Evaluation and Optimization of LTE-V2X Mode 4 under Aperiodic Messages of Variable Size

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Evaluation and Optimization of LTE-V2X Mode 4 under Aperiodic Messages of Variable Size

Master's Thesis

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Abstract

Vehicular networks connect vehicles for improved road safety and efficiency with the assistance of wireless information exchange. Vehicular networks are based on the frequent broadcast of awareness messages referred to as CAM (Cooperative Awareness Messages) or BSM (Basic Safety Message) in the ETSI and SAE standards, respectively. Vehicular network technology mostly used nowadays is based on cellular networks (LTE-V2X, 5G NR-V2X). LTE-V2X is an evolution of the 3GPP standard for 4G/LTE that allows vehicles to exchange information with other vehicles, pedestrians, or fixed objects such as traffic lights in their surroundings without the requirement of any infrastructure support. Reliable transmission of this information is important in LTE-V2X technology to confirm safety on the roads and effectively manage traffic flow. Most of the available studies are based on simplified data traffic models that generate CAMs at periodic intervals and with a fixed message size. In reality, the size and interval between the messages are not fixed and different from the simplified model. There are a few studies based on the real CAM generation (also known as the Empirical CAM Model) that show the significant deviations in results found with an unrealistic simplified traffic model. The Empirical CAM Model generates aperiodic messages of various sizes which leads to certain inefficiencies that affect the performance of LTE-V2X. In this thesis, those inefficiencies due to the realistic CAM generation are addressed and some mechanisms are also proposed and analyzed to overcome those effects. The results obtained in this thesis could be used not only for a better configuration of LTE-V2X but also for future standardization of its evolution.

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Contents

List of figures

List of tables

List of acronyms

3GPP	Third Generation Partnership Project
CAM	Cooperative Awareness Message
C-V2X	Cellular V2X
DMRS	Demodulation Reference Signals
ETSI	European Telecommunications Standardization Institute
LTE	Long Term Evaluation
MAC	Medium Access Control
MCS	Modulation and Coding Scheme
OFDM	Orthogonal Frequency Division Multiplexing
PRB	Physical Resource Block
PSCCH	Physical Sidelink Control Channel
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RSU	Road-Side Unit
SCI	Sidelink Control Information
SPS	Semi-Persistent Scheduling
TB	Transport Block
TTI	Transmission Time Interval
V2I	Vehicle-to-Infrastructure
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything

Popular Science Summary

In recent years, we have seen a remarkable surge in two technologies: cell phones and self-driving cars. These self-driving cars, or "smart cars," are designed to operate with minimal human intervention by communicating with each other on the road. To better understand the importance of this technology and my research in improving it, let us delve into this fascinating world.

Imagine a world where cars can not only drive themselves but also talk to each other. This is not science fiction; it is the reality of today's rapidly advancing automobile industry. Smart cars have the potential to revolutionize our roads, making them safer and more efficient.

The key to smart cars' success lies in their ability to communicate with each other seamlessly. Picture a group of friends embarking on a road trip. To ensure a smooth journey, they need to share essential information, such as their speed, location, and destination. Shouting or using hand signals is not practical on the road, so they use advanced communication systems, similar to high-tech walkie-talkies. These systems allow them to chat via cell phone towers or directly, allowing for efficient information exchange.

However, there is a challenge lurking on the horizon. Sometimes, when the group ventures into remote areas without cell phone signal, communication becomes unreliable. Here is where my thesis comes into play. I have dedicated my research to improving how these smart vehicles communicate, regardless of their location or how congested the "communication channels" become. One fundamental aspect of my research is to ensure that critical messages, such as warnings about road obstacles or potential collisions, always reach their intended recipients. This is like giving these messages top priority on a communication channel. Just as you would want an emergency message to be heard clearly on a walkie-talkie, it is crucial that smart cars can reliably convey critical information to avoid accidents and keep everyone safe.

Imagine you are using a walkie-talkie with your friends, and the signal isn't perfect. There might be static, and parts of the conversation might get lost or garbled. We have worked on techniques to ensure that, even in less than ideal conditions, the main message gets through. It is similar to improving the clarity of your walkie-talkie conversation so that, despite some interference, you can still understand the essential points.

Another vital aspect of my research involves managing how these "communication channels" are used. Think of it as ensuring that your friends do not talk over each other, allowing you to hear each person's message clearly. We have developed methods to ensure that smart cars use these "channels" in an organized way, minimizing confusion, and enhancing the efficiency of communication. By addressing these challenges and implementing innovative solutions, my research aims to ensure that smart cars can always communicate effectively and safely, regardless of their location or the level of activity on their "communication channels." This, in turn, contributes to safer roads and more efficient traffic flow for everyone.

The potential benefits of smart car communication are enormous. Beyond convenience, it has the power to reduce accidents and save lives. Imagine a future where cars can alert each other to dangerous road conditions or imminent accidents, allowing for quick and coordinated responses to prevent tragedies. It is a future where traffic flows smoothly, with vehicles working together like a well-orchestrated symphony. Of course, there are challenges along the way. Like any technological advancement, smart car communication faces obstacles that must be overcome. Ensuring privacy and security in this interconnected world of vehicles is a priority. Additionally, making sure that all vehicles, regardless of their make or model, can communicate effectively is another challenge on the horizon.

However, these challenges also present opportunities for innovation and collaboration. Researchers, engineers, and automakers are working together to refine smart car communication systems, making them more secure, reliable, and accessible. As we navigate the road ahead, it is essential to recognize the potential of smart car communication in transforming our transportation landscape. It has the capacity to make our roads safer, more efficient and environmentally friendly. My research is just one small step in this exciting journey that aims to ensure that smart cars can communicate effectively and reliably, bringing us closer to a future where our vehicles work together for the greater good of all.

In closing, smart car communication isn't just about technology; it is about the promise of safer roads, improved traffic flow, and the potential to save lives. It is about vehicles becoming smarter, so we can all travel more efficiently and safely toward a brighter future.

1. Introduction

Information exchange between vehicles (V2V) and between vehicles and other nodes (infrastructure and pedestrians) is possible due to V2X communications. These types of communication are shown in Fig. 1. To improve traffic safety, precise information about the surrounding environment is necessary that can be extracted from the exchange of information.

At present, there are two main communication technologies used for V2X communications. Dedicated short-range communications (DSRC) in the US and ITS-G5 in Europe are two types of 802.11p technology [1]. The Third Generation Partnership Project (3GPP) published the first version of Release 14 in September 2016 where advanced features have been added to enable direct communications for the specific scenario of vehicular networks. The standard is commonly referred to as LTE-V, LTE-V2X, cellular V2X or LTE-V2X. LTE-V2X is seen as a potential replacement for IEEE 802.11p, which is currently the dominant technology for V2X communications.

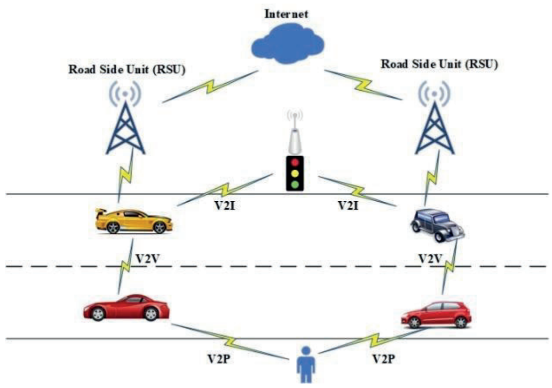


Fig. 1. V2X Communications

V2X networks support the connected and automated vehicles with the help of wireless exchange of information. This type of exchange of information is based on messages that are usually broadcasted over the networks. These messages contain the position, speed, and basic status information of the transmitting node. Reliable transmission of these messages is very important in V2X communication. Most studies found in the literature are generally based on simplified data traffic models that generate messages at periodic intervals or with a constant message size. These models do not accurately represent the real generation of messages in a vehicular network because the messages are not constant in sizes and time intervals in case of realistic networks. There are also a few studies in the literature with realistic generation of data traffic in V2X networks which present some negative effects of having variable message sizes and time intervals among the messages. In this thesis, the V2X network under realistic messages has been studied and different solutions are proposed to overcome the negative effects of these types of messages. There exist different environment platforms that supports simulations for vehicle communication with the necessary tools and freedom for extension of the existing implementation, but the most known are NS3 and OMNeT++. OMNeT++ will be used as the main environment platform in this thesis, since a detailed implementation of LTE-V2X is available. Implementation of the 802.11p and LTE stacks is already done in OMNeT++. These frameworks offer the possibility for various network and vehicular simulation by using wireless communication technologies. However, the implementation of the latest LTE stack has still not been completed for the OMNeT++ framework.

1.1. Background

Vehicle-to-Everything (V2X) communication has seen substantial evolution in recent years, offering promising solutions to improve road safety and traffic efficiency. Significant research efforts have been directed toward optimizing the performance of V2X technologies, specifically Long-Term Evolution for Vehicle-to-Everything (LTE-V2X) and addressing the complexities inherent in transmitting various types of message.

One of the fundamental challenges encountered in LTE-V2X communication is the efficient management of network resources, particularly in dealing with aperiodic messages of variable sizes. These messages include real-time traffic updates, emergency notifications, and safety-critical alerts, requiring their reliable and timely delivery to ensure road safety. A comprehensive understanding of the challenges and potential solutions is provided through a review of relevant studies and research findings.

Resource allocation strategies have been explored for periodic messages with different sizes within the LTE-V2V context, underscoring the importance of optimizing resource utilization to meet various communication requirements [9]. The ETSI specification of the cooperative awareness basic service (C-ITS) serves as a fundamental reference for understanding the basic applications and requirements of V2X communication systems [13]. Empirical models have been developed to generate cooperative awareness messages in vehicular networks, contributing to a more realistic simulation environment to evaluate V2X communication [15]. A comprehensive evaluation of IEEE 802.11p and LTE-V2X has been conducted, considering periodic and aperiodic messages of varying sizes. This analysis provides information on their comparative performance [16].

These references collectively lay the foundation for understanding the challenges and opportunities in LTE-V2X communication, particularly regarding the handling of aperiodic messages of variable sizes. The following sections of this thesis will delve deeper into these challenges and propose innovative solutions to address them.

1.2. Objective

The main goal of this Master thesis is the optimization of LTE-V2X under variable and realistic data traffic. The performance and efficiency of LTE-V2X considering realistic CAM generation models will be analyzed and used as a starting point to design and evaluate mechanisms that can be used to mitigate the negative effects of having variable message sizes and time intervals. The main challenge is the close relationship between these negative effects; the design of mechanisms to solve one effect could influence the other effects.

This thesis aims to answer the following questions:

- How does LTE-V2X perform under realistic and variable data traffic conditions, and what are the key performance metrics affected by such variability?
- What are the challenges posed by realistic Cooperative Awareness Message (CAM) generation models in LTE-V2X, and how do they impact system efficiency and reliability?
- How can mechanisms be designed to address the negative effects arising from variable message sizes and time intervals in LTE-V2X communications, and what trade-offs need to be considered in the design process?

1.3. Approach and Methodology

The approach and methodology of the Master thesis will consider: (1) review of the state of the art, including the study of realistic CAM generation models and the analysis the performance and efficiency of LTE-V2X under realistic data traffic; (2) identification of main issues and potential mechanisms to solve them; (3) design and implementation of the identified mechanisms in Omnet++, evolving an existing LTE-V2X system level simulator; (4) analysis and optimization of the simulation results; (5) conclusions and future work.

1.4. Thesis Structure and Contribution

This thesis is organized as follows:

Chapter 2 provides essential background information on LTE-V2X technology. This chapter emphasizes two primary modes of communication, with and without cellular infrastructure support, and also delves into radio resource allocation management.

Chapter 3 provides an overview of the current state of LTE-V2X technology. It explores various CAM generation models and their implications on LTE-V2X.

In the initial part of Chapter 4, we examine the real-world effects of CAM generation, highlighting the challenges that stem from variable message sizes and time intervals between messages. The second section of this chapter introduces proposed algorithms designed to mitigate these inefficiencies.

Chapter 5 introduces the simulator used in this research and outlines the setup of the simulation scenario.

Chapter 6 delves into the findings and analysis of the conducted experiments, shedding light on the outcomes.

Finally, Chapter 7 presents the conclusions drawn from the research and outlines potential avenues for future work.

2. LTE V2X

There are two radio interfaces in the LTE-V standard. The cellular interface (named Uu) supports vehicle-to-infrastructure (V2I) communications, while the PC5 interface supports V2V communications based on direct LTE sidelink. The LTE side link (or device-to-device communication) was introduced for the first time in Release 12 for public safety and includes two modes of operation: mode 1 and mode 2. These two modes were designed to prolong battery life at the cost of increasing latency. Highly reliable and low-latent V2X communications are necessary for connected vehicles; therefore, modes 1 and 2 are not suitable for vehicular applications.

There are two new communication modes (modes 3 and 4) in Release 14 that are designed for V2V communications. For the purpose of direct V2V communication, vehicles use the cellular networks in communication mode 3. In mode 4, vehicles autonomously select radio resources for their V2V communications. Mode 4 can operate without a cellular network, and this is required for these types of safety applications.

2.1. LTE-V2X Mode 3

In Mode 3, vehicles communicate using sidelink or V2V communications. However, the base station (or evolved NodeB) is responsible for managing the selection of subchannels. Mode 3 is therefore only available when vehicles are within cellular coverage. The 3GPP has defined the essential enhancements to the cellular architecture to support LTE-V2X. The LTE-V2X control function (used by the network) is one of these improvements to manage radio resources and to provide vehicles (User Equipment) with the sidelink LTE-V2X configurable parameters. Mode 3 uses the same subchannel arrangements as defined for mode 4. In Mode 3, vehicles must also transmit an associated SCI/TB, and the transmission of the SCI/TB must take place in the same subframe. In opposition to mode 4, the standards do not specify a resource management algorithm for mode 3. Each operator can implement its own algorithm, which should fall into one of these two categories [2]:

- Dynamic scheduling: The vehicles for each packet transmission.
- SPS: The eNB reserves subchannels for the periodic transmissions from a vehicle like in mode 4. However, in contrast to mode 4, it is

up to the eNB to decide how long the reservation should be maintained (i.e., mode 3 does not define a reselection counter).

Vehicles operating in mode 3 can be supported by different mobile operators or by public land mobile networks (PLMNs). For enabling direct communications, the 3GPP has defined an inter-PLMN architecture that can support the following scenarios:

- Vehicles supported by different PLMNs communicate with different carriers.
- Vehicles supported by different PLMNs share the same carrier, but each PLMN is assigned part of the RBs of the carrier.

For direct communications among the vehicles, in mode 3, the cellular networks select and management of the radio resources used by the vehicles. Vehicles autonomously select radio resources for the communication among them in mode 4. Hence, in mode 4, there is no need for a cellular network for V2V communications. This is why mode 4 is considered the baseline V2V mode because safety applications should not depend on the availability of cellular network coverage.

2.2. LTE-V2X Mode 4

In this section, the description of the Physical layer used in LTE-V2X will be discussed in the beginning. Then LTE-V2X Mode 4 communication will be discussed including the scheduling algorithm used in this type of communication.

2.2.1. Physical Layer and Sub-channelization

LTE-V2X adopts single carrier frequency division multiple access (SC-FDMA) at the PHY and MAC layers and supports 10- and 20-MHz channels. Each channel is divided into subframes, resource blocks (RBs) and subchannels as shown in Fig. 2. The subframes have a duration of 1 ms, similar to the transmission time interval (TTI). Resource blocks are allocated in pairs, corresponding to 180 kHz bandwidth (12 subcarriers with 15 kHz space) and 1 ms duration (14 OFDM symbols, 9 of them carry data, 4 are used for channel estimation, and 1 for timing adjustments and possible tx-rx switch).

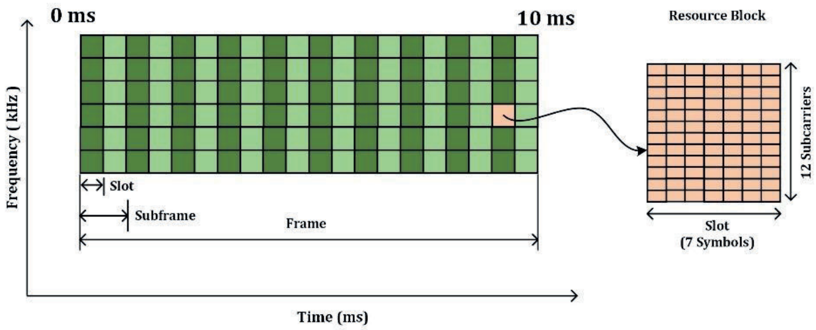


Fig. 2. LTE frame (1.4 MHz, Normal Cyclic Prefix)

A subchannel consists of a group of RBs in the same subframe. The number of RBs per subchannel can vary. To transmit the data and control information, the subchannels are used. Physical Sidelink Shared Channels (PSSCH) are used to transmit data in Transport Blocks (TBs), and Physical Sidelink Control Channels (PSCCH) are used to transmit Sidelink Control Information (SCI) messages [3].

The Cooperative Awareness Messages (CAMs) are sent as a packet through a TB. A node must also send the associated SCI to transmit the TB; this is also known as Scheduling Assignment. There is important information such as the Modulation Coding Scheme (MCS) used to transmit the TB, the associated RBs, and the Resource Reservation Interval (RRI) for the Semipersistent Scheduling (SPS) inside the SCI.

The SCI must be correctly received. In order to do that, the information is critical for other nodes to be able to receive and decode the transmitted TB. Within the same subframe, a TB and the associated SCI must be transmitted.

The adjacent SCI-TB (or adjacent PSCCH-PSSCH) scheme and the nonadjacent SCI-TB scheme (or non-adjacent PSCCH-PSSCH) are the two subchannelization schemes shown in Fig. 3. The SCI and TBs are transmitted in the contiguous RBs in case of adjacent schemes. In the case of non-adjacent schemes, the SCI and TBs are separated into two resource pools. The upper pool is only used to transmit the SCI, whereas the lower pool is only used for TB transmission.

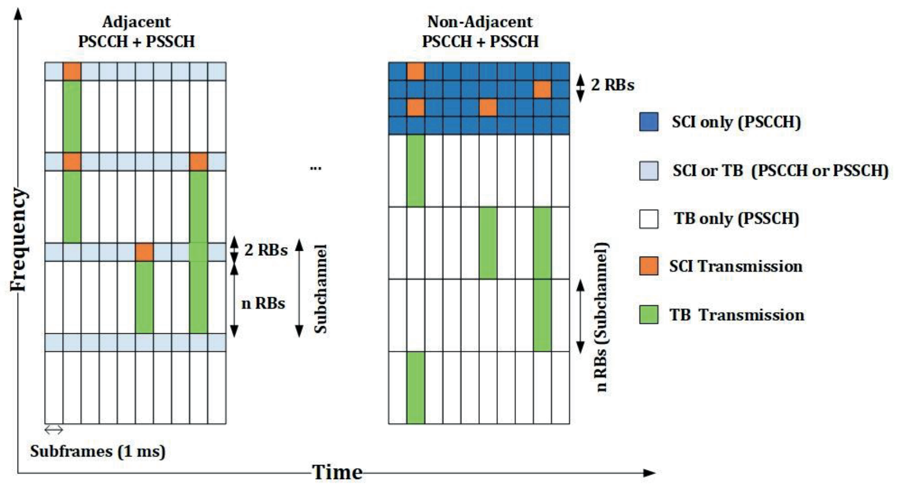


Fig. 3. LTE-V Subchannelization

Generally, quadrature phase shift keying (QPSK) or 16 quadrature amplitude modulation (QAM) is used to transmit the TBs and QPSK is always used to transmit the SCI. LTE-V2X uses turbo coding and an ordinary cyclic prefix.

There are a total of 14 symbols per subframe in LTE-V2X. To combat the Doppler effect at high speeds, four of these symbols are dedicated to the transmission of demodulation reference signals (DMRSs).

DMRSs are transmitted in the third, sixth, ninth, and 12th symbol of each subcarrier per subframe [4]. The maximum transmit power is 23 dBm, and the standard specifies a sensitivity power level requirement at the receiver of –90.4 dBm and a maximum input level of –22 dBm [5].

2.2.2. Scheduling

In Mode 4, vehicles communicate utilizing the side link (V2V communications) and autonomously select their radio resources independently without the help of the cellular infrastructure. The network is only responsible for setting up the LTE-V2X channel for vehicles under the cellular coverage. In this case, the network also informs vehicles through the sidelink LTE-V2X side links [6]. The message includes the carrier frequency of the LTE-V2X channel, the LTE-V2X resource pool, synchronization references, the subchannelization scheme, the number of subchannels per subframe, and the number of RBs per subchannel, among other parameters. Without cellular coverage, vehicles utilize a preconfigured set of parameters to replace the configurable LTE-V2X sidelink parameters. However, there is no concrete value for each parameter specified in the standard. The subframes of a channel used for LTE-V2X are indicated by the LTE-V2X resource pool. The rest of the subframes can be used by other services, including cellular communications. It is also possible to divide the LTE-V2X resource pool based on geographical areas (referred to as zoning [6]). In this case, vehicles in an area can only utilize the pool of resources that have been assigned to such areas.

Vehicles in mode 4 using the sensing-based semi-persistent scheduling (SPS) scheme based on sensing specified in Release 14 [3], [7]. The selected subchannels are reserved by a vehicle for a number of consecutive reselection counter packet transmissions. The vehicle adds the counter value in the SCI, which is randomly set between 5 and 15. After each transmission, the value of the selection counter is decremented by one. New resources must be selected and reserved with probability (1–*P*) when the value of the selection counter reaches zero. The value of P can be set between zero and 0.8 by each vehicle. There are some cases where the packet to be transmitted does not fit into the previously reserved. In this case, new resources must be reserved. When new resources, the reselection counter is randomly selected. Packets are usually transmitted every 100 subframes (i.e., ten packets per second) or in multiples of 100 subframes (up to a minimum of 1 packet per second). Each vehicle includes its reservation interval (RRI) in the resource reservation field of its SCI.

Step 1: In the context of vehicle communication, when a vehicle (V) seeks to reserve new subchannels at a specific time (T), it does so within a defined time period known as the "selection window." This selection window extends from time T to a maximum latency of 100 ms [3]. The vehicle identifies the candidate single-subframe resources (CSRs; also referred to as candidate resources) within the selection window. The CSR should be reserved for all groups of adjacent subchannels within the same subframe where the SCI + TB to be transmitted will fit.

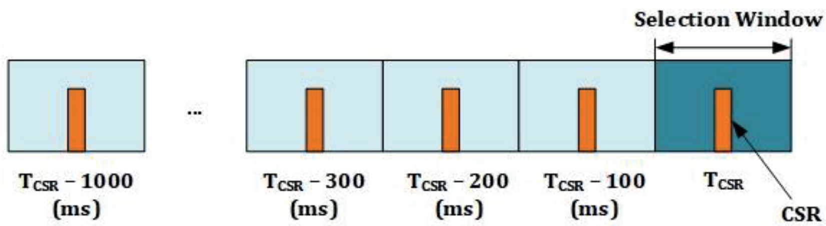
Step 2: All the information received in the 1000 subframes before T is analyzed by vehicle V and a list (L1) of CSRs is created that it could reserve. The list includes all the CSRs in the selection window except those that have the following two conditions.

1. V has correctly received an SCI from another vehicle notifying that it will use this CSR at the same time in the last 1,000 subframes where V will need it to transmit any of its next reselection counter packets.

2. Vehicle V evaluates an average reference signal received power (RSRP) over the RBs utilized to transmit the TB associated to the SCI higher than a given threshold. The threshold is set according to the priority of the packet. This priority is set by higher layers according to the relevance and importance of the application. From the same interfering vehicle reserving a given CSR, if vehicle V receives several SCIs, it will use the most recent one to evaluate the average RSRP.

To exclude a CSR, it is necessary to meet the above two conditions for vehicle V. Vehicle V also rejects all CSRs of subframe F in the selection window if V was transmitting during any previous *subframe* $F\text{-}100^*j$ $(j \varepsilon N, 1 \leq j \leq 10)$. It should be noted that V cannot receive transmissions from other vehicles in the same subframe it is transmitting because of half-duplex (HD) transmissions.

L1 should include at least 20% of all CSRs in the selection window after step 2 is executed. If this condition is not met, step 2 is iteratively executed until the 20% target is met. In each iteration, the RSRP threshold is incremented by 3 dB.



$$Average\ sensed\ RSSI = \frac{\sum_{j=1}^{10} RSSI\,\{T_{CSR} - 100 * j\}}{10}$$

Fig. 4. The average RSSI of a candidate resource (in ms).

Step 3: The second list (L2) of CSRs is created by vehicle V. The total number of CSRs in L2 should be equal to 20% of all CSRs in the selection window. L2 consists of the L1 CSRs (after Step 2) that have the lowest average received signal strength indicator (RSSI) over all its RBs. This RSSI value is averaged over all the previous $T_{CSR}\text{-}100^*j$ subframes ($j \varepsilon N, 1 \leq j \leq 10$) as shown in Fig. 4. One of the CSRs in L2 is chosen randomly by vehicle V and reserves it for the next reselection counter packet transmission.

3. Challenges of LTE-V2X for Aperiodic Messages of Variable Sizes

3.1. State of the Art

Vehicular communications are based on the continuous exchange of data packets that carry essential status information to neighboring vehicles. In Europe, the European Telecommunications Standards Institute (ETSI) defines these packets as Cooperative Awareness Messages (CAMs), while in the United States of America (USA), the Society of Automotive Engineers (SAE) defines them as Basic Safety Messages (BSMs).

Applications enabled by V2X depend heavily on these messages, which include basic vehicle position, speed, and basic status information. Such messages play a critical role in various wireless technologies, including ITS-G5, 5G-V2X, and LTE-V2X. Numerous studies have focused on ensuring their reliable transmission.

Previous studies often employed simplified traffic models to generate awareness messages. These models typically produced messages at periodic time intervals (typically ranging from 100 ms to 1 s) with fixed message sizes (between 200 and 400 bytes). This simplified model was used with LTE-V2X in [8][9], and the performance of LTE-V2X was compared to DSRC in [10]. During the LTE-V2X standardization process, 3GPP recommended a traffic model with two message sizes and a fixed time interval between CAMs [11]. Subsequently, an aperiodic traffic model was introduced in [12], but it did not conform to the rules for CAM message generation [13]. These rules specify the timeframe for message generation and content of CAMs. Current standards now generate CAMs with varying time intervals and message sizes, as experimentally demonstrated in [14] in urban, suburban, and highway scenarios using standard-compliant and commercial V2X devices. In particular, there are significant differences between collected traces and CAM messages generated with simplified traffic models, as demonstrated in [14], which can significantly impact the findings of studies based on the simplified model.

In [15], the first set of empirical models was presented to realistically generate CAMs in vehicular networks, and these models were validated in [14]. Additionally, [16] explored the performance of LTE-V2X when transmitting aperiodic messages with variable sizes. This thesis extends this line of research by considering a realistic model that generates messages following the ETSI CAM standard.

In this thesis, our objective is to analyze the performance of LTE-V2X for aperiodic messages with variable sizes and develop mechanisms to address the challenges arising from the implementation of aperiodic traffic with variable message sizes.

3.2. CAM generation in LTE-V2X

The standard CAM is one of the main messages defined by the ETSI [17] for transmitting information with relevant data for other vehicles. CAM messages are generated at the Facilities layer of the ETSI ITS Communications Architecture. The format of CAMs and the CAM generation rules were defined in ETSI. The format and generation rules are applicable regardless of the technology used for the access layer (e.g., IEEE802.11p or LTE-V2X). The ETSI rules specify that CAMs should be generated every 100 ms to 1 s.

CAMs are only triggered when a set of rules is met:

- The distance between the current position of the vehicle and the position included in its previous CAM exceeds 4 m.
- The absolute difference between the current speed of the vehicle and the speed included in its previous CAM exceeds 0.5 m/s.
- The absolute difference between the current direction of the vehicle and the direction included in its previous CAM exceeds 4 °.
- The time elapsed since the last CAM was generated is equal to or greater than 1s.

A vehicle checks the above conditions everyT_CheckCamGen≤100ms, i.e., at least 10 times per second. The time interval between CAMs is then variable and is a multiple of T_CheckCamGen. It is uncommon that the time between consecutive CAMs is constant for more than 3 CAMs (except when the vehicle is stopped) [18].

A CAM message consists of one ITS PDU header and multiple mandatory or optional containers [19]. Inside the header, there are data elements (DE) such as the protocol version, the message type, and the ID of the vehicle or RSU (Road Side Unit) that transmits the CAM. Each container includes a series of optional and mandatory DEs described in **Error! Reference source not found.**.

Table 1. Containers in CAMs

Container Name	***Mandatory/ Optional DEs***	***Contains***
Basic	Mandatory	Information of the transmitting vehicle (e.g., the type of vehicle or its position)
High Frequency	Mandatory	Highly dynamic information of the transmitting vehicle (e.g., its acceleration, heading or speed)
Low Frequency	Optional	Static and dynamic information of the transmitting vehicle (eg, the status of the exterior lights and the vehicle's path history)
Special Vehicle	Optional	It is transmitted by specific vehicles such as public transport, emergency vehicles, or vehicles transporting dangerous goods.

The size of CAMs depends on the optional containers and the DEs included. The ITS PDU header and the basic container have a fixed size, and these are mandatory. The high frequency container is mandatory. However, 7 of its 16 DEs are optional. The size of this container can vary depending on the manufacturer and the context conditions of the vehicle [18]. As the name suggests, the low-frequency container usually transmitted less frequently than the high-frequency container. It has three mandatory DEs, including PathHistory. This DE states the path that a vehicle has followed. The size of PathHistory is not fixed as the description can use between 0 and 40 path entries. The number of path entries is completely dependent on the driving conditions and the implementation. Security also has an impact on the amount of data that is finally transmitted. Security certificates might be attached to a CAM before transmission. The certificate is created whenever a new neighboring vehicle is detected or once per second. The certificate can also be sent on demand when an RSU request for it. The size of the security certificates usually varies between 100 and 150 bytes [18]. Under all these circumstances, the size of CAMs can vary between 200 and 800 bytes. These variations are significant and should be considered to accurately estimate V2X performance.

Analysis of the performance and efficiency of LTE-V2X requires considering realistic conditions. However, related studies use simplified data traffic models for the generation of awareness messages, which can significantly affect the performance and operation of LTE-V2X. These models typically generate awareness messages at periodic time intervals (100ms to 1s) or with a constant message size (200-400 bytes). These simplified models are used, for example, in [7][20] with IEEE 802.11p, [8][9] with LTE-V2X, and [10] for comparing the performance of LTE-V2X and DSRC.

3GPP recommended in TR 36.885 during the LTE-V2X standardization process, a traffic model with two message sizes and a fixed time interval between CAMs [21]. An aperiodic traffic model was introduced later in TR 37.885 [22], but the model is not compliant with the ETSI rules for the generation of CAM messages defined in EN 302 637-2 V1.4.1. These rules specify when vehicles should generate CAMs, and what should be their content, as described in the previous subsection. The C2C-CC experimentally demonstrated that current standards create CAMs with different time intervals and variable size. This was observed in urban, sub-urban and highway scenarios using commercial and standard-compliant V2X devices. These devices implemented different Facilities layer profiles and were embedded in vehicles of two OEMs. The statistics reported by the C2C-CC [15] show significant differences between the collected traces and the CAM messages generated with the simplified traffic models shown in Fig. 5.

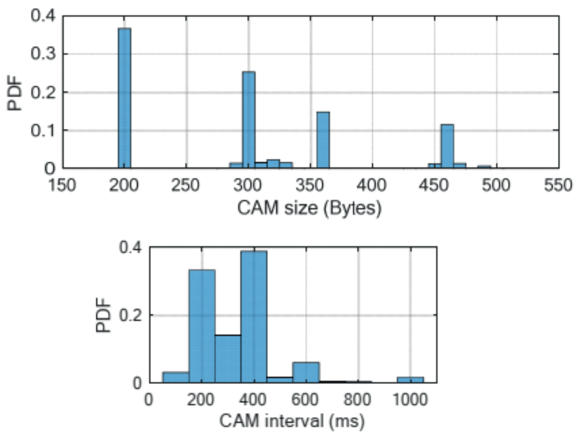


Fig. 5. CAM Sizes and CAM Intervals [15]

4. Mechanisms to overcome the impacts of Aperiodic Messages of Variable Size

In this chapter, the challenges posed by aperiodic messages of variable sizes and varying time intervals in LTE-V2X communications will be explored. To begin, the impact of Realistic CAM generation on LTE-V2X will be examined in the first section. Subsequently, a comprehensive summary of the impacts of variable message sizes and time intervals between messages will be presented in the second section. Finally, in the third section, mechanisms will be outlined, with the aim of effectively addressing and minimizing these challenges. The objective of this chapter is to provide a clear understanding of these issues and present practical solutions to enhance the reliability and efficiency of LTE-V2X communication.

4.1. Impact of the realistic CAM generation in LTE-V2X

Given the periodic nature of the resources reserved by the sensing-based SPS scheduling scheme described previously [23], LTE-V2X is particularly designed to operate efficiently operate under the transmission of periodic messages of equal size. Researchers have recently analyzed the performance and efficiency of LTE-V2X under realistic data traffic using a model derived from the traces collected by the C2C-CC previously described. The results obtained [15] show that the performance and efficiency of LTE-V2X can be significantly degraded when considering realistic data traffic with variable message size and time interval. Some of the identified issues are described below:

4.1.1. Reselections

When the Reselection Counter is 0, a vehicle may reselect its subchannel(s). The neighboring vehicles will be unaware of the new selected subchannel(s) until the next TB is transmitted. This can generate packet collisions. In Fig. 6, two vehicles A and B reselect their subchannels at T_A and T_B. If their selection windows overlap, as shown in Fig. 6, and they transmit any packet in this region, packet collision may occur. The collisions will persist until at least one of the two vehicles reselects new subchannels.

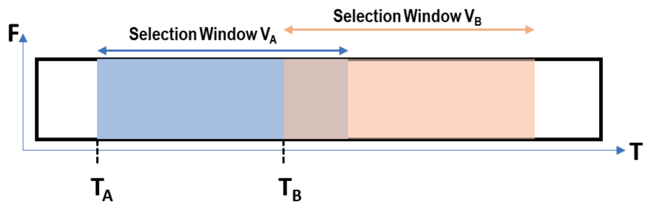


Fig. 6. Reselections in LTE-V2X; Vehicles A and B reselect their sub-channels at T_A and T_B respectively

4.1.2. Additional Reselections

Variation in message sizes and time intervals between messages can lead to the generation of additional reselection events. When a new message cannot fit within the subchannel originally reserved for larger messages, it triggers a reselection event known as Size Reselection. The scenario is illustrated in the left side of Fig. 7. A vehicle first generates a TB at T_{G1} and reserve two sub-channels for transmission at T_{R1}. The next TB is generated at T_{G2} and is larger in size than the first TB. Therefore, it will not fit in the previously reserved subchannels at T_{R2}. Then the vehicle must reselect new subchannels to transmit the new message.

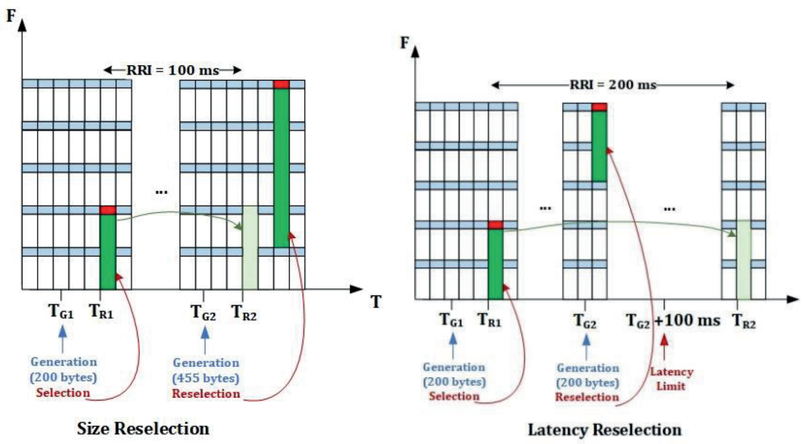


Fig. 7. Additional reselections due to Variable Message Size (left) and variable time interval between messages (Right)

When there is variation in the time between messages, extra reselection may occur, which is called latency reselection. Extra reselection can occur when sub-channel(s) are reserved with an RRI larger than the minimum time interval between messages. On the right side of Fig. 7, a vehicle produces a

TB at T_{G1} and reserves two subchannels at T_{R1} for transmission. It also reserves subchannels for its next transmission after RRI = 200 ms. If there is a new incoming packet with a latency deadline of 100 ms at T_{G2}, then it must be transmitted within (T_{G2} + 100 ms). If (T_{G2} + 100 ms) is less than T_{R2}, then the vehicle must reselect new subchannels for the transmission.

4.1.3. Unused subchannels due to change in Size of the Messages

If the new generated TB is smaller than the reserved sub-channels, then the reserved sub-channels will remain unused partially. These unused sub-channels cannot be selected by other vehicles because they will consider it as reserved. The unused sub-channels due to size change is illustrated in Fig. 8.

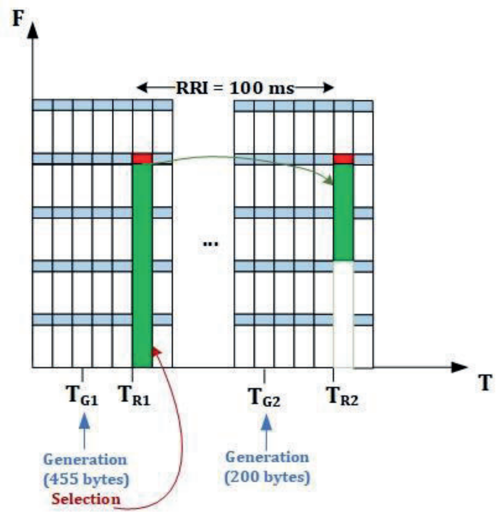


Fig. 8. Unused subchannels due to change in Size of the Messages

4.1.4. Unutilized Reservations

Due to variations in the size of the messages and time interval between messages, reselections can occur. The previously reserved sub-channels will be left unutilized for these reselections. The other vehicles will consider these subchannels as reserved, and they will not select these sub-channels for their transmission. This issue is reflected in Fig. 9. Here, the reservations at T_{R2} are left unutilized as the other vehicles consider these subchannels as previously reserved. Unutilized reservations reduce the number of available subchannels to the other vehicles and increase the possibility of packet collision.

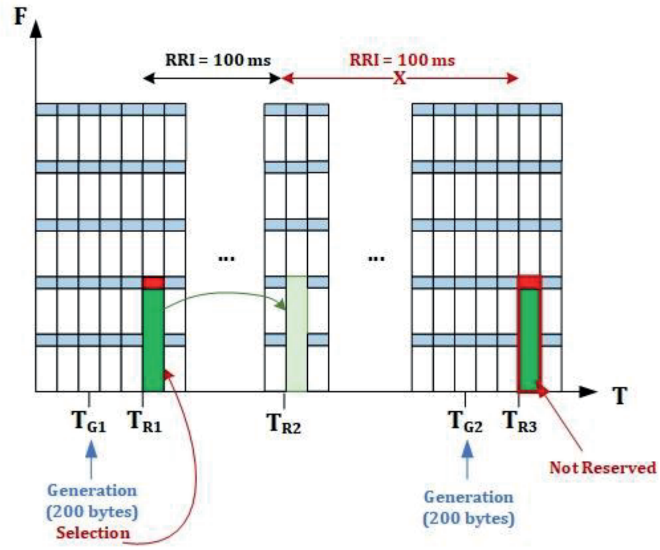


Fig. 9. Unutilized Reservations Due to longer Resource Reservation Interval

Reservations can also be left if the time between messages or TBs is larger than the RRI. This scenario is visible in Fig. 9. The first generated packet at T_{G1} reserves two sub-channels at T_{R2}. If the next TB T_{G2} arrives after T_{R2}, then it will reselect new sub-channels at T_{R3}. Thus, the reserved subchannels at T_{R2} are left unutilized.

4.2. Summary of the Impacts of the Variable Message Sizes and Time Interval between Messages

In this section, a concise, yet comprehensive summary of the diverse effects resulting from the variability in message sizes and the time intervals between these messages in LTE-V2X communications will be provided. As these factors play a pivotal role in shaping the efficiency and reliability of the communication system, it is crucial to gain a clear understanding of their impacts. By summarizing the observed consequences, an effort will be made to shed light on the challenges posed by variable message characteristics and lay the groundwork for the subsequent discussion on proposed mechanisms to mitigate these effects.

4.2.1. Impacts of Additional Reselections

If the size of messages varies, a reselection will occur when a new message does not fit in the previously reserved subchannel(s). For this reselection (due to variable message sizes), the remaining number of Sub-channels will be reduced for other vehicles. There will be more packet collision due to this reselection for variable message sizes.

Additional reselections can occur when subchannel(s) are reserved with an RRI larger than the minimum time interval between messages or TBs. For this reselection (due to variable time between TBs), the remaining number of Sub-channels will be reduced for other vehicles. There will be more packet collisions due to this reselection of variable time between messages.

4.2.2. Impacts of Unutilized Reservations

Reselections due to variations in the size of messages can leave previously reserved subchannel(s) unutilized. However, other vehicles will believe that these previously reserved sub-channel(s) are still reserved and will not consider them as candidate sub-channels. Thus, the number of available sub-channels for other vehicles to select is reduced. There will be more packet collision due to this unutilized reservation for variable message sizes. Reselections due to the variable time interval between messages can also leave previously reserved sub-channel(s) unutilized.

Again, the number of available sub-channels for other vehicles to select is reduced. There will be more packet collisions due to this unutilized reservation for variable time interval between messages. Reservations can also be left unutilized if the time between messages or TBs is larger than the RRI. The number of available sub-channels for other vehicles to select is reduced. There will be more packet collisions because the time between TBs is larger than RRI.

4.2.3. Impacts of Unused Subchannels

Variations in the size of the TBs can also result in unused subchannels even if this variation does not generate an additional reselection. This can occur if the new TB is smaller than the reserved sub-channels. In this case, there will be no additional reselection, but some of the reserved sub-channels will be left unused.

Other vehicles cannot utilize the unused subchannels, since they are reserved. This reduces again the number of available subchannels and increases the risk of packet collisions with the network load.

4.3. Proposals

To solve the above inefficiencies, this thesis proposes a modified version of the sensing-based SPS scheme, which will help to reduce the Size and Latency Reselections. In the following sections, the mechanism of the modified scheme will be explored, as well as the different configurations to implement the scheme for the aperiodic messages of different sizes and time intervals.

4.3.1. Proposal for One-shot transmission

The sensing-based SPS scheme can have certain inefficiencies in case of variable Message Sizes and Time Interval between Messages. The messages require a different number of subchannels to be reserved according to their various sizes. For example, a 200-byte message requires two subchannels, and a 300-byte message requires three subchannels. A reservation made for a 200-B message will not be maintained for the following reselection counter transmissions, since a 300-B message will be generated before the counter is equal to zero. The 300-B message will make a new reservation and the three subchannels will be maintained for the reselection counter transmissions. This is highly inefficient, as the following few transmissions correspond to 200-B messages with a need of only two subchannels. For this reason, the sensing-based SPS scheme excludes more resources than the actual requirement, and more vehicles will compete for the nonexcluded resources.

To overcome this issue, a modification in the sending-based SPS scheme is proposed in this thesis when the packets to be transmitted have different message sizes and the larger messages are less frequent than the smaller ones (a likely scenario in vehicular communications). The proposals consider that no subchannels will be reserved when transmitting the larger messages (300-B in the given example above). To transmit this larger message, the sensing-based SPS scheme will be used to select the subchannels. However, for the following reselection counter transmissions, the selected subchannels will not be reserved, and the sensing-based SPS scheme will be again applied to select the subchannel used to transmit the next 200-B packet. The selected subchannel will be the one reserved for successive reselection counter transmissions. This strategy can also be used if the messages have a different time interval. In the following sections, this proposed method will be mentioned as 'One-shot' transmission.

When there is a need for size reselection or latency reselection, one-shot transmission will be triggered instead of the reselection process. It can be applied to avoid size reselections, latency reselections or both. It will prevent Size and Latency Reselections.

4.3.2. One-shot in combination with different Message Sizes and Time Interval

The implementation of One-shot can have an impact on the performance that depends on the SPS configuration: number of subchannels reserved and time interval (RRI). There are multiple ways to configure SPS depending on the size and interval of the reservations.

For the RRI, there will be three options such as the following [24]:

- *RRI Strategy 1:* The time interval is fixed to 100 ms. It is the minimum time interval between the CAMs. There will be no latency reselections, but many resources may remain unused.
- *RRI Strategy 2:* RRI is fixed to 200 ms in this case. Latency reselections will be needed only when the latency deadline is below 200 ms. The most probable time interval according to the *Empirical CAM Model* [15] is 200 ms and 400 ms.
- *RRI Strategy 3:* In this RRI strategy, the time interval of the last message is used as the RRI. It has been observed from *Empirical CAM Model* that two messages with the same interval are generated consecutively.

For the Size Reservation strategies, three possible configurations are used in this thesis.

- *Baseline SPS:* This is the usual SPS strategy. It reserves the number of subchannels according to the need for the new message. Reselections are needed when the new message does not fit into the reserved subchannels.
- *Most Probable Message Size:* This configuration is used because it was found from [15] that approximately 46% of the CAM found in the real-time traces requires 3 subchannels to transmit the CAMs. Therefore, in this strategy, the most probable number of subchannels (3 Subchannels) will always be reserved irrespective of the number of subchannels required. If the new message is equal or smaller in size, no size reselections would be needed. Reselections will be needed only for the larger messages. Many resources can be left unused in this strategy.

- *Largest Message Size:* The largest message size requires reservation of 4 subchannels to be transmitted. In this strategy, 4 subchannels will always be reserved for the transmission of the CAMs. There will be no size reselection, but more resources will remain unused. This strategy is chosen to evaluate the performance when there will be no reselections due to variable message sixes.

The above size reservation strategies will be analyzed through simulation with the combination with the three RRI strategies. All possible combinations are shown in Table 2:

Table 2. Combination of Size Reservation and Time Interval Strategies

SPS Size Reservation				SPS Interval Reservation (RRI)		
Config.	**Baseline SPS**	**Most Probable Size**	**Largest CAM Size**	**100 ms**	**200 ms**	**Last CAM**
1	√			√		
2		√		√		
3			√	√		
4	√				√	
5		√			√	
6			√		√	
7	√					√
8		√				√
9			√			√

There are total 9 types of configurations in the table above, which will be simulated at first. As can be seen here, the configuration 1 is the combination of the Baseline SPS with 100 ms time interval. Later, in combination 2, the Baseline SPS is configured with 100 ms, and so on. One-shot transmission is not considered in any of these combinations.

Later, the above 9 configurations will be combined with One-shot for Size reselection, One-shot for Latency Reselection, and One-shot for both Size and Latency Reselection together.

First, One-shot will be only applied when there is a reselection due to variable message sizes. All possible combinations are presented in Table 3:

Table 3. Combination of One-shot for Size Reselection with different RRI and Size Reservation Strategies

	SPS Size Reservation			**SPS Interval Reservation (RRI)**			**One-shot**	
Config.	**Baseline SPS**	**Most Probable Size**	**Largest CAM Size**	**100 ms**	**200 ms**	**Last CAM**	**Due to Size**	**Due to Latency**
1	√			√			√	X
2		√		√			√	X
3			√	√			N.N*	X
4	√				√		√	X
5		√			√		√	X
6			√		√		N.N*	X
7	√					√	√	X
8		√				√	√	X
9			√			√	N.N*	X

*N.N = Not Needed

When the Largest CAM Size is selected as SPS reservation strategy, there is no need of One-shot because there will be no reselections due to variable message sizes (the maximum number of subchannels are already reserved for each transmission). Here, when the new message requires a latency lower than the time interval of the reservation, a latency reselection will occur. Again, One-shot will only be applied when there is a reselection due to variable time interval between messages. All the possible combinations are presented in Table 4:

Table 4. Combination of One-shot for Latency Reselection with different RRI and Size Reservation Strategies

	SPS Size Reservation			SPS Interval Reservation (RRI)			One-shot	
Config.	**Baseline SPS**	**Most Probable Size**	**Largest CAM Size**	**100 ms**	**200 ms**	**Last CAM**	**Due to Size**	**Due to Latency**
1	√			√			√	N.N*
2		√		√			√	N.N*
3			√	√			N.N*	N.N*
4	√				√		√	√
5		√			√		√	√
6			√		√		N.N*	√
7	√					√	√	√
8		√				√	√	√
9			√			√	N.N*	√

*N.N = Not Needed

In the above combinations, One-shot for Latency reselections are not needed when the RRI Strategy is 1 (RRI =100 ms). In case of the other two strategies, One-shot transmission for the latency reselections will be needed. Here, if the new message is larger than the reservation, a size reselection will occur.

Finally, One-shot transmission will be considered for both Size and Latency reselections, as in Table 5.

Table 5. Combination of One-shot for both Size and Latency Reselection with different RRI and Size Reservation Strategies

	SPS Size Reservation			SPS Interval Reservation (RRI)			One-shot	
Config.	**Baseline SPS**	**Most Probable Size**	**Largest CAM Size**	**100 ms**	**200 ms**	**Last CAM**	**Due to Size**	**Due to Latency**
1	√			√			√	N.N*
2		√		√			√	N.N*
3			√	√			N.N*	N.N*
4	√				√		√	√
5		√			√		√	√
6			√		√		N.N*	√
7	√					√	√	√
8		√				√	√	√
9			√			√	N.N*	√

*N.N = Not Needed

From the Tables above, in total, 36 strategies will be simulated in this thesis to evaluate the performance of LTE-V2X under realistic traffic with variable message sizes and time interval between the messages.

5. Simulation Platform

Simulation software models the functionality of a process or an environment based on theoretical and quantitative analysis. It is extremely helpful to develop, plan, and testing products without the use of actual infrastructure. The network simulator is one such software, for prediction of network behavior in various scenarios. Due to the structural and procedural complexity of networks, simulators are a must need. Many provide reusable and configurable components for layers, messages, and events that can be easily programmed. Many provide a graphical user interface for visualization of the simulations. Popular network simulators available are OMNeT++, NS, OPNET, and NetSim.

Road traffic and network communication simulators are complex. Therefore, hybrid frameworks are often required to perform the simulation. A hybrid simulation framework Veins (Vehicles in Network Simulation), composed of the network simulator OMNeT++ and the road traffic simulator SUMO, is used in this thesis [34]. This chapter represents a brief description of these simulators available in the literature. In a later section, the configurations of the simulation are presented.

5.1. Simulators

In this subsection, the network simulator, road traffic simulator and the hybrid framework will be discussed briefly.

5.1.1. OMNeT++

OMNeT++ is a well-known discrete network simulator platform that is built using C++ libraries and is available for academic use under a free license. This platform provides users with the tools and libraries to create and perform simulations. The modules in OMNeT++ are written in C++ and offer extensive support through their documentation for various network and wireless operations. The platform is designed in a simple and easy-to-understand structure, making it easy for users to reuse modules or create new ones. The modules in OMNeT++ are connected through gates, and the platform is available for multiple operating systems such as Linux, Mac OS, and Windows. The graphical user interface is a great feature for users who want to debug or investigate what is happening behind the scenes. Furthermore, OMNeT++ includes its own analysis tool, which provides users with a comprehensive environment to conduct various analyses and investigations.

5.1.2. Simulation of Urban Mobility (SUMO)

Simulation of Urban Mobility (SUMO) is an open source, highly portable, continuous, microscopic, and continuous traffic simulation tool that can handle large networks. It offers a visual editor called NETEDIT for creating and modifying road networks [35]. The simulation models individual vehicles with specific positions and speeds, which are updated at each time step. SUMO also includes various modes of transportation, such as cars, public transportation systems, and even pedestrians. Simulations can be deterministic, and the option of adding randomness is available.

5.1.3. Veins

Veins is an open-source simulation platform that provides the tools to conduct simulations of vehicular networks. It leverages the capabilities of two highly regarded simulation tools, OMNeT++, which specializes in event-based network simulations, and SUMO, a microscopic, continuous traffic simulator.

Veins is an open-source framework designed to simulate vehicular networks. It comes equipped with a collection of simulation models that simulate different aspects of vehicular networks, including traffic flow, communication networks, and road networks. These models are executed using an event-based network simulator (OMNeT++) and a road traffic simulator (SUMO). In addition, Veins includes components that handle the setup, execution, and monitoring of simulations.

Veins provides a simulation framework that serves as a foundation for creating customized simulation code. Although it can be utilized as is, with slight adjustments for particular applications, its primary purpose is to act as a platform for user-written code. Typically, this code represents an application that will be evaluated through simulation. The framework handles all other aspects, including modeling lower protocol levels and node mobility, establishing the simulation, overseeing its proper execution, and gathering results during and after the simulation.

Veins performs simulations by executing two parallel simulators, OMNeT++ for network simulation and SUMO for road traffic simulation, which are connected through a TCP socket. The communication protocol used is known as the Traffic Control Interface (TraCI), which facilitates bidirectional linking of road traffic and network traffic simulations. Vehicle movements in the SUMO road traffic simulator are reflected as the movement of nodes in the OMNeT++ network simulation, enabling nodes to interact with the ongoing road traffic simulation.

5.2. Simulation Setup

For this thesis, simulation was used to evaluate the performance of LTE-V2X mode 4 communication having variable message sizes and time intervals. In particular, Veins simulation framework was used, which integrates the OMNET++ network simulator and the road traffic simulator SUMO. The LTE-V2X mode 4 radio interface was implemented following 3GPP standards [25]. The implementation was validated in [26].

5.2.1. Simulation Scenario

This thesis was simulated on a 5-kilometer highway scenario. For the statistical collection, vehicles located in the center of the 2 km were considered. This is to avoid border effects. For this simulation, four different traffic densities were used, as indicated in Table 6.

Table 6. Traffic densities used in the simulation

Traffic density	Number of Lanes	Speed
60 veh/km	3	140 km/h [27]
120 veh/km	3	70 km/h [27]
200 veh/km	3	70 km/h
400 veh/km	5	70 km/h

5.2.2. Configuration of LTE-V2X

LTE-V2X is configured to operate on a 10 MHz channel in the 5.9 GHz frequency band. Following the 3GPP simulation guidelines in [27], the pathloss is modeled using the WINNER+ B1 model with an antenna height of 1.5 m for transmitter and receiver. Shadowing effects are modeled using a log-normal distribution with zero mean and a standard deviation of 3 dB. The spatial shadowing correlation is modeled according to the 3GPP guidelines in [27], with a decorrelation distance of 25 m. The PHY layer performance of LTE-V2X is modeled using BLER (Block Error Rate)-SINR (Signal to Interference plus Noise Ratio) curves from [28] where both technologies are evaluated under the same conditions (including the fast fading model specified in [29]).

LTE-V2X is configured to transmit at 23 dBm and uses the Modulation and Coding Scheme (QPSK with a coding rate of 0.5, that is, MCS 6). Simulations have been conducted using the minimum sensitivity levels (-90.4 dBm) defined in the corresponding standards [30]. Simulations have also been conducted with better sensitivity levels corresponding to those achieved by commercial devices or prototypes; these values are used as a baseline in this study. The sensitivity level of the prototype used here is -103.5 dBm as in [31].

We configure LTE-V2X with 5 subchannels per subframe following the ETSI recommendations in [32]. Each subchannel has 10 RBs and we consider the adjacent PSCCH-PSSCH configuration (i.e. a TB and its associated SCI are transmitted in adjacent RBs). Table 7 shows the number of subchannels needed to transmit CAMs of different sizes considering the configured subchannelization and the use of MCS 6 (i.e. QPSK with a coding rate of 0.5). The reported CAM sizes correspond to those used in the different CAM message generation models.

According to the ETSI recommendations in [19], LTE-V2X is configured with 5 subchannels per subframe. There are 10 RBs in each subchannel, and the adjacent PSCCH-PSSCH configuration (i.e., a TB and its associated SCI are transmitted in adjacent RBs) is considered. Considering the configured subchannelization and the use of MCS 6 (i.e., QPSK with coding rate of 0.5), the number of subchannels needed to transmit CAMs of different sizes is shown in Table 7. The reported CAM sizes correspond to those used in the different CAM message generation models.

Table 7. Different CAM Sizes

Packet Size (bytes)	**CAM Model**	**Number of Subchannels**
190	3GPP	2
200	Simplified, Empirical CAM, Empirical-size	2
300	3GPP, Empirical CAM, Empirical-size	3
360	Empirical CAM, Empirical-size	3
455	Empirical CAM, Empirical-size	4

To ensure that the sensing-based SPS scheme excludes all subchannels for which an SCI from another vehicle is correctly received, the RSRP threshold has been configured with a low value (-140 dBm). This is the best configuration [33] of the RSRP threshold, since Step 2 of the sensing-based SPS scheme is more effective than Step 3 in excluding the subchannels that are more likely to experience high interference levels. In [33] the author used the simplified model and the 3GPP model to achieve the results. Using the same simulation conditions, this study was analyzed with Empirical CAM generation models.

When the reselection counter is depleted, the probability P is selected to maintain the same subchannels as 0 like in [33]. Performance is not improved by increasing P, but it can produce packet collisions that persist over longer periods of time. As packet retransmissions lead to channel and reducing performance, LTE-V2X is configured without it.

The selection of RRI is a key parameter to configure in the LTE-V2X. There is no particular method to configure the RRI. To evaluate the performance of LTE-V2X, in this thesis three different RRI strategies (RRI Strategy 1, RRI Strategy 2 and RRI Strategy 3) defined in [16] are used. In Section 5.2.3, these strategies are elaborated.

5.2.3. Performance Metrics

To measure and evaluate the performance of LTE-V2X, several metrics are used. The performance is mainly measured by means of the Packet Delivery Ratio (PDR) and the Packet Interception (PIR). The PDR is the average ratio of successfully received messages to the total number of messages transmitted. This is considered a function of the distance between the transmitting and receiving vehicles. The time between two successful transmitted packets by the same vehicle is called the PIR. To monitor errors due to persistent packet collisions, the PIR is used. For this purpose, the PIR is represented as a cumulative distribution function (CDF) of all transmissions between vehicles at a maximum distance of 100 m. To observe errors from persistent packet collisions, a short distance of 100 m is selected. The propagation effects will generate more errors if a larger distance is chosen and it will be more challenging to notice the impact of persistent packet collisions.

The average ratio of packet lost due to propagation errors and packet collisions is also estimated. These ratios are also indicated as a function of the distance between the transmitting and receiving vehicles. The average ratio of the lost packet is estimated by the Propagation Error. Generally, lost packets are received with a signal strength below the sensitivity level or because the signal-to-noise ratio (SNR) is too low to correctly decode the packet. The average ratio of packets lost due to packet collisions is estimated by collision error. This error occurs when packets collide and a packet cannot be correctly decoded because the SINR is too low due to the interference generated by other vehicles.

There are some other metrics to measure the challenges experienced by the LTE-V2X mode 4 sensing-based SPS scheme when transmitting variable size aperiodic messages. The following metrics will be computed:

- *Size Reselection Ratio:* Ratio of messages that generates a size reselection to the total number of messages produced.
- *Latency Reselection Ratio*: Ratio of messages that generate a latency reselection to the total number of messages produced.
- *Counter Reselection Ratio:* Ratio of messages for which there is a reselection due to the implementation of the Reselection Counter to the total number of messages produced.
- *Total Reselection Ratio:* Ratio of messages that produce a reselection (counter, size, or latency) to the total number of messages generated. Note that this ratio is not equal to the sum of the other three ratios since it is possible that a message generates several types of reselection, and this is counted as a single reselection when computing the total reselection ratio.
- *Ratio of Unused Subchannels:* Average ratio of unused sub-channels in the reserved sub-channels used to transmit a message or TB.
- *Ratio of Unutilized Reservations:* Average ratio of reservations that are completely left unutilized (i.e., no subchannels in the reservation are used) to the total number of reservations. This metric only accounts for unutilized reservations that are not due to an additional reselection. The additional reselections are already counted in the size and latency reselection ratios.

6. Results

The objective of this thesis is to evaluate the performance of LTE-V2X mode 4 under realistic traffic. To evaluate the performance, the performance metrics described in Chapter 5 are used. The metrics are evaluated in the following subsections in four parts (Impacts of Size Reservation Strategies, Impacts of One-shot for Size Reselection, Impacts of One-shot for Latency Reselection, and Impacts of One-shot for both Size and Latency Reselection).

6.1. Impacts of Size Reservation Strategies

In this subsection, the effects of the Size Reservation Strategies will be discussed. Three types of size reservation technique are used in this configuration. The first one is the baseline configuration for the Semi-persistent Scheduling Scheme. Then, this is compared with the Most Probable Size (always reservation of 3 Subchannels) and Largest CAM Size (always reservation of 4 Subchannels) configurations. All of these configurations are also evaluated for the three different Resource Reservation Interval (RRI) strategies.

6.1.1. Effects on Size Reselection Ratio

In Fig. 10, the Size reselection ratios are presented in the Y-axis. On the X-axis, the three size reservation strategies are presented with different RRI strategies.

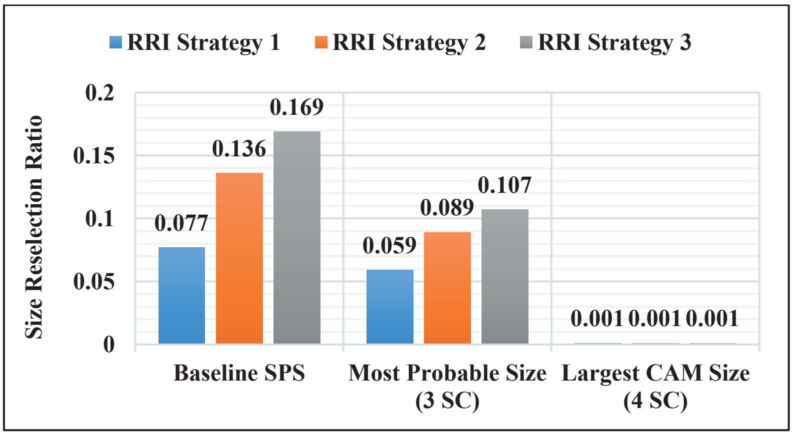
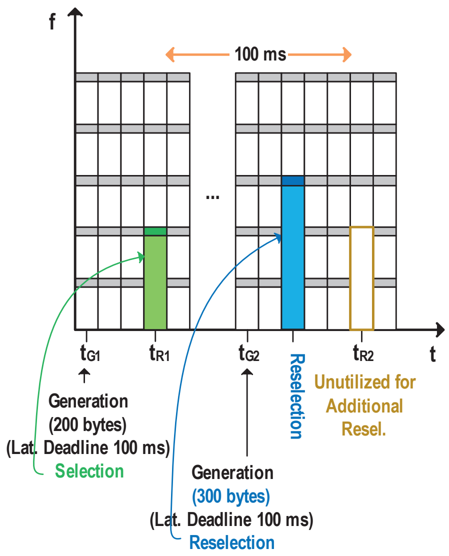


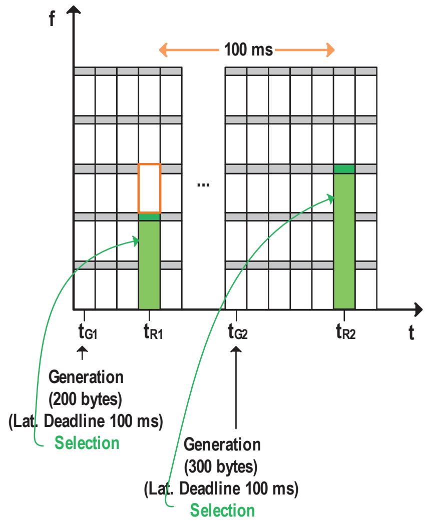
Fig. 10. Size-Reselection Ratio (Size-Reservation Strategies)

From Fig. 10, it is observed that the size reselection ratio is decreased for the other two Size reservation strategies from the Baseline SPS. This effect occurs because other configurations are reserving more subchannels than the baseline configuration. When Largest CAM size is used for the reservation, there is no reselection as the maximum number of subchannels are always reserved. The value 0.001 corresponds to the jitter. Fig. 11 illustrates why this effect is produced with an example. Fig. 11 (a) represents a scenario where Baseline SPS configuration is used with RRI strategy 1. A vehicle generates a first message (or TB) at t_{G1} and reserves two subchannels for its transmission at t_{R1}. The next message generated at t_{G2} is larger and does not fit in the two reserved subchannels at t_{R2}. The vehicle must then reselect new subchannels to transmit the new message.

In Fig. 11(b), instead of using Baseline SPS, Most Probable CAM Size (Always reserving 3 Subchannels) is used with RRI Strategy 1. The generated message at t_{G2} is transmitted to the reserved subchannels at t_{R2} as the reservation is always done with 3 subchannels. That is why the Size Reselection Ratio decreased when the reservation was made with always 3 subchannels.



(a) Scenario with Baseline SPS configuration and RRI strategy 1



(b) Scenario with Most Probable CAM Size (3 Subchannels) and RRI strategy 1

Fig. 11. Effect on Size Reselection Ratio (Size Reservation Strategies)

This is obvious that if 4 subchannels are always reserved in case of Fig. 11(b), there will be no size reselection as 4 subchannels are the maximum number that a message can require.

6.1.2. Effect on Latency Reselection Ratio

In Fig. 12, the Latency Reselection Ratio are shown considering the three types of Size Reservation Strategies.

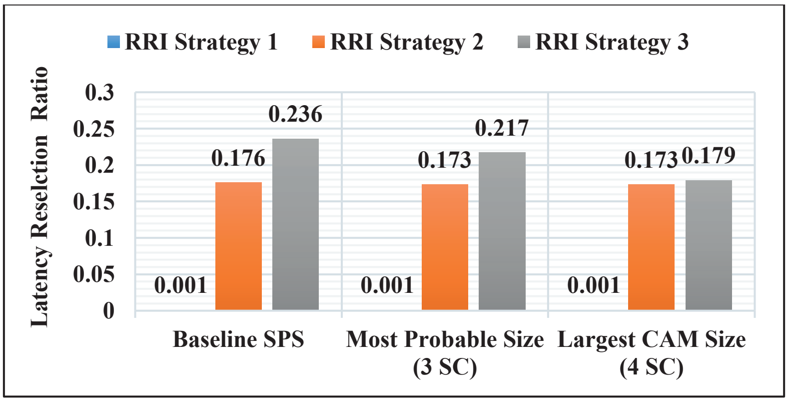
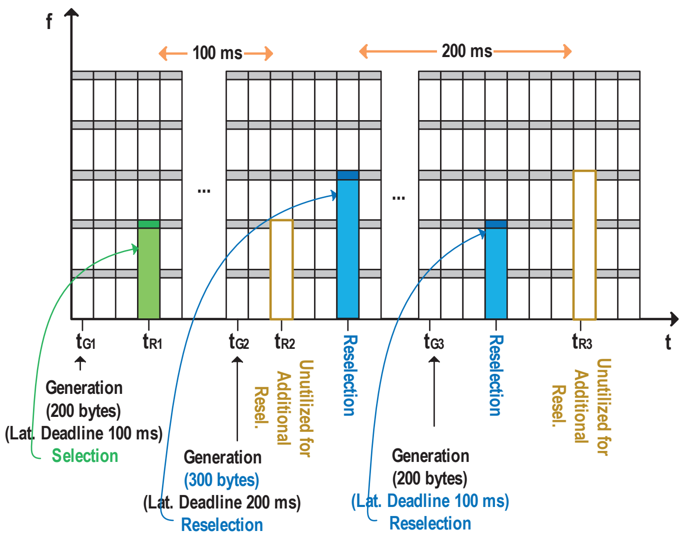


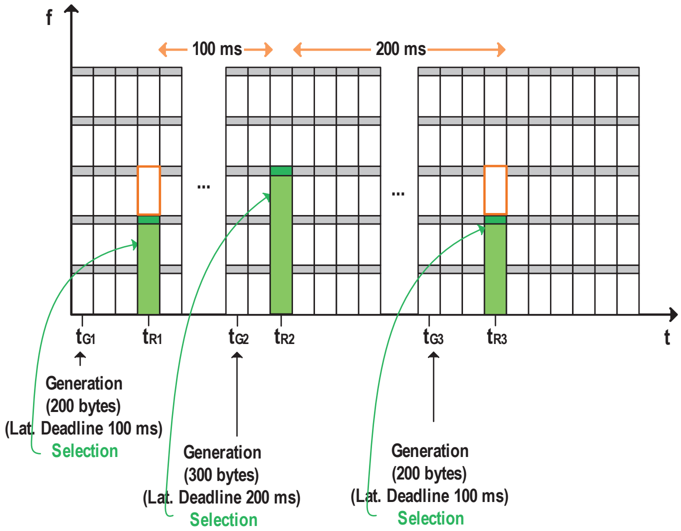
Fig. 12. Latency Reselection Ratio (Size Reservation Strategies)

From Fig. 12, it is observed that the latency reselection ratio is almost the same in the three different Size reservation strategies in case of RRI Strategies 1 and 2. This is because for RRI Strategy 1, there is no latency reselection for the minimum time interval of 100 ms. The reduction in the the ratio in case of RRI Strategy 2 is also less, as it uses a time interval of constant 200 ms. It can also be observed that the latency reselection ratio is reduced only for RRI strategy 3 for the other two size reservation strategies.

Fig. 13(a) that represents a scenario where Baseline SPS configuration is used with RRI strategy 3. A vehicle generates a first message (or TB) at t_{G1} and reserves two subchannels for its transmission at t_{R1}. The next message generated at t_{G2} is larger with a latency deadline of 200 ms and does not fit in the two reserved subchannels at t_{R2}. The vehicle must then reselect new subchannels to transmit the new message. After this reselection, the next reservation is made after 200 ms. The next message arrives at t_{G3} with a latency deadline of 100 ms. As (t_{G3} + 1oo ms) is less than t_{R3}, this new message cannot be transmitted in the reserved subchannels at t_{R3} and will be reselected again.



(a) Scenario with Baseline SPS configuration and RRI strategy 3



(b) Scenario with Most Probable CAM Size (3 Subchannels) and RRI strategy 3

Fig. 13. Effect on Latency Reselection Ratio (Size Reservation Strategies)

In Fig. 13(b), instead of using Baseline SPS, Most Probable CAM Size (Always reserving 3 Subchannels) is used with RRI Strategy 3. The generated message at t_{G2} is transmitted to the reserved subchannels at t_{R2} as the reservation is always done with 3 subchannels. The next reservation is made after 200 ms from t_{R2}. The next generated message in t_{G3} can be transmitted in the reserved subchannels at t_{R3} because (t_{G3} + 100 ms) is greater than in t_{R3}. There is no latency reselection if 3 subchannels is always reserved if the above two figures are compared.

That is why the Latency Reselection Ratio decreased when the reservation is done with always 3 subchannels. In Fig. 13, if 4 subchannels are always reserved, similar results will be produced.

6.1.3. Effect on Unutilized Reservation Ratio

In Fig. 14, the Unutilized Reservation Ratio is shown considering the three types of Size Reservation Strategies.

From Fig. 14, it is observed that the unutilized reservation ratio is increased for the other two size reservation strategies. This happened because when more subchannels are used for the reservation, there is a

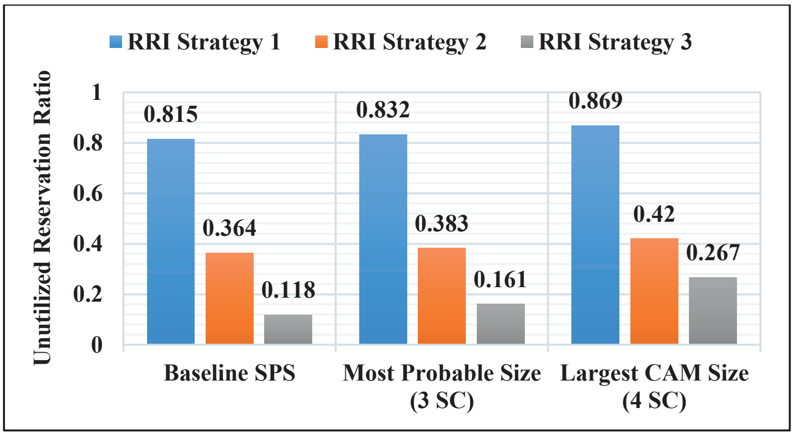
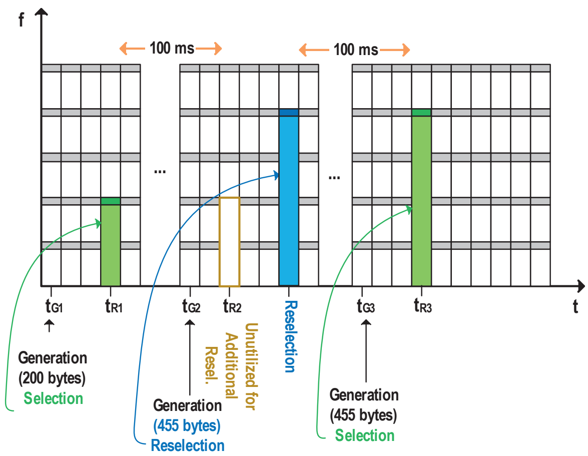
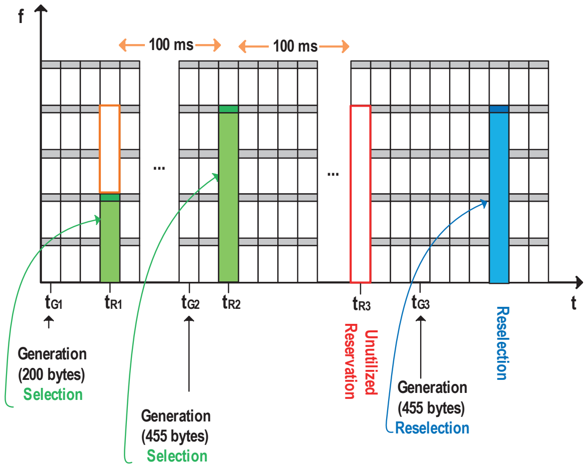


Fig. 14. Unutilized Reservation Ratio (Size Reservation Strategies)

possibility of having no reselection compared to the Baseline SPS scheme. If there are less reselections, it may happen that there are more time intervals than the requirement. It may result in Unutilized reservations, which will be discussed now with an example.



(a) Scenario with Baseline SPS configuration and RRI strategy 1



(b) Scenario with Largest CAM Size (4 Subchannels) and RRI strategy 1

Fig. 15. Effect on Unutilized Reservation Ratio (Size Reservation Strategies)

Fig. 15(a) that represents a scenario where Baseline SPS configuration is used with RRI strategy 1. A vehicle generates a first message (or TB) at t_{G1} and reserves two subchannels for its transmission at t_{R1}. The next message generated at t_{G2} is larger and does not fit in the two reserved subchannels at t_{R2}. The vehicle must then reselect new subchannels to transmit the new message. After this reselection, the next reservation is made after 100 ms. The next large message arrives at t_{G3} and can be transmitted in the reserved subchannels at t_{R3} because the reservations are made with 4 subchannels.

In Fig. 15(b), instead of using Baseline SPS, Largest CAM Size (Always reserving 4 Subchannels) is used with RRI Strategy 1. The message generated on t_{G2} is transmitted in the reserved subchannels on t_{R2} as the reservation is always done with 4 subchannels. The next reservation is made after 100 ms from t_{R2}. The next generated message in t_{G3} cannot be transmitted in the reserved subchannels at t_{R3} because t_{G3} is greater than t_{R3}. The message is generated after the reservation and is reselected. So, there is an Unutilized reservation at t_{R3}. That is why the Unutilized Reservation Ratio increased when the reservation was made with always 4 subchannels.

6.1.4. Effect on Unused Subchannel Ratio

In Fig. 16, the Unused Subchannels Ratio are shown considering the three types of Size Reservation Strategies.

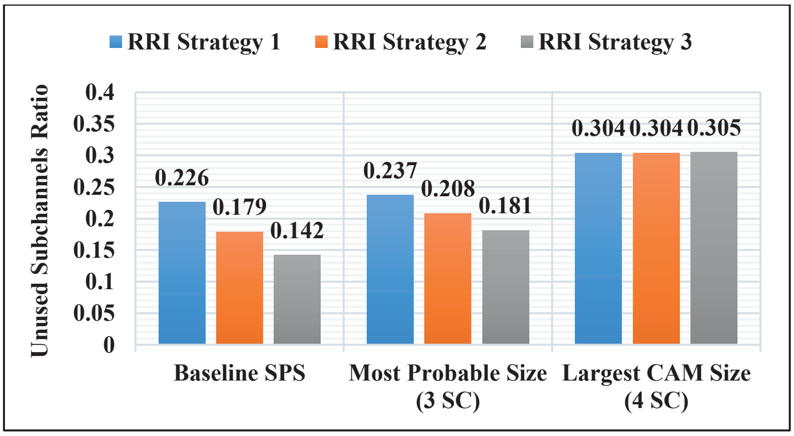
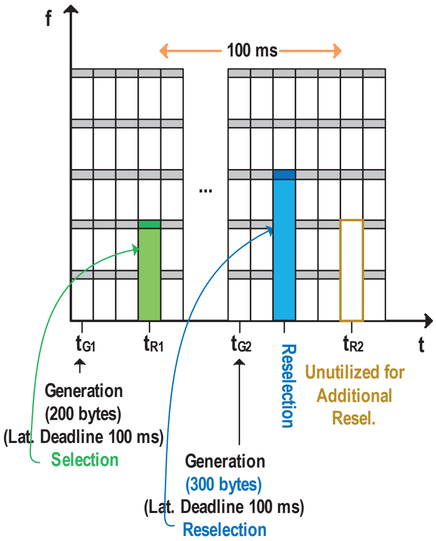


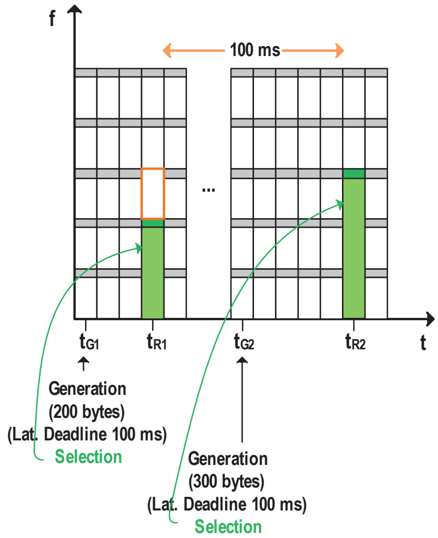
Fig. 16. Unused Subchannel Ratio (Size Reservation Strategies)

In Fig. 16, the unused reservation ratio increases when the other two size reservation strategies are used. This happens due to larger reservations than the baseline configurations. When the reservation



(a) Scenario with Baseline SPS configuration and RRI strategy 1

is always larger than the requirement, the number of unused subchannels will increase.



(b) Scenario with Most Probable CAM Size (3 Subchannels) and RRI strategy 1

Fig. 17. Effect on the Unused Subchannels Ratio (Size Reservation Strategies)

Fig. 17(a) that represents a scenario where Baseline SPS configuration is used with RRI strategy 1. A vehicle generates a first message (or TB) at t_{G1} and reserves two subchannels for its transmission at t_{R1}. The next message generated at t_{G2} is larger and does not fit in the two reserved subchannels at t_{R2}. The vehicle must then reselect new subchannels to transmit the new message.

In Fig. 17(b), instead of using Baseline SPS, Most Probable CAM Size (Always reserving 3 Subchannels) is used with RRI Strategy 1. The first generated message at t_{G1} requires 2 subchannels reservation but at t_{R1}, the reservation is made with 3 subchannels. So, the message is transmitted at t_{R1} and there are 1 Unused subchannels. The generated message at t_{G2} is transmitted to the reserved subchannels at t_{R2} as the reservation is always done with 3 subchannels.

It can be observed that the Unused Subchannels ratio increases when the other size reservation strategies are implemented rather than the Baseline SPS.

6.2. Impacts of One-shot for Size Reselection

At first, the One-shot strategy is applied in case of Size reselection. The effects of this strategy will be discussed in the following subsections.

6.2.1. Effects on Size Reselection Ratio

In Fig. 18, the One-shot for Size Reselection Ratio is presented alongside with the ratio before One-shot is applied to see the effect of using One-shot for the Size Reselection. It can be seen that the Size Reselection Ratio is zero for all the configurations. This is because all the Size Reselections are replaced with a One-shot transmission.

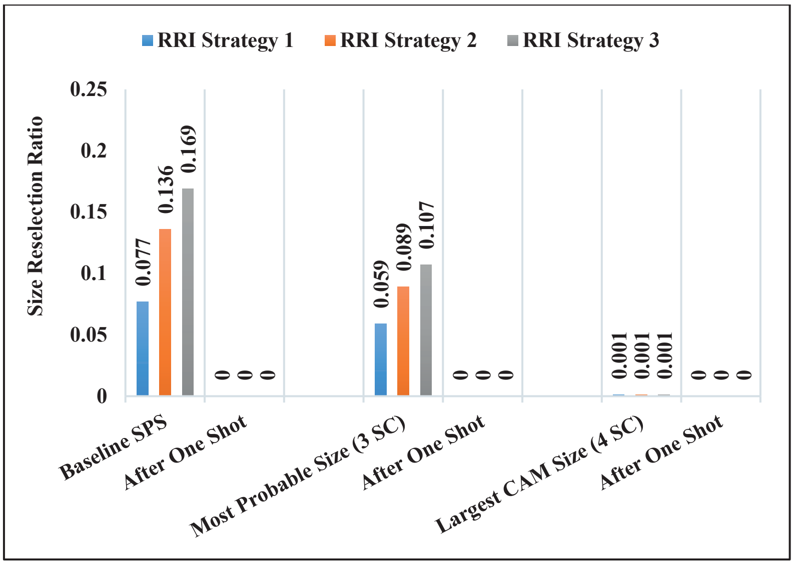


Fig. 18. Size Reselection Ratio (Using One-shot for Size Reselection)

6.2.2. Effects on Latency Reselection Ratio

In Fig. 19, the effect on Latency Reselection Ratio is shown after using One-shot transmission for Size Reselection. It is observed that for the Largest CAM Size, there is no effect of One-shot for Size Reselection. Because the maximum number of subchannels are always reserved in this configuration. In all the Size Reservation strategies, for RRI 1 and RRI 2, there is no change in the ratio after using One-shot transmission. This is due to having constant Resource Reservation Interval of 100 ms and 200 ms, respectively for RRI 1 and RRI 2. The Latency Reselection ratio is increased for RRI 3 in case of

Baseline SPS and Most Probable CAM size. In RRI 3, the last TB's RRI is taken for the next TB. This may create more latency reselections. All these observations will be discussed with examples in Fig. 20 and Fig. 21.

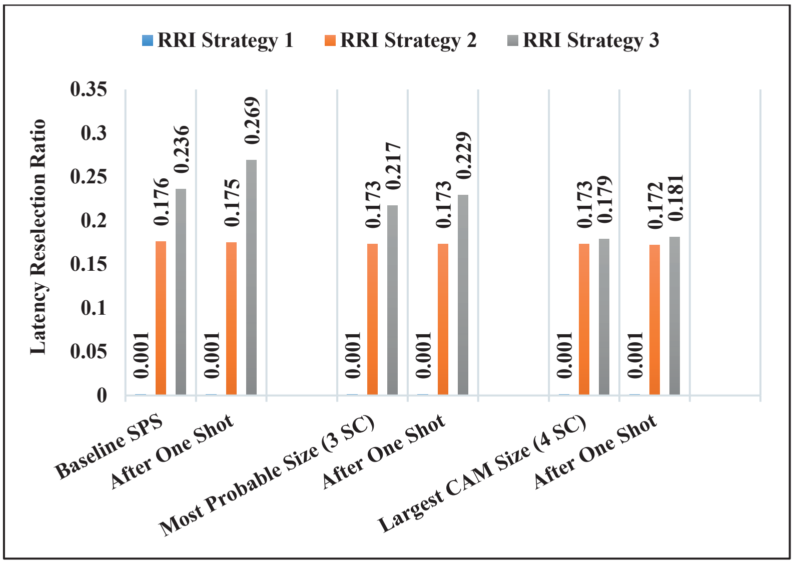
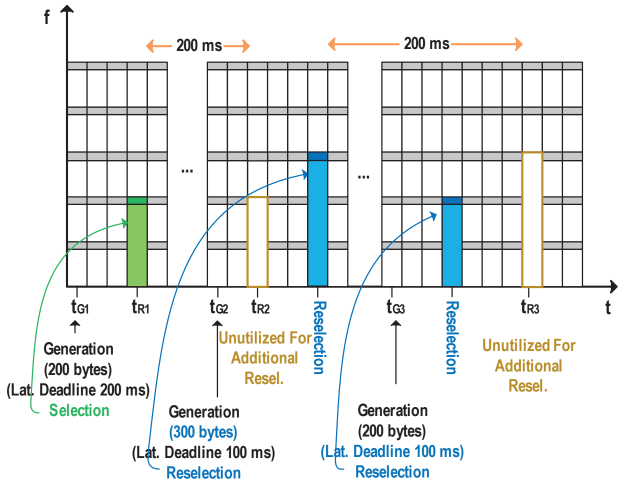


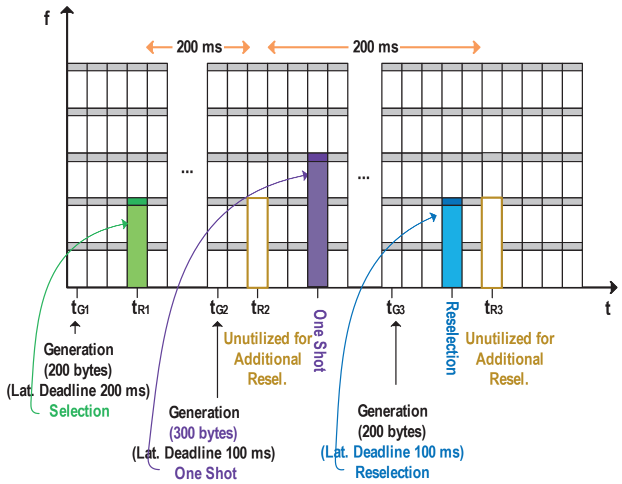
Fig. 19. Latency Reselection Ratio (Using One-shot for Size Reselection)

There is also no change in the latency reselection ratio for RRI 2 (Time Interval = 200 ms). Fig. 20(a) that represents a scenario where a vehicle generates a first message (or TB) at t_{G1} and reserves two subchannels for its transmission at t_{R1}. The next message generated at t_{G2} is larger and does not fit in the two reserved subchannels at t_{R2}. The vehicle must then reselect new subchannels to transmit the new message. The next reservation is done at tR3, which is 200 ms away from the reselected subframes. At tG3, the new generated message has a latency deadline of 100 ms. As (t_{G3} + 100 ms) is less than t_{R3}, and hence this packet needs a Latency Reselection.

In Fig. 20(b), One-shot is used instead of the Reselection due to the larger message size generated at t_{G2}. This One-shot cannot prevent the latency reselection that occurred for the transmission of the generated message at t_{G3}. That is why there is no change in Latency Reselection Ratio when One-shot for Size Reselection is used.



(a) Scenario with Baseline SPS and RRI strategy 2 (Before One-shot)

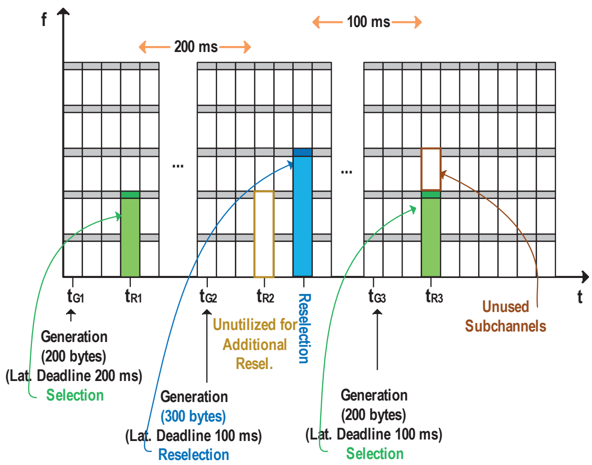


(b) Scenario with Baseline SPS and RRI strategy 2 (After One-shot)

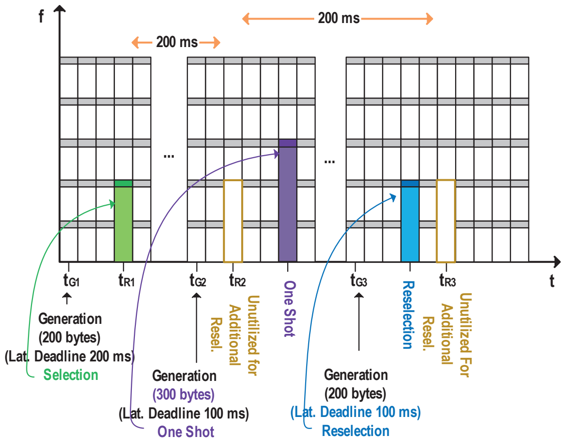
Fig. 20. Effect on Latency Reselection Ratio (One-shot for Size Reselection)

The Latency Reselection ratio is increased for RRI 3 in case of Baseline SPS and Most Probable CAM size. Fig. 21(a) that represents a scenario with Baseline SPS and with RRI 3 where a vehicle generates a first message (or TB) at t_{G1} and reserves two subchannels for its transmission at t_{R1}. The next message generated at t_{G2} is larger and does not fit in the two reserved subchannels at t_{R2}. The vehicle must then reselect new subchannels to transmit the new message. The next reservation is done at tR3, which is 100 ms away from the reselected subframes. For RRI Strategy 3, the reselected subchannels always take the latency deadline of the last generated CAM as RRI.

At tG3, the new generated message has a latency deadline of 100 ms. As (t_{G3} + 100 ms) is greater than tR3, this packet will be transmitted at t_{R3}. In Fig. 21(b), One-shot is used instead of the Reselection due to the larger message size generated at t_{G2}. This One-shot cannot prevent the latency reselection that occurred for the transmission of the generated message at t_{G3}.



(a) Scenario with Baseline SPS and RRI strategy 3 (Before One-shot)



(b) Scenario with Baseline SPS and RRI strategy 3 (After One-shot)

Fig. 21. Effect on Latency Reselection Ratio (One-shot for Size Reselection)

That is why Latency Reselection Ratio increased when One-shot for Size Reselection is used for RRI 3.

6.2.3. Effects on Unutilized Reservation Ratio

The effect of Unutilized Reservation Ratio after using One-shot for Size Reselection is shown in Fig. 22. The ratio is increased for the Baseline SPS and the Most Probable Size configuration when One-shot is used for Size Reselection. In Baseline SPS, the additional reselections help to get adjusted with the variable message sizes. But when One-shot is used, it holds the reservation until the Reselection Counter reaches zero. This leads to having more unutilized reservations. This effect is explained in Fig. 23 in the next pages.

Again, variations in the size of the messages and the time intervals between the messages create Unutilized reservations. Now in case of Baseline SPS and Most Probable CAM Size, One-shot is considered for eliminating the size reselection. Thus, there will be no effect of size reselection in this case. There will be effect of Latency reselection only. As RRI 1 has no Latency reselection, the unutilized reservation ratio is same for this strategy but different for the RRI 2 & RRI 3.

It has been also observed that when the Largest CAM Size configuration is considered, there is no size reselection as the maximum number of subchannels is reserved always. In this scenario, the effect on Unutilized reservation ratio will be only by the Latency Reselection.

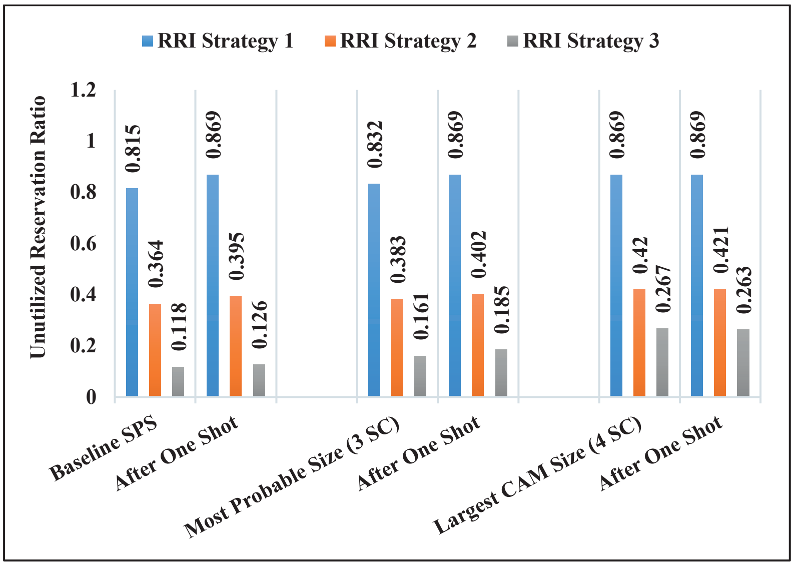
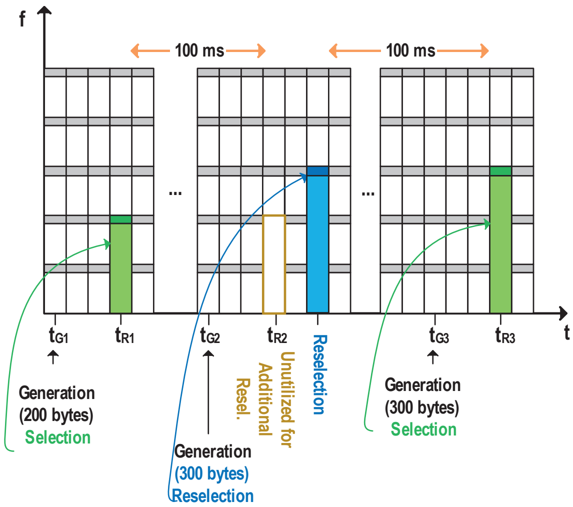


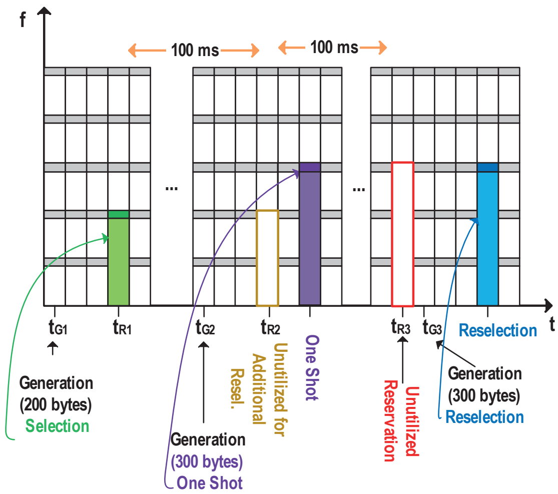
Fig. 22. Unutilized Reservation Ratio (Using One-shot for Size Reselection)

Fig. 23(a) that represents a scenario where Baseline SPS is used with RRI Strategy 1. A vehicle generates a first message (or TB) at t_{G1} and reserves two subchannels for its transmission at t_{R1}. The next message generated at t_{G2} is larger and does not fit in the two reserved subchannels at t_{R2}. The vehicle must then reselect new subchannels to transmit the new message. The next reservation is done at tR3, which is 100 ms away from the reselected subframes. In t_{G3}, the new generated message will select the subchannels for transmission at t_{R3} because the reservation size is changed from 2 subchannels to 3 subchannels due to the previous reselection.

In Fig. 23(b), One-shot is used instead of the Reselection due to the larger message size generated at t_{G2}. So the next reservation is made 100 ms from t_{R2}. The next message generated at tG3 is greater than (t_{R2} + 100 ms). Therefore, the reservation is left unutilized in t_{R3}.



(a) Scenario with Baseline SPS and RRI strategy 1 (Before One-shot)



(b) Scenario with Baseline SPS and RRI strategy 1 (After One-shot)

Fig. 23. Effect on Unutilized Reservations Ratio (One-shot for Size Reselection)

6.2.4. Effects on Unused Subchannel Ratio

In Fig. 24, the effect of using One-shot for size reselection is shown on Unused Subchannels ratio. The unused subchannels are reduced in case of Baseline SPS and Most Probable CAM Size. Let there is a SPS configuration with reservation of 2 subchannels. The next packet arrives with a requirement of 3 Subchannels. One-shot is used when the reserved subchannels (e.g., 2 subchannels) are smaller than the requirement (e.g., 3 subchannels). When One-shot is used, the next reservation is done according to the last reservation (e.g., 2 subchannels). If One-shot is not used in this case, and the size reselection occurs, then the next reservation should be with 3 Subchannels. Now when there will be another incoming packet that requires 2 subchannels, there will be 1 unused subchannels if size reselection occurs. But if One-shot is used, there will be no unused subchannels. Hence One-shot for size reselection reduces the number of unused subchannels. This effect is explained in Fig. 25.

Again, in case of Largest CAM Size, there is no effect of One-shot as there will be no size reselection.

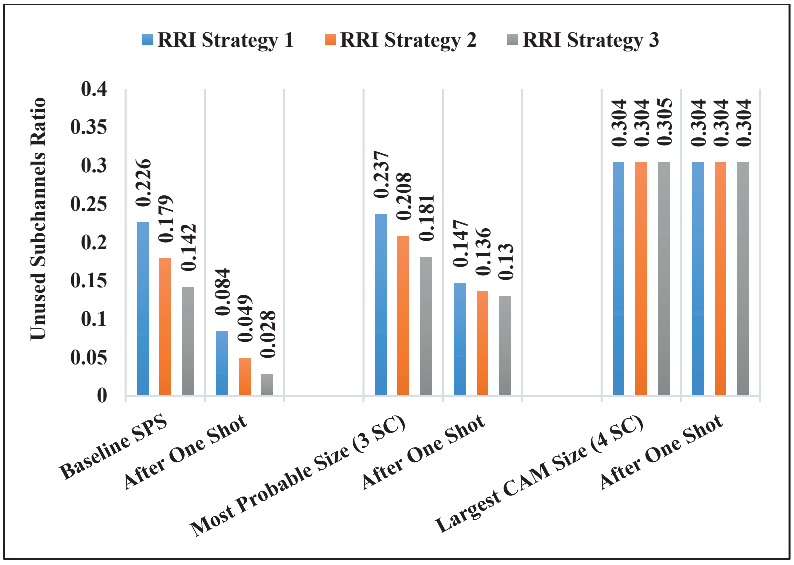
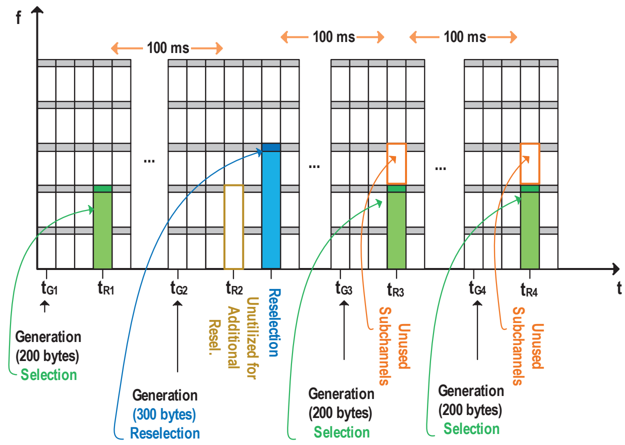
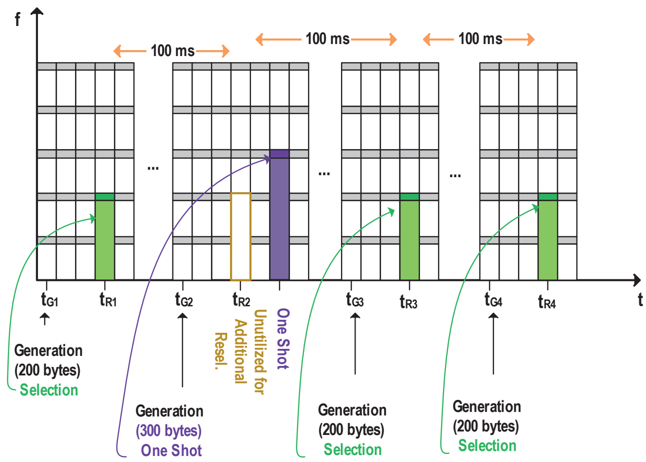


Fig. 24. Unused Subchannels Ratio (Using One-shot for Size Reselection)

Fig. 25(a) that represents a scenario where a vehicle generates a first message (or TB) at t_{G1} and reserves two subchannels for its transmission at t_{R1}. The next message generated at t_{G2} is larger and does not fit in the two reserved subchannels at t_{R2}. The vehicle must then reselect new subchannels to transmit the new message. The next reservation is done with 3 subchannels at tR3, which is 100 ms away from the reselected subframes.



(a) Scenario with Baseline SPS and RRI strategy 1 (Before One-shot)



(b) Scenario with Baseline SPS and RRI strategy 1 (After One-shot)

Fig. 25. Effect on Unused Subchannels Ratio (One-shot for Size Reselection)

At tG3, the new generated message has a latency deadline of 100 ms. As (t_{G3} + 100 ms) is greater than tR3, this message will select the subchannels at t_{R3}. Here there is 1 unused subchannel because the reservation was done with 3 subchannels and the generated message needs 2 subchannels.

In Fig. 25(b), One-shot is used instead of the Reselection due to the larger message size generated at tG2. Since this is One-shot, the next reservation was made 100 ms from t_{R2} at t_{R3} with 2 subchannels. Therefore, there are no unused subchannels.

6.3. Impacts of One-shot for Latency Reselection

The One-shot strategy is also applied in case of Latency reselection. The effects of this strategy will be discussed in the following subsections.

6.3.1. Effects on Size Reselection Ratio

The effects on Size Reselection Ratio when One-shot is used for Latency Reselection are shown in Fig. 26. In all the Size Reservation Strategies, for RRI Strategy 1, the Size Reselection Ratio did not change. This is because for RRI Strategy 1, there is no Latency Reselection, and hence there is no One-shot transmission used in this scenario.

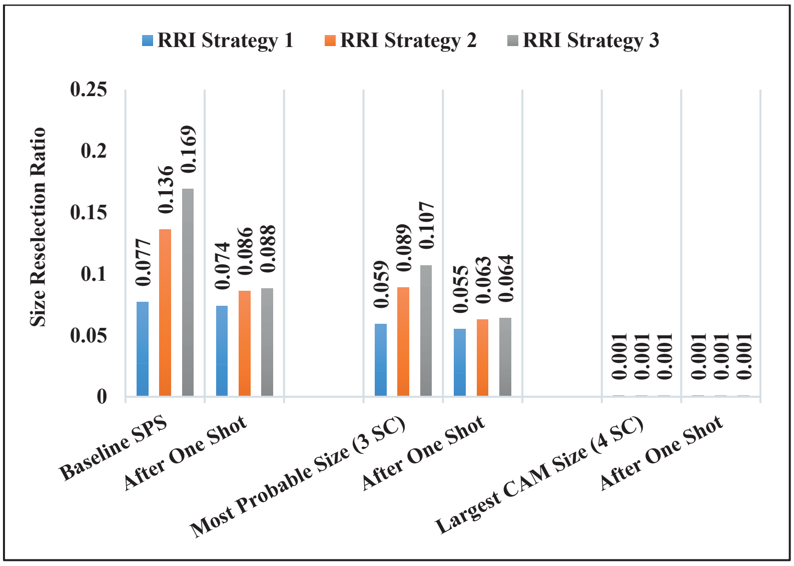
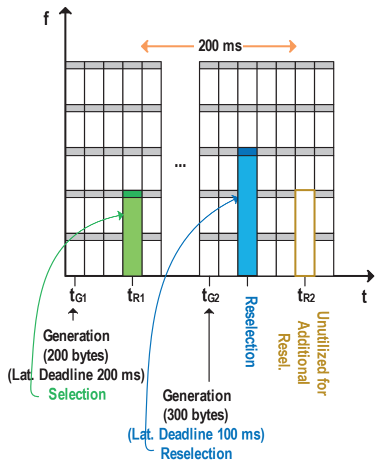
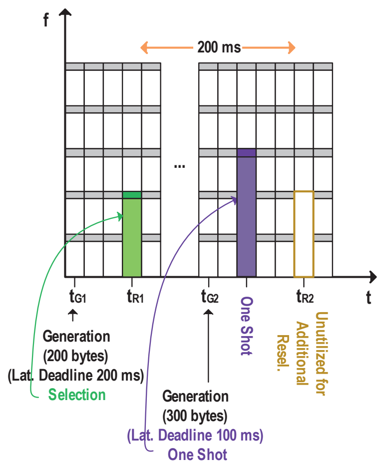


Fig. 26. Size Reselection Ratio (Using One-shot for Latency Reselection)

The size reselection ratio in the case of RRI 2 and 3 is reduced when One-shot for latency reselection is used. This is due to the use of One-shot instead of using the reselection for the different time Interval between the messages. For RRI 2 and 3, there is always a possibility of having different time interval between the messages which creates Latency Reselections.



(a) Scenario with Baseline SPS and RRI strategy 2 (Before One-shot)



(b) Scenario with Baseline SPS and RRI strategy 2 (After One-shot)

Fig. 27. Effect on Size Reselection Ratio (One-shot for Latency Reselection)

Fig. 27(a) that represents a scenario where Baseline SPS is used with RRI Strategy 2. A vehicle generates a first message (or TB) at t_{G1} and reserves 2 sub-channels for its transmission at t_{R1}. The next message generated in t_{G2} is larger and does not fit in the 2 reserved sub-channels at t_{R2}. This new message also has a latency deadline of 100 ms. The reservation made for this message is not sufficient to use in terms of both the required message size and the time interval. The vehicle must then reselect new subchannels to transmit the new message.

In Fig. 27(b), the message generated at t_{G2} will be transmitted with One-shot for the latency deadline. The size reselection is thus prevented with One-shot for the Latency Reselection. Hence, the Size Reselection Ratio has been reduced.

6.3.2. Effects on Latency Reselection Ratio

Fig. 28 represents the effect on Latency Reselection ratio after using One-shot for the Latency Reselections. It can be observed that there is no Latency Reselections when One-shot is used. The value 0.001 is due to the jitter.

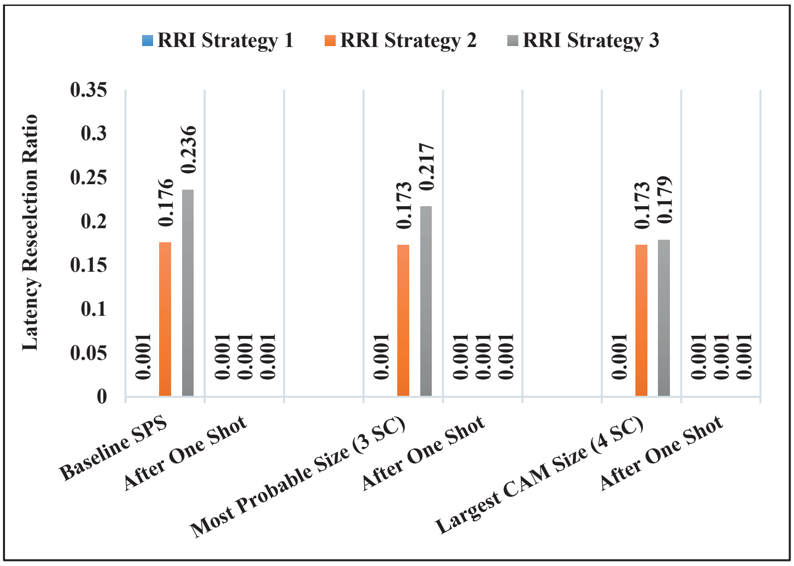


Fig. 28. Latency Reselection Ratio (Using One-shot for Latency Reselection)

6.3.3. Effects on Unutilized Reservation Ratio

In Fig. 29, the effects on Unutilized Reservation Ratio after using One-shot for Latency Reselection are shown. In all Size reservation strategies, for

RRI 1, there is no change in the ratio. Due to the usage of the minimum time interval between messages, there is no Latency Reselection, and therefore, no One-shot transmission is needed.

The unutilized reservation ratio is increased for RRI Strategy 2. This effect will be discussed later with Fig. 30. In RRI 3, the unutilized reservations have increased for baseline SPS configuration and for Most Probable CAM Size. In contrast, the ratio is decreased for the Largest CAM Size configuration. These effects will be explained with examples in Fig. 31 and Fig. 32, respectively.

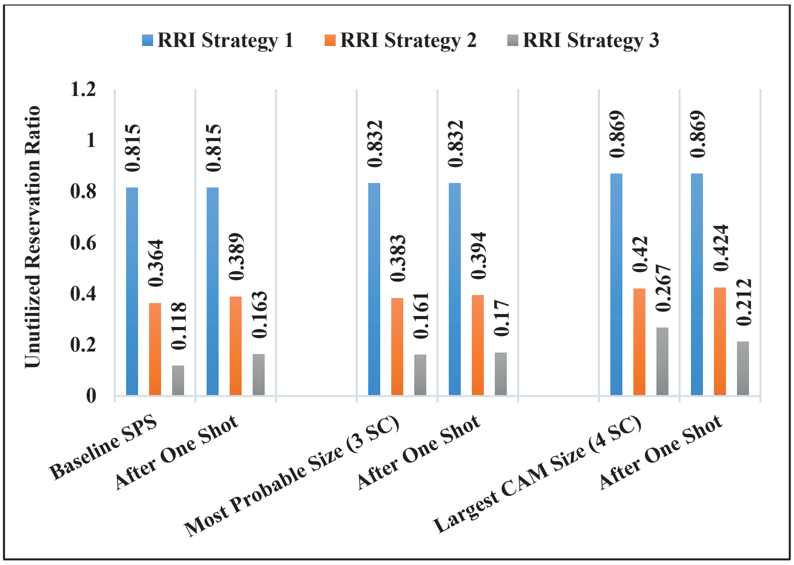
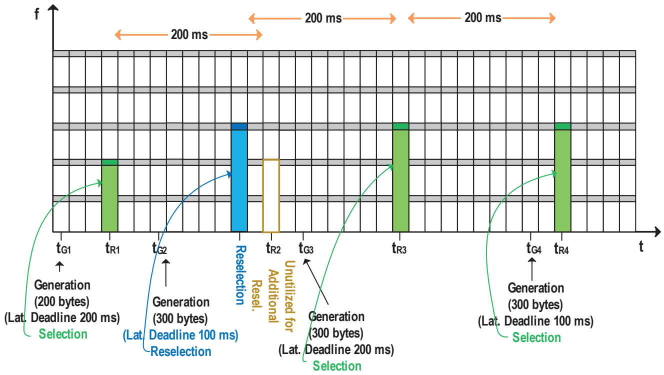
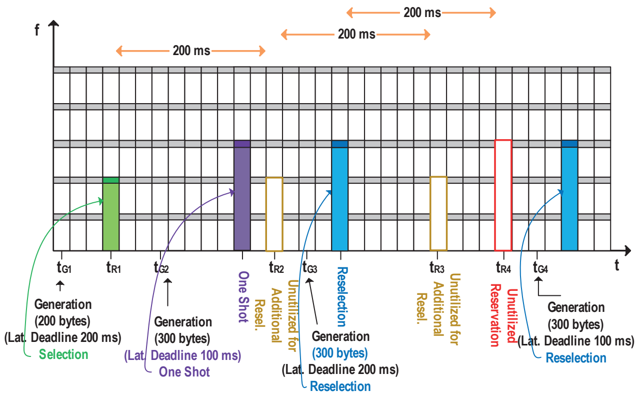


Fig. 29. Unutilized Reservation Ratio (Using One-shot for Latency Reselection)

Fig. 30(a) that represents a scenario where the Baseline SPS is used with RRI of 200 ms. A vehicle generates a first message (or TB) at t_{G1} and reserves 2 sub-channels for its transmission at t_{R1}. The next message generated at t_{G2} is larger than the reservation size and it has a latency deadline of 100 ms where (t_{G2} + 100 ms) is less than t_{R2}. That is why it cannot be transmitted in the reserved subchannels at t_{R2} and the reserved sub-channels are left unutilized. The vehicle must then reselect new subchannels to transmit the new message. The next reservation was made with 3 subchannels at 200 ms away (at t_{R3}) from the reselected subchannels. A new message is generated at t_{G3} with the requirement of 3 subchannels and a latency deadline of 200 ms which is transmitted at the reserved subchannels t_{R3}. The next reservation is made at t_{R4} and the generated message at t_{G4} can be transmitted in the reservation.



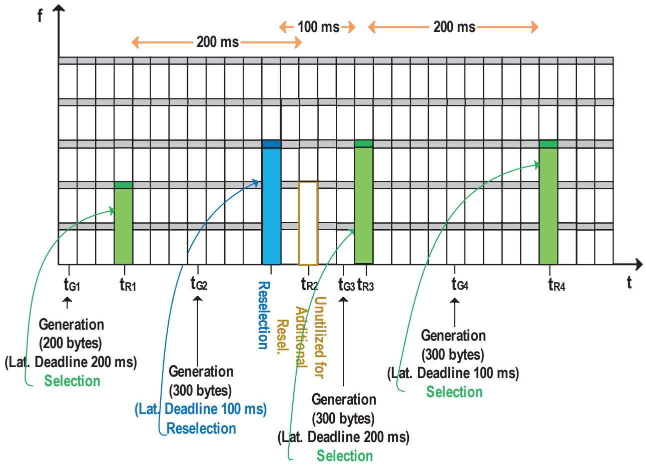
(a) Scenario with Baseline SPS and RRI strategy 2 (Before One-shot)



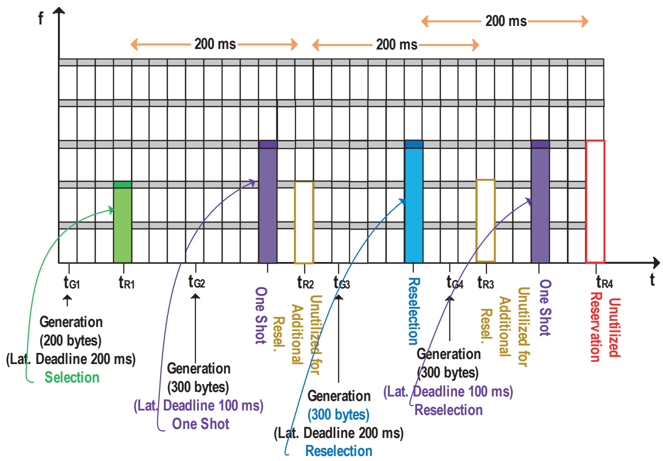
(b) Scenario with Baseline SPS and RRI strategy 2 (After One-shot)

Fig. 30. Effect on Unutilized Reservation Ratio (One-shot for Latency Reselection)

Fig. 30(b) represents the scenario when One-shot for Latency Reselection is used. When One-shot transmission was implemented for the generated message in t_{G2} instead of latency reselection, it also caused an unutilized reservation due to additional reselection. It should be observed here that when One-shot is used, the reservation is made after 200 ms from t_{R2} at t_{R3}. The next generated message at t_{G3} is larger than the reservation, and that is why it is reselected. The next reservation is 200 ms away from the reselected subframe at t_{R4}. The next message arrives after t_{R4}. Therefore, the reservation in t_{R4} remains unutilized. It can be seen that the Unutilized Reservation Ratio has been increased when One-shot for Latency Reselection is used.



(a) Scenario with Baseline SPS and RRI strategy 3 (Before One-shot)



(b) Scenario with Baseline SPS and RRI strategy 3 (After One-shot)

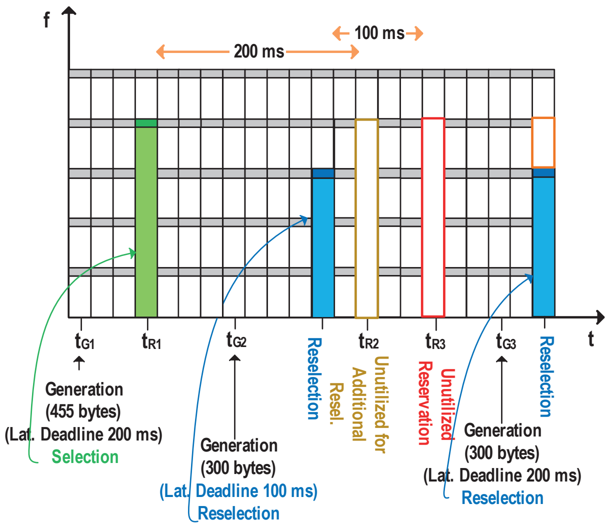
Fig. 31. Effect on Unutilized Reservation Ratio (One-shot for Latency Reselection)

Fig. 31(a) that represents a scenario where the Baseline SPS is used with RRI strategy 3. A vehicle generates a first message (or TB) at t_{G1} and reserves

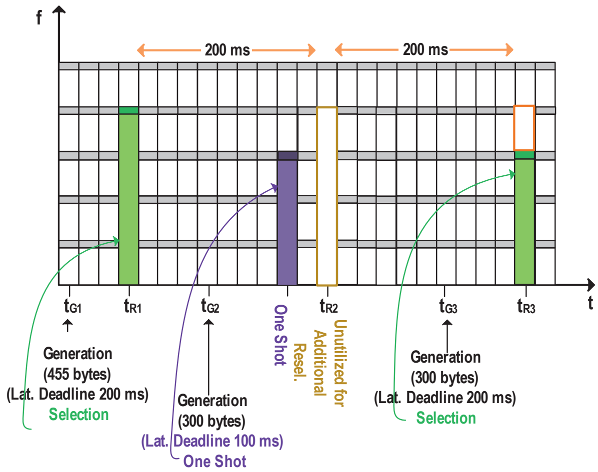
2 sub-channels for its transmission at t_{R1}. The next message generated at t_{G2} is larger than the reservation size and it has a latency deadline of 100 ms where (t_{G2} + 100 ms) is less than t_{R2}. That is why it cannot be transmitted in the reserved subchannels at t_{R2} and the reserved sub-channels are left unutilized. The vehicle must then reselect new subchannels to transmit the new message. The next reservation was made with 3 subchannels 100 ms away (at t_{R3}) from the reselected subchannels. A new message is generated at t_{G3} with the requirement of 3 subchannels and a latency deadline of 200 ms which is transmitted at the reserved subchannels t_{R3}. The next reservation is done 200 ms away at tR4, and the generated message at t_{G4} can be transmitted in the reservation.

Fig. 31(b) represents the scenario when One-shot for Latency Reselection is used. When One-shot transmission was implemented for the generated message in t_{G2} instead of latency reselection, it also caused an unutilized reservation due to additional reselection. It should be observed here that when One-shot is used, the reservation is made after 200 ms from t_{R2} at t_{R3}. The next generated message at t_{G3} is larger than the reservation, and that is why it is reselected. The next reservation is 200 ms away from the reselected subframe at t_{R4}. The next message arrives before t_{R3} and has a latency deadline of 100 ms. This packet is transmitted in one shot. Therefore, the reservation in t_{R4} remains unutilized. It can be seen that the Unutilized Reservation Ratio has been increased when One-shot for Latency Reselection is used.

Fig. 32(a) that represents a similar scenario like the previous one where Largest CAM size reservation (Always reserve 4 subchannels) is used with RRI strategy 3. A vehicle generates a first message (or TB) at t_{G1} and reserves 4 subchannels (Always reserves 4 subchannels) for its transmission at t_{R1}. The next message generated at t_{G2} has a latency deadline of 100 ms where (t_{G2} + 100 ms) is less than t_{R2}. That is why it cannot be transmitted in the reserved subchannels at t_{R2} and the reserved subchannels are left unutilized. The vehicle must then reselect new subchannels to transmit the new message. The next reservation was made again with 4 subchannels 100 ms away (at t_{R3}) from the reselected subchannels. A new message arrives at t_{G3} after t_{R3}. The generated message at t_{G3} cannot be transmitted in t_{R3} and this reservation will remain Unutilized.



(a) Scenario with Largest CAM Size and RRI strategy 2 (Before One-shot)



(b) Scenario with Largest CAM Size and RRI strategy 2 (After One-shot)

Fig. 32. Effect on Unutilized Reservation Ratio (One-shot for Latency Reselection)

Fig. 32(b) represents the scenario when One-shot for Latency Reselection is used. When One-shot transmission was implemented for the generated message in t_{G2} instead of latency reselection, it also caused an unutilized reservation due to additional reselection. It should be observed here that when One-shot is used, the reservation is made after 200 ms from t_{R2} at t_{R3}. The next generated message in t_{G3} is transmitted at t_{R3} as the latency deadline is 200 ms. It can be seen that the Unutilized Reservation Ratio has been decreased when One-shot for Latency Reselection is used.

6.3.4. Effects on Unused Subchannel Ratio

In Fig. 33, the effects on the Unused Subchannels ratio after using One-shot for Latency Reselection are shown. The ratio increased for RRI 2 and 3. When the reselections are done for the different time interval between messages, the reservation size gets adjusted according to the reselections. Therefore, there will be fewer Unused Subchannels in this case. In contrast, when One-shot is used, there is no effect on reserved number of subchannels. This scenario will be discussed with an example in Fig. 34.

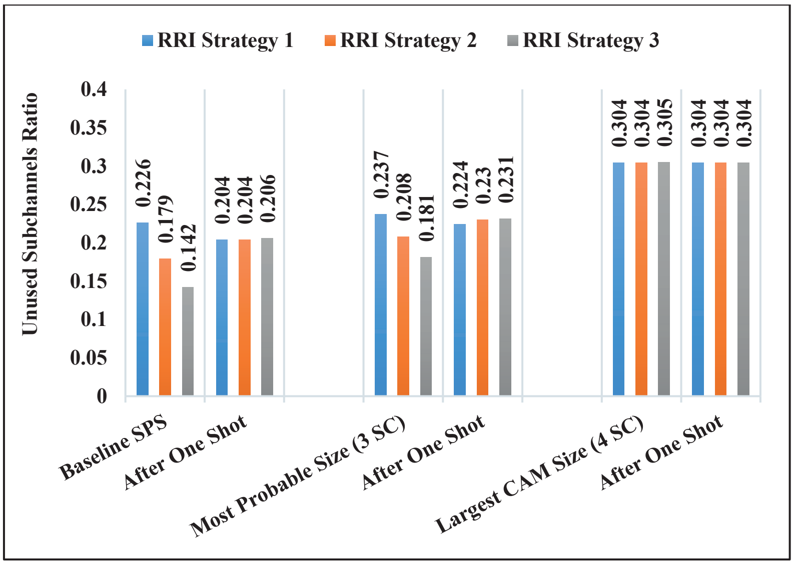
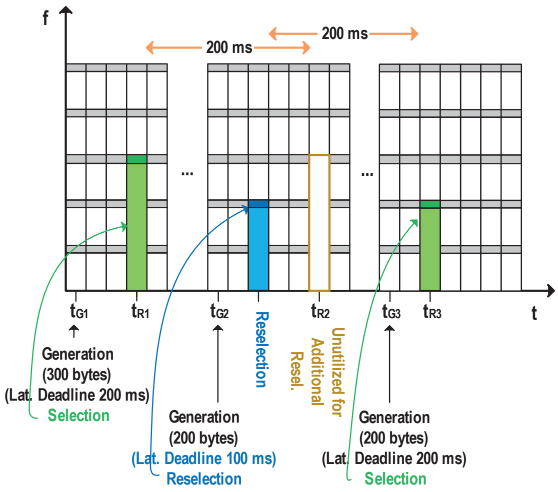


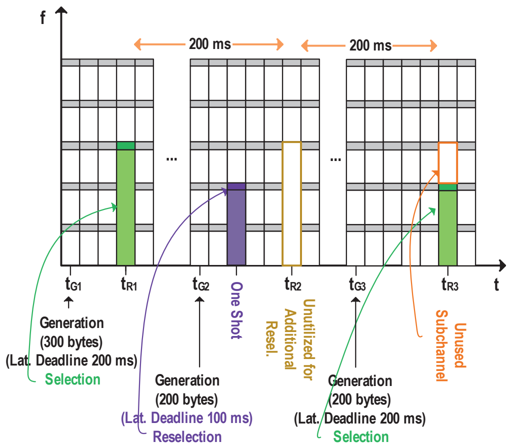
Fig. 33. Unused Subchannels Ratio (Using One-shot for Latency Reselection)

Again, the three RRI strategies almost have a similar unused subchannels ratio. This is because all the latency reselections for RRI 2 and 3 are removed by One-shot and there is only effect of the size and counter reselections. As

RRI 1 has only the effects of the size and counter reselections, these three RRI Strategies have the same unused subchannels ratio.



(a) Scenario with Baseline SPS and RRI strategy 2 (Before One-shot)



(b) Scenario with Baseline SPS and RRI strategy 2 (After One-shot)

Fig. 34. Effect on Unused Subchannels Ratio (One-shot for Latency Reselection)

Fig. 34(a) that represents a scenario where the Baseline SPS reservation is used with RRI 2. A vehicle generates a first message (or TB) at t_{G1} and reserves 3 subchannels for its transmission at t_{R1}. The next message generated at t_{G2} is smaller in size than the reservation, but it has a latency deadline of 100 ms, where (t_{G2} + 100 ms) is less than t_{R2}. That is why it cannot be transmitted in the reserved subchannels at t_{R2} and the reserved sub-channels are left unutilized. The vehicle must then reselect new subchannels to transmit the new message. The next reservation was made with 2 subchannels 200 ms away (at t_{R3}) from the reselected subchannels. A new message is generated at t_{G3} with the requirement of 2 subchannels and a latency deadline of 200 ms and transmitted at the reserved subchannels at t_{R3}. In this scenario, there are no unused subchannels.

Fig. 34(b) represents the scenario when One-shot for Latency Reselection is used. When One-shot transmission was implemented for the generated message on t_{G2} instead of latency reselection, it also caused an unutilized reservation. It should be observed here that when One-shot is used, the reservation is made with 3 subchannels after 200 ms from t_{R2}. where (t_{G3} + 200 ms) is greater than t_{R3}. Hence, the next generated message at t_{G3} will be transmitted at t_{R3} without One-shot leaving 1 unused subchannel. Thus, the Unused Subchannels Ratio has been increased when One-shot for Latency Reselection is used for the RRI strategy 2 and 3.

6.4. Ratio of One-shot Transmission

In this section, the ratio of total One-shot transmission for the Size Reselection and Latency Reselection are compared both theoretically and by simulation results.

6.4.1. One-shot for Size Reselection

In Fig. 35, the total ratio of One-shot transmission for Size Reselection is shown. This is calculated as the ratio of the One-shot Transmission due to Size Reselection and the total number of transmissions.

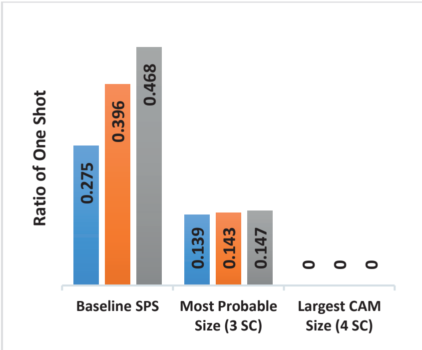


Fig. 35. Ratio of One-shot Transmission due to Size Reselection

The CAM Size and Probability for the Empirical CAM model are found in [15] and shown in Table 8. These values will be compared with the values found in this thesis in case of RRI Strategy 1 where there is no Latency Reselection.

Table 8. CAM Size and Probability [15]

CAM Size	Req. Subchannels	Probability
200 Bytes	2	0.3726
300 Bytes	3	0.3127
360 Bytes	3	0.1579
450 Bytes	4	0.1568

In case of RRI 1, there will be Size Reselection in the following two scenarios.

- The probability of having 2 and (having 3 or 4 Subchannels) together.
- The probability of having 3 & 4 subchannels together.

The One-shot is applied when there is a Size Reselection. Therefore, the probability of One-shot for Size reselection in case of RRI strategy 1 will be found adding the probabilities of the above two scenarios,

Let,

A = Probability of transmission of 2 Subchannels = 0.3726

B = Probability of transmission of 3 Subchannels = (0.3127+0.1579) = 0.4706

C = Probability of transmission of 4 Subchannels = 0.1568

The probability of having A and (having B or C) together will be: A*(B+C)

= 0.3726*(0.4706+0.1568) = 0.2338

The Probability of having B & C subchannels together is: B*C

= 0.4706*0.1568 = 0.0738

The total probability of having One-shot for Size reselection is:

[A*(B+C)] + [B*C]

=0.2338+0.0738 = 0.3076

This value of 0.3076 is close to the value found in Fig. 35 which is 0.275. Therefore, it can be concluded that the simulation results are showing a similar pattern of results found in the real CAM generation model in the literature.

6.4.2. One-shot for Latency Reselection

In Fig. 36, the total ratio of One-shot transmission for Latency Reselection is shown. This is calculated as the ratio of the One-shot Transmission due to Latency Reselection and total number of transmissions.

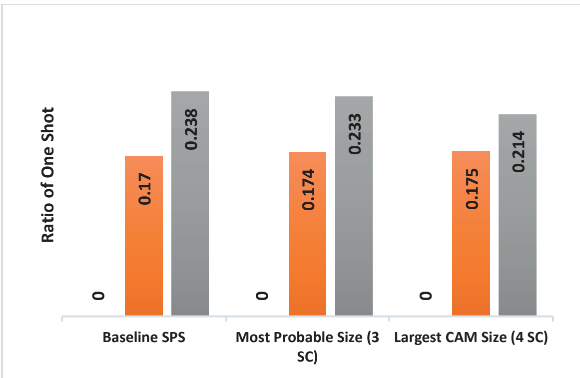


Fig. 36. Ratio of One-shot Transmission for Latency Reselection

In Table 9, the data from [16] and from this simulation are presented for comparison.

Table 9. Latency Reselection Ratio and One-shot Ratio

	Latency Reselection Ratio	**One-shot Ratio for Latency Reselection**		
	Data From [16]	**Baseline SPS**	**Most Probable Size (3 SC)**	**Largest CAM Size (4 SC)**
RRI 1	0.001	0	0	0
RRI 2	0.17	0.17	0.174	0.175
RRI 3	0.233	0.238	0.233	0.214

The latency reselection ratio found in [16] and the One-shot Ratio for Baseline SPS is shown in second and third column of the table above. It can be seen that the One-shot ratio for RRI 1 is 0 as there are no latency reselection in RRI 1 (the value 0.001 is due to jitter). Other similar values represent that One-shot is applied when there is a latency reselection. In example, for RRI 2, 17% packet has latency reselection and One-shot is applied for all of them.

6.5. Packet Delivery Ratio (PDR)

LTE-V2X performance is mainly estimated by the means of the Packet Delivery Ratio (PDR). The PDR is the average ratio of correctly received to the total number of transmitted packets. The idea of using One-shot was to improve the performance of the LTE-V2X. In [23], the author showed that the simplified traffic model with One-shot improves the PDR. However, it has been observed that PDR is not improved after using One-shot instead of the Reselection when the Empirical CAM model [15] is used.

When the simplified model were used in [23], there was redundant transmissions per packet. In this thesis, only one transmission per packet is considered. The simplified model is also simulated with aperiodic traffic and a single transmission per packet. The results (Table 10 and Table 11) showed similar characteristics as [23].

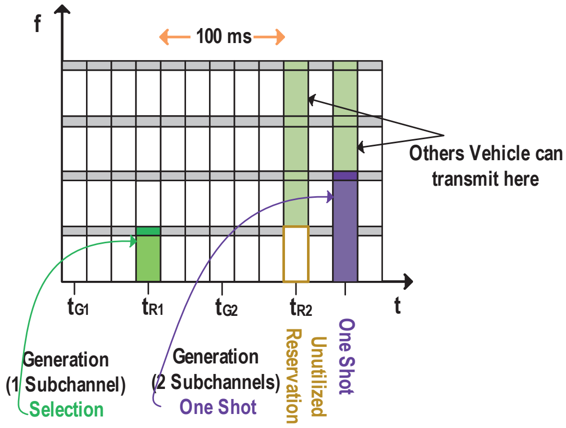
Table 10. Simplified Model with Baseline SPS

Baseline SPS		
Packet Per Second (pps)	**Rate of Unutilized sub-reservations**	**Rate of Unused Subchannels**
20	0.369	0.357
50	0	0.381

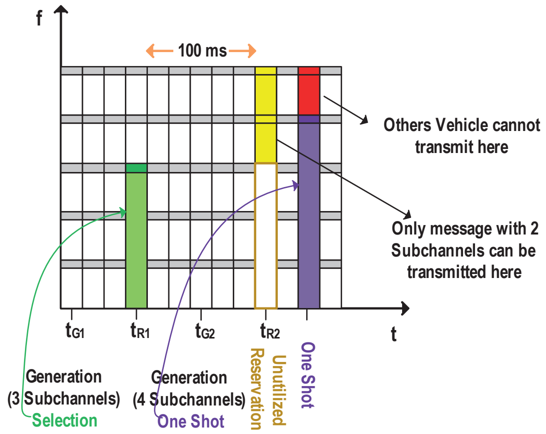
Table 11. Simplified Model with One-shot

Baseline SPS		
Packet Per Second (pps)	**Rate of Unutilized sub-reservations**	**Rate of Unused Subchannels**
20	0.321	0.073
50	0	0.074

When the empirical model is used, it has been observed that the ratio of unused subchannels is decreased as like the simplified model. However, the unutilized reservation ratio increases in the empirical CAM model. Therefore, PDR is degraded in this experiment. There is another issue which is observed in this study, which is also responsible for the increment of packet collision. The scenario is shown in Fig. 37 below:



(a)



(b)

Fig. 37. (a) Simplified Model with One-shot (b) Empirical Model with One-shot

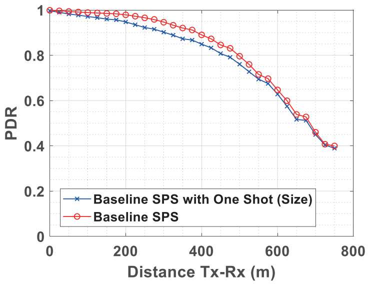
When the simplified model is used in [16], there were two types of message size. The 190 bytes message requires 1 subchannel to be transmitted, and the 300 bytes message requires 2 subchannels. There are a total of 4 subchannels in a subframe. In Fig. 37(a), a message of 190 Bytes is generated at t_{G1} and transmitted at t_{R2}. Reservation is made on t_{R2} with 1 subchannel. A new message is generated at t_{G2} with a requirement of 2 subchannels, and this message cannot be transmitted at t_{R2}. Therefore, the generated message at t_{G2} is transmitted with One-shot and the reservation at t_{R2} is left unutilized. It can be seen that there are 3 unused subchannels left in the subframe in t_{R2}. Other vehicles can transmit in these 3 unused subchannels. In the subframe where One-shot is transmitted, 2 subchannels are left unused and can be used by other vehicles too. It can be concluded that other vehicles can transmit their messages on the subframes with unutilized reservations and One-shot transmission.

There were three types of message sizes in the Empirical CAM model. The 200 Bytes message requires 2 subchannels to be transmitted, the 300 Bytes message requires 3 subchannels and the 455 bytes message requires 4 subchannels. There are 5 subchannels in a subframe. In the above Fig. 37(a), a message of 300 byte is generated at t_{G1} and transmitted at t_{R2}. A reservation is made at t_{R2} with 3 subchannels. A new message is generated at t_{G2} with a requirement of 4 subchannels, and this message cannot be transmitted at t_{R2}. Therefore, the generated message at t_{G2} is transmitted with One-shot and the reservation at t_{R2} is left unutilized. It can be seen that there are 2 unused subchannels left in the subframe at t_{R2}. Other vehicles with the requirement of 2 subchannels can only transmit in these 2 unused subchannels. If other vehicles generate a message larger than 2 subchannels, that message cannot be transmitted in that subframe. In the subframe where One-shot is transmitted, 1 subchannel is left unused and cannot be used by other vehicles. It can be concluded that, in most cases, other vehicles cannot transmit their messages on the subframes with unutilized reservations and One-shot transmission. Therefore, the packet collision increases in the Empirical Model, and the Packet Delivery Ratio (PDR) degrades when One-shot is used.

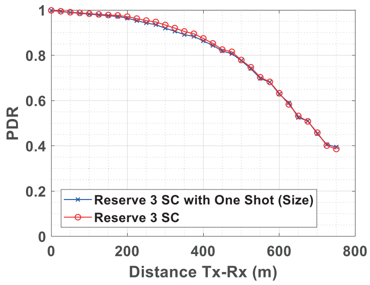
In the next sections, the PDR and the propagation-collision of the 3 configurations (One-shot for Size Reselection,, One-shot for latency Reselection and One-shot for both Size and Latency Reselection) are discussed.

6.5.1. One-shot for Size Reselection

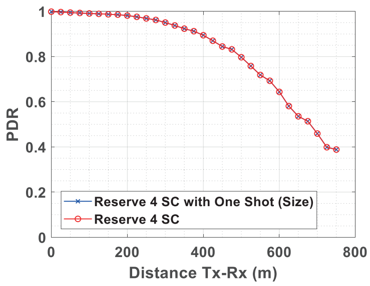
In Fig. 38, the PDR and the propagation-collision are shown due to One-shot for Size Reselection for the three Size Reservation Strategies.



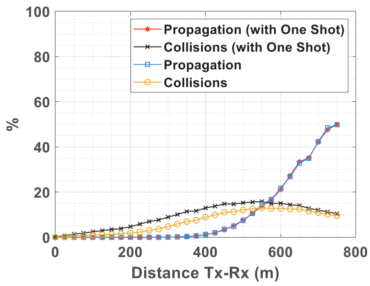
(a) Baseline SPS



(b) Most Probable Size



(c) Largest CAM Size



(d) Propagation-Collision (Baseline SPS with RRI 1)

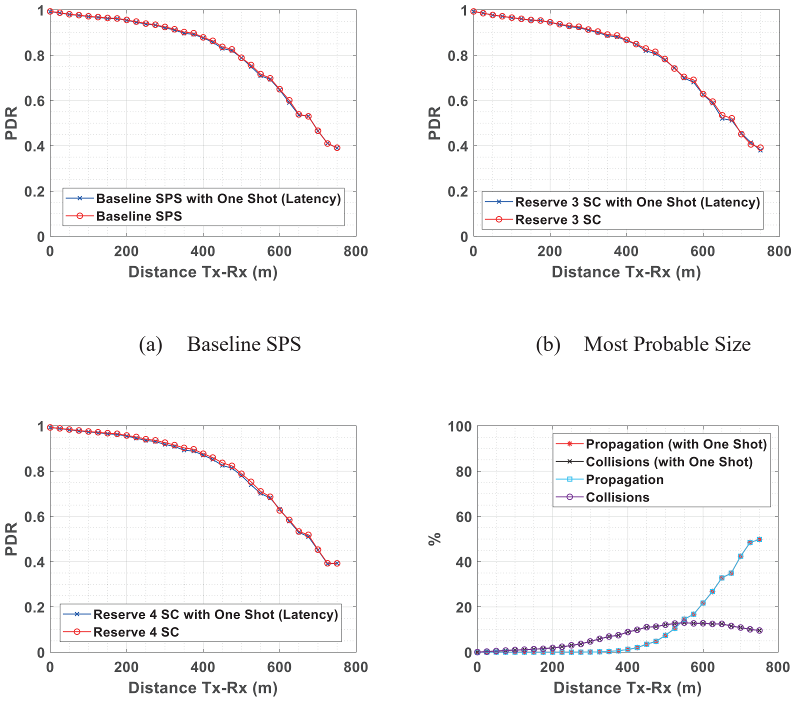
Vehicle speed 60 km/hr with RRI Strategy 1

Fig. 38. Comparison of Packet Delivery Ratio when One-shot for Size Reselection Ratio is used

Fig. 38 is for the scenario where RRI strategy 1 is considered with a vehicle speed of 60 km per hour. Though the unused subchannels have been decreased when One-shot for Size reselection is used, due to the increase of Unutilized Reservation, the packet collision increased (Fig. 38 (d)). As a result, the PDR was degraded in both Fig. 38(a) and (b). In Fig. 38(c), there is no change in PDR, as there is no Size reselection (Largest CAM Size is being reserved).

6.5.2. One-shot for Latency Reselection

In Fig. 39, the PDR and the propagation-collision are shown due to One-shot for Latency Reselection for the three Size Reservation Strategies.



(a) Baseline SPS

(b) Most Probable Size

(c) Largest CAM Size

(d) Propagation-Collision (Baseline SPS with RRI 2)

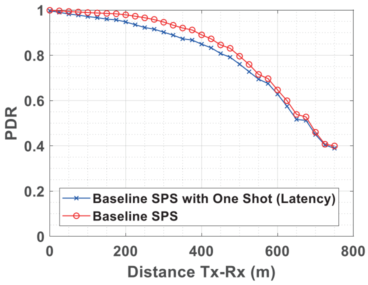
Vehicle Speed 60 km/hr with RRI Strategy 2

Fig. 39. Comparison of Packet Delivery Ratio when One-shot for Size Reselection Ratio is used

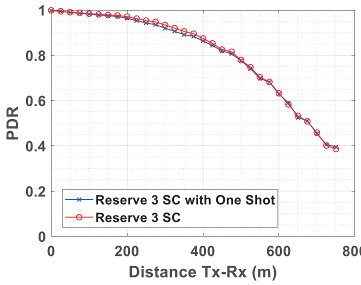
Fig. 39 is for the scenario where RRI strategy 2 (Latency Reselection is not present in RRI strategy 1) is considered with a vehicle speed of 60 km per hour. There is no change in unutilized reservation ratio when One-shot for Latency Reselection is used. Therefore, there is no change in packet collision and packet delivery ratio.

6.5.3. One-shot for both Size and Latency Reselection

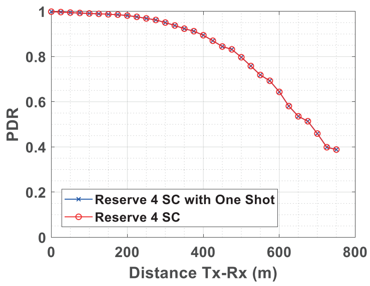
In Fig. 40, the PDR and the propagation-collison are shown due to One-shot for Size and Latency Reselection for the three Size Reservation Strategies.



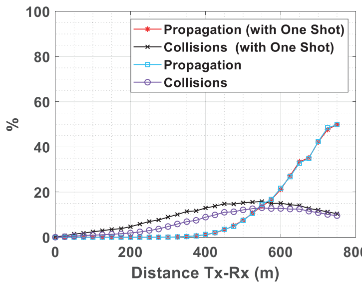
(a) Baseline SPS



(b) Most Probable Size



(c) Largest CAM Size



(d) Propagation-Collision (Baseline SPS with RRI 1)

Vehicle speed 60 km/hr with RRI Strategy 1

Fig. 40. Comparison of Packet Delivery Ratio when One-shot for both Size and Latency Reselection Ratio is used

Fig. 40 is for the scenario where RRI strategy 1 is considered with a vehicle speed of 60 km per hour. Though the unused subchannels has been decreased when One-shot for both Size and Latency reselection are used, due to the increase of Unutilized Reservation, the packet collision increased (Fig. (d)). As a result, the PDR degraded in both Fig. 40(a) and (b). In Fig. 40 (c), there is no change in PDR, as there is no Size reselection (Largest CAM Size is being reserved).

The summary of all the statistics is shown in Appendix B.

7. Conclusions

In conclusion, in this thesis, the performance of LTE-V2X has been analyzed under realistic conditions characterized by aperiodic messages of varying sizes. The primary focus of this investigation has been the evaluation of how system performance is affected by these variables, namely the message sizes and the intervals between them.

To address the challenges posed by variable message sizes, two innovative strategies, namely the "Most Probable CAM Size" and the "Largest CAM Size," were introduced alongside the baseline SPS configuration. These strategies were implemented and simulated with an empirical CAM generation model, with the aim of reducing the size reselection ratio while increasing the unutilized reservation ratio. However, these improvements were accompanied by an increase in packet collisions and a degradation in the Packet Delivery Ratio (PDR).

Subsequently, the concept of "One-shot transmission" was introduced to eliminate size reselections. Although this approach successfully eliminated size reselections, it did not result in an improved PDR due to an increase in unutilized subchannels. Additionally, a significant number of reselections occurred due to the variable time intervals between message generation. To mitigate this issue, One-shot transmission was employed for latency reselection, resulting in a reduction in the number of reselections, albeit with an increase in the unutilized reservation and unused subchannel ratios.

In light of these findings, it is evident that the LTE-V2X system, particularly the sensing-based SPS scheme, faces notable challenges when dealing with aperiodic messages and variable message sizes. These challenges have been thoroughly elucidated, and various mechanisms have been proposed to address them. However, it is important to note that complete resolution of these challenges is not achievable with the current configurations of LTE-V2X as defined by the 3GPP standard. Each configuration analyzed here appears to alleviate one challenge while exacerbating others.

Throughout this research, the following key objectives posed by the thesis have been addressed:

Insights have been provided into LTE-V2X performance under variable and realistic data traffic conditions, with a focus on identifying key performance metrics affected by such variability.

The challenges posed by realistic Cooperative Awareness Message (CAM) generation models in LTE-V2X have been elucidated, with emphasis placed on their impact on system efficiency and reliability.

Mechanisms have been designed and evaluated with the aim of mitigating the adverse effects arising from variable message sizes and time intervals in LTE-V2X communications. This endeavor has highlighted the need to carefully consider trade-offs during the design process.

In summary, this thesis has provided valuable insights into the complexities and trade-offs inherent in LTE-V2X communication under realistic conditions. It has shed light on the challenges that remain to be addressed in the pursuit of efficient and reliable vehicular communication systems.

8. Future work

The algorithms proposed in this thesis partially solve the inefficiencies due to the implementation of realistic CAM in LTE-V2X. However, it has been observed that these algorithms solve some issues by generating other problems. The technical aspects of our contributions conducted in this research open up several directions and configurations for future works. These new configurations are not studied due to the time limitation of this thesis. A direction of future work and research are mentioned in the following.

It has been observed that there are a large number of unutilized resources that can be used by other vehicles to transmit their messages. It would have been possible to use those unutilized resources if counter information can be exchanged to notify other vehicles about the resources when there is an unutilized reservation.

It would have been more effective if it was possible to cancel the unutilized reservation and exchange the counter information together. This will lead to efficient use of resources. This will also reduce packet collision among the vehicles and improve the packet delivery ratio.

It is also possible that a packet can be transmitted using a lower number of subchannels by increasing the MCS. This can also reduce the packet collision and improve the PDR.

This thesis has been organized considering the ETSI CAM standard. Other regions can go for the implementation of other standards for the basic awareness messages. It is possible that a different standard may generate messages with different sizes and time intervals. It would be interesting if studies were conducted using different message patterns and replicate this type of analysis considering these standards.

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Appendix A: Summary of the Statistics

Table 12. Reselection Rates of Size Reservation Strategies without One-shot

Baseline SPS				
RRI Strategy	**Latency Reselection**	**Size Reselection**	**Counter Reselection**	**Total Reselection**
1	0.001	0.077	0.08	0.155
2	0.176	0.136	0.046	0.318
3	0.236	0.169	0.03	0.389
Most Probable Size (3 Subchannels)				
RRI Strategy	**Latency Reselection**	**Size Reselection**	**Counter Reselection**	**Total Reselection**
1	0.001	0.059	0.082	0.138
2	0.173	0.089	0.048	0.285
3	0.217	0.107	0.035	0.327
Largest CAM Size (4 Subchannels)				
RRI Strategy	**Latency Reselection**	**Size Reselection**	**Counter Reselection**	**Total Reselection**
1	0.001	0.001	0.099	0.1
2	0.173	0.001	0.061	0.231
3	0.179	0.001	0.059	0.235

Table 13. Unutilized Reservatios and Unused Subchannels Ratio of Size Reservation Strategies without One-shot

Baseline SPS		
RRI Strategy	**Rate of Unutilized sub-reservations**	**Rate of Unused Subchannels**
1	0.815	0.226
2	0.364	0.179
3	0.118	0.142
Most Probable Size (3 Subchannels)		
RRI Strategy	Rate of Unutilized sub-reservations	Rate of Unused Subchannels
1	0.832	0.237
2	0.383	0.208
3	0.161	0.181
Largest CAM Size (4 Subchannels)		
RRI Strategy	Rate of Unutilized sub-reservations	Rate of Unused Subchannels
1	0.869	0.304
2	0.42	0.304
3	0.267	0.305

Table 14. Reselection Rates when One-shot for Size Reselection is used

Baseline SPS					
RRI Strategy	Latency Reselection	Size Reselection	Counter Reselection	Total Reselection	One-shot
1	0.001	0	0.099	0.1	0.275
2	0.178	0	0.074	0.244	0.396
3	0.268	0	0.057	0.311	0.467
Most Probable Size (3 Subchannels)					
RRI Strategy	Latency Reselection	Size Reselection	Counter Reselection	Total Reselection	One-shot
1	0.001	0	0.1	0.101	0.139
2	0.174	0	0.064	0.234	0.144
3	0.232	0	0.046	0.271	0.146
Largest CAM Size (4 Subchannels)					
RRI Strategy	Latency Reselection	Size Reselection	Counter Reselection	Total Reselection	One-shot
1	0.001	0	0.099	0.1	0
2	0.174	0	0.061	0.231	0
3	0.182	0	0.058	0.237	0

Table 15. Unutilized Reservatios and Unused Subchannels Ratio when One-shot for Size Reselection is used

Baseline SPS		
RRI Strategy	Rate of Unutilized sub-reservations	Rate of Unused Subchannels
1	0.869	0.084
2	0.392	0.049
3	0.128	0.028
Most Probable Size (3 Subchannels)		
RRI Strategy	Rate of Unutilized sub-reservations	Rate of Unused Subchannels
1	0.87	0.145
2	0.41	0.134
3	0.182	0.128
Largest CAM Size (4 Subchannels)		
RRI Strategy	Rate of Unutilized sub-reservations	Rate of Unused Subchannels
1	0.869	0.304
2	0.42	0.304
3	0.261	0.304

Table 16. Reselection Rates when One-shot for Latency Reselection is used

Baseline SPS					
RRI Strategy	Latency Reselection	Size Reselection	Counter Reselection	Total Reselection	One-shot
1	0.001	0.074	0.08	0.155	0
2	0.001	0.086	0.081	0.168	0.17
3	0.001	0.088	0.08	0.169	0.238
Most Probable Size (3 Subchannels)					
RRI Strategy	Latency Reselection	Size Reselection	Counter Reselection	Total Reselection	One-shot
1	0.001	0.055	0.082	0.138	0
2	0.001	0.063	0.083	0.147	0.174
3	0.001	0.064	0.082	0.147	0.233
Largest CAM Size (4 Subchannels)					
RRI Strategy	Latency Reselection	Size Reselection	Counter Reselection	Total Reselection	One-shot
1	0.001	0	0.099	0.1	0
2	0.001	0	0.099	0.1	0.175
3	0.001	0	0.1	0.101	0.214

Table 17. Unutilized Reservatios and Unused Subchannels Ratio when One-shot for Latency Reselection is used

Baseline SPS		
RRI Strategy	Rate of Unutilized sub-reservations	Rate of Unused Subchannels
1	0.815	0.204
2	0.389	0.204
3	0.163	0.206
Most Probable Size (3 Subchannels)		
RRI Strategy	Rate of Unutilized sub-reservations	Rate of Unused Subchannels
1	0.832	0.224
2	0.394	0.23
3	0.17	0.231
Largest CAM Size (4 Subchannels)		
RRI Strategy	Rate of Unutilized sub-reservations	Rate of Unused Subchannels
1	0.869	0.304
2	0.424	0.304
3	0.212	0.303

Table 18. Reselection Rates when One-shot for both Size and Latency Reselection is used

Baseline SPS					
RRI Strategy	Latency Reselection	Size Reselection	Counter Reselection	Total Reselection	One-shot
1	0.001	0	0.099	0.1	0.275
2	0.001	0	0.1	0.101	0.396
3	0.001	0	0.1	0.101	0.451
Most Probable Size (3 Subchannels)					
RRI Strategy	Latency Reselection	Size Reselection	Counter Reselection	Total Reselection	One-shot
1	0.001	0	0.099	0.101	0.139
2	0.001	0	0.1	0.101	0.285
3	0.001	0	0.099	0.1	0.349
Largest CAM Size (4 Subchannels)					
RRI Strategy	Latency Reselection	Size Reselection	Counter Reselection	Total Reselection	One-shot
1	0.001	0	0.099	0.1	0
2	0.001	0	0.099	0.1	0.175
3	0.001	0	0.1	0.101	0.214

Table 19. Unutilized Reservatios and Unused Subchannels Ratio when One-shot for Size and Latency Reselection is used

Baseline SPS		
RRI Strategy	Rate of Unutilized sub-reservations	Rate of Unused Subchannels
1	0.869	0.084
2	0.425	0.096
3	0.149	0.106
Most Probable Size (3 Subchannels)		
RRI Strategy	Rate of Unutilized sub-reservations	Rate of Unused Subchannels
1	0.87	0.145
2	0.428	0.169
3	0.164	0.179
Largest CAM Size (4 Subchannels)		
RRI Strategy	Rate of Unutilized sub-reservations	Rate of Unused Subchannels
1	0.869	0.304
2	0.424	0.304
3	0.212	0.303

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