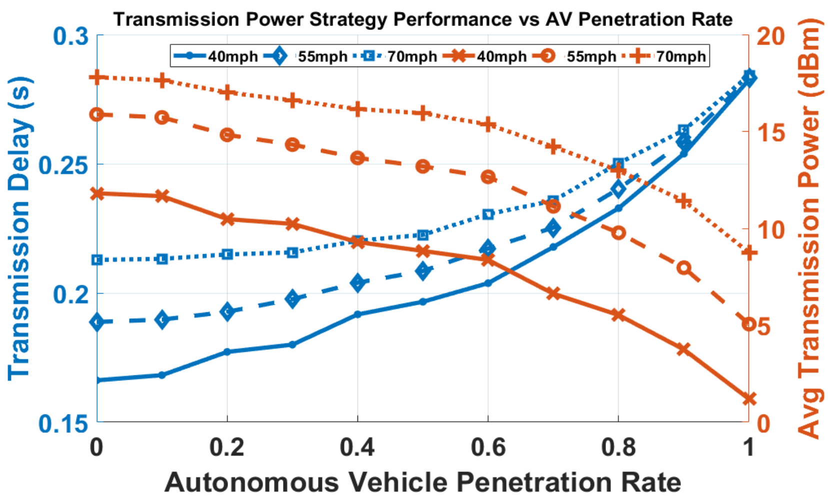

Figure 7: Performance of the transmission power modulation strategy as the autonomous vehicle penetration rate increases. The transmission delay and transmission power are plotted on the left and right vertical axes, respectively.

need to increase the range to ensure safety. In other words, the system will believe each vehicle has significantly more time to come to a stop than they do, and this will lead to a significant number of accidents, as the chosen ranges will result in a higher delay than can be tolerated. Then, that the reaction time of drivers must be considered to ensure the safety of vehicles in the network using this system.

As shown in Fig. 7, we can see that as the AV penetration rate increases, the average transmission delay of the system increases. In other words, as more vehicles are able to respond instantly to received safety messages, the less likely the system is to increase the transmission range in order to meet a tolerable delay, which will result in the increased average transmission delay. Subsequently, as the AV penetration rate increases, the power allocated to the transmitter decreases. In cases of high AV penetration rate, the system changes from primarily increasing the transmission range to ensure safety to decreasing range to reduce power consumption.

3.5 Summary

In this chapter, we have presented a novel transmission power allocation strategy for vehicle-to-vehicle safety messaging that utilizes network-awareness of drivers' reaction times to determine the transmission range necessary to ensure all vehicles can avoid a collision. The goal is to minimize the power allocated to the transmitter subject to the necessary condition that the transmission delay to each vehicle is within tolerable limits. Our simulations have shown that there are ample scenarios in which this strategy can prevent a potential accident. We have investigated the performances of the designed strategy in the presence of autonomous vehicles. The simulation results have demonstrated that with enough AV's in the network the power allocation strategy allows vehicles to conserve power while remaining safe.

However, the impact of the results shown in this chapter are limited, as the work was based upon a simplified model of a VANET. Most importantly, the transmission delay was calculated using an estimation that minimized the effect of network density on the performance of the strategy. Since estimation of the transmission delay is paramount to the premise of the strategy, and because the results in this chapter demonstrate the narrow window for error in this estimation, this oversimplification must be accounted for to verify these results. Furthermore, the unrealistically basic model of a highway limits the applicability of the analysis and the scope of diversity in traffic scenarios. These shortcomings will be addressed in Chapter 4.

Chapter 4 Range Modulation Strategy for V2V Safety Message Distribution under Non-Ideal Transmissions

This chapter describes an extended investigation of the proposed transmission range modulation strategy under a more generalized model. By analyzing the effect of non-ideal transmissions on the dissemination of safety messages in a general VANET, a model for the performance of the proposed strategy under different network loads will be shown. The results of this section further demonstrate the potential benefits of the proposed strategy and validate the conclusions of Chapter 3. Furthermore, the analysis presented in this chapter is applied to characterize the performance of RSUs and provide guidelines for their deployment for the sake of the proposed scheme.

4.1 Introduction

Though there have been countless effective advancements in automotive safety, accidents still account for nearly 40,000 deaths and 4.5 million injuries each year in the United States alone [26]. This motivates much of the extensive work in developing real-time vehicular communication and computation systems. With the advancements of such vehicular networks, drivers can both stay more aware and react quicker to avoid potential accidents [13] [4] [27]. Vehicles connected in a vehicular ad-hoc network (VANET) can broadcast their location and speed and future intentions, allowing other drivers to have a more complete picture of the traffic around them and making the movement of traffic more predictable for all. For these reasons – and many more, such as improved traffic efficiency and infotainment applications – it is expected to be implemented as a standard feature in U.S. vehicles before long [44] [45].

Improving the passive awareness of drivers is not the only way that VANETs can improve automobile safety, however, and nor are such improvements sufficient for preventing automotive accidents. Making the movement of vehicles more predictable to all helps prevent accidents due to human error or misunderstanding, but some incidents are inherently unpredictable. For example, a person or animal jumping out into the highway will cause an immediate emergency that could not have been predicted. In such a situation, the difference between if a driver has a collision or not is purely whether or not they can react quickly enough to avoid crashing into the braking vehicle before them. VANETs can be utilized to disseminate a warning message alerting drivers to the emergency before they would have noticed it otherwise, giving drivers more time to react and avoid the collision.

When disseminating an ESM, the first priority is obviously to distribute the message as quickly as possible to give as much early warning as possible to the endangered vehicles. This would mean transmitting and forwarding this message at the highest range possible, so that the message reaches all affected vehicles in as few steps (or hops) as possible. However, when considering non-ideal wireless transmission, transmitting at high range could actually delay the message further by causing large amounts of interference. Furthermore, VANETs have many different prospective applications that would be impacted by this dissemination strategy. Using a smaller range will cause less interference, but the transmission will take more hops to reach every vehicle in the affected network. Therefore, when disseminating an ESM in the event of a sudden, unpredictable emergency on the road, a strategy for selecting a transmission range that’s a satisfactory balance between speed and interference is needed.

Ideally, this balance achieves a transmission delay that is low enough to reach each vehicle in time for it to avoid a collision while minimizing the amount of interference introduced into the network. To do this, however, it would become necessary to know not only the speed and position of each other vehicle in the network, but the reaction times of the drivers as well. Without this information, it would not be possible to make an accurate prediction of how much time each vehicle has before an automotive accident is unavoidable. However, in traditional vehicular ad hoc network (VANET) protocol, it is not reasonable for vehicles to be able to know the reaction times of other vehicles.

In order to ensure that every vehicle is aware of neighboring vehicles' complete information, in this work, a digital-twin-based cloud-centric network architecture that will allow vehicles to share more information and enable adaptive modulation of the transmission range of the vehicle-to-vehicle communications is proposed. Digital twin architectures utilize cloud services to construct a digital mock-up of the physical system from collected sensor data. Using the more powerful computing power of the cloud, the reaction time of drivers can be modeled, predicted, and shared with other vehicles. By using real-time data of neighboring vehicles, a system can significantly improve safety in the event of unsafe driving conditions such as tailgating or icy roads by tailoring safety message broadcast range specifically to the present needs of the nearby vehicles.

Additionally, the continuing evolution of automated technology can deliver greater safety benefits and automated driving systems, bringing up an undeniable growing trend of increase in the number automated vehicles (AVs) in use each year [28]. It is foreseeable that AVs will coexist with human-driving vehicles (HDVs) for a long time to come, and their impact on transportation systems is the topic of much research [29] [30] [31]. Thus, the coordination between these two types of vehicles will be critical in improving road safety for all. The distinct differences in the nature of these two types of vehicles, however, makes a mixed system more complicated than a homogeneous one. AV's are divergent from HDVs in the way they behave as well as in the way they interface with a vehicular network. Firstly, it has long been known that the reaction time of drivers is a significant factor in their safe driving and in the overall traffic flow [32]. AV's, on the other hand, are driven by computers that can react with negligible delay to stimuli. Secondly, AV's can interface more directly with the network than HDVs can, both communicating more information and potentially making use of more of the shared information. In contrast, for HDVs, information from the network must be synthesized into notifications that are useful and understandable to the human drivers. Given the inevitable coexistence of HDV's and AV's, future proposed systems for automotive safety must consider the unique traits of AV's and the effect of AV penetration rate on the performance of the system.

In short, the proposed strategy for dissemination of ESMs is as follows. Increasing the transmission range of the vehicle-to-vehicle safety message will decrease the transmission delay by reducing the number of hops the message takes, but increasing it too far causes critical levels of interference, causing greater delay. By predicting the delay tolerance of each vehicle in the network, the minimum necessary transmission range for the safety message such that each vehicle receives the message in time to avoid a collision can be predicted. Then, of the range of transmission ranges that would satisfy this requirement, the ideal transmission range is that which minimizes the amount of interference in the network.

This strategy provides a safety measure to vehicles that is not provided by other non-VANET safety features. For example, most vehicles manufactured in 2022 and beyond include automatic braking systems that use radar sensors to automatically apply the brakes if an imminent collision is detected [46]. This feature can prevent collisions by applying the brakes before the human driver is aware of the need to, but it is only designed for “low-speed,” and has reported issues with false detections [46] [47]. Using VANET to give early warning has a few distinct advantages over this system. Firstly, a VANET is capable of delivering the emergency warning message regardless of the speed of traffic. Secondly, the proposed system imposes no control over the vehicles, making it less likely to cause serious harm in the event of a fault or failure. It is capable of doing this because it accounts for the estimated reaction time of drivers, so it can deliver a message in time for the driver to react to it and avoid the accident.

The concept of modulating the transmission range of vehicle-to-vehicle communications has been proposed to reduce delay by minimizing medium congestion in [22] [27]. Aygun et al. developed a scheme for modulating transmission range to maintain a required level of passive awareness in the vehicular network [23]. However, few existing works have dealt with the range modulation problem considering the coexistence of AVs and HDVs or directly integrated human reaction time into the strategy design. The work presented in Chapter 3 gives a simple version of the work presented here. Though the results demonstrated the viability of the proposed scheme, the system model and theoretical backing rested on simplifying assumptions, such as 1-dimensional roads and ideal transmissions. Because wireless transmission interference is crucial to the performance of the proposed system, this chapter will make full consideration of them. The results shown in Section 4.4 will more closely reflect the actual performance of the proposed range modulation scheme in a physical application.

The remainder of the chapter is organized as follows: Section 4.2 provides an overview of the network architecture and the system model in which the proposed strategy is considered. Section 4.3 provides the theoretical analysis of the delay tolerance prediction and the performance of wireless transmission in a VANET and provides the problem formulation. The simulation of the proposed strategy is discussed in Section 4.4, and Section 4.5 concludes the chapter.

4.2 System Model

As there are various different kinds of roads, traffic patterns, and possible VANET configurations, it would be impossible to analyze the performance of the proposed transmission range modulation strategy in general terms. In this section, the specific model considered in this thesis is described. Section 4.2.1 described the physical model i.e., the type of road, the location of vehicles, etc. Section 4.2.2 describes the specific means of V2V and V2I communication and describes the network framework utilized in this thesis. Finally, section 4.3.3 declares the proposed strategy for determining the ideal transmission range for dissemination of ESMs.

4.2.1 Physical Model

4.2.1.1 Fixed-Density Vehicle Distribution Configuration

To demonstrate the proposed range modulation strategy, a realistic model of highway traffic connected as a VANET is presented. The network consists of human-driven vehicles (HDVs) and autonomous vehicles (AVs), and varying rates of AV penetration are considered in the model. As shown in Fig. 8, a six-lane, bidirectional highway is considered. The road is straight with a length of 1 kilometer, and vehicles move along it in realistic distributions. Each vehicle is given a random lead headway time, chosen from a distribution observed in [Traffic Flow Fundamentals]. For example, Vehicle C stays 1.3 seconds behind Vehicle B, who stays 0.6 seconds behind Vehicle A. The distribution of lead headway times depends on the traffic density, ergo multiple traffic densities are considered. In very sparse traffic, clusters of vehicles are too small and far apart to form VANETs sufficiently complex for this study. On the other hand, in very dense traffic, the lead headway time distribution approaches a constant value, where all vehicles are nearly uniformly distributed. Between these extremes, lead headway time can be modeled as a Pearson Type-III distribution [39]; in this chapter, six possible densities in this range are considered, ranging from 10 vehicles per minute to 37 vehicles per minute.

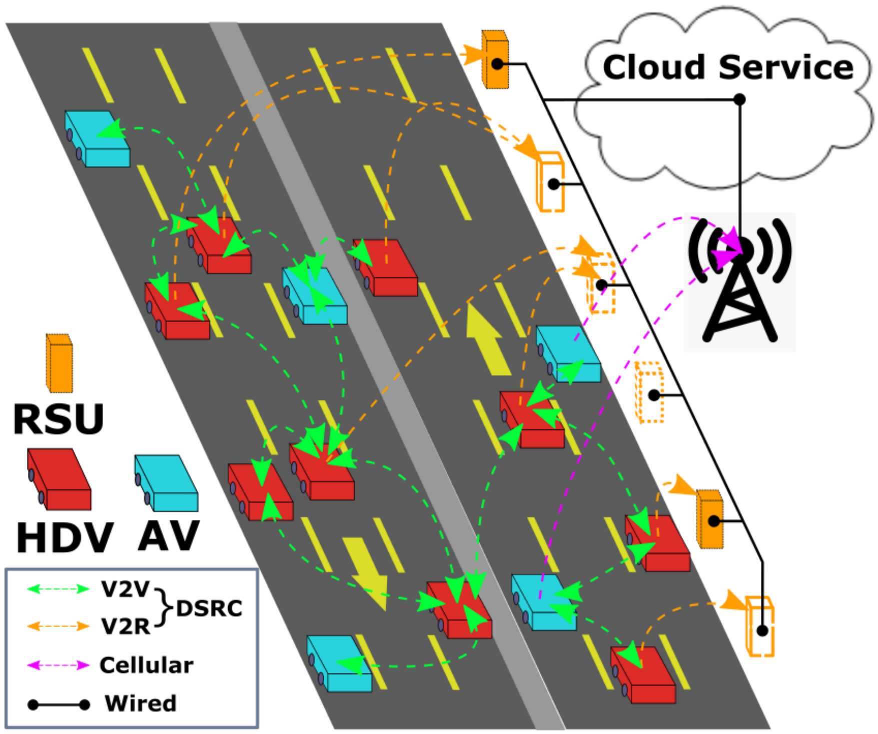

Figure 8: Illustration of proposed system model. Dashed RSU's indicate the variable density of RSU deployment.

As in a typical U.S. highway, vehicles in the left lanes travel at a higher speed than vehicles in the right lanes. For a given average highway traffic speed v_{avg} miles per hour, the vehicles in the left-most lane will be travelling at an average speed of v_{avg} + 5 miles per hour, and the vehicles in the right-most lane will be travelling at an average speed of v_{avg} – 5 miles per hour. In this model, multiple average traffic speeds are considered, ranging from 20 to 70 miles per hour. Within each lane of the highway, each vehicle selects a speed at random (uniformly about that lane's average speed). With each vehicle given a lead headway time and a velocity, the vehicles can be placed spatially along the highway. For each of the M vehicles along the road, its position is designated as x_m and its velocity v_m, where m ∈ [1,...,M].

Finally, in order to accurately predict the safety of the proposed range modulation strategy, the reaction time of each driver must be considered. A study conducted on the cognitive response of drivers found that reaction time in highway environments follows a normal distribution [38]. AVs are considered to have a reaction time of 0 seconds. Based on this, each vehicle m ∈ [1,…,M] in the model is assigned a random reaction time r_m. In the application of the range modulation strategy, there could be multiple approaches to considering this time. The simplest option would be to assume each vehicle to have an average or maximum reaction time. Alternatively, a prediction of each driver's reaction time could be distributed to other vehicles in the network, allowing each vehicle to know the specific reaction time of all other vehicles. This is discussed further below.

This model of a vehicular network on a highway road has distinct advantages over the system model presented in Chapter 3. The chief difference is in the number of lanes; considering a road with multiple lanes in each direction is both more realistic and more generalizable. Vehicles' positions (and therefore the distance between them) is two-dimensional, meaning the model is easily generalizable to more or less lanes. Furthermore, calculating the number of vehicles within range of a transmission is critical to the interference and delay analysis, and a one-dimensional model cannot realistically capture the same volume of vehicles as a two-dimensional one. This model also considers a diversity of velocities, which makes the network architecture dynamic over time.

4.2.1.2 Real-time Network Density Prediction

The proposed transmission range modulation strategy selects and utilizes a transmission range to disseminate an ESM in a very short time frame – on the order of seconds at most. Because of this, characteristics of the road such as network density are considered to be fixed for the purposes of the proposed strategy. It is assumed that the immediate network density can be measured through a combination of sensors and V2V communications, and this is sufficient for the theoretical analysis presented in section 4.3 and simulations given by section 4.4. Nevertheless, the network density of a given highway does change over time. For example, highways near urban areas most likely experience a spike in traffic density during rush hour. This change in density can be predicted for a particular highway by using real-world collected data to train a machine-learning model. Doing so would free up resources in the VANET from needing to measure and compute traffic density, further improving performance. As a demonstration, a prediction model of vehicle density on a section of highway approaching downtown Beijing is presented in this section.

Vehicle data is collected minutely by separating the region into small grids, which are chosen to be small enough that characteristics such as traffic density and traffic speed are homogenous within. An algorithm to determine the grid density for each grid at a particular time reference *t* is developed. The procedure of this algorithm is to sort through the location of each vehicle in the region and determine the number of vehicles currently within the given grid at any time *t*. This value is used in combination with the length of the road segment within the given grid and the rate of change of vehicles' location (the velocity of the vehicles) to calculate the vehicle density in units of vehicles per minute for any given time *t*.

Using this time-series data, an LSTM model was trained for each grid in the region. For the purposes of this thesis, one grid containing a straight segment of highway (as in the model described in section 4.2.1.1) southwest of the city center is highlighted. The LSTM model used two layers with *n* units each, a dropout of 0.05, and a dense layer with one unit. During fitting, a batch size of thirty was used in ten separate epochs. For a single grid, the processing is normalized according to Equation 9.

$$D_i' = \frac{D_i}{\bar{D}} + 5. \tag{9}$$

In the above equation, D_i' is the normalized density, D_i is the original density, and $\bar{D}$ is the average of densities in a specific grid. The first 3000 minutes of vehicle data are used for training the model, and the prediction is compared to the next 2000 minutes. The results are shown in Fig. 9 below.

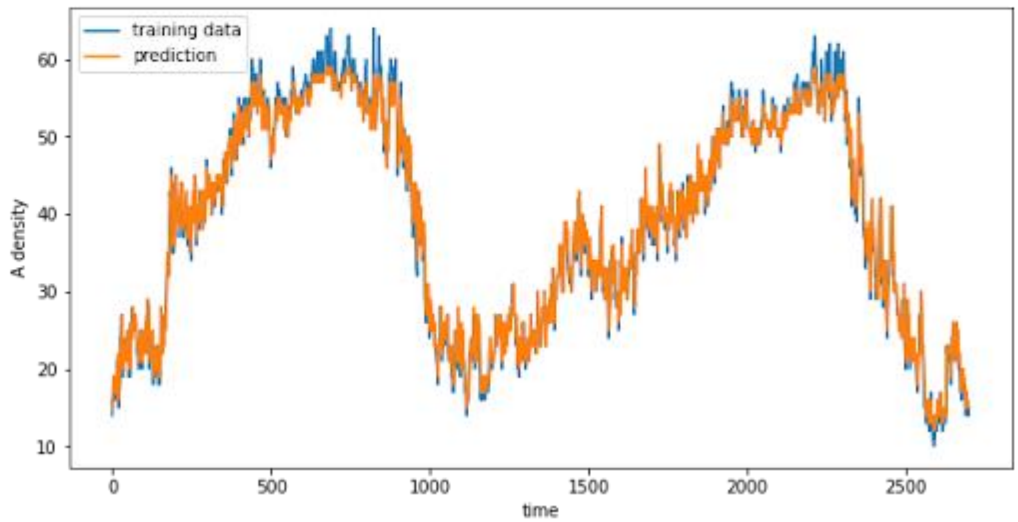

Figure 9: LSTM Traffic Density Prediction Model

By using this model, the traffic density can be predicted for any time of day. This prediction may be used to predict the number of vehicles within a given distance of a point, or to estimate the performance of an RSU. As network density is critically important to the performance of non-ideal transmissions, the theoretical analysis presented in section 4.3 makes direct use of the vehicle density which is predicted here.

4.2.2 Network Model

In the proposed system model, each vehicle is considered to be connected in a VANET. In typical fashion, network awareness is maintained through periodic beacon messages sent and distributed throughout the network by individual vehicles. These allow each vehicle in the network to know the position x_m and velocity v_m (among other things) of each other vehicle m in the network. Furthermore, each vehicle is also connected to a cloud-computing service through a digital-twin architecture. A digital-twin architecture is a network architecture designed to mimic real-world scenarios in real time in order to utilize higher computing power for prediction and calculation on the real-world scenario [48] [49]. There are four main components in a digital-twin architecture: the core cloud, the edge cloud, the digital twin, and the end user. The core cloud houses the bulk of the high-end computing power, and it is connected to the edge clouds via high-speed optical links. Edge clouds house the digital twin and are the interface layer between the end user and the core cloud. They provide quick access and connectivity to the end users while controlling and optimizing the utilization of the core cloud. The digital twin is stored in the edge clouds and is a digital mockup of a single vehicle and its surroundings. The physical vehicle (the end user) transmits data to the edge cloud regarding its position, velocity, and the information it has about neighboring vehicles, and the digital twin is able to mimic the highway environment. This digital twin can then be used to make real-time calculations or predictions about the real-world scenario. This architecture benefits the system in two ways. Firstly, by using cloud resources to execute more complex computations, the system does not require individual vehicles to be equipped with unnecessary computing power, making the system more easily implemented. Secondly, by having the network information shared between digital agents in the cloud network, vehicles don't need to rely on frequent and unreliable beacon broadcasts to know the relative position and speeds of others in the network.

The VANET is connected to the digital-twin cloud service through road-side units (RSU's) which are installed along the highway as wireless access points to the larger cloud network. For most of the analysis presented in this chapter, the RSU's are considered to be deployed densely, meaning that vehicles along the road are always connected to the cloud service and that the delay in connecting to this network is negligible. However, varying densities of RSU's deployment are also considered, with the goal of determining an ideal RSU deployment density for a given traffic density.

When the ESM is generated and transmitted from the source vehicle, it is forwarded throughout the network in a manner that mitigates redundant transmissions and reduces unnecessary wireless interference. In the ideal case, each transmission designates one and only one receiver as the forwarding transmitter. This prevents what is often referred to as a broadcast storm, in which several nodes retransmit a message and cause a significant increase in interference [13] [10]. However, because non-ideal transmissions have a significant chance of failure, forwarding strategies that designate only one relay node are prone to failure when the designated relay fails to receive the message. Instead, a relay node is "elected" by a random process wherein recipients select a random time to wait before retransmitting the ESM. If a recipient receives the held message again, it cancels its retransmission and disregards the repeat message [50]. Since the objective of the scheme is to disseminate the ESM in the most efficient manner possible, vehicles farther away from the source vehicle will have a bias towards selecting smaller waiting times, meaning they will more often become the relay vehicle. As a note, these forwarding delays are considered to be negligible on a human time scale, and are therefore not considered in the calculation of transmission delay.

If successful, this results in only one (and always at least one) relay vehicle per hop along the transmission link, minimizing strain on the network. However, there is a possibility of "spurious forwarding," wherein multiple recipients of a message elect to act as relay nodes. This can occur if either a recipient fails to receive the properly-elected relay vehicle's duplicate message or if two recipients select delay times close enough to one another [50]. The probability of this failure increases with the number of recipients to a message i.e., with larger transmission ranges.

4.2.3 Proposed Transmission Range Modulation Strategy

The objective of the proposed range modulation scheme is to analyze the specific road scenario at the moment of emergency and select the ideal transmission range for the dissemination of an ESM. This range is selected to guarantee a delivery time fast enough to allow each recipient enough time to come to a full stop if necessary as well as minimize the probability of causing undue interference in the network. In reality, motor accidents can be avoided by performing maneuvers other than braking to a full stop. However, in designing a system for guaranteeing safety for all, we consider only the slowest emergency maneuver so that it may perform well in any scenario. In the proposed system, it is assumed that each retransmission of the ESM uses the same transmission range as the original broadcast. To avoid unnecessary load on the network, only one recipient of a transmission is designated to retransmit the message [50]. To meet these conditions, the source vehicle must first be able to predict the delay tolerance of each vehicle; in other words, how long of a delay can be tolerated in receiving the message before it is too late. This tolerance can be compared to a function relating transmission range to expected transmission delay. This will be discussed in more detail in section 4.3.

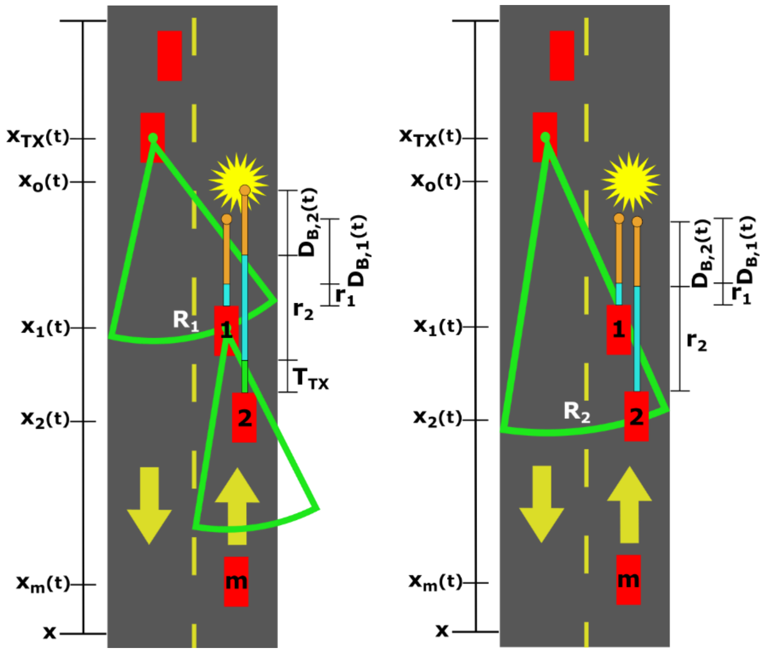

Figure 10a: Depiction of problem scenario with static range *r_1*

Figure 10b: Illustration with adaptively chosen range *r_2*

Figure 10: Comparison of two scenarios using different transmission ranges to deliver a safety message

As an example, consider the set of vehicles shown in Fig. 10a. Vehicle 1 has a short reaction time, so it will be able to come to a full stop before the collision point x_o. Vehicle 2 is travelling at the same speed, so it has the same braking distance D_B. However, vehicle 2 has a significantly longer reaction time. If the message is delivered to vehicle 1, who then retransmits it to vehicle 2, the transmission delay T_{TX} will be too great and vehicle 2 will not be able to avoid a collision. If, however, the source vehicle (at position x_{TX}) selects a greater transmission range, the message can be delivered to vehicle 2 in one hop (Fig. 10b), reducing the delay and avoiding an accident. The source vehicle could choose to use an even greater range, but doing so would cause undue interference with other messages being sent in the network. Therefore, the best transmission range is the minimum range that still reaches vehicle 2 in one hop.

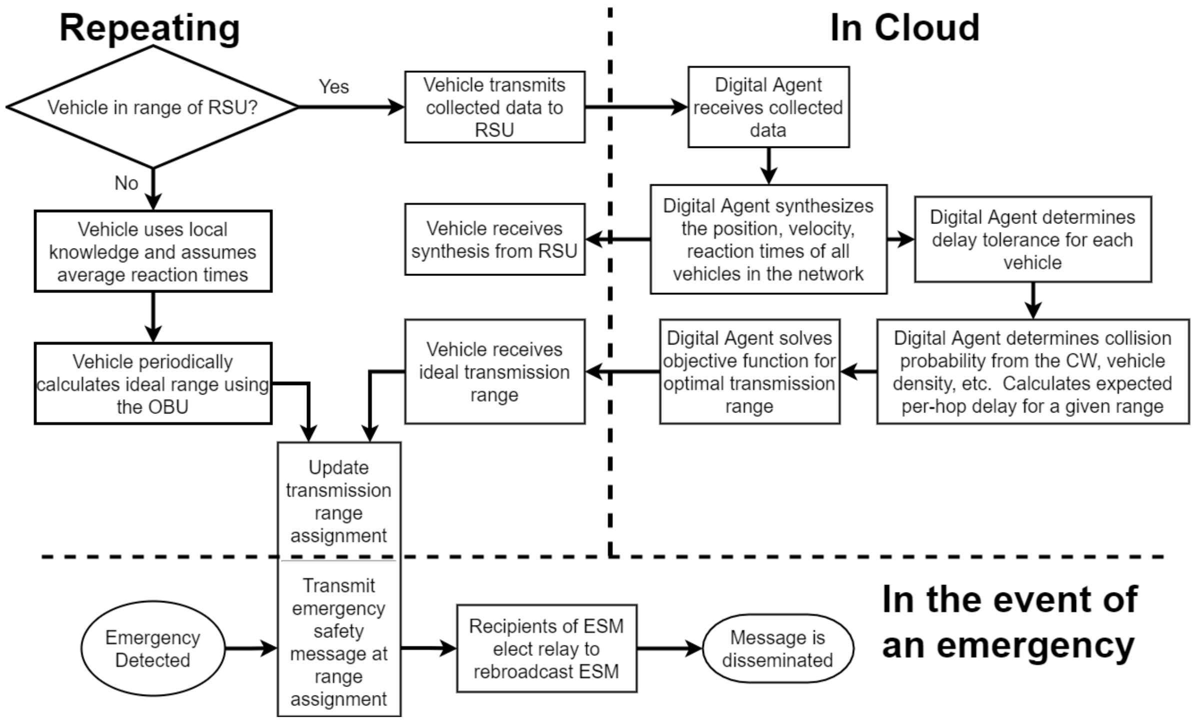

Figure 11: Framework for proposed range modulation strategy

This example shows the intuition behind why the transmission range is varied. In application, it is vital that the source vehicle is able to select the optimal range with as little delay as possible. Therefore, the digital-twin architecture is used to pre-allocate the ideal transmission range assignment to each vehicle before an emergency is detected. A diagram of the strategy is shown in Fig. 11. When a vehicle is connected to an RSU, it periodically transmits collected data regarding its position, velocity, and gathered information from other vehicles. This information is collected by the digital agent, which can exchange information with the digital agents of other vehicles at high speeds within the edge clouds. The digital twin calculates the delay tolerance of each vehicle in the network as well as the expected delay to each vehicle for each possible transmission range. It then solves for the optimal transmission range, and relays this to the vehicle in question. This process occurs periodically, so that when an emergency is detected, and up-to-date transmission range assignment can be used right away.

When a vehicle is disconnected from the cloud network, such as being out of range of an RSU or being amongst heavy traffic that is congesting access to an in-range RSU, it cannot rely on cloud services to aggregate network data and provide an optimal range assignment. To prevent unnecessary delay at the time of an emergency, it is still necessary to pre-calculate the emergency message transmission range assignment. With only the computing resources of the vehicle's on-board-unit (OBU), however, this calculation must be simplified and performed less often. The consequence is that, if the traffic topology changes since the last approximated calculation was performed, the transmission range assignment may be sub-optimal. The risk of this occurring can be related to the periodicity of the OBU calculation and the rate of change of the traffic topology. In other words, in cases of high velocity diversity and disconnection from the cloud network, the proposed range modulation strategy may perform sub-optimally. This effect will be discussed in more detail in Section 4.3.

4.3 Theoretical Analysis and Problem Formulation

4.3.1 Transmission Range Optimization for Emergency Safety Message Dissemination

In the following section, a theoretical analysis of network interference, transmission delay, and vehicle's delay tolerance is given. In chapter 3, it was assumed that each transmission of a message took a static amount of time to complete. This approximated the true delay, which can be broken into three components. In a one-way non-ideal transmission, the transmission delay is given in Equation 10

$$\text{Packet Delivery Time} = \text{Transmission Time} + \text{Propagation Delay}. \quad (10)$$

In VANETs, the propagation delay is negligible, as the transmission travels a short distance at the speed of light. The transmission time depends on the size of the packet being sent; in VANET, these are typically small. Therefore, the packet delivery time of a wireless transmission in VANETs should be negligible. In reality, the majority of the actual delay to transmission occurs when a message is transmitted during the same time interval as another message and the transmission must be repeated. When this happens, most MAC protocols will require the sources of both failed transmissions to wait a randomly selected amount of time, known as the back-off time, before attempting retransmission. This value is chosen from the interval $[0, 2^k \cdot W_t]$, where k is the number of previous consecutive message collisions and W_t is the contention window. The expected delay can then be derived from calculating the probability of a collision within one time frame and the expected back-off time. In [51], the expected waiting time is given by $\frac{\overline{W_t}+1}{2}$, where $\overline{W_t}$ is given by Equation 11

$$\overline{W_t} = \sum_{k=0}^{s} 2^k \cdot W_t \cdot P(k\ failed\ transmissions \mid successful\ transmission) \quad (11)$$

where s is the maximum allowed consecutive transmission failures. The complete analysis of the expected per-hop delay remains to be completed; to be utilized in the proposed range modulation scheme, the relationship must be expressed with the transmission range as the independent variable.

Crucial in this calculation is the probability of a successful transmission. Deriving an equation for this probability that is appropriate for the context of the system model is the first task to complete. Formally, the probability of a successful transmission can be expressed as the probability that, during a given timeframe, for each vehicle in range of the transmission, none of the other vehicles that are within range transmit a message. If each vehicle has probability p of transmitting a beacon message in time frame *t*, then the probability of an emergency message transmission failure can be expressed as shown in Equation 12

$$p_t^f = 1 - (1 - p)^S. \quad (12)$$

Here, *S* indicated the total number of vehicles that are within range of the recipient of the transmission in question. This number will depend on the density of traffic as well as the range used for potentially interfering messages. More specifically, for each particular recipient *m*, the value of *S* will depend on the local traffic density, which could vary with space along the relevant section of the highway. Figure 12 shows an example of how local traffic density changes along a given set of vehicles along a road.

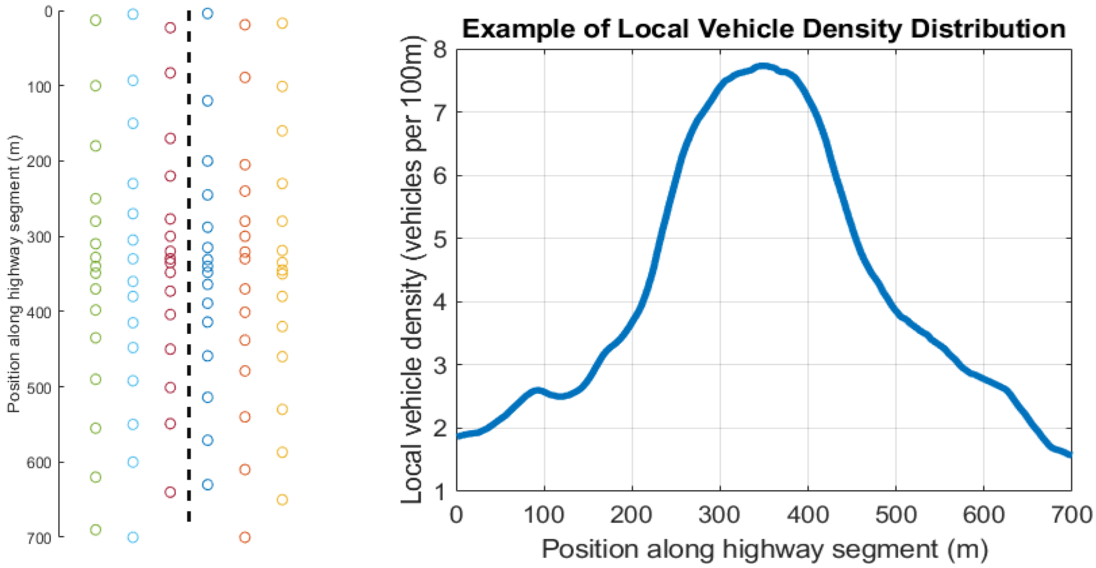

Figure 12a: Example diagram of highway

Figure 12b: Example of local vehicle density in the highway shown in Fig. 12a

Figure 12: A diagram of an example highway traffic pattern and the associated chart showing the local network density along the highway segment

Let $\rho_i(x)$ represent the local vehicle density of lane i at 1-D distance x from the start of the highway segment in question, expressed in vehicles per kilometer. To calculate the number of vehicles within an interfering range R_b meters of a vehicle m at position x_m, the local vehicle density is multiplied by the length of highway in each lane that is within R_b meters of vehicle m. For the 6-lane bi-directional highway considered in this chapter, the equation of S is given by Equation 13

$$S(x, R_b) = \frac{R_b}{1000} \sum_{i=1}^{6} \rho_i(x) \,. \qquad (13)$$

Applying this to Equations 11 and 12, the expression for the expected delay of a transmission to a vehicle at position x can be calculated. When a transmission requires multiple hops to be delivered to a recipient, this calculation must be done repeatedly for each hop. Given that the traffic density considered is considered intermediate density, an approximation assuming evenly spaced vehicles will be sufficient for estimating the number of hops $N_m(x)$ a transmission of range R_{TX} will require to reach a recipient at position x. This approximation is given in Equation 14

$$N_m(x, R_{TX}) = \frac{x_{TX} - x}{R_{TX}}. \quad (14)$$

The total delay to a given vehicle is the sum of the delays for each hop. Once again, because of the intermediate density of the traffic, the delay for each intermediate hop is calculated using the local density of points in space evenly spaced between the source of the message and the ultimate recipient. Though there may not be a vehicle precisely at these points, the smooth nature of the local density $\rho_i(x)$ implies that the true intermediate vehicle would incur a very similar expected delay. Therefore, if $\phi(x,R_{TX})$ represents the delay incurred for a transmission to a vehicle at position x, then the total delay to a vehicle at position x using a transmission range of R_{TX} is given in Equation 15

$$T_m(x, R_{TX}) = \sum_{n=0}^{N_m(x,R_{TX})-1} \phi(x - n \cdot R_{TX}, R_{TX}). \quad (15)$$

This function can be tabulated for each receiving vehicle in the network for each possible transmission range assignment. To select the optimal transmission range, this delay will be compared to the delay tolerance of each vehicle. In the event of an emergency, a vehicle's delay tolerance is the maximum possible delay a transmission could take to be received by said vehicle with the vehicle still being able to come to a full stop without collision. It can be broken down into three components, as shown in Eq. 16.

Delay Tolerance = Time to Collision – Reaction Delay – Braking Delay,

$$U_m(t) = \frac{x_m(t) - x_{c,m}(t)}{v_m(t)} - r_m - \frac{v_m(t)}{2a}, \quad (16)$$

where $x_{c,m}(t)$ is the collision point of vehicle m – the point at which vehicle m will collide with the vehicle before it – and a is the deceleration constant of braking (typically about 7.35 m/s^2 [40]). To complete the theoretical analysis of the comparison of delay tolerance and transmission delay, an explicit expression for the collision point of each vehicle in the network must be given. There are multiple ways one could define the point of collision in a potential motor accident; to strike a balance between simplicity and realism, the following Eq. 17 is used in this chapter to define the collision point. It represents the point at which the lead vehicle would come to a rest if it were to begin breaking after an amount of time equal to the total transmission delay to its location, given a transmission range.

$$x_{c,m}(t, R_{TX}) = x_m(t) - x_{m-1}(t) + \frac{v_{m-1}(t)^2}{2a} + r_{m-1} \cdot v_{m-1}(t) + T_m(x_{m-1}(t), R_{TX}) \cdot v_{m-1}(t). \tag{17}$$

Comparing Eq. 15 and Eq. 16 for each vehicle in the network, it is possible to calculate a lower bound for acceptable transmission ranges; the transmission ranges R_{TX} that satisfies the inequality

$$U_m(t, R_{TX}) < T_m\,(x_m(t), R_{TX})\ \forall\, m \in [1,\ldots,M]. \tag{18}$$

at the time of an emergency are guaranteed to arrive at each recipient in the network in time for all to come to a full stop without collision. From the range of viable transmission ranges, the ideal transmission range assignment is the one that results in the minimum amount of interference in the network. It can be shown that this is equal to the minimum transmission range that satisfies the inequality given by Equation 18. In the ideal case, the ESM is disseminated throughout the network in multiple hops, with each transmission forwarded by only one vehicle at a time. In this case, regardless of the transmission range used, the network only experiences one transmission at a time as the message is disseminated.

In reality, however, there can be no guarantee that only one recipient relays the ESM at each hop. The forwarding protocol described in section 4.2.2 involves a risk of spurious forwarding, which imposes a redundant load on the system and increases the amount of wireless interference present in the network. The probability of this occurring is given by Eq. 19 below, where S is the number of vehicles within range of the transmission, $\mathrm{RN_{TX}}$ represents the transmission of the properly-elected relay node, t_{RM} is the forwarding delay chosen by the properly-elected relay node, t_m is the forwarding delay chosen by vehicle m, and T is the time threshold. This threshold represents the minimum difference in forwarding delay two nodes must choose for the first node's retransmission to cancel the second node's transmission.

$$p_t^{spur} = 1 - P(\mathrm{RN_{TX}}\text{ does not fail})^S P(t_m - t_{\mathrm{RN}} > T)^S. \tag{19}$$

Given that S, the number of vehicles within range of the transmission of the ESM, only increases as the transmission range increases, the probability of a spurious forward similarly only increases as the transmission range increases. Therefore, the transmission range that minimizes the probability of spurious forwarding while guaranteeing safety to each vehicle in the network is the minimum transmission range that satisfies the inequality given in Eq. 18.

4.3.2 RSU Deployment Optimization

When considering the ideal deployment of RSU's along the highway, much of the theoretical analysis presented in section 4.3.1 can be adapted to calculate the interference probability of an RSU under different network density conditions. The ideal RSU deployment density balances cost with quality of service for the traffic network. In other words, the objective of this section is to present an expression for the maximum distance between RSUs that will provide acceptable performance to the users of a highway with a given peak traffic density. Table 3 contains a list of the parameters that are relevant to this section.

Table 3: Description of Symbols

Symbol	Description
p_t	Probability that a vehicle will transmit in time frame t
S	Number of vehicles concurrently serviced by an RSU
I_{max}	Maximum tolerable interference probability
D	Distance between adjacent RSUs
$\bar{\rho}$	Average traffic density of highway segment
R_{RSU}	Transmission/Reception range of an RSU

To provide a balanced quality of service to drivers, it is assumed that RSU's will be deployed uniformly, with equal distances between each unit. In regions where vehicles could reach multiple RSU's, the load is assumed to be split evenly among all possible RSU recipients. The performance threshold I_{max} will depend on the specifics of the application, so the theoretical analysis here is carried out in general terms. To eliminate asymptotic behavior, a minimum distance between RSU's of 100 meters is assumed. Additionally, the maximum distance considered is equal to $2 \cdot R_{RSU}$. To compare the performance of different values of D, the expected probability of transmission failure p_t^f can be calculated using Eq. 3 above, replacing S with Eq. 20 below.

$$S = \frac{D^2}{2 \cdot R_{RSU}} \cdot \bar{\rho}\ . \qquad (20)$$

It can be noted that S is quadratic and therefore convex with respect to D. Looking at Eq. 3, then, it can be further proven that p_t^f is convex with respect to D, because the exponential function is convex by definition. To find the optimal distance between RSU's for a given traffic density, the optimization problem can be proposed as shown in Eq. 21 below.

$$Z = \max\ |x_i - x_{i-1}|$$
$$\text{s.t}\ \ p_t^f < I_{max}. \qquad (21)$$

4.4 Simulation Results

In this section, the simulations used to verify the theoretical analysis given in section 4.3 and analyze the performance of the proposed transmission range modulation scheme under non-ideal transmissions are presented. The simulations each analyze randomly generated highway scenarios for multiple metrics of performance. Additionally, simulation of inter-RSU spacings show the ideal deployment density for a given traffic density. Section 4.4.1 describes the configuration of the simulations and various tests, and section 4.4.2 presents a discussion of the results.

4.4.1 Simulation Configuration

In the following section, the configuration for the simulation of the proposed transmission range modulation strategy is presented. Because the range allocation occurs at the moment of an accident and the safety message is disseminated very quickly, the process can be considered to be time independent. In other words, the calculation for the ideal transmission range depends on the conditions of the neighboring traffic at the moment of the inciting incident. These conditions do change over time, but the change is negligible over the brief span of time that the transmission range is calculated and the message is disseminated. Therefore, to analyze the performance of the proposed transmission range modulation strategy, the strategy is applied to randomly generated road conditions, coded in MATLAB.

In particular, a two-kilometer segment of road is populated by vehicles randomly placed according to a Pearson Type-III distribution of time-headways. Traffic densities of 10, 15, 20, 25, 30, and 37 vehicles per minute are simulated by applying different distribution parameters [39].

The latter two distributions are based on measured time headways in [43], and the former four are given in Appendix A of [39]. Furthermore, the average traffic speed varies between 20, 40, 55, and 70 miles per hour. Traffic in the left lane travels on average 5 miles per hour faster than the average speed, and traffic in the right lane similarly travels on average 5 miles per hour slower than the average speed. Each vehicle is given its own velocity by a uniform distribution between the lane's average speed ±5 miles per hour. With each vehicle assigned a velocity and a time-headway, they are placed spatially along the highway segment. Finally, each vehicle is given a random reaction time according to a normal distribution. The distribution has a mean of 1336 ms and a standard deviation of 333 ms [38].

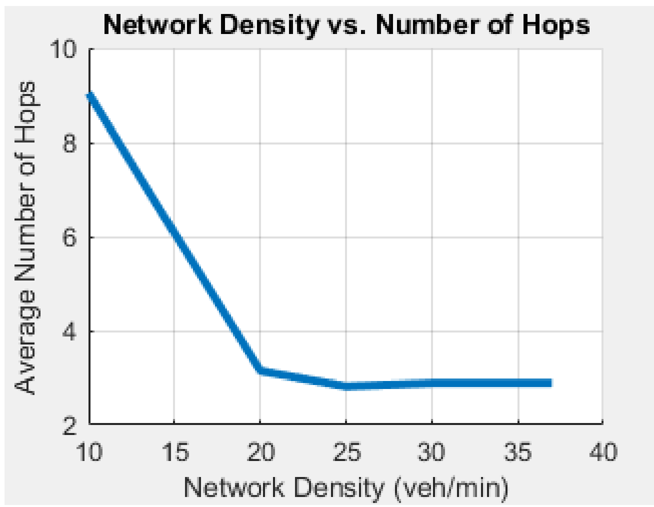

Figure 13: Relationship between network density and the average number of hops in transmission.

Each vehicle transmitted beacon messages with a probability of $p_t = 2\%$ per time frame and at a range of $R_b = 500$ meters. The contention window was considered to be $W_t = 2$ ms, and a maximum of $s = 10$ failed transmissions are permitted. For the ESM, the ideal transmission range was selected from 50 to 1000 meters based on the criterion given by Eq. 18. A separate simulation was performed to analyze the impact of various hop limits on the interference and safety of a network, and the results conclude that they are not necessary to reduce network congestion. This simulation simulated a random highway as described above and measured the change in interference probability for all vehicles in the network as a message is transmitted in controlled numbers of hops. The null hypothesis that was tested was that messages transmitted by way of many hops will create significant interference for other vehicles in the network. The results of the simulation show that vehicles in the network experience a 2% increase in interference likelihood for the time periods in which the ESM is disseminated. Given that most vehicle-to-vehicle transmissions (such as beacon messages) are not highly time-sensitive, this small and transient effect on the network is considered insignificant. Further examination, shown in Fig. 13, shows that a wide variety of hops are utilized depending on the network density. When a high number of hops is employed, the selected transmission range is comparatively small. As shown in section 4.3.1, minimizing the transmission range similarly minimizes the interference in the network. Enacting a hop limit would only serve to force the scheme to occasionally increase the transmission range beyond the chosen value, increasing the network load. Therefore, the simulation of the transmission range modulation strategy imposes no limit on the number of hops a transmission can make.

The ESM forwarding is simulated to emulate the protocol described in Section 4.2. With each hop, the receiving vehicle that is furthest from the transmitting vehicle is designated as the forwarding transmitter of the message. In calculating the delay across the entire transmission link, the forwarding vehicle is assumed to be located at the transmission's edge of each hop. There may not be any vehicle at that precise location, but, because the density of traffic is intermediate, it is certain that a vehicle is nearby. This is an acceptable approximation because the transmission delay for each hop depends on the local traffic density about the position of the receiving vehicle, which is not sensitive to small changes in position. Furthermore, any error this introduces will be overshadowed by the random nature of the highway generation, which is in turn handled by presenting the results after 500 trials are averaged together.

This configuration has a few key differences from the one presented in Chapter 3. Most obviously, the method of placing vehicles randomly in a simulated highway now incorporates multiple lanes with varying speeds and a general mobility diversity across vehicles. Additionally, instead of involving a set number of vehicles, the simulation fills a set length of road with a varying number of vehicles. As previously discussed, no limit is place on the number of hops the ESM is allowed to take as it disseminates through the network. Finally, the consideration of non-ideal transmissions requires a more complex calculation of transmission delay and delay tolerance.

To analyze the performance of the proposed transmission range modulation strategy, several simulated measurements are presented. Because of the special emphasis on transmission interference considered in this chapter, the effect of traffic density on the transmission range selection protocol is of significant importance. As shown in Fig. 14, as more vehicles occupy the highway segment, the probability of a failed collision will increase (see Eq. 12). Consequentially, the delay for each hop in the transmission link will increase, which will directly impact the transmission range selection strategy. For each traffic density listed above, the simulation for generating a random road scenario and solving for the ideal transmission range is run 500 times. This is repeated for each of the four average traffic speeds considered. The results are shown in Fig. 15 in Section 4.4.2.

Similarly to section 3.4, a simulation varying the presence of AVs in the network was carried out. AV penetration rates from 0 to 100% are analyzed; for each rate, the appropriate proportion of the total number of vehicles generated are selected at random to become AVs. As before, AV are represented in the simulation as having a reaction time of zero seconds. For this chapter, because network density has a much larger direct impact on the system, multiple densities are considered. Results for 15, 25, and 37 vehicles per minute are shown in Fig. 16.

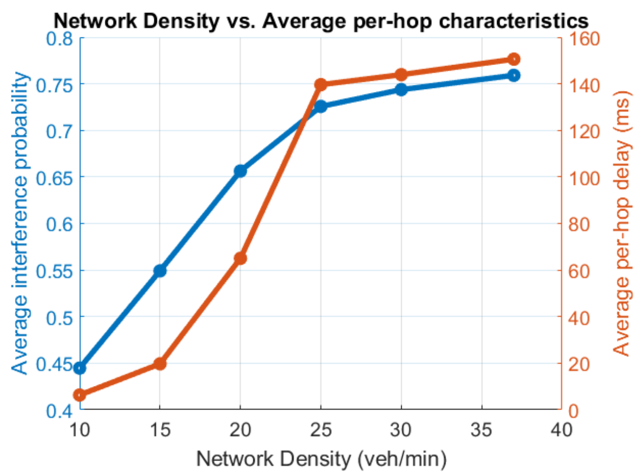

Figure 14: Per-hop delay and transmission failure probability versus network density

Finally, a demonstration of the relationship between network density and RSU performance is given. For varying interference thresholds (10% -50%), the maximum possible distance between RSUs as a function of traffic density is shown in Fig 17. This result is simulated under the assumption that RSUs with overlapping service areas share network load from the overlapping area equally. The RSU's are considered to have a range of 500 meters, and the RSU spacings considered lie between 100 and 1000 m. Past 1000 meters, regions of highway are disconnected from the RSU network, which degrades the performance of the proposed transmission range allocation strategy.

4.4.2 Simulation Results

Figure 14 illustrates the trend between traffic density within the VANET, interference probability, and the average expected delay for each hop along the transmission link. The interference probability begins to level off as density increases because, at higher densities, the number of potential interferers within range of a receiving vehicle increases by a proportionally smaller amount. For example, increasing the network density from 15 vehicles per minute to 20 vehicles per minute may increase the number of interferers from, 40 vehicles to 50, which is a 25% increase. However, when increasing the network density from 25 vehicles per minute to 30 vehicles per minute, the number of interferers increases from 60 to 70, which is only a 17% increase. Because the interference probability begins to level off as higher densities are reached, so too does the expected per-hop delay.

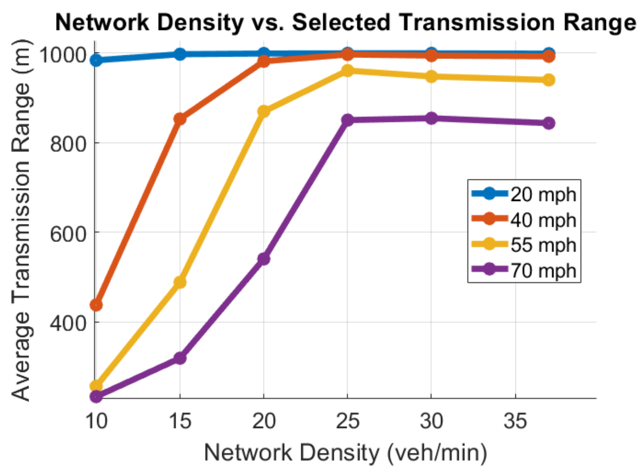

Figure 15: Average selected transmission range versus network density at different average traffic speeds.

This trend is mimicked in Fig. 15, which shows the relationship between the network density and the selected transmission range. As the density increases, the transmission range selected by the range modulation strategy increases. This corresponds to the results shown in Fig. 14; the expected per-hop delay increases while vehicles become more packed, having the double-impact of reducing the delay tolerance for many vehicles while increasing the time spent for each hop. As a result, a higher range must be selected in order to reduce the number of hops necessary to reach all affected vehicles in the network (see Fig. 13).

This result may seem unintuitive at first; the reader may expect that the selected transmission range would decrease as the network density increased. After all, as the network density increases, the expected interference would also increase, so the transmission range must be decreased to compensate for this change. However, importantly, the probability of a transmission failure depends only on the range of the interfering nodes, which in not being controlled by this scheme. For example, if vehicles in the network transmit with a beacon range of 500m, a vehicle within 50m of the ESM source vehicle is surrounded by just as many interfering vehicles as a vehicle 900m away. Additionally, as vehicles become closer to one another, they have less space to come to a full stop before collision. Therefore, the transmission range must be increased to reduce the number of hops in the transmission link.

Another feature demonstrated in Fig. 15 is the effect of average traffic speed on the selected transmission range for an ESM. At higher speeds, the simulation selects a smaller range of transmission at all density levels. This is due to the mobility diversity of the traffic on the simulated highway. Traffic in the opposite direction is utilized to carry transmissions down-traffic more rapidly, and this effect is more prominent at higher speeds because the difference in velocity between the source vehicle and the forwarding vehicle in the opposite side is greatest at higher speeds. At low speeds, the absence of this effect causes the system to utilize the maximum transmission range (1000 m) in order to deliver the message in time. Furthermore, at low speeds and low densities, vehicles are spaced further apart such that a large transmission range is necessary simply to reach the next-nearest vehicle in the link.

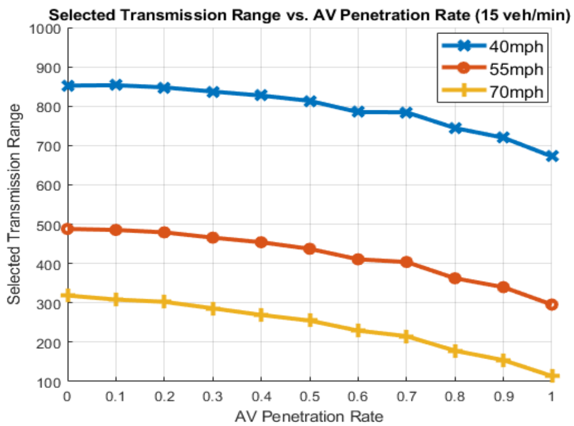

Figure 16a: 15 vehicles per minute

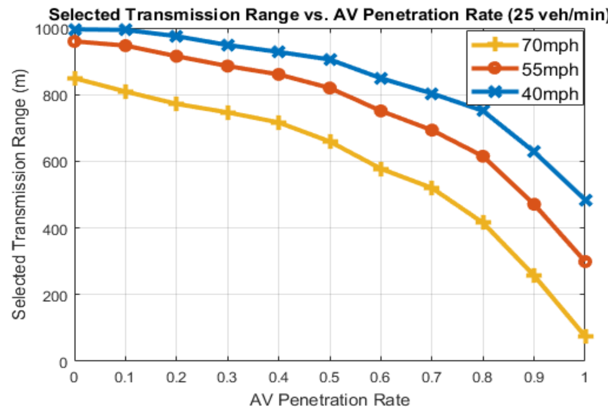

Figure 16b: 25 vehicles per minute

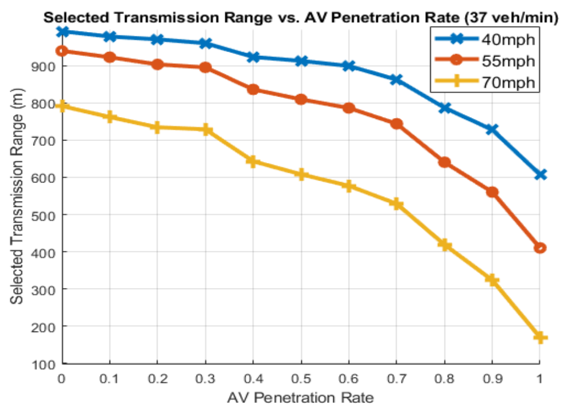

Figure 16c: 37 vehicles per minute

Figure 16: Selected Transmission Range vs AV Penetration Rate for varying traffic densities

To further verify the conclusions of the preliminary work shown in chapter 3, the performance of the proposed transmission range modulation strategy under non-ideal transmissions is analyzed for the spectrum of AV penetration rates. The trend, shown in Fig. 16, is decreasing, with the rate of change becoming greater as AV penetration rate grows. This trend matches the trend found in section 3.4.2. Another pattern seen in Fig. 16 is the effect of network density on the trend. At low densities (15 veh/min) AV penetration has a less significant impact. At 25 vehicles per minute, the trend is much stronger, resulting in up to an 80% decrease in the selected range from 0 to 100% AV presence. Increasing the density further to 37 veh/min, however, does not seem to have a significant impact on the relationship. Referring back to Fig.

15, this matches the levelling off of the selected transmission range. As before, this is due to the diminishing marginal effect of additional interfering vehicles at higher densities.

Finally, the theory supporting the calculation of the ideal transmission range for distribution of ESMs in VANETs is also applied to illustrate RSU deployment requirements. Figure 17 shows several level curves relating the necessary distance between deployed RSUs along a road of a given density for several different QoS requirements. Each level curve follows the same trend: as the expected traffic density increases, RSUs must be placed closer together to share users and keep the probability of failed transmissions below the given value. An interesting implication of this is that VANET infrastructure projects that aim to equip high-traffic highways must be designed with a high transmission failure rate in mind, or else face an unreasonable cost of deployment.

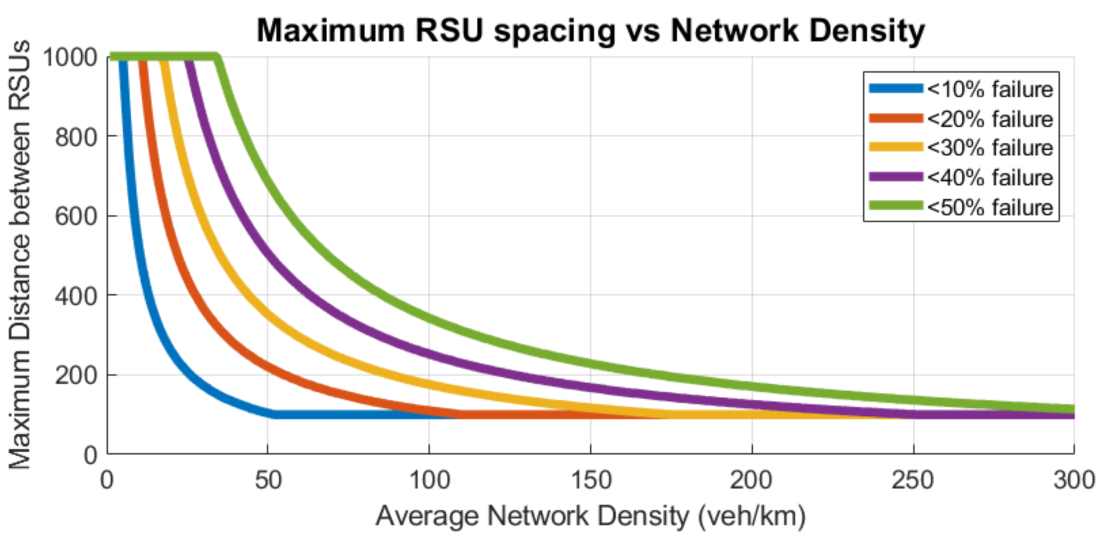

Figure 17: Maximum allowable inter-RSU spacing to maintain QoS level vs. average network density

4.5 Summary

In this chapter, a more complete model of both wireless transmission in VANETs and highway traffic were applied to the novel transmission power allocation strategy for vehicle-to-vehicle safety messaging introduced in Chapter 3. A full theoretical analysis of transmission delay, wireless interference, and delay tolerances defined the mathematical calculation that is capable of giving the best possible transmission range for dissemination of an ESM in any given vehicular network. The selected transmission range guarantees that each recipient will be able to avoid an accident while minimizing the impact of the transmission on the performance of the network. Through simulation, the novelty and aptitude of the proposed strategy are plainly illustrated, and the results shown in Section 3.4 are justified. Furthermore, an investigation of RSU deployment in highway VANET systems is given.

The results shown in this chapter proves the need for an adaptive strategy towards determining the transmission range of emergency safety messages. The analysis of the interference present in the dissemination of emergency safety messages proves the optimality of the proposed strategy, and verifies the safety benefits shown in Chapter 3. The strategy utilizes only elements that are commonly proposed in other VANET systems, meaning that the strategy is an intelligent method for utilizing VANET resources to guarantee the safety of all.

Chapter 5 Conclusions & Future Work

This chapter concludes the thesis, presenting major conclusions and discussing potential directions for future research on the subject. Closing remarks regarding the novelty and motivation for the proposed scheme emphasize the importance of the unique strategy presented in this thesis.

5.1 Conclusions

In this thesis, a novel strategy for adjusting the transmission range of ESMs in VANETs in order to guarantee safety and minimize interference is presented. The scheme uses a digital-twin architecture to compare the estimated delay tolerance of each endangered vehicle to the expected delay of transmission at all possible transmission ranges and select the optimal value. This is distinct from other VANET protocols because of its dynamic quality-of-service criteria, its consideration of individual human reaction times, and its digital-twin architecture. The system allows for VANET communications to be utilized for improving automotive safety for all without overtaking network resources or unnecessarily disrupting other VANET applications.

The strategy was described in detail and analyzed its performance under simplifying assumptions first, as presented in Chapter 3. A basic theoretical framework for estimating delay tolerance and transmission delay served as a proof-of-concept for the strategy. Simulated results demonstrated a potential for strong improvements against non-adaptive transmission, so the work was extended into a complete analysis of the strategy in a more general setting with non-ideal transmissions. A more in-depth theoretical analysis describes the relationship between network topology, transmission range, and delay tolerance. This analysis is extended to examine ideal RSU deployment densities, and the performance of the transmission range modulation strategy is analyzed through more rigorous simulation, as described in Chapter 4.

The results of the empirical and theoretical analysis demonstrate the behavior of the strategy under different traffic speeds and densities. The results show that a wide range of transmission ranges are found to be optimal, depending on the circumstances of the road. This further suggests the importance of utilizing an adaptive strategy for determining transmission range. In particular, at higher densities, a large transmission range is often necessary to counter the effect of higher delays due to congestion and reduced delay tolerances due to short headways. If a shorter transmission range is used, many avoidable accidents may occur in the event of an emergency. On the contrary, if a large transmission range is used in most low-density scenarios, the performance of all other VANET functions will be degraded by the unnecessary additional interference. In brief, no one transmission range is appropriate for all scenarios.

5.2 Future Work

The work presented in this thesis provides an in-depth consideration of aspects of VANET considered to be within the declared scope. Certain aspects of the proposed system model are given cursory attention, and could serve as points of further investigation in future work. For example, a detailed analysis of the performance and network logistics of the digital-twin based cloud service that this work relies on would further fortify the viability and novelty of the work presented here. Alternatively, the random simulated road environments could be substituted for road environments constructed from real-world traffic data in order to more accurately model highway traffic. Finally, with the availability of necessary resources, the results shown here through simulation could be verified in a physical prototype trial.

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