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Decentralized approach for IVI

Infrastructure-vehicle-information

Intelligent Transport Systems ITS

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Sammanfattning

Med det ökande antalet fordon på vägarna har att förbättra trafiksäkerheten och effektiviteten blivit en stor utmaning. En av de lovande lösningarna är implementeringen av Intelligent Transport Systems (ITS), som utnyttjar kommunikationstekniker för att underlätta realtidsinformationsdelning mellan fordon och infrastruktur. Denna forskning syftar till att bidra till området (ITS) för att förbättra trafiksäkerheten och effektiviteten och uppnå Vision Zero-målet. I denna avhandling fokuserar vi på prestandaanalys av två kommunikationsprotokoll som används för två signal spridningstekniker för IVI (infrastructure-vehicle-information communication). Periodic, som skickar signaler vid fasta intervall och On-demand som skickar signaler vid användarbegäran. Resultaten av våra experiment visade att det finns avvägningar mellan periodiska och på begäran-metoderna i V2I-kommunikationer. On-demand-metoden presterar bättre närr det gäller PER (Packet error ratio), men det resulterar i högre latens även med låg trängsel. Å andra sidan uppvisar den periodiska metoden högre PDR (Packet delivery ratio) men lider av ineffektivitet på grund av överföring av redundanta meddelanden vilket resulterar i högre PER. Våra resultat har implikationer för skalbarheten av V2I-kommunikationer och kan översättas till andra tillgängliga teknologier som används inom ITS.

Abstract

With the growing number of vehicles on the road, improving traffic safety and efficiency has become a major challenge. One of the promising solutions is the implementation of Intelligent Transportation Systems (ITS), which utilizes communication technologies to facilitate real-time information sharing between vehicles and infrastructure. This research aims to contribute to the field of Intelligent Transportation Systems (ITS) improving traffic safety and efficiency achieving the Vision Zero goal. In this thesis, we focus on the performance analysis of two communication protocols used for two signal dissemination techniques for IVI (infrastructure-vehicle-information communication). Periodic, which sends signals at fixed intervals and On-demand which sends signals upon request from road users. The results of our experiments showed that there are trade-offs between the periodic and on-demand approaches in V2I communications. The on-demand approach performs better in terms of PER (Packet error ratio), but it results in higher latency, even with low congestion. On the other hand, the periodic approach exhibits higher PDR (Packet delivery ratio) but suffers from inefficiencies due to the transmission of redundant messages resulting in higher PER. Our findings have implications for the scalability of V2I communications and can be translatable to other access technologies used in ITS.

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1. Introduction

Road accidents leading to fatalities and severe injuries continue to be a major concern in countries across the world. Through time several initiatives have been put forward to encahnce road and transportation safety and aim to eliminate the number of fatilities, and one of these initiatives is Vision Zero. Vision Zero is a global road safety initiative introduced at first by the swedish government and approved by the parliament in 1997. It aims to adjusting the countries' transportation system and road infrasturucture focusing on preventing fatalities and serious injuries in transportation [1][2].

1.1 Motivation

Technologies such as Intellegt transportation systems (ITS) and Vehicular ad-hoc networks (VANETs) are being developed and used in Cooperative, Connected and Automated Mobility (CCAM) to achieve vision zero. CCAM is a framework that enables ITS stations to provide and consume information with applications that range from safety and traffic efficiency to infotainment. The European Telecommunications Standards Institute (ETSI) has defined specifications for CCAMs in Europe, and the ETSI ITS-G5 VANET protocol stack provides support to services that will enable Vision Zero [3].

The European Commission (EC) has delineated a four-stage approach towards achieving Vision Zero, referred to as "Days," each of which pertains to distinct technologies necessary for fulfilling the vision. The initial stage, Day 1 (Awareness), involves vehicles exchanging data and incorporating Advanced Driver Assistance Systems (ADAS). In Day 2 (Automation), more advanced automation and sensors are implemented to perceive additional trajectory data. Day 3 (Cooperation) involves using this trajectory data to facilitate vehicle cooperation, while Day 4 (Future Mobility) encompasses fully automated vehicles capable of cooperation, coordination, and negotiation. The expected timeline for this to be realized on the road is 2045 [3].

Vision Zero proposes a fully (CCAM) system, leveraging in day 1 the use of Infrastructure to Vehicle Information (IVI) services and digital signage as an ADAS to improve traffic efficiency and road safety. Despite the potential benefits of IVI services, their deployment remains mostly centralized, hindering their use in suburban and rural areas. In this context, this thesis proposes an intelligent IVI system that optimizes the deployment of Road Side Units (RSUs), enabling a decentralized approach that can react to local conditions and provide better services.

1.2 Problem

This thesis aims to address the challenges and limitations of the current centralized deployment of Intelligent Transportation Systems (ITS) and Infrastructure to Vehicle Information (IVI) services which hinders their presence in suburban and rural areas where decentralized approaches are more suitable. For example, in large cities Intelligent Transportation Systems (ITS) are controlled from central stations powered by a transport authority. However, such centralized deployments are expensive and challenging to maintain, limiting their application in areas with lower population density where the decentralized approach poses significant enhancment in road saftey thus achieving the goal of vision zero. Therefore, the thesis will explore the possibilities of decentralized approaches to ITS and IVI deployment, examining their benefits and limitations in enhancing road safety and providing real-time information that is relevant to drivers and passengers' immediate surroundings, such as road conditions, traffic signals, hazards, and traffic congestion. This approach can also reduce the cost of deployment and maintenance in these areas. The study will investigate the effectiveness and reliability of the decentralized aproach in achieving vision zero, enhancing road safety, and reducing the cost of deployment and maintenance.

1.3 Research questions

1. What is the optimal deployment strategy for RSUs in a decentralized IVI system, and how does it affect the system's reliability?
2. What are the benefits and drawbacks of periodic signal broadcasting versus on-demand signal broadcasting in an IVI system, and which is better suited for a decentralized system?
3. How does the use of IVI contribute to achieving Vision Zero goals, and what are the key factors that impact its effectiveness in improving road safety and traffic efficiency?

1.4 Contributions

In this research, we aim to contribute to the field of Intelligent Infrastructure to Vehicle Information (IVI) by proposing a system that tests the decentralized approaches. By evaluating these approaches, we will **demonstrate** how the deployment of decentralized ITS can be more effective in suburban and rural areas where more localized and responsive solutions are needed to ensure road safety.

Furthermore, we will **show** how the proposed IVI system can make a significant contribution towards Vision Zero. By leveraging the capabilities of IVI services, the system will optimize the deployment of Roadside Units

(RSUs) to **ensure** that signals are transmitted reliably, and vehicles receive them on time, and in a coordinated manner.

The system in the decentralized approach will react and adjust to local conditions such as changing speed limits in response to the presence of pedestrians or animals on the road or adapting to traffic jams. By taking these local factors into account, the system can ensure that drivers receive the most up-to-date and relevant information to make informed decisions and avoid accidents. The contribution of this thesis are as follows:

1. Proposing a system for intelligent IVI that can operate in decentralized mode.
2. Evaluating the deployment of the decentralized IVI system in suburban and rural areas.
3. Testing two different schemes for RSU deployment and evaluating their performance in terms of reliability and accuracy.
4. Demonstrating how IVI systems can contribute to the Vision Zero goal of road safety and traffic efficiency by providing reliable and accurate information to drivers.
5. Designing a framework to measure the performance of the IVI system in terms of accuracy, reliability, latency, and data usage.
6. Providing insights into how different signal dissemination techniques can impact the reachability and accuracy of IVI systems while minimizing network usage.

2 Background

Over the past few decades, the number of vehicles on roads worldwide has grown significantly, making road transportation a critical aspect of modern-day life. In response, automotive manufacturers and organizations have invested heavily in Vehicle-To-Everything (V2X) communications technology to optimize the driving experience and enhance transportation safety, passenger infotainment, and vehicle traffic optimization. V2X communication comprises four main categories: vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-pedestrian (V2P), and vehicle-to-network (V2N) communications.

For safe and efficient transportation, it is essential to have a robust infrastructure-to-vehicle communication (IVI) system in place. Such a system can provide drivers with real-time information about road conditions, traffic, weather, and other relevant data, enabling them to make informed decisions and avoid accidents, thereby achieving vision zero. In recent years, there has been a growing interest in developing IVI communication systems that integrate with in-vehicle infotainment concepts, which are Advanced Driver Assistance Systems (ADAS) designed to assist vehicle drivers and autonomous systems with real-time information about road conditions, traffic incidents, and road signage [4].

This research will focus on V2I communications and the integration of IVI concepts, specifically In-vehicle Infotainment, to assist vehicle drivers and autonomous systems with real-time information about road conditions, traffic incidents, and road signage.

2.1 Intelligent transports system (ITS)

Intelligent transportat systems (ITS) represent a revolutionary approach to mobility that integrates cutting-edge technologies to tackle transportation issues, including safety and efficiency. By incorporating communication and awareness technologies, ITS creates an intelligent transportation environment that enhances the user experience. The involved actors that build up this system and establish communication between each other are called ITS-Stations (ITS-Ss), which range from vehicles and pedestrians to road-side units (RSUs) and more. In this context, cooperative ITS (C-ITS) emerges as a derived category of ITS, where ITS-Ss cooperate their trajectory and communication to achieve a more efficient and safe transportation system. As the next generation of transportation systems, ITS harnesses the power of advanced technologies such as IVI to improve safety and efficiency while reducing traffic congestion [5][6].

2.2 Vehicle-to-Infrastructure (V2I) Communications

Vehicle-to-Infrastructure (V2I) communication plays a crucial role in enhancing transportation safety and efficiency. By facilitating the exchange of information between vehicles and infrastructure elements like traffic lights and road signs [7]. V2I communication has garnered significant attention in recent years.

2.2.1 Importance of V2I communications for safe and efficient transportation

V2I communication has emerged as a promising solution for improving road safety and optimizing traffic flow. It enables the seamless flow of information between vehicles and roadside infrastructure, empowering drivers and autonomous systems with real-time data that can enhance decision-making and situational awareness.

2.2.2 Definition and features of IVI

IVI (Infrastructure-to-Vehicle Information) systems as an implementation of the V2I concept and are designed to enable road safety and traffic efficiency through the provision of real-time information to vehicles. These systems rely on the exchange of information between roadside infrastructure (such as traffic signals) and vehicles equipped with on-board units providing information to assist the drivers or autonomous systems [8].

2.2.3 Importance of IVI for driver assistance and safety

IVI systems are essential in ensuring the reception of different information from different road agents of current road conditions, including any speed limits, construction zones, or accidents that may have impact on traffic conditions. However, the effectiveness of IVI systems depends on their ability to provide accurate and reliable information in a timely manner, while also minimizing the use of network resources [9][10].

2.3 In vehicle signage

In-vehicle signage is a type of digital signage that is integrated into vehicles, typically in the form of electronic displays or integrated in the system itself. It is connected to the ITS infrastructure to provide real-time traffic information and other relevant data to drivers and passengers. In-vehicle signage can be used to display information such as traffic signs, current traffic conditions, road work alerts and emergency alerts. This technology can improve road safety and reduce traffic congestion by providing drivers and autonomous systems with up-to-date information to make informed decisions while driving [11].

There are different types of digital signage systems available, including DSRC-based systems that use short-range communications to display information on the vehicle terminal, GPS-based systems that use digital road data to present traffic sign data, and image processing systems that automatically detect and recognize traffic signs from image data. The use of RFID as digital traffic signing is also being explored. While digital signage has the potential to improve driver safety and reduce the likelihood of accidents, issues such as cost, space requirements, and visibility need to be addressed for wider adoption [12][13].

3 Method

In this section, we present the methodology employed in this report to address the research questions and achieve the contributions of this thesis. Starting by providing a general overview of the proposed system, to the experimental setup and experiment design and finishing with the evaluation of the system and the limitation of this experiment.

3.1 Proposed system

The project's central focus is on the performance of the decentralized IVI systems. We will conduct experiments to evaluate the reliability, accuracy, and latency of the system and contribution to traffic and road safety in suburban and rural areas. The experiments will also help us determine the optimal deployment strategy for RSUs in decentralized IVI systems and how it affects the system's reliability.

To achieve the research goals, a miniature street model will be constructed to simulate real-world scenarios for IVI systems. The model will consist of several road segments, traffic lights, and road-side units (RSUs) that will be strategically placed along the model to facilitate communication with the robot car. The robot car will be equipped with a Wi-Fi-transceiver “nRF24L01” to send and receive signals to and from the RSUs.

3.1.1 Decentralized mode

In the decentralized deployment of the IVI, the system will be composed of few elements which makes the deployment easier and less expensive.

1. RSUs: several RSUs in each segment presenting different traffic signals/rules takes configurable by accessing the RSU itself.
2. Road user: A robot car uses short-range communication to communicate with different RSUs in the road segment and reacts to the information received about road rules and traffic signals accordingly.

In addition, we test two different schemes for RSUs deployment and evaluating the performance of the decentralized deployment of the IVI. The two schemes are:

- On-demand signal broadcast: when the car enters the street segment it will contact the RSU and ask for the rules needed on the segment. In other words, the RSU will only send the information if asked to.
- Periodic signal broadcast: the transmission of the signal follows a pattern at specific intervals. This pattern is repeated continuously, ensuring that the signal is broadcasted consistently all the time regardless of the existence of any road users.

The metrics will be used to evaluate the performance of the IVI deployments are as follows:

1. Reliability: Refers to the system's ability to consistently deliver information without errors or disruptions. In the evaluation of the IVI system, reliability will be assessed by measuring the consistency and dependability of the information transmission process, taking into account factors such as signal interference. The evaluation metrics used for reliability are the Packet-delivery Ratio (PDR) and the Packet-error Rate (PER). The PDR represents the fraction of transmitted messages that are received correctly by the destination, indicating a higher accuracy in transmitting the intended rules to the road users. On the other hand, the PER measures the rate at which received messages are incorrectly decoded or contain errors, indicating the system's reliability in delivering information without disruptions or errors.
2. Latency: We will measure how long it takes a vehicle to learn all the rules it needs before it enters a segment. This will give us insight into the performance of the system in terms of delivering information in a timely manner.

By testing the different schemes for RSU deployment and the different signal dissemination techniques we will be able to evaluate the IVI deployment and ensure which is the best deployment suitable.

The IVI deployment will be integrated with another project working on maneuver coordination simulating an overtaking scenario on a suburban road and how it can contribute to the Vision Zero goal of road safety and traffic efficiency by providing reliable and accurate information to drivers.

3.2 Experimental setup

In this section, we present the experimental setup, which encompasses the hardware and software components employed in the experiment. The description of the hardware and software used provides essential information for replicating the experiment and serves as a valuable resource for future expansions of the vision.

3.2.1 Hardware

The hardware platform we have used to conduct our experiments is explained in the followings:

4 pieces of Arduino Uno: One is used as a traffic sign (RSU), one is used as a receiver (Road user) and two Arduinos are used as jammers programmed to

simulate several scenarios of interference presenting different levels congestion in the network.

4 pieces of nRF24L01 connected to each of the Arduino boards. nRF24L01 is a is a low-cost, high-performance radio transceiver module that is commonly used for wireless communication in various electronic projects and devices. It is a 2.4GHz transceiver that uses the Nordic Semiconductor GFSK (Gaussian Frequency Shift Keying) modulation scheme to provide reliable and efficient data transmission over short distances.

3.2.2 The employed software

Arduino Integrated Development Environment (IDE) is a software program used to create, write, and upload code to an Arduino board. It includes a text editor, a compiler, a bootloader, and a serial monitor that allows communication between the Arduino board and the computer. The language used to program the Arduinos using the IDE is C++.

3.3 Experiment design

Initially, the project aimed to employ a robot car that would be equipped with an Arduino Uno board to react to the signals transmitted by the traffic signals. However, as the work on the project progressed, the team discovered that the robot car was only necessary for the demonstration of the project. Instead, decided to monitor the response on the serial monitor within the Arduino IDE. It also made it easy to test the system and troubleshoot any issues that arose during the development process.

The experiment consists of using two different signal dissemination techniques to deploy the RSUs in the decentralized IVI system. Both techniques have two main elements:

1) RSU: traffic sign, traffic light
2) Road user: the car.

The communication protocol in each technique is different. While the periodic needs only one message structure (which is sent from the signal to the car), the On-demand has two: a message sent from the car to the signal and another structure for the response received from the signal.

The message structures both consist of several integer fields to pass the information. The reason why it is integers and not strings when sending information using Arduino and nRF24L01 is because it's more memory-efficient and faster to send binary data in the form of integers. The nRF24L01 is a low-power radio transceiver that is designed to transmit data wirelessly over short distances. It has a limited data rate and sending strings of characters can take up a lot of memory and slow down the transmission.

3.3.1 Periodic signal broadcast

The traffic signal periodically sends information about its state, including its ID, heading, sign type, and sign state, to the car. The car listens for this information using the nRF24L01 module and receives it as a series of integers in a specific format. The information sent by the traffic signal is packaged into a struct data type called "InfraMessage". This struct contains four integer fields: "id", "heading", "sign_type", and "sign_state".

The "id" field contains the ID of the traffic signal, the "heading" field contains the direction the traffic signal is facing, the "sign_type" field contains the type of sign displayed on the traffic signal (speed limit, overtaking, traffic light, etc..), and the "sign_state" field contains the state of the sign (e.g. allow, Not allowed, green, yellow, or red). The period the signals sends the information is adjustable and is provided as a delay in milliseconds. Figure 3A/3B shows the behavior of the signal and car in the Periodic approach.

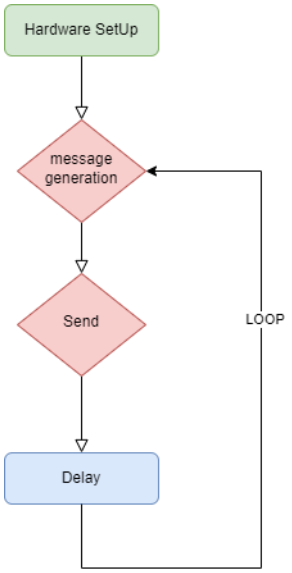

Figure 3.A Periodic sign behavior

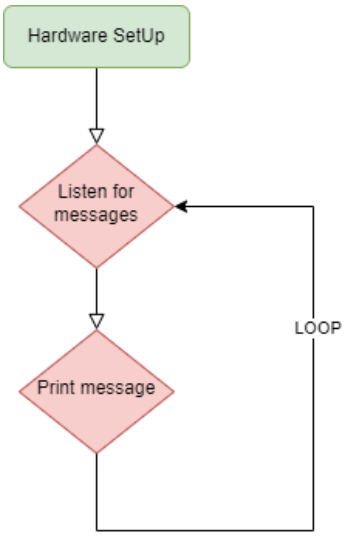

Figure 3.B Periodic Car behavior

3.3.2 On-demand signal broadcast

The On-demand technique has a similar structure for the "InfraMessage" which is the message struct sent from the signal. However, the car is different because of how the protocol works. When the car is in the area of coverage of the signal, the car broadcasts a request to the signals. The signals with the relevant information and has the same directions as the car responds to the car with the “InfraMessage”. The request the car sends is packaged into a struct data type called “CarMessage” which contains two integer fields: “id” and “heading”. The car sends the request to the signal and wait a specific amount of time, after the time has passed it is either positive or negative. Figure 3C/3D shows the behavior of the signal and car in the On-demand approach.

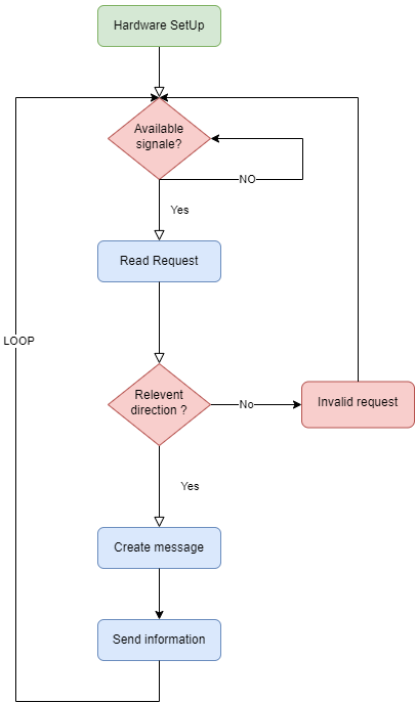

Figure 3.C On-demand Sign behavior

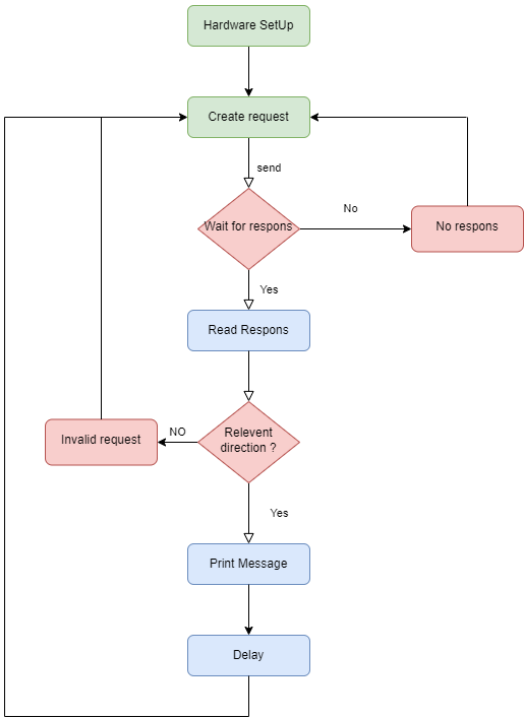

Figure 3.D On-demand Car behavior

3.4 Evaluation

The experiment was conducted to evaluate the efficiency of the system using the previously mentioned metrics

PDR: (Packet Delivery ratio)

$$\text{PDR} = \frac{\text{packets received}}{packets\ sent}.$$

PER: (Packet Error Ratio)

$$\text{PER} = \frac{\text{packets received wrong}}{packets\ recived}.$$

Latency where we test the time it takes the car to receive the relevant information in both techniques and compare them.

The jammers mentioned before are used in the testing and evaluation of the system by using them to send the same structure just on another pipe simulating different levels of congestion in an ITS. The different levels of congestion are:

1) No congestion: the systems run freely with no interference.
2) Moderate congestion: the jammers are sending with 100 ms delay between each signal.
3) High congestion: the jammers are running with no delays.

During the development and testing of the communication protocols several problems were encountered, and many tests were conducted to find the right solution.

3.5 Limitations

One limitation of this study is that it only tested the communication performance of two devices, without exploring how the system would behave in a larger network or under different environmental conditions. Additionally, while the study focused on end-to-end communications, the reaction from the vehicle was not within the scope of this experiment. Therefore, further research would be needed to fully assess the potential of this communication system in a real-world setting.

4 Results

To address the research questions and achieve the above contributions, the experimental setup was designed and implemented. The experiment was run for 5 times and 30 seconds each and an average of the performance was calculated for each time.

The results obtained from the experiments show that the periodic signal broadcasting scheme has a higher packet delivery ratio (PDR) than the on-demand scheme two out of three of the congestion scenarios. The PDR for the periodic scheme was measured at 99.81% for no congestion, 93.73% for moderate congestion, and 83.35% for high congestion. On the other hand, the PDR for the on-demand scheme was measured at 99.63% for no congestion, 95.66% for moderate congestion, and 25.19% for high congestion. Which shows us how both techniques had quite close performance with no/moderate congestion but affected the On-demand drastically in the high congestion scenario. Fig 4.A shows a histogram of the performance of both schemes regarding the PDR.

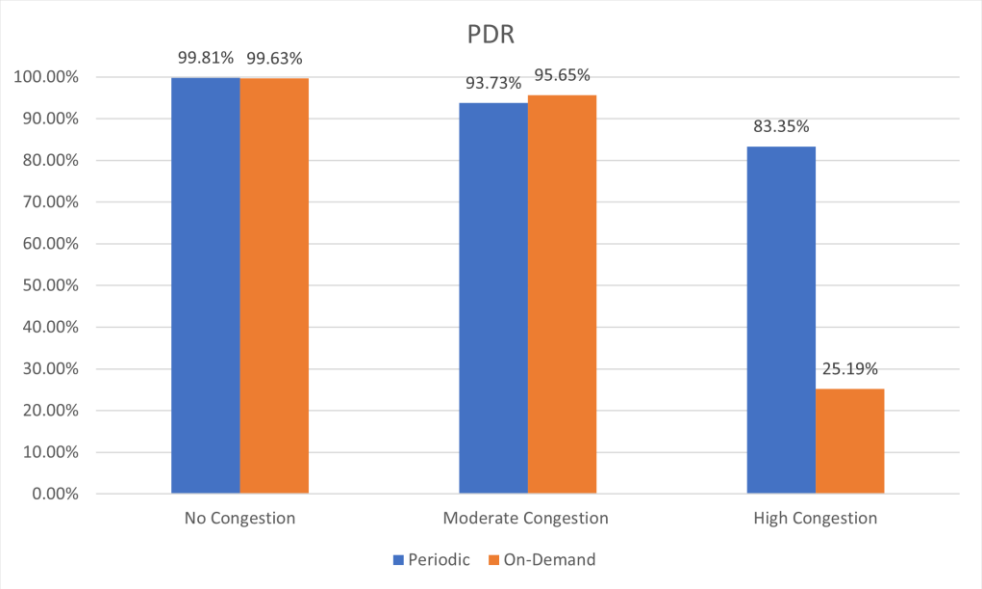

Figure 4.A Packet Delivery Ratio (PDR)

The results also show that the average packet error ratio (PER) for the periodic scheme was higher than the on-demand scheme for all congestion scenarios. The PER for the periodic scheme was measured at 0.38% for no congestion, 0.285% for moderate congestion, and 0.779% for high congestion. On the other hand, the PER for the on-demand scheme was measured at 0% for all congestion scenarios. While a higher PER may initially appear as a negative aspect for the periodic scheme, it is important to consider the presence of redundant packets in this scheme. The periodic scheme includes the transmission of multiple packets, allowing for compensation if any one packet

is faulty. This redundancy contributes to maintaining a higher level of reliability in the overall transmission process, even with a slightly higher PER. Therefore, the higher PER in the periodic scheme should not be solely regarded as a negative point but rather as an inherent characteristic of the scheme that ensures reliability through redundancy. Fig 4.B shows a histogram of the performance of both schemes regarding the PER.

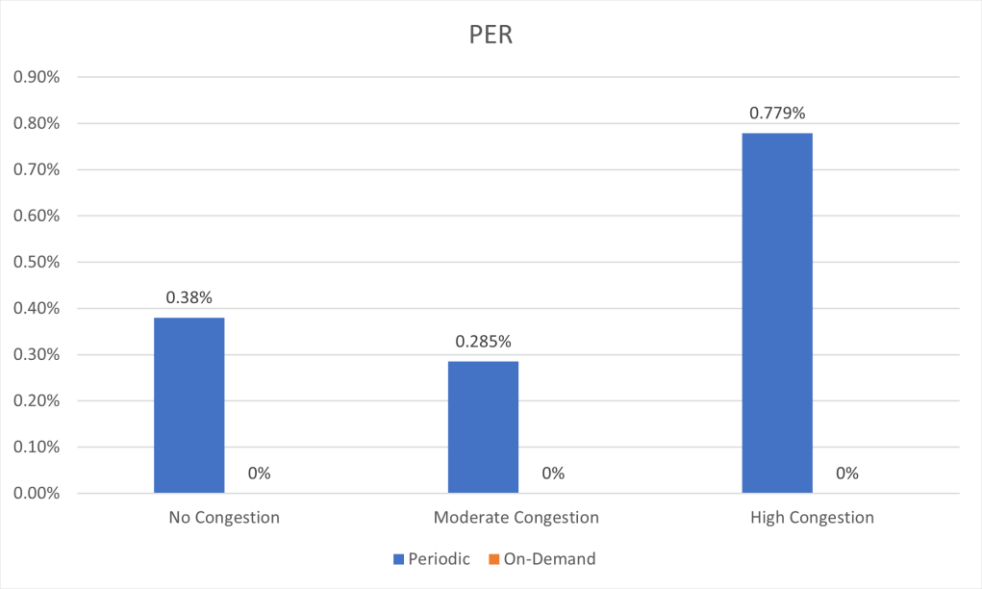

Figure 4.B Packet Error Ratio (PER)

In terms of latency, the average latency for both techniques was comparable, with periodic broadcasting having a slightly lower latency of 71ms compared to 91.2ms for on-demand broadcasting. However, in the moderate congestion scenario, the latency for periodic broadcasting remained constant at 71ms, while the latency for on-demand broadcasting increased to 99.2ms. In the high congestion scenario, the latency for on-demand broadcasting increased significantly to an average of 745.8ms, while the latency for periodic broadcasting increased to 76.8ms. The results suggest that the periodic broadcasting technique offers lower latency in most scenarios, with on-demand broadcasting being more susceptible to higher latency under moderate to high congestion scenarios. Fig 4.C shows a histogram of the performance of both schemes regarding the Latency.

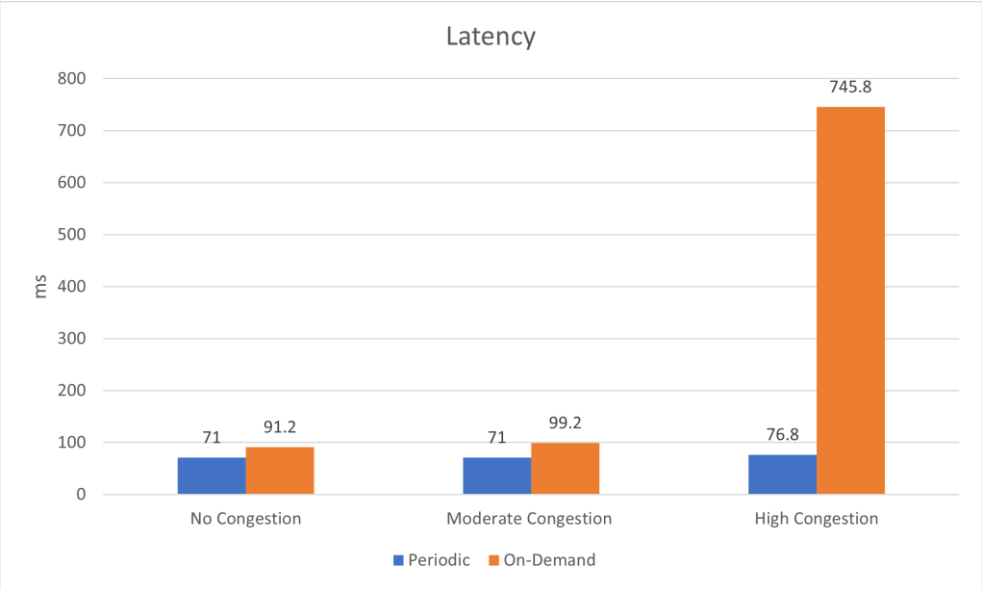

Figure 4.C Latency

The results of our experiments highlight several key takeaways. Firstly, there is a trade-off in performance (in terms of PDR that translates in latency) when more messages are present in the medium, when contention times increase, collisions occur, and the noise floor is risen, causing stations to struggle to send and receive messages. Secondly, conservative approaches (e.g., on demand) are safer in terms of PER, however, in this 1-to-1 setup, latency increases even with low congestion, and this would become even worse in 1-to-many setups, which would hinder scalability. Lastly, numbers for PDR exhibit that a quantity of messages are wasted, with a subjacent inefficient usage of resources (e.g., the worst case for the on-demand approach shows that at least 3 out of every 4 messages are lost, which translate in a 4:1 ratio for data usage and the same ratio for energy). Our experiments also tested the limit of the medium (in this case, the access medium for the nRF24L01), which was sensed as congested at a 20Hz rate (messages being generated every 50ms). Stations would effectively send messages at 12Hz, which means there would be a limit for the amount of signals each station can carry in the periodic mode or the number of requests it can serve in the on-demand mode. These results can be translatable to other access technologies, such as the ones used by standardized ITS (e.g., 802.11p).

Reflection on the research questions:

1. What is the optimal deployment strategy for RSUs in a decentralized IVI system, and how does it affect the system's reliability?
   This research question has been addressed through the experimental evaluation of two different signal broadcasting schemes: periodic broadcasting and on-demand broadcasting. The results show that the periodic scheme achieved higher packet delivery ratios (PDR) in most

congestion scenarios, indicating its effectiveness in reliably transmitting information. However, it was found that the on-demand scheme exhibited higher reliability in terms of packet error ratio (PER), indicating its suitability for delivering information without errors or disruptions. Choosing the optimal deployment strategy relies on several factor such as: Coverage Area, Traffic Density, Communication Range, Cost and Budge and many others.

2. What are the benefits and drawbacks of periodic signal broadcasting versus on-demand signal broadcasting in an IVI system, and which is better suited for a decentralized system?
   This research question has been addressed by comparing the performance of periodic signal broadcasting and on-demand signal broadcasting. The results reveal that periodic broadcasting demonstrated higher PDR in most congestion scenarios, indicating its advantage in transmitting messages accurately. However, the on-demand scheme exhibited a lower PER, highlighting its reliability in delivering information without errors. The latency analysis showed that both techniques had comparable latencies, with periodic broadcasting having slightly lower latency in most scenarios. Overall, the findings suggest that the choice between periodic and on-demand broadcasting depends on the specific requirements of the decentralized IVI system.

3. How does the use of IVI contribute to achieving Vision Zero goals, and what are the key factors that impact its effectiveness in improving road safety and traffic efficiency?
   The findings related to testing the system provide insights into the factors that impact the effectiveness of IVI systems in improving road safety and traffic efficiency. By understanding the trade-offs between different performance metrics, policymakers and system designers can make informed decisions regarding the deployment and optimization of IVI systems to contribute to Vision Zero goals

5 Conclusion

Based on the research questions and the results presented, it can be concluded that the optimal deployment strategy for RSUs in a decentralized IVI system depends on various factors, such as the system's size, traffic density, and communication technology used. A trade-off exists between system performance, measured in terms of Packet Delivery Ratio (PDR) and latency, and the number of messages present in the medium. Conservative approaches, such as on-demand signal broadcasting, are safer in terms of PDR, but they are not scalable and result in increased latency in larger systems. The periodic signal broadcasting approach is more efficient in terms of data and energy usage, but it suffers from increased contention times, collisions, and rising noise floors.

Furthermore, the study found that the use of IVI contributes significantly to achieving Vision Zero goals by improving road safety and traffic efficiency. However, the key factors that impact its effectiveness include the deployment strategy, signal dissemination techniques, and the communication technology used. In addition, the impact of signal dissemination techniques on the performance of IVI systems depends on the number of messages in the medium, and protocols should be designed to optimize reachability and accuracy while minimizing network usage.

In terms of reliability and accuracy, the on-demand approach was more effective, as it delivered messages only to the requesting vehicles. On the other hand, the periodic approach was more efficient in terms of latency and energy consumption, as it broadcast messages to all vehicles in its range. However, the periodic approach suffered from increased contention times, collisions, and rising noise floors.

Finally, the study highlights the importance of selecting the right access medium for IVI systems, as the access medium's limit can affect the number of signals each station can carry in the periodic mode or the number of requests it can serve in the on-demand mode. Overall, the findings of this study can provide valuable insights to system designers, policymakers, and researchers in the field of intelligent transportation systems, helping them to design more efficient, reliable, and scalable IVI systems that contribute to improving road safety and traffic efficiency. Further work needs to be performed to analyze the effect of these metrics on vehicle behavior.

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