Adaptive IEEE 802.15.4e LLDN Scheduler for Wireless Network Control Systems

by:

Kiana Karimpoor

A Thesis Submitted in Partial Fulfillment

of the Requirements for the Degree of

Masters of Applied Science

in

The Faculty of Engineering and Applied Science

And the program of Electrical and Computer Engineering

University of Ontario Institute of Technology

Supervisor:

Dr. Ramiro Liscano

December 2015

Abstract

An active area of research in the automotive research community is the stability of Long Commercial Vehicles (LCVs) using active trailer steering and/or braking. These LCVs rely on sensor data located across different regions of the tractor and trailers and compose the LCV. Communication of the sensor data to the Electronic Control Unit (ECU) of the active trailer system is performed through a conventional wired bus. The benefits of wireless communication for an LCV are improved flexibility, maintenance, elimination of physical socket connections and, reduction of weight related to the wires in the vehicle. In LCVs there is a natural demarcation point between the tractor and trailers where wireless communications can replace the wired communication bus. This thesis investigates the latency and throughput of wireless communication using IEEE 802.15.4 and IEEE 802.15.4e Low Latency Deterministic Network (LLDN) protocols for different sensor sampling rates in an LCV scenario and creates a guidelines for the system designers to select the right sensor sampling times. Furthermore, it proposes a new adaptive IEEE 802.15.4e LLDN algorithm that computes the optimal timeslot and superframe duration based on the sensor node data inter-arrival times to achieve the desired LCV controller latency that will exhibit stable behaviour. Simulation results confirm that this adaptive IEEE 802.15.4e LLDN algorithm can configure the IEEE 802.15.4e LLDN that present the best results for delay as well maximum throughput for a desired latency.

Acknowledgement

I would like to express my gratitude to my supervisor, Dr. Ramiro Liscano, whose expertise, understanding, and patience, added considerably to my graduate experience. His direction, technical support, understanding and kindness were invaluable.

A special thank you goes out to my colleague, Tina, for all of her support and encouragement guidance in getting me caught up in the project, and for assisting me in thesis writing.

I would also like to thank my family those that never stopped supporting me, Mahta, Mahroo, Majid, Minou and Tirgan. I must acknowledge my husband and best friend, Ali, for all of his assistance, without whose love, I would not have finished this thesis.

Contents

List of Figures

List of Tables

Abbreviations

ACC	Adaptive Cruise Control
ACK	Acknowledgement
BI	Beacon Interval
BO	Beacon Order
CACC	Cooperative Adaptive Cruise Control
CAN	Controller Area Network
CAP	Contention Access Period
CFP	Contention Free Period
CSMA/CA	Carrier Sense Multiple Access With Collision Avoidance
CTS	Clear to Send
DSME	Deterministic and Synchronous Multi-channel Extension
DSRC	Dedicated Short Range Communication
FCS	Frame CheckSum
FDMA	Frequency Division Multiple Access
GACK	Group Acknowledgement
GTS	Guaranteed Time Slots
IFS	Inter Frame Space
IVC	Inter Vehicle Communication
LCVs	Long Inter Frame Space
LLDN	Low Latency Deterministic Networks
LR-WPAN	Low-Rate Wireless Personal Area Networks
MFR	MAC Footer
MHR	MAC Header
MSDU	MAC Service Data Unit
NCS	Network Control System
OPNET	Optimized Network Engineering Tools
PSDU	Physical Service Data Unit
RTS	Request to Send
SIFS	Short Inter Frame Space
SO	Superframe Order

STDMA	Space Time Division Multiple Access
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
TSCH	Time-Slotted Channel Hopping
WNCSs	Wireless Network Control Systems
WPAN	wireless Personal Area Networks
WSNs	Wireless Sensor Networks
XSIFS	Extra Short Interframe Space

1 Introduction

Over the past seven decades, the goods transportation industry has found long commercial vehicles (LCVs) to be the lowest in cost and the most effective, amongst common freight methods. However, commercial heavy trucks attribute to approximately 45 percent of automobile accidents in North America resulting in fatalities and personal injury [1].

Existing in-vehicle controllers, communicate with sensors/actuators through the Controller Area Network (CAN bus) protocol which is a hard wired protocol for real-time communication. One of the proposed improvements to the LCVs is to replace the wired network with a wireless communication system allowing for increased flexibility. The purpose of this change is to increase commercial vehicle stability while reducing accident rates, an evaluation of wireless control networks in cartrailer systems is a necessity. This analysis is particularly true when considering the relative reduction in system stability of wireless systems compared to the less flexible stability of the wired alternatives.

The LCV is a vehicle towing few number of trailers. There are many physical configurations in the trailer's body which determine various control stability criteria. In a typical configuration, the controller is located at the second trailer and the sensors are at the tractor and the first trailer, shown in Figure 1. The trailers are equipped with some sensors to transmit unstable motion information of each trailer. The controller and the sensors have wireless nodes for communication. The wireless replacement between the articulated units assists to disconnection probability reduction in the LCVs. Increasing number of trailers in LCVs decreases the maneuverability and lateral stability which increases the probability of car crashes. Maneuverability and stability of LCVs can be improved through the use of a control

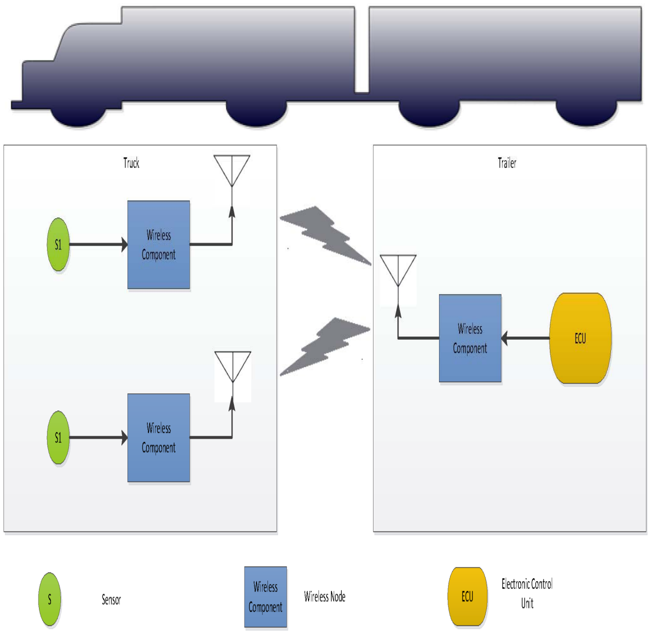

Figure 1: Depiction of WNCS on an LCV.

system. Improvements on the roll and yaw stability of the commercial vehicles are required to reduce the chance of encountering instability during motion. There have been numerous attempts directed to system stabilization through the use of diverse control strategies [2–4]. An optimal control system can compensate for the effects of unstable dynamic behaviour, such as swaying, jack-knifing, and rollover which are directly related to the trailer's response. Sun, T., et al. [3] utilizes Linear Quadratic Regulator (LQR) techniques to propose braking controller and improve the lateral stability of car-trailer systems. The previous paper shows that the enhanced impact of the differential braking control on the lateral stability.

Another approach is to choose the optimum wireless communication protocol to achieve delay reduction in LCV applications. Although recent dedicated Short Range Communication (DSRC) protocol is developed for Vehicle-To-Vehicle or Vehicle-To-Infrastructure applications, it does not conform to the LCV application requirements due to the none deterministic specification. Additionally, DSRC utilizes the broadcast mechanism for safety applications which may result in the congestion and long delay. The desired delay for delivering data from sensors to the control depends on the physical configuration of the LCVs. Therefore, the evaluation of Low Latency Deterministic Networks (LLDN) in the IEEE 802.15.4e protocol with a different MAC layer is considered a natural progression to another possible protocol other than DSRC which should introduce a new era for Wireless Network Control Systems (WNCSs) in vehicular applications. This thesis will study the results of simulator experiments and subsequently compare the original IEEE 802.15.4 standard which is a short range protocol designed for Wireless Sensor Networks (WSNs) with IEEE 802.15.4e results. Moreover, this research introduces an Adaptive IEEE 802.15.4e LLDN scheduler that can tune itself based on the number of sensors and sensor inter-arrival rate.

Wireless communication is used in a LCV which is categorized under WNCS applications and requires low-latency between the sensors and the controller to allow for the stabilization of the system. Furthermore, it is usually assumed that the controller and the sensors are equipped with wireless communications and are part of a PAN known. For this thesis it is assumed that the controller and actuator, which are generally located within the same unit in the vehicle are physically connected.

This study will investigate the possibility and conditions of deployment for the IEEE 802.15.4e protocol in LCVs especially within the above mentioned delay constraints. For this reason, an implementation of the IEEE 802.15.4e protocol with LLDN mode is conducted to transfer information between the sensors and the controller. Moreover, the results for the performance of this protocol will produce a guideline for other WNCS applications with the same configuration criteria.

Different scenarios with varied sensor rates will be examined. The MAC sub-layer in IEEE 802.15.4e tailors the timeslot and superframe durations to both the required application delay and the data payload. The timeslot size was varied in a range which can accommodate the frame transmission of a sensor within desired latency. Different factors which affect the delay of the system include:

- MAC Service Data Unit (MSDU) inter-arrival in each sensors: The time between generation of two consecutive MSDUs.
- MSDU size: The MSDU is known as the header plus the payload in the MAC sub-layer.
- Data rate: The data rate of the physical layer in the wireless protocol.
- Buffer size: The buffer size of the MAC layer.
- Superframe Order (SO): It is a variable which determines the duration of the superframe.
- ACK: The acknowledgment of transmitted frame.
- Number of sensors: Number of sensors which exists in a PAN.

The simulation is conducted in Optimized Network Engineering Tools (OPNET) Modeler which is a discrete-event network simulator application. OPNET has many advantages which can be leveraged in the development of the Adaptive IEEE 802.15.4e LLDN scheduler simulation model, these include:

- A powerful graphical use interface.
- Great accuracy.
- Accurate WSN node models.
- Actual packet formats and MAC specifications for IEEE 802.15.4.

This work takes advantage of Jurcik, P., et al. [5] paper mostly for the implementation of the protocol, as there was no existing implementation of the IEEE 802.15.4e LLDN in OPNET as far as this investigation could determine. This thesis presents a MAC scheduling mechanism to reach the minimum delay in an IEEE 802.15.4e LLDN communication model by tuning the timeslot and superframe duration. The suitability of employing this design is compared to the requirements of WNCS especially for a Long Commercials Vehicles (LCV) application.

1.1 Problem Statement

Establishing a connection between controllers and sensors with utilizing traditional wired networks, presents many challenges. Maintenance and troubleshooting are two of the main factors that exist with such the networks. Moreover, switching trailers within different tractors is confusing for drivers. Since drivers may not have the necessary wiring knowledge, which could result in false socket connections which in turn may lead to a system malfunction which can result in vehicle accidents.

The optimal wireless protocol should satisfy the main design challenges in WNCSs. Wireless networks generally encounter a few key difficulties:

- Channel fading.
- Delay.
- Packet loss.
- Low reliability.
- Shadowing.
- Interference.

- Congestion.

- Bandwidth constraint.

These challenges all need to be addressed. In WNCS, there are two main challenges which determine system stability. These are delay and reliability, while all other challenges can be categorized as sub-sections of these two major problems.

Sensor information should be transmitted at regular intervals wirelessly while the controller needs to supply the calculated data frames to the actuators through a wired network. If the inter-arrival time between two consecutive frames of the data from sensors is tight, the shared network may become saturated with excess frames leading to overflowed packets which are discarded from the transmitters buffer and long queueing delay.

However, very low inter-arrival sensor times may affect the control stability and thus reduce the accuracy of the system. From a control perspective the effectiveness of the system is determined by the sensor inter-arrival time which directly influences the design of the wireless network protocol. This paper studies how varied sensor data intervals can influence the total delay in IEEE 802.15.4 and the reason for discarding its usage in LCVs.

The delay is the time duration between the first sensors being ready to transmit data to the receipt of the last piece of data by the sensor, since all the information coming from all the sensors is utilized simultaneously by the controller. Thus, a tuned protocol according to the IEEE 802.15.4e standard is designed dependent of the superframe duration in order to facilitate the fast data frame transmission and stabilize the required control system delay.

1.2 Motivations and Contributions

Establishing connection between controllers, sensors and actuators utilizing old-fashioned wired network, presents many issues. The maintenance and trouble shoot are two main factors that always exists with such networks. Moreover, switching trailers within different tractors is confusing for drivers. Sometimes drivers forget to connect the wires between the ECU and the sensors. False socket connection among different types of connectors by commercial vehicle drivers may lead to system malfunctioning. As a matter of the fact, while the an LCV is moving along the road, the angle between the articulated units is continuously changing which leads to the physical disconnection and damages. However, replacing the wires with wireless systems increase the flexibility, road safety and collision avoidance. Furthermore, it reduces the possible human mistakes, maintenance expense and control system cost. Also wireless networks assist to achieve considerable vehicle mass reduction up to 50 kg which leads to fuel efficiency [6].

This work in this thesis presents the following contributions:

- This research presents the theoretical analysis of delay bounds and throughput for a WNCS based on IEEE 802.15.4e and IEEE 802.15.4 for a given number of sensors, sensor packet size and varied sensor data inter-arrival time with the goal of providing guidelines for a system designer in choosing the right configuration for the specific WNCS application. The original IEEE 802.15.4 OPNET model with GTS mode which is developed by Jurcik, P., et al. [5] is utilized as a simulation basis of this work and a new implementation of IEEE 802.15.4e LLDN which extends the original IEEE 802.15.4 in OPNET is developed in this thesis. Therefore, designers having specific delay and throughput requirements over control and sensor nodes can choose the relevant sensors with the appropriate sensor arrival data rates. They in turn can assure a specific range of throughput and delay for the timeslot allocation designed in the IEEE 802.15.4e LLDN.

- An adaptive IEEE 802.15.4e LLDN scheduler diminish the delay in LCV or Trailer-To-Trailer communication applications that automatically sets the superframe duration to achieve the desired delay. Subject to the network status the coordinator adjusts the timeslot of each node within a superframe.

One of the advantages of an Adaptive IEEE 802.15.4e LLDN scheduler is that it can self-regulate the communication scheduling intelligently when environmental factors alter, such as rate of data generation. The second example is that if the number of nodes in a vehicle reduces or increases, possibly due to the addition of extra functionality in the system, the coordinator is required to set the timeslot size for each sensor to achieve the low latency requirements. Changing sensor type may lead to inter-arrival variations in the system. Adaptive MAC capabilities eliminate the need for technicians to modify MAC parameters in order to reach low delay communication for each type of sensor. Thus the intelligence built into the MAC sub-layer allows for self-healing and self-organization, leading to adaptive behaviour in order to meet unexpected challenges.

1.3 Adaptive IEEE 802.15.4e LLDN Algorithm

Low-latency WNCS application in Intra-Vehicle environments usually do not utilize wireless communications for sensors and nodes for the purpose of collision prevention. For this reason, if a Time Division Multiple Access (TDMA) based MAC protocol is customized in a way that fulfills low latency requirements, the controller receives the consecutive streams of data from the sensors and manipulates the system to achieve stability.

An adaptive superframe and timeslot duration in IEEE 802.15.4e is presented to facilitate different type of sensor specifications. The PAN coordinator recognizes the number of nodes at the Discovery state with a broadcasting fashion. It should be noted that the number of nodes does not change after the Discovery level in LCV applications. Considering this point, an automatic adaptive design of the MAC layer becomes even more relevant.

The PAN coordinator recognizes the nodes and the topology of the network at the Discovery state and carries on with the same information for each node. The PAN coordinator conducts the sophisticated planning for all nodes and transmits synchronization, the timeslot access and, the superframe information to each node in the Configuration states in the original IEEE 802.15.4e. The Adaptive IEEE 802.15.4e LLDN scheduling count is based on the number of nodes, MSDU inter-arrival times of the sensors, and the desired delay to keep the buffer state stable to achieve a low communication latency.

This scheduling allows for the adjustment of the timeslot duration and transmission start time of each sensor that needs access to the shared network during a super frame. If the regular timeslot durations do not satisfy the low latency requirement, the length of superframe and timeslots are changed to reduce the number of frames related to sensor data in the MAC queue. Moreover, the coordinator designs the format of the superframe. For instance, it schedules data transmission in such a way that dictates sensor data to be received prior to the time that it needs to be used by the controller, which sits at the same location as a PAN coordinator. This adaption mechanism helps with the security of the network by guaranteeing against the joining of undesired nodes to the PAN while maintaining low latency. This is because joining requests from the new nodes can be declined during the Online state which all nodes leverage to access the shared media. Furthermore, other parameters of the network like MSDU inter-arrival times, stay the same during each Online state.

Relying on the fact that the mobility of the nodes in LCVs is not considered as the large scale mobility, the physical signal from the transmitters does not fluctuate with large enough amplitude to affect the quality of the signal at the receivers. The small scale variations can result in signal phase changes at the physical layer which can be resolved by utilizing various techniques [7]. The aim of this project is to enhance just the MAC layer of a Low-Rate IEEE 802.15.4e LLDN protocol to react to the changes of the MAC sub-layer parameters. The evaluation of the physical layer parameters is beyond the scope of this thesis.

The number of nodes and the sensor inter-arrival times are two factors that are application based in real-time WNCS areas. Sensor inter-arrival rate is the crucial attribute that influence the traffic load of the network at the controller. On the other hand, sensor data inter-arrival guarantees the stability of the WNCSs. Sensor inter-arrival is defined in the control field as how often a sensor should transmit its measured data to the controller to achieve the stability of the whole system [8, 9]. The controller has the responsibility for the calculation and timely transmission of new data to the actuators. Nevertheless, sensor data inter-arrival time has a different concept in wireless network systems. It represents the arrival traffic rate at the coordinator in the star topology which impacts packet delay, throughput, and buffer situation. The star topology is defined as a set of nodes which are connected to a central node and communicate through a central hob. It is presented in Figure2.

Furthermore, Long timeslot and superframe durations can display significant influence on the delay within the MAC layer, since the remaining assigned timeslot where nodes do not transmit data is wasted. Thus the wasted timeslots can be used for transmission to speed up the communication in real-time applications. The PAN

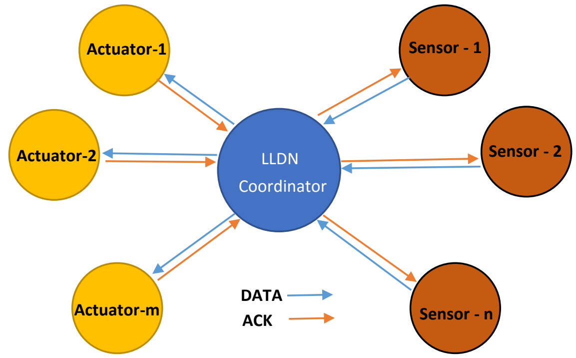

Figure 2: LLDN star topology in WNCS

coordinator can consider sensor MSDU inter-arrival at the beginning of the Discovery state and assign the relevant timeslot size to the nodes. This research requires the calculation of the timeslots and the superframe durations. Additionally, if the assigned timeslot duration does not convey the expected results due to network changes, the coordinator can combat the effect of changes with the modifications in the superframe duration. This can be achieved through the use of a-learning process that the controller monitors for the delay values in the network. By relying on the fact that every frame needs a minimum timeslot size for transmission, the coordinator make a superframe size equal to the sensor inter-arrival rate if the sensor inter-arrival time is less than the desired latency, unless the coordinator determines the superframe duration equivalent to the desired latency. In fact, one node plays the roles of both PAN coordinator and the controller simultaneously. This node should be armed with a reasonable processor with the ability to consume power from a continuous source to prevent energy exhaustion.

Most of the time-sensitive WNCS applications require having high throughput as well as low latency. There is always a trade-off between the throughput and the delay. TDMA approach has another advantage in terms of delay reduction through the use of collision prevention. Also, Acknowledgement (ACK) transmissions verify the reception of packets at the receiver. For the Adaptive IEEE 802.15.4e LLDN algorithm, ACK transmission is utilized to enhance the throughput results. Besides throughput improvement, ACK transmission located in the beacon timeslot reduces delay and elevates utilization. With the aid of the Adaptive IEEE 802.15.4e LLDN algorithm, packet loss can be caused by buffer saturation which can be remedied by increasing the sensor inter-arrival times and a suitable buffer size.

The superframe structure and Beacon Intervals are changed to meet a specific control range and delay boundary within a given duty cycle. This thesis concludes the optimal timeslot size which ensures low delay for a given data rate (protocol data rate) and guaranteed amount of data and bandwidth for a distinct LCV application. Despite the verification of a special case, the algorithm can be extended to other time-sensitive WNCSs, since there are different configuration of LCVs in terms of the number of attached trailers, trailer height and tractor to trailer distance. Moreover, the investigation of this paper can be applied to other WNCS applications in terms of different given MSDU inter-arrival times and the desired latency.

The physical layer implementation remains the same as before in order to maintain integrity, since changing the radio transmission strategies increases the cost of nodes which can include their need to be more intelligent and integrated with the previous version of the protocol. Even minor changes in the radio design, introduces high levels of expenditure, such as adding Frequency Division Multiple Access (FDMA) ability on top of TDMA [10]. To reduce the design cost, the MAC sub-layer can be changed instead of physical layer, which leads to software or firmware upgrades of the nodes. Additionally, the physical layer of IEEE 802.15.4 is an appropriate option for Multi-trailer applications given the minor mobility of the nodes which is insufficient to alter the physical parameters in a meaningful way.

1.4 Structure of Thesis

The organization of the chapters for this thesis provides the reader with imperative information of two main protocols and how they behave in terms of delay and throughput for different situations of the WNCS. Chapter 2 identifies with relevant research previously constructed in the field. This knowledge provides in depth insight of the simulation and analysis sections. Two major related research fields are studied: relevant works to application domain, and delay reduction in IEEE 802.15.4 and IEEE 802.15.4e protocols.

While the background material reviews the specification of these two protocols in Section 2.3, the concept of their performance including maximum delay theoretical calculations are covered in Chapter 3. The purpose of Chapter 3 is to introduce the concept of the work which has been conducted to reduce delay in the protocol and presents the Adaptive IEEE 802.15.4e LLDN algorithm in Section 3.5. Chapter 4 provides a brief rationale for why a simulation approach was taken to verify the superframe and timeslot allocation method in IEEE 802.15.4e. Chapter 4 justifies how simulation attributes and parameters are selected. It also explains the simulation scenarios for IEEE 802.15.4e in OPNET Modeler which is followed by results and analysis in Chapter 5 for diverse scenarios and arrival sensor inter-arrival times. Chapter 6 concludes that verification and suitability of the Adaptive IEEE 802.15.4e LLDN scheduler in IEEE 802.15.4e to be applied on semi-trailer applications.

2 Related Work and Background

2.1 Domain-Specific Related Work

Considerable work has been conducted on heavy vehicle improvements around controller and communication protocols to prevent human error during emergencies in passenger vehicles. However, not much attention has focused on Trailer-to-Trailer communication within the same vehicle. The proposed enhancements produce the collision warning applications to alarm the driver. Wang, C., and Thompson, J., et al. [11] and Yang, X., et al. [12] illustrate that if the driver of the vehicle can have the warning at least one-half a second before to collision, the 60 percent of roadway collisions might not happen. [11, 12]. While some proposals review different schemes not only to warn the driver, but also to take action in order to compensate for the slow human reaction response [13]. The second application requires constraint communication and processing delay to achieve the deadline. This study aims to represent a longitudinal accident which may happen due to the lack of driver attention or hard braking scenarios, especially on highways under harsh weather conditions. For this scenario, warning systems are deemed sufficient.

Many Trailer-To-Trailer applications can be accomplished by local sensors and without wireless communication. Nevertheless, applications with wireless technology are enhanced by gathering information from sensors of the other vehicles, especially when the local sensors of the vehicle cannot detect significant information quickly as Chisalita, L., and Shahmehri, N., et al. [14] explain. Additionally, most of the work in this area is focused on lane changing and vehicle following challenges [14].

A similar project as above was performed in [6] which calculates the performance of the IEEE 802.15.4 protocol in intra-vehicle communications theoretically. In this analysis, a controller and the sensor or actuator communicate with IEEE 802.15.4

protocol wirelessly. The sensors transmit with uplink, although the controller transmits data to the actuators by downlink with the star topology. The latency of this protocol was calculated such that the frame processing delay in the nodes and frame transmission delay are deterministic and not included in the latency calculations. An IVC application needs to operate with minimum timeslot duration in order to maintain low communication latency in distributed networks. Consequently, uplink latency increases with the number of nodes [6]. The previous mentioned research demonstrated that the protocol responds are based on the number of nodes sharing the same media and are not able to reach the sufficient time delay within required deadline to stabilize WNCS, since the focus of the paper is to provide timeslots within a superframe for plentiful vehicular sensors in IEEE 802.15.4.

Pape, D., et al. [1] utilizes IEEE 802.11n for multi trailer communication. This research is the only report that aims to accomplish the same multi-trailer communication application. Other projects investigate Inter-Vehicle Communication (IVC) in platooning, explained in greater detail later in this chapter and Cooperative Adaptive Cruise Control (CACC) applications in a car and not multi-trailer case [15, 16]. Because the requirements of the WNCS for these projects are similar to the case of this research which studies the LCV applications. This thesis reviews the two closest related applications: platooning and Cooperative Adaptive Cruise Control (CACC).

For these reason, this paper studies wireless communication with similar applications in the two main groups mentioned above.

2.1.1 Platooning

It is an application of IVC to move a fleet of vehicles in tight formation [17]. Platooning contains all control and wireless strategies and algorithms to lead a group of vehicles. IVC helps to decrease gaps between vehicles to improve fuel efficiency, traffic jam, air pollution and driver safety by warning messages and collision avoidance system [1, 18]. Platooning application can assist in achieving the above mentioned advantages, if the probability of system fault is less than human error which can be facilitated by real-time wireless communication. This can be done by acquiring information from the leader vehicle with the aid of IVC [19]. Each platoon creates a cooperative system which distributes the sensor, controls, and actuation information, which in turn is exchanged between the vehicles [20].

The control system is a combination of external data from the leader and internal information from local sensors of individual followers [20]. The wireless network encounters additional challenges such as high network loads arriving from several platoons and interferences from background traffic signal noise interference. Platooning includes many sub applications such as: Car-following, maintaining the distance (Adaptive Cruise Control and CACC), joining the platoon, leaving platoon and lane changing. Some studies attempt to incorporate all sub-applications within one project [21]. While others consider one or two of these sub-applications, such as proximate car following [14, 22]. Although mentioned works could solve the problems with control theory, some communication issues remain open challenges in platooning.

There have been European projects in platooning such as PROMOTE CHAUFFEUR I+II [18] and Truck platooning German national project KONVOI [23]. Some research has been done to decrease the distance between members of the platoon to improve fuel efficiency. These include PATH, Energy ITS, SCANIA and iQFleet [22, 24–26]. These projects mostly concentrate on control strategies and standard methods of communication and less consideration is given to the underlying wireless protocols.

2.1.2 Cooperative Adaptive Cruise Control (CACC)

These applications are dependent on distance information from proximity sensors and data from other vehicles to maintain distance and stability control. In other words, it is a sub-application of platooning. This process relies on up-to-date information from all other vehicles within a platoon to prevent collisions using wireless communication between 10-Hz standard sensors and a controller (1 ms sampling time). Some applications accommodate the communication requirements with DSRC/WAVE protocol [27]. The CACC applications require information from both the lead and front vehicles to take immediate action. Fernandes, P., and Nunes, U., et al. [28] reviewed a few TDMA based protocols to improve the performance of CACC by calculating dynamic adaption priority for timeslots according to vehicle positions. This model reduces channel contention and collisions. Segata, M., et al. [29] investigates the performance of 802.11p protocol in CACC application when the protocol broadcasts the dynamic information of vehicles within an interval with CSMA/CA scheme between the leaders in different adjacent clusters. They utilize TDMA mechanism for MAC communication among the members of a platoon with a touch of Space Time Division Multiple Access (STDMA) [29]. This paper uses clustering for a variety of vehicles. The STDMA approach is another method for MAC layer in CACC and platooning applications. It divides the road to diverse cells and maps the location of the vehicles to timeslots [30, 31].

Unlike CACC application, Adaptive Cruise Control (ACC) applications only require data from the predecessor vehicles to maintain distance for safety and fuel efficiency purposes [32]. Both ACC and CACC are sub-categories for Collision Avoidance applications due to their characteristics of maintaining distance with the front vehicle. Additionally, they both tend to apply longitudinal control schemes to achieve the stability of a string of vehicles. As mentioned above, the main advantages of

CACC in comparison with ACC applications is the reduced gap between vehicles due to consideration given to the leader's information as well as predecessor vehicle which enhances system accuracy [33].

The most recent and developed project in CACC applications is the SARTER project which introduces following the leader vehicle both laterally and longitudinally with the use of DSRC protocol [34, 35]. The idea behind this work is to form an autonomous platoon that allows varieties of unmanned vehicles to travel on highways following a human-driven leader. Furthermore, this research involves Vehicle-To-Infrastructure communication which is out of the scope of this paper.

2.2 Protocol-Specific-Related Work

IEEE 802.15.4 is developed for Industrial applications for its low-power consumption capability. Many papers have mentioned that this protocol does not satisfy the requirements of real-time applications [6, 36, 37]. For instance, ElBatt, T., et al. [6] analyzes theoretically and illustrates that IEEE 802.15.4 beacon-enabled is not able to support low delay.

Many papers customize or alter the CSMA/CA mechanism in IEEE 802.15.4 to raise utilization which can be fulfilled with shortening the timeslots [38]. Yoo, S., et al. [39] optimizes the scheduling of the Guaranteed Time Slot (GTS) model to reduce delay . This paper will build a scheduling method by keeping the same frame format, $BeaconOrder$ (BO) and $SuperframeOrder$ (SO) constraints of the IEEE 802.15.4 standard. In addition to maintaining the minimum Contention Access Period (CAP), the algorithm determines GTS allocation based on message length and Inter Frame Space (IFS) to reach maximum utilization of the remaining timeslots in the Contention Free Period (CFP) with regulating SO and BO. The IFS time generally is defined as the time that the MAC layer requires to process the received data from the physical layer and it includes the time that the radio needs to convert from transmitter to a receiver and vice versa. The authors of the paper examined their work with actual implementation on a node [39].

Ding, X., et al. [40] developed an adaptive GTS allocation algorithm, according to the transmission priority of the nodes. They designed the priority algorithm based on the significance of a sensors work to diminish the MAC delay. Unlike the work of Ding, X., et al. [40], all sensors are treated with the same priority for the purpose of this thesis. Koubaa, A., et al. [41] implemented a timeslot sharing solution. Thus nodes can share a timeslot to transmit their data with a round robin approach. They overcame the challenges of distributed networks to improve the bandwidth utilization [41]. Bergenhem, C. E. J. R., et al. [20] proposes a scheduling mechanism by changing the parameters of the superframe for the IEEE 802.15.4 in GTS mode to reach optimal delay with different number of nodes. Sharma, G., et al. [42] investigates the impact of Beacon Order BO and SO values on energy consumption, throughput and delay in beacon-enabled IEEE 802.15.4 in terms of the duty cycle and the Active period of the protocol (the period that nodes are awake). Most of the research around the parameters of IEEE 802.15.4 focuses on scalability challenges and the number of sensors in a PAN [43]. Anwar, M., et al. [44] concludes that the proportion of physical Service Data Unit (PSDU) payload decreases with the increasing number of timeslots in a superframe with different superframe sizes in IEEE 802.15.4e LLDN. The author states different security levels and clarifies that the number of timeslots with increasing PSDU decreases for security enabled scenarios in comparison to the packets without security octets. Also, the superframe size surges with the increasing level of security for the same number of timeslots in a superframe, since the superframe size is optional for IEEE 802.15.4e LLDN.

However, minor attention is concentrated on the implementation of IEEE 802.15.4e

LLDN application in terms of delay and throughput especially in the WNCS area. Chen, F., et al. [36] implements the fundamental changes in the MAC of IEEE 802.15.4 to attain IEEE 802.15.4e and use it in a specific application. Chen, F., et al. [36] evaluated the performance of the implemented IEEE 802.15.4e protocol with End-To-End delay and throughput (the amount of payload data that is successfully received per second), considering varied Beacon Order (BO)values. They compared their results with their calculations of the protocol, since in theoretical calculation it is applicable to calculate the worst case delay and in simulation the average End-To-End delay can be measured. They compare the performance of the IEEE 802.15.4e LLDN protocol with the previous IEEE 802.15.4 in terms of end-to-end delay, packet loss rate and throughput. However, the above mentioned research does not cover the burst size variance and mostly focuses on channel saturation limit by traffic intervals [36]. Chen, F., et al. [36] studies the performance of GTS mechanism for IEEE 802.15.4 in OMNET++ simulator considering simple star topology with $SO = 0$ scenario. The author illustrated the impact of the inter-arrival time on End-To-End delay, packet loss rate and throughput [36]. The previous mentioned paper introduces a threshold value for inter-arrival time that causes delay increases with increasing BO. The results in [36] concentrate on evaluating the delay threshold as a function of the number of nodes for two different energy consumption approaches: beacon tracking enabled and beacon tracking disabled methods. B. Yen, explores the well-known pendulum control stabilization with 802.15.4e LLDN focusing more on reliability of the protocol. Different numbers of retransmission are examined to study the response of the control system.

Koubaa, A., et al. [45] proposes an approach to analyze the GTS mechanism in IEEE 802.15.4 by using the Network Calculus method. They calculate the delay bounds as a function of GTS allocation, Duty Cycle, and burst size for unacknowledged frames. Also they illustrated that the GTS throughput and delay are a function of data rate, data inter-arrival times, and burst size. The IFS category has a remarkable impact on GTS delay and throughput as it dominates the frame size. They showed that for small burst size data (the amount of data which can be passed through a GTS), delay increases monotonically with increasing SO and the most efficient SO for this case is determined to be $SO = 0$ [45]. On the other hand, transmission of high burst size data is not guaranteed during one GTS for small SO (less than 2).The influence of guaranteed bandwidth is highlighted more than the worst case latency. Therefore, in Wireless Sensor Network (WSN) cases in which the burst sizes and data rates are low, low SO is an appropriate choice for time sensitive guaranteed transmission.

Jurcik, P., et al. [5] simulates and investigates the impact of IFS and arrival data rates for throughput and delay as a function of SO in IEEE 802.15.4. They evaluated their results with MAC delay and throughput values. The propagation delay is ignored in their calculation. They use a fixed size buffer, two frame sizes (40 and 41 bits) which lead to Short Inter Frame Space (SIFS) and Long Inter Frame Space (LIFS) in the frame format respectively. For higher SO, using SIFS or LIFS makes no discernible difference to the throughput results. This means that, the wasted bandwidth for IFS in higher SO is due to wasted bandwidth for long periods between the creations of data. Finally, Jurcik, P., et al. [5] illustrated that the delay increases with increasing SO.

Xia,F., et al. [46] produces an adoptive timeslot size in IEEE 802.15.4 based on payload size to diminish delay and raise the utilization. The end-nodes take the responsibility of required timeslot size and synchronization themselves. The previous mentioned paper's goal is to increase the number of nodes utilizing the CFP. It alters the format of beacon frames and replace some unnecessary information with GTS

Type which is defined according to three main timeslot sizes including short, medium and long timeslots. The devices transmit the request of the GTS allocation based on their payload size and predefined timeslot types. Then the coordinator checks for availability of the requested timeslots. Additionally, the coordinator grants the allowance of the data transmission into that timeslots to the nodes. Xia,F., et al. [46] represents that the new algorithm enhances the delay and utilization in a superframe and more devices can be accommodated in a superframe when the packet size is increased. However the proposed approach performs the same as the original IEEE 802.15.4 for heavy traffic load in terms of delay and throughput especially for low MSDU inter-arrival times.

2.3 Background

From the WNCS point of view, there is a trade-off between network delay and reliability of the network and stability of the platoon. Provided the number of retransmission of sampled data increases, the delay increases as well. This thesis attempts to compensate for the delay by selecting a suitable TDMA protocol, focusing on MAC layer strategies. This research surveys the specification and performance of the wireless protocol IEEE 802.15.4e LLDN and compares it with the IEEE 802.15.4 GTS mechanism. This work intents to produce a novel scheduling method, in order to minimize the delay and enhance throughput.

To achieve stability in a group of trailers, all the sensor information needs to be exchanged between trailers through wireless communication. The communication may face obstacles in delivering the sensor data to the controller. The prior trailers or tracktor in a heavy vehicle have valuable information for their followers. In the CACC applications, the data from the leader of the platoon, the information from the predecessors and the vehicles own local sensor data play a crucial role to maintain distance [47]. As many sensors and vehicles share the same bandwidth, the collision is one of the significant issues in vehicle-to-vehicle communication. Moreover, the interference from nodes which communicate with the same frequency range creates another problem to mitigate the performance of the communication system. Additionally, noise is usually one of the key elements in causing network delay [48].Furthermore, packet collision and packet loss are considered substantial causes of communication delay and a subsequent surge in the number of retransmission attempts. Consequently all aforementioned statements have an induced influence on communication delay [48].

It can be determined that the challenges and requirements of wireless communication in Inter-Vehicle Communication (IVC) applications are in the same vein as the problems being considered in this study [8, 9]. Therefore the general communication challenges of both WNCS and IVC fields are addressed in this thesis:

A. Delay: Latency is the time it takes to successfully receive a message from a transmitter (including the time that network protocols and operating systems spent to transmit and receive). The wireless communication delay causes instability in WNCS and IVC applications which are studied in [8] and [49] respectively.

B. Fading: Signal fading is the effect of multi-path communication between two nodes which is caused by signal propagation attenuation. This is not considered in this research due to the small distances involved.

C. Collision: Network collision caused by simultaneous transmission from different stations attempting to transmit packets across a network. CSMA/CA mechanism does not completely guarantee the avoidance of network collision while increasing retransmission and subsequently delay [50]. In order to avoid collision, this thesis utilizes the TDMA approach.

D. Interference: Existence of unrelated surrounding signals within close frequency range is the main cause of interference in a network. Interference increases the packet error rate and decreases the signal to noise ratio which leads to delay. This research does not study the Interference impact, since it has the physical layer nature.

E. Congestion: Congestion happens when a link/node loses its quality of service due to large quantities of data, which may result in packet loss. Congestion in the wireless channel can occur through emergency broadcast messages, which overload the receivers buffer. This behaviour declines delivery packet ratio and throughput and is one of the main challenges of DSRC protocol [51]. As the number of sensors are minor in this study, low data inter-arrival times causes congestion in the MAC layer of the node. The nodes need to queue the data and wait for their assigned timeslots for transmission. If the number of generated frames are more than the buffer size, the frames are dropped at the MAC sub-layer of the node. In this case packet loss happens. Hence, this study matches the transmission rate of the frames with the generated data inter-arrival rate.

F. Constraint Bandwidth: In general, efficiency in bandwidth usage plays an important role in choosing a protocol for the desired application. Low bandwidth can make the control system unstable,since the sampling time of the controller is reduced [52]. IEEE 802.15.4 is a Low-Rate protocol which has low physical data rate. Therefore the optimum transmission scheduling and timeslot allocation methods come to attention in MAC sub-layer to decrease the delay for all nodes.

G. High Reliability: One of the approaches that guarantees the packets are received by the desired destination is Acknowledgement (ACK) frames by the receiver. Other solutions are increasing the retransmission attempts, adding state-estimators at the receivers and jitter aware controllers to the system which impose network delay and complexity in the system [17]. Transmission Control Protocol (TCP) is usually not the preferred protocol for emergency messages due to creating congestion in the network. Unlike IEEE 802.11e protocol, the IEEE 802.11p does not employ ACK in terms of packet reception, since this protocol is designed for high dynamic and mobile schemes. DSRC is not able to tackle the overwhelming ACKs for the broadcast messages and transmission of Request to Send or Clear to Send (RTS/CTS) process [34]. Additionally, if the packet loss is caused by collision or consecutive back-off delay, deterministic MAC protocol can be used to tackle the problem. Many protocols increase the data retransmission numbers to surge the reliability, although this method raises traffic load, wastes bandwidth and finally increases End-To-End delay [53].

In the end, all these problems lead to latency in the system. For this reason, all mentioned challenges will be considered as a major section under the delay category. Furthermore, some of these problems can be compensated through the use of control techniques. However, many papers endeavour to tackle these issues through the use of networking solutions independent from the control system [54]. This thesis utilizes IEEE 802.15.4e LLDN protocol which is based on the IEEE 802.15.4 standard. A quick review on both protocols IEEE 802.15.4 and IEEE 802.15.4e LLDN is as follows:

2.3.1 IEEE 802.15.4

This standard consists of two layers: physical and MAC layer for Low-Rate Wireless Personal Area Networks (LR-WPAN). It operates in the 2.4 GHz band. The possible topologies are Star, Tree, and Mesh topology. The MAC layer is divided into two main configuration modes: beacon-enabled and non-beacon-enabled modes. Most of the existing protocols in the market ZigBee Pro, 6LoWPAN/RPL, IP500 or IEEE 802.15.5 based on this standard (IEEE 802.15.4) are defined with non-beacon-enabled mode which use CSMA/CA communication [55]. Furthermore, it has an ability to work in beacon-enabled mode which defines Contention Access Period (CAP) operating with CSMA/CA and Contention Free Period (CFP) operating with TDMA such as the newly released protocol IEEE 802.15.4e. Basically CAP (Contention Access Period) is referred to a period that the nodes compete to access the network and CFP (Contention Free Period) is referred to a period which nodes access to the network based on their schedule. The beaconing enabled version of the protocol is usually used for time-constraint applications [56].

2.3.2 ZigBee

ZigBee protocol is a protocol stack which functions based on the IEEE 802.15.4 physical and MAC layer with 240 kbps data rate in 868 MHz (in EU), 902-928 MHz (in America) and 2.4 GHz (worldwide). It is designed for short range and low power consumption communication and utilizes CSMA/CA to access the channel [57]. The nodes communicating via the ZigBee protocol have two working states; Active and Inactive. In the Active mode, the nodes communicate with a low data rate and a low amount of exchanged data. In Inactive mode, they sleep. This working mechanism consumes less power in comparison with other protocols. The topology of the network is master-slave in ZigBee. This protocol has been recently used in industrial control systems which do not have time constraint problems due to low cost and low power consumption features.

2.3.3 IEEE 802.15.4e LLDN

This protocol employs the same physical layer and partly MAC sub-layer of IEEE 802.15.4. The new addendum of IEEE 802.15.4 protocol (IEEE 802.15.4e) proposes a new MAC mechanisms which can be used in different applications with diverse requirements. In other words, it removes the CAP and inactive period and allocates the number of GTS based on the number of nodes. Low Latency Deterministic Network (LLDN) mode is one of the MAC modes of IEEE 802.15.4e which has the same physical implementation as IEEE 802.15.4 standard operating in the 2.4 GHz frequency band. The deployment is suitable for star topologies. The major transmission method for access to the media is TDMA based. Frequency Hopping is an optional version of MAC for this protocol to reduce the effect of interference, although it entails more cost.

The new addendum to IEEE 802.15.4 (IEEE 802.15.4e) introduces three substantial approaches for different MAC behavior modes:

- Time-Slotted Channel Hopping (TSCH): It provides both Frequency hopping, Time-slotted and Multi-channel transmission approaches. It is usually used in process automation for dynamic multi-hop networks due to acquire less energy consumption. It provides high throughput with simultaneously transmission in different channels [37].

- Deterministic and Synchronous Multi-channel Extension (DSME): It exploits both time and frequency division multiplexing in CFP by multi-superframe structure. It is designed for industrial and commercial applications to achieve low latency with high throughput [58].

- Low latency deterministic network (LLDN): It is designed for factory and process automation applications, such as automotive robots. The aim is to facilitate very constraint communication delay for small networks with star topology. The superframe concept is utilized to provide synchronization and deterministic delay [37].

The LLDN mode utilizes TDMA mechanisms for the MAC layer to ensure a deterministic time delay. This configuration in WNCS is applicable only to the star topology, when sensors transmit or receive information within specific timeslots with the PAN coordinator. The next chapter elaborates on these protocols in terms of MAC sub-layer performance in WNCS.

3 Timeslot Allocation of MAC in IEEE 802.15.4 and 802.15.4e LLDN

The MAC sub-layer has a remarkable impact on delay for time sensitive applications. This chapter is dedicated to the review of the MAC sub-layer of IEEE. 802.15.4 and the newer IEEE. 802.15.4e protocols. Delay plays a crucial role in automotive applications. It is considered from the instant the sensors transmit and up to the moment the ECU receives the packet. Generally speaking, delay includes three sub-delay sections which are transmission, propagation and queuing delay. Transmission delay ($\frac{FrameSize}{LinkBitRate}$) depends on the physical data rate of the protocol, number of assigned slots and packet size.

The propagation delay is typically around nanoseconds and for the purpose of this study can be ignored due to the short distances involved. The queuing delay is measured from the moment data is generated at the application layer up to the moment the sensor transmitter gets access to media. If sensor transmissions are scheduled properly, based on sensor generating sample times, the queuing delay can be minimized. Such a delay is considered from one single sensor to the controller. Control systems need a deterministic network with low latency.

Each sensor measures a specific parameter and converts it to digital bits which is fairly small at approximately 4 - 8 bytes for WNCS applications [44]. This small amount of data provides the possibility of transmission in a timeslot with a superframe. The location, start time, and duration of timeslots in a superframe imposes the application to approach the low-latency communication applicable for such a WNCS. Furthermore, deployment of the star topology with a single hop reduces delay by eliminating the requirement for an ACK and its associated overhead with the added stop and wait. Distinctively, in broadcast frames the use of ACK should be limited considering congestion in the network. Some implementations utilize group acknowledgement (GACK) to tackle this issue [59]. Additionally, Ulusoy, A., et al. [60] attempts to categorize traffic between uplink and downlink to fit more nodes in a superframe.

3.1 IEEE 802.15.4 MAC Layer

IEEE 802.15.4 has been used in control and automation applications due to its associated low data rate and energy consumption. It has been employed mostly in home and building automation [45], as it can have diverse MAC configurations and it can accommodate different control applications. For instance, a CFP can be used for deterministic applications, although CAP style is leveraged for delay-tolerant applications similar to those offered using the ZigBee protocol.

IEEE 802.15.4 can employ two general channel access mechanisms: non-beacon mode and beacon-enabled mode. In non-beacon mode, carrier sense multiple access with collision avoidance (CSMA/CA) is used for data exchange and results in unbounded jitter on the data transmission in the system.

The beacon-enabled includes Active and Inactive parts that determine working time and sleeping time for PAN members as illustrated in above Figure 3. The Active part is divided into the CAP and CFP utilizing slotted CSMA/CA and TDMA MAC fashions respectively. It is called beacon-enabled as it broadcasts timeslots at the beginning of each superframe. In the CFP, nodes can transmit in Guaranteed Time Slots (GTS). Due to the fact that nodes accessed through CSMA/CA with random back-off and limited numbers of GTS, IEEE 802.15.4 cannot facilitate real-time transmission for control applications [61]. The superframe duration contains 16 timeslots except during inactive periods. The duration of the superframe depends on the timeslot duration which may vary from 15.36 ms to 4 min in respect to standard

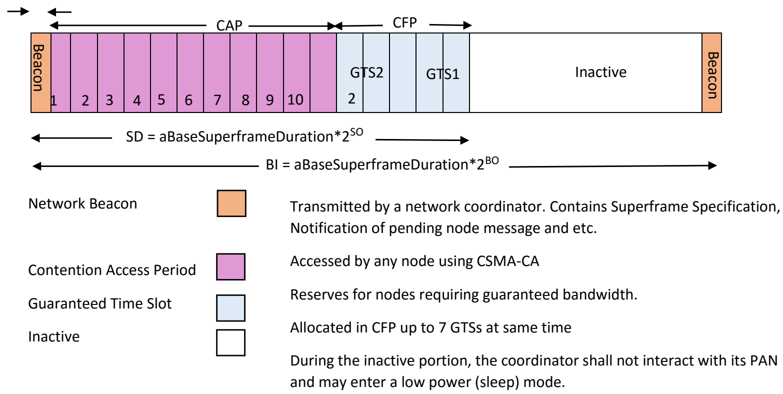

Figure 3: MAC superframe of IEEE 802.15.4

definitions in IEEE 802.15.4.

In the beacon-enabled approach, the standard definition of beacon interval can vary to include a broad range of application specifications. The general equation is as follows:

$$BeaconInterval = aBaseSuperframeDuration \times 2^n \tag{1}$$

where $n = 0$ to 14. On the other hand, there are some definitions of $SuperframeDuration$ from the IEEE 802.15.4 standard perspective [62].

$$SuperframeDuration = aBaseSuperframeDuration \times 2^{SO} \tag{2}$$

$$SlotDuration = aBaseSlotDuration \times 2^{SO} \tag{3}$$

$$aBaseSuperframeDuration = aBaseSlotDuration \times 16 \tag{4}$$

where SO refers to MAC superframe Order which can be between 0 and 14, and $aBaseSlotDuration$ contains 240 bits. Therefore, $aBaseSlotDuration$ and $aBaseSuperframeDuration$ last for 0.96 and 15.36 ms respectively, according to 250

Kbps data rate.

As minimum delay, represents minimum $SuperframeDuration$ and consequently minimum $aBaseSuperframeDuration$ when the SO value is zero. Regarding the equation 2 and 4 then minimum $SuperframeDuration$ is 3840 bits.

Considering that IEEE 802.15.4e supports 250 kbps, the above variables are assumed in calculation and simulation procedures. For instance, the minimum $SuperframeDuration$ is set to be 15.36 ms in the time domain. In this case, the $aBaseSlotDuration$ is 0.96 ms. Also, the Inactive period has not been considered for the purpose of this paper.

The minimum timeslot size is determined according to transmission and IFS times. The standard designates 104 bits for the header and 1016 bits for $aMaxPHYPacketSize$ (including MAC header, frame payload and PHY header).

3.2 Background IEEE 802.15.4e LLDN

The MAC layer of IEEE 802.15.4 has been modified to reduce transmission delay and make the enhanced protocol suitable for automation applications (specified as IEEE 802.15.4e with LLDN mode). This implementation works only with the Star topology, where the PAN coordinator is the centralized controller for the PAN. This protocol utilizes the physical layer and partly the MAC of IEEE 802.15.4. The nodes access the media by a time schedule pulled by the coordinator. It includes three states:

- Discovery.
- Configuration.
- Online state.

In the Discovery state, the node that needs to join the PAN listens for the beacon frames and transmits a request to join the network, according to the PAN information in the beacon frames. The Discovery state is a set-up phase and the configuration state is the second set-up part of the protocol. The coordinator transmits an acceptance acknowledgment to the node joining the network, followed by information of the PAN and assigned timeslots.

In the Online state, nodes enter the communication mode which is after the set-up states [63]. After two phases of Discovery and Configuration, all the devices are paired to the PAN.

The frame format is presented in Figure 4. The beacon slot begins the superframe followed by the optional management timeslots for control commands. The beacon frames contain synchronization, PAN information and assigned timeslots for the nodes. Despite Uplink timeslots representing the communication from devices to the coordinator, Bidirectional slots provide communication in both directions: Uplink and Downlink. The numbers of nodes which can exchange information during a superframe determines the size of the superframe. For low latency in control applications, if the number of devices surge, multiple ways can be utilized to enhance disadvantages of scalability and overcome interference issue. These include the communication of each group using different frequencies with a multi-transceiver coordinator [63]. According to Figure 4, each device communicates with the PAN coordinator and it is at this point where the two areas of research in Network and Control Systems interconnect. It is assumed that the controller is collocated with the coordinator node to accommodate two roles for the end-nodes simultaneously. The coordinator calculates control signals and makes decisions according to information received from the sensors.

MAC overhead is designed to be short in order to reduce processing delay. This

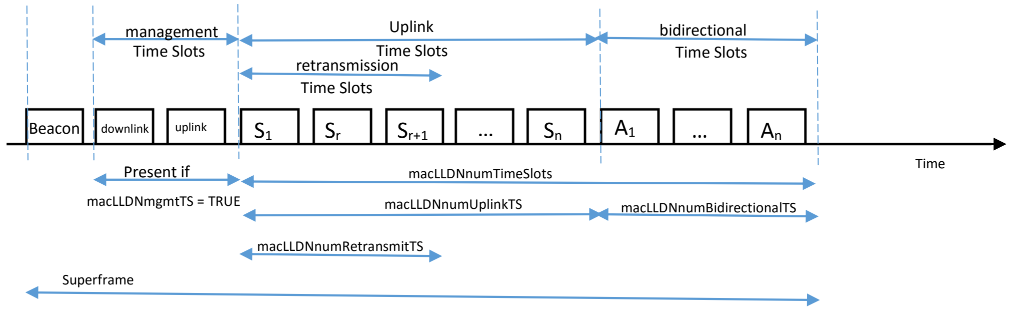

Figure 4: Superframe format and order of the timeslots in IEEE 802.15.4e LLDN.

is the reason for the sole use of a TDMA based scheme in LLDN applications. Furthermore, Centralized TDMA mechanism requires the synchronization of all members in a PAN through periodic beacon transmission by the coordinator. It is assumed that each GTS can handle the transmission of 60 symbols. The physical layer of IEEE 802.15.4 (including 6 Octets header) has not been changed to ensure compatibility with the IEEE 802.15.4e protocol radio strategies. An optional Extra Short Interframe Space (XSIFS) can be used between GTSs within a superframe to increase throughput. This XSIFS is a smaller version of SIFS aimed at preserving the timeslot duration.

If the MSDU size stays constant, and the value of MSDU inter-arrival increases, the throughput results remain the same for low superframe duration with different arrival data rate. It means that the protocol is using its maximum ability and bandwidth to transmit in low MSDU inter-arrival times. High MSDU inter-arrival with high data size experience the same results as low MSDU inter-arrival times. On the other hand, for large-duration superframes, the throughput drops with increasing MSDU inter-arrival times. The throughput can be defined as the number of bits per second that a node can deliver or it is the number of packets per second that successfully reach their destination [5].

The superframe contains control information, created by the coordinator deduced from the last received information from sensors. In other words, the coordinator makes decisions based on the latest received superframe information. The most applicable WNCS deterministic protocol is designed in a way that allows sensors to transmit during some timeslots, then group ACKs are transmitted followed by retransmission of any packets not yet received [44]. Group Acknowledgement (GACK) is a convenient way to save the time and ensure that the coordinator has received the sensor data during a superframe transmission.

Thus after the reception of the GACK, sensors with unsuccessful transmission needs to find a timeslot beyond the retransmission timeslots to transmit their information by the superframe. The nodes can retransmit their data within the retransmission timeslots.

Bidirectional transmission timeslots are assigned after the retransmission procedure for the coordinator to communicate with the actuators. In WNCS, the coordinator transmission is referred to as controller transmission to the actuators.

LLDN has four frame format models:

- LL-Beacon
- LL-Data
- LL-ACK
- LL-Command

Figure 4 represents the general MSDU format for the LLDN protocol. According to Figure 5, the first octet of LLDN frame format belongs to the control Frame and consists of LLDN frame types (including Beacon, Data, ACK and MAC), frame security and frame ACK requirement [44,55]. The two other parts, Sequence Number

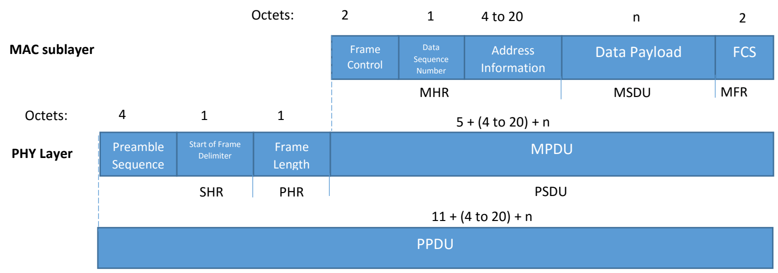

Figure 5: IEEE 802.15.4e LLDN MAC and physical layer frame formats

and Auxiliary Security Header fields for address information, show up in the frame format if the security in Frame Control is activated. The payload is located in the Frame Payload field with the Frame CheckSum (FCS) ending the frame format to ensure the correctness of any received data.

MAC Service Data Unit (MSDU) containing frame payload with maximum 104-bit size header. The MAC frame is finished with MAC Footer (MFR).

3.3 Theoretical Maximum Delay Bound Analysis for IEEE 802.15.4

In order to calculate the theoretical delay of IEEE 802.15.4 and IEEE 802.15.4e LLDN protocols, three major papers are surveyed in a time sensitive WNCS application [5, 6, 44]. This section starts with the investigation of the IEEE 802.15.4 protocol for automotive low-latency WNCS applications. Generally, the End-To-End delay contains three sub-delay sections: transmission, propagation and queuing delay.

$$TotalLatency(i) = SLatency(i) + ProcessingLatency_C \tag{5}$$

where i, $SLatency$ and $ProcessingLatency_C$ represent each node, total latency of each node and processing latency for the controller. If the $ProcessingLatency$ at the coordinator is negligible, then:

$$TotalLatency(i) < DesiredLatency \qquad \forall i \tag{6}$$

$$SLatency(i) = QLatency(i) + TXTime(i) + PropagationDelay \tag{7}$$

$QLatency(i)$ denotes as the buffering delay, $TXTime(i)$ is the transmission delay and $PropagationDelay$ is the latency of wave travelling through the air to reach the destination. It can be ignored due to the short distance between nodes.

Although equation 6 denotes as $TotalDelay$ in wireless communication, the critical delay which determines the control updating interval includes $SLatency$. The total latencies defines the entire time to transmit the sensor data to the controller. The goal is to determine if the total latency is below an admissible delay. For example, in the LCV scenario presented by Mirfakhraie, T., et al. [64] this minimal delay was calculated as 9 ms. The first assumption of this thesis is that the sensors communicate with the coordinator wirelessly and the controller has a wired connection to the actuator. Transmission delay can be defined as;

$$TXTime(i) = \frac{(PacketSize(i))}{(LinkBitRate)} \tag{8}$$

$$QLatency(i) \leqslant DesiredLatency(i) - TXTime(i) \qquad \forall i \tag{9}$$

it has been considered that a 40-bit MSDU frame per timeslot can be transmitted and the sensor data transmission would be completed within a timeslot. The MSDU inter-arrival time and packet transmission time both are deterministic values. However, $Q - latency(i)$ can vary predominantly based on the capacity of the buffer, MSDU inter-arrival time, number of the transmitter nodes and the timeslot which is assigned to the node (i). If the number of transmitter nodes and the MSDU inter-arrival time within a superframe, are too few to leave the buffer of each node with sufficient vacant space, the packet created at node (i) is transmitted immediately following the assigned timeslot to node (i) for transmission in MAC. Therefore, $0 < MinQLatency < 1$ slot and $MaxQLatency < [M(N-1)+9] \times aBaseSlotDuration$ which is the last timeslot of the superframe, considering all nodes are equally able to transmit during M timeslots in a superframe. The minimum number of timeslots assigned to CAP is 8 and a timeslot is allocated to the beacon transmission. Thus minimum 9 timeslots are assigned to CAP and synchronization. The number of CFP does not affect the CAP duration. It is assumed that the worst case $QLatency(i)$ is $MaxQLatency$. It would happen when the data in a node is generated right after the timeslots have been assigned to the node. Thus the MSDU needs to be stored in the buffer for the next assigned timeslots in the next superframe which takes $[(N-1) \times M+9] \times SlotDuration$ s. In other words, the node should buffer the received data until the first assigned node (i)'s timeslot arrives. Considering all nodes experience the same transmission and the worst case buffering delay, therefore

$$\begin{gathered}[M(N-1)+9] \times aBaseSlotDuration \leqslant \\ (DesiredLatency) - (TXTime)\end{gathered} \tag{10}$$

where M is the number of $aBaseSlotDuration$ assigned to each node and it is set to be equal for each node. Then according to equations 8 and 10;

$$aBaseSlotDuration \leqslant \frac{DesiredLatency - (Packet - size)}{LinkBitRate/[M(N-1)+9]} \tag{11}$$

As seen from equation 11 above, the MAC parameter ($SlotDuration$) is characterized by Physical Layer parameters such as $LinkBitRate$ which is a significant parameter for the speed of the protocol. The $DesiredLatency$ is defined by the control algorithms, calculating the required interval times to deliver control data to the actuators [64].

The other seven timeslots can be assigned to the nodes to transmit during left CFP in a superframe in IEEE 802.15.4 standard specification. The sensor delay includes the worst case queuing delay and transmission delay. The GTS transmission can be completed in any of the remaining assigned 7 slots. The maximum capacity of each $aBaseSlotDuration$ is 240 bits. In other words, during each $aBaseSlotDuration$ the protocol can dispatch maximum 240-bit data from its queue to the network. By assuming that the superframe duration is $([M(N-1)+9] \times aBaseSlotDuration)$ and each node only allows to transmit in its M assigned slots, the $TXTime$ is defined as a time for a frame (includes the payload, MAC header and IFS) to be transmitted completely from the MAC queue to the air by radio;

$$IEEE802.15.4SensorLatency = (QLatency) + (TXTime) \tag{12}$$

$$= ((M(N-1)+9) \times aBaseSlotDuration) + \frac{MSDUSize + Header + IFS}{LinkBitRate} \leqslant DesiredLatency \tag{13}$$

Where M is the number of slots assigned to a node. The variable $TotalSlots$ defines the entire slots in a superframe. The MAC header is set to be 104 bits by IEEE 802.15.4 standard. The $MSDUSize$ is the data payload. IFS depends on the payload size. The $abaseSlotDuration$ is usually defined by the protocol which is 0.96 ms in IEEE 802.15.4.

3.3.1 LCV Example using IEEE 802.15.4

The assumption is that the $MSDUSize$ is 40 bits which would add up to 48-bit IFS and 104-bit header [44]. The $DesiredLatency$ is 9 ms and 10 ms for semi-trailer and well-known pendulum control problems respectively [64,65]. If a sensor is used in the PAN to consume entire bandwidth, the worst case delay for a frame is equal to the CAP plus the beacon timeslot which is $9 \times 0.96 \times 10^{-3} + (40 + 104 + 48)/(250 \times 10^3) = 9.408 \times 10^{-3}$ referring to equation 13 which is still higher than the desired delay for semi-trailer and suitable for pendulum scenarios. Increasing the number of nodes makes the transmission and $QLatency$ even worse due to increasing N.

Considering that the packet size is defined by PPDU which has 104-bit header and 40-bit payload, the transmission delay is 0.76 ms. As can be seen in equation 13, the number of nodes (N) and the number of assigned timeslots play crucial roles in $SensorLatency$. According to the IEEE 802.15.4 family, 9 timeslots should be passed to start CFP within a superframe [6]. Thus the minimum $SLatency$ is 9.408 ms which is more than the $DesiredLatency$ (9 ms) for semi-trailer or single-trailer LCVs. This introduces the lack of IEEE 802.15.4 specifications to be used in automotive or Real-Time applications. Therefore, a new addendum of this protocol IEEE 802.15.4e which ensures low delay bounds is reviewed in the next section.

3.4 Theoretical Maximum Delay Bound Analysis for IEEE 802.15.4e LLDN

Since the IEEE 802.15.4e LLDN protocol supports TDMA at the MAC sub-layer for Real-Time data transmission, the CAP duration is not included in the $SuperframeDuration$. So the 8 assigned timeslots to CAP are removed from the equation 13. The same assumption of the timeslot duration for IEEE 802.15.4 is made that each timeslot contains 240 bits. If the first timeslot of the superframe is set-aside for the beacon interval and synchronization purposes, then the rest of the superframe can be used with Contention Free Mechanism transmission. The sensor latency ($SLatency$) can then be determined in equation 14.

$$([(M \times N) + 1] \times aBaseSlotDuration) + \frac{MSDUSize + Header + IFS}{LinkBitRate} \leqslant DesiredLatency \tag{14}$$

It has been assumed that the node faced with the worst case $QLatency$ and $TXTime$. Maximum $QLatency$ occurs when the frame is generated during the last possible assigned node's timeslots so the node is not able to transmit the packet during the remaining limited time and it needs to wait $M \times N + 1$ slots in the next superframe for transmission. The $TXTime$ can be defined as transmission time of a frame in the assigned timeslot. The controller needs all the sensor's information to process it together, so the entire superframe needs to experience less than $DesiredLatency$.

3.4.1 LCV Example Using IEEE 802.15.4e LLDN

Using the same assumptions as in Section 3.3.1, 40-bit payload, 104-bit header, 0.96-s $aBaseSlotDuration$ and 48-bit IFS are considered. According to equation 14, $[M \times N + 1] \times 0.96 \times 10^{-3} + \frac{40+104+48}{250 \times 10^{-3}} \leqslant DesiredLatency$ can be employed to determine the maximum number of sensors and number of assigned timeslots to the semi-trailer and the pendulum control problems. The value for $M \times N$ is 7 and 8 for the semi-trailer and the pendulum applications respectively.

If the number of sensors in a PAN is not large, the assigned number of timeslots to a node can be scheduled during a superframe by the coordinator in terms of low-delay communication. Then the maximum number of nodes to support a 9-ms control delay is 7 in a semi-trailer, referring to above calculation. Each timeslot can be assigned to a node.

If two nodes exist in a PAN, 3 slots can be assigned to each node, since the 7 timeslots are divided by the number of sensors. If just one sensor is considered to communicate with a coordinator, the maximum delay is the beacon duration plus the $TXTime$. Provided the sum of $SLatency$ for two node is needed to be less than 9 ms, the number of timeslots is divided by 2 to achieve the desired delay 9 ms. Therefore, 3 timeslots can be assigned to each node. The time delay from the generation of the frame at the first node to the time that the transmitted frame by the second sensor is received at the coordinator is less than 9 ms.

The IEEE 802.15.4 standard which has a fixed timeslot assigned to CAP and the load of the traffic in GTS cannot change the length of the CAP to less than 8 timeslots. However, IEEE 802.15.4e LLDN MAC layer does not include CAP in a superframe. Therefore, this design outperforms the IEEE 802.15.4 standard in terms of low-latency communication which can be fulfilled through only TDMA.

3.4.2 Calculation of Minimum Timeslot Duration in IEEE 802.15.4e

In deterministic MAC protocols, the size of a timeslot determines the data delay under ideal network conditions without interference and packet loss. Timeslot size needs to be equal to at least the minimum size of each frame for IEEE 802.1.5.4e which performs at 2.4 GHz without any security options according to Figure 5.

If the frame length ($MSDUSize$) is smaller than 40 bits, the value of SIFS (Short Inter Frame Space) is added to the timeslot, so that it contains 48 bits. If the length of the frame exceeds the 40 bits, the Long Inter Frame Space (LIFS) is used which is 160 bits in length.

The Inter Frame Space (IFS) period is the time between two transmitted frames

Octet:1	0/1	0/1/5/6/14	Variable	2
Frame Control	Sequence Number	Auxiliary Security Header	Frame Payload	FCS
MAC Header (MHR)			MAC Payload	MFR

Figure 6: General LLDN frame format

that the MAC layer needs to process the received frame from the physical layer. The main parameter that impacts timeslot size is PSDU (Physical Service Data Unit) which can represent Short IFS (SIFS) or Long IFS (LIFS). The timeslot size for a control application is usually 35-65 bytes long. Therefore the type of sensor chosen, impacts the timeslot duration in terms of IFS.

If the minimum timeslot size chosen is the same as IEEE 802.15.4 standard, it is equal to 240 bits which can accommodate at least one transmission.

The timeslot size is associated with the frame size including the payload, the header, and the IFS based on equation 15. IEEE 802.15.4e has different security levels for data format and authentication. For instance, different security containing minimum, medium and maximum levels have a distinctive timeslot size for beacon frame, data frame, command frame and retransmission frames. The higher the security levels go, the header size increases. Anwar, M., et al. [44] provides timeslot sizes of different frame formats in IEEE 802.15.4e LLDN within different security levels. The author utilizes a frame format to calculates the possible timeslot size in IEEE 802.15.4e LLDN, as shown in Figure 6. By relying on the frame size, and the associated timeslot calculations, the following statements calculate the number of timeslots for diverse scenarios.

In single-node scenario, if a sensor needs to transmit in a superframe and all the timeslots belong to that sensor except the beacon, the maximum delay equals the beacon *SlotDuration* plus the transmission delay (referring to Section 3.4) in each level of security. In single node scenario, If two sensors are being served in a superframe, the number of assigned timeslots to each sensor determines the End-To-End delay for either of them. However, the superframe duration needs to be less than the desired latency. If two sensors are contributing with the same number of timeslots in a superframe, the maximum allowed number of timeslots for each sensor is 5, 4, 4 and 3 timeslots for no security, minimum, medium and maximum security levels respectively. These results are based on their calculated beacon and regular timeslot durations which are close to this research's assumption and calculation for the two sensor scenario with IEEE 802.15.4e in Section 3.4.

$$SlotDuration = \frac{MACHeader + MSDUSize + PHYHeader + IFS}{LinkBitRate} \tag{15}$$

3.5 Adaptive IEEE 802.15.4e LLDN Algorithm

According to Section 3.4, the superframe and the number of assigned timeslots to a node is altered to achieve *DesiredLatency* based on control application needs.

The maximum End-To-End delay for a sensor is illustrated in equation 14. As evident, the MSDU inter-arrival time is not included in the equations. Therefore, the calculated number of timeslots is not able to guarantee the *DesiredLatency* for all MSDU inter-arrival times. Although *QLatency* impacts the sensor delay drastically, MSDU inter-arrival time is another factor which influences the load of data and finally the delay. For instance, if the number of created frames during the superframe is more than the number of frames that can be transmitted in a superframe, the delay increases cumulatively. Thus two main variables dominate the End-To-End delay at the coordinator: number of assigned timeslots to each node and MSDU inter-arrival times. It has been assumed that all nodes generate the frames with the same size and MSDU inter-arrival times and experience the same timeslot durations. The number of assigned timeslots, namely M, influence the $QLatency$ in equations 14. On the other hand, MSDU inter-arrival variable regulates the arrival data load. The IEEE 802.15.4 family protocol is designed as a low-rate wireless protocol for LR-WPANs, since the Maximum physical data rate is 250 Kbps. This feature affects the outgoing data rate. The outgoing data rate is the number of data that can be transmitted during a second. If the arrival data rate is higher than the outgoing data rate, the frames required to be stored in the MAC buffer and wait for the next assigned timeslot to be transmitted. Moreover, the TDMA mechanism itself reduces the useful bandwidth, since it assigns a reserve bandwidth to a node at the time.

Section 3.4 designed a custom superframe duration allocation based on $DesiredLatency$ which is defined by the control application. Hence the superframe duration is needed to be less than the $DesiredLatency$, although this design accommodates data inter-arrival times higher or equivalent to superframe duration. the maximum delay belongs to $QLatency$ according to equation 14. It is then assumed that the frame is transmitted during a superframe and is not stored in the buffer for too long. This means that in the worst case the maximum queue latency is defined when the generated frame leaves the MAC buffer in the next up coming superframe. Consequently the produced arrival data rate is needed to match the outgoing data rate to prevent large buffer queuing delay. Otherwise cumulated generated frames need to wait for more than two or three superframes to be transmitted.

The generated data has a data rate of $(FrameSize)/\ (MSDUInterArrival)$ bps. The frame size $(MSDUpayload + header + IFS)$ determines how many minimum slot duration it needs to be transmitted:

$$\frac{FrameSize}{aBaseSlotDuration} \tag{16}$$

where *aBaseSlotDuration* is considered in bits which is defined as number of bits that can be transmitted during minimum timeslot with 250 kbps data rate. As M timeslot assigned to each node in the PAN, the number of outgoing frames during M assigned slots to a node is:

$$\frac{M}{FrameSize/aBaseSlotDuration} \tag{17}$$

The number of generated data (MSDU inter-arrival time) during a superframe is needed to be less than the number of outgoing data during the superframe. The number of outgoing data in M slots equals the number of outgoing data during the entire superframe duration. $M \times N$ is referred to superframe duration, since the beacon does not take so long and is usually 0.5 ms. A timeslot of 0.5 ms from the beginning of the superframe is allocated for beacon. This value is negligible, so it can be ignored in this study. The number of accommodated outgoing frames in the superframe should be less than the number of generated frames with MSDU inter-arrival times. Therefore

$$\frac{M \times N}{FrameSize/aBaseSlotDuration} \leqslant MSDUInterArrival \tag{18}$$

by having the above condition, the maximum *QLatency* is provided for IEEE 802.15.4e as shown by equation 14. The M results from the equation above:

$$M \times N \leqslant \frac{(MSDUInterArrival \times FrameSize)}{aBaseSlotDuration} \tag{19}$$

From the above equation M is calculated for each node and the slots are assigned to the nodes. This procedure constructs the superframe. This algorithm is suitable for $MSDUInterArrival \leqslant DesiredLatency$, although for $MSDUInterArrival \geqslant DesiredLatency$, the maximum $QLatency$ affects the End-To-End delay more adverse than the MSDU inter-arrival time. The Adaptive IEEE 802.15.4e LLDN algorithm is designed based on these two variables.

Furthermore, there is an approach in IEEE 802.15.4e LLDN in which the coordinator monitors the usage of the allocated timeslots in the protocol standard. If the assigned timeslots are not used at a specific time which is proportional to double of the duration of the superframe, that the slot is deallocated from that node's possession. Obeying this rule in IEEE 802.15.4e LLDN enhances the utilization and prevents the wasting of bandwidth by the nodes. To prevent this process, a stage will be added to the Adaptive IEEE 802.15.4e LLDN algorithm to accommodate higher MSDU inter-arrival times with small superframe and timeslot durations.

Figure 7 represents the flowchart of the Adaptive IEEE 802.15.4e LLDN algorithm. First it checks the End-To-End delay ($E2EDelay$) at the coordinator. If the delay is more than the desired minimum delay, the algorithm checks the MSDU inter-arrival time (load of data). If the $MSDUInterArrival < DesiredLatency$, the coordinator adapts the superframe size with the arrived frame. If $MSDUInterArrival \geqslant DesiredLatency$, the coordinator sets the superframe duration (SD) equal to $DesiredLatency$. If $MSDUInterArrival \geqslant DesiredLatency$ and the MSDU inter-arrival time is higher than the $2^{SO} \times aBaseSuperframeDuration$, the coordinator increments SO to match the MSDU inter-arrival and superframe durations. This process is designed to prevent the deallocation mechanism. The deallocation is a process in which the coordinator monitors and checks the usage of timeslots and deallocates the timeslots that are not being used for more than the double of the superframe

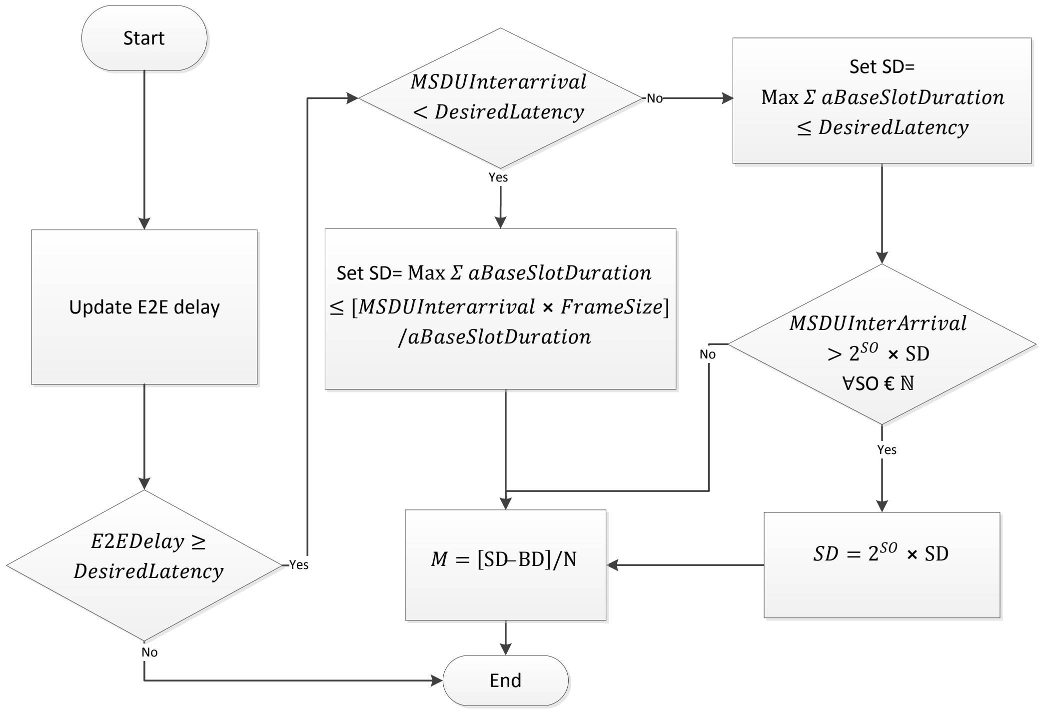

Figure 7: Adaptive IEEE 802.15.4e LLDN algorithm Flowchart.

duration. If none of above conditions are met, the protocol carries on the original superframe duration with $SO = 0$ for End-To-End delay less than desired latency.

4 Simulation Configuration

4.1 Simulation Justifications

Koubaa, A., et al. [45] concluded that the theoretical calculations of throughput in IEEE 802.15.4 introduce the difference from the simulation results in the presence of diverse arrival data rate for low superframe Order (SO), although the results match for high SO. The theoretical analysis section considers consecutive bit stream data which are generated by the MAC layer, although the simulation provides more actual data management in frame formats like what the real nodes perform for transmission. In other words, the simulation groups payload and headers and then dispatches the frame to the network. However, the theoretical calculations consider the frames as a consecutive bit stream. Therefore, frame-format simulation models the SO, Buffer Capacity, MSDU inter-arrival Time and MSDU Size which are modeled as detached frames, while continuous bit stream is used in the theoretical analysis approach. The analytical calculations provide an upper bound for delay and throughput analysis, although there may exist a huge gap between the upper bound values and the real simulation results. Jurcik, P., et al. [5] concluded that the simulation outcomes are more important than the analytical calculus approach for low superframe cases due to the frame oriented point of view. For this reason, this research studies the performance of the IEEE 802.15.4, IEEE 802.15.4e LLDN and, the Adaptive IEEE 802.15.4e IEEE 802.15.4e LLDN algorithm with OPNET simulator. Also the theoretical calculations for MAC TDMA deployment requires sophisticated methods to count buffer status and saturation at each moment of the simulation. This study utilizes the IEEE 802.15.4 from [Open-ZB] model as a fundamental model and replaces the TDMA for the MAC sub-layer to develop IEEE 802.15.4e LLDN. Moreover, it builds the new adaptive IEEE 802.15.4e LLDN MAC scheduler mechanism to achieve low delay for all MSDU inter-arrival times in IEEE 802.15.4e.

4.2 Simulation Parameters and Design Justifications

Different LCVs have diverse body and shape configurations and this results in different configurations of the Network Control System (NCS). For instance, in a single trailer scenario, there are only one sensor and one controller equipped with wireless nodes to communicate wirelessly. This sensor measures the parameters that the controller requires to use in its calculation. The controller is located at the trailer and the sensor is in the tractor, as shown in Figure 1. The maximum distance between these nodes are 100 meters based on the worst case configuration. Therefore the first implemented scenario starts with single node and a coordinator. Additionally, some other LCV configurations which have more than one trailer needs more nodes, at least one node per trailer. The second scenario emerges with two nodes and a coordinator.

The simulation begins with a simple scenario including a sensor and a coordinator in a PAN. Anwar, M., et al. [44] mentions that automotive sensors typically have an MSDU size from 30-60 bits and on average it is 40 bits. According to results from Anwar's work [44], the experiment can be started with 40 bits for MSDU size and kept constant to study impact of the MSDU inter-arrival time for low-payload sensors. Also the purpose of this thesis is not to study the impact of Long IFS (LIFS) in data transmission, although it investigates the control applications that need to transmit lower payload sizes than 40 bits. The original IEEE 802.15.4 has been used to explore its behaviour in the presence of different network parameters in this thesis, such as MSDU inter-arrival and superframe duration (SO). In addition to performance evaluation of IEEE 802.15.4, IEEE 802.15.4e LLDN is implemented to study the comparison of the reaction of these two protocols. Finally, IEEE 802.15.4e LLDN with a new superframe duration allocation algorithm is implemented to enhance the

End-To-End delay for LCV wireless applications.

The two retransmission and GACK sections in IEEE 802.15.4e are optional. The location of the retransmission timeslots are after the uplink transmission of the same superframe or they can be relocated at the beginning of the next superframe to save time [63]. Additionally, the maximum number of retransmission timeslots is half of the number of uplink timeslots. The concept of GACK is introduced to IEEE802.15.4e protocol to achieve both low latency and reliability for control applications with high number of uplinks [44]. The tendency of this research is to have all sensor data within one superframe to accommodate input of the controller for new calculations which can be used by the wired actuator [64]. Moreover, the number of devices being served in a superframe is fixed and few according to Anwar, M., et al. [44]. In the other hand, it is critical that the latency reach low values. For this reason, the coordinator's ACK reply to the sensor transmission during beacon timeslot. This design saves more timeslots for sensor transmissions instead of having GACK slot. This also makes the beacon interval more useful to increase the utilization of bandwidth. Instead of using fewer timeslots or increasing the length of the timeslot just for ACK transmission, the coordinator transmits the ACKs in the beacon frame with other information, such as synchronization and management commands.

The required control and sensors sampling times, number of devices in the network and the transmitted data payload determine the network control system configuration. A restriction which has to be met is that the End-To-End duration cannot surpass 9 ms for semi-trailer application [64]. The sensors transmit based on schedules determined by the coordinator with IEEE 802.15.4, IEEE 802.15.4e LLDN and Adaptive IEEE 802.15.4e LLDN MAC sub-layer protocol in separate experiments for two LCV scenarios.

The PAN coordinator which acts as a controller as well transmits control frames to the sensors in the beacon timeslots according to the standard. If the coordinator schedules more timeslots in a superframe to a node, the End-To-End delay is reduced for a single node scenario.

For the second scenario in this study, the number of assigned timeslots to each node should be scheduled in a way that it does not keep the other node waiting too long to transmit.

The MAC delay is the same value as the buffering delay and it is defined from when the application layer creates the traffic until the MAC layer allows the data to be transmitted to the physical layer. In order to maintain such a hypothesis, the superframe duration would change based on arrival data rate. In this case, the queuing delay is defined to be the same as the queuing delay.

Jurick, P., et al. [5] concludes that the most proper superframe duration for time sensitive WSN applications are provided by $SO = 0$. Therefore the commencement of the experiment is based on 15.36 ms superframe duration in this work. Subsequently, variation of MSDU inter-arrival amounts represents varied reactions of the wireless network protocol to study.

The evaluation of IEEE 802.15.4 beacon-enabled mode revealed that low latency applications are not well protected with this protocol due to the existence of at least 8 timeslots for the CSMA/CA mechanism. The best design of this protocol for low latency is to assign the rest of the CFP to a node for the whole period of transmission. In this case the maximum delay is equal to the beacon periods plus the whole CAP which would be around 9.804 ms considering $SO = BO = 0$. Furthermore, a 40-bit MSDU size is utilized in the experiments which can be supported for one timeslot transmission when SO is set to 0. This timeslot duration is the least possible standard value for IEEE 802.15.4. Additionally, the 40-bit results in SIFS being utilized. More than 40 bits data payload requires LIFS which has 160-bits length and leads to a higher delay value and reduction of throughput.

In dynamic control applications, the sampling time of sensors is mostly set to 10 ms [53]. If the assumption is to have at least one sample required to be transmitted per superframe and the superframe duration is set to the a desired 9 ms delay for a single trailer LCV as in Section 3.4 for IEEE 802.15.4e LLDN, the sensor MSDU inter-arrival time should be higher than 9 ms to meet the 9 ms desired latency. If the duration of the superframe is set to 9 slots (superframe duration should be less than desired latency) and the first and the second timeslots are assigned to beacon and management commands respectively, 7 timeslots remain for data transmission. These conditions are calculated based on a 0.96-ms timeslot duration. Considering one sensor transmission in these 7 timeslots, a MSDU inter-arrival higher than 7 ms can result in lower delay than desired LCV latency, presented in Section 3.4. If two sensors with the same specification (data payload) exists in a PAN with 7 timeslots and these 7 slots are divided by the number of sensors, either of the sensors can transmit within a maximum 3 assigned timeslots. However, the delay is less than the desired LCV latency, when the MSDU inter-arrival time is greater than 2.88 (3×0.96) ms.

In comparison the IEEE 802.15.4e can transmit a 40-bit payload in a timeslot. As the superframe duration changes in each scenario, the worst case MSDU inter-arrival times are different which then results at some point as the worst performance of the protocol. The MSDU inter-arrival needs to be examined in the experiments to investigate the delay trend when frames are being generated every two or three superframes. For this reason 16, 18, 20 and, 30 ms are examined in the experiments. MSDU inter-arrival amounts less than the superframe duration values are implemented to show the reaction of each protocol for a higher data rate, for example 7, 9, 10, 12, 14 and, 15 ms. Additionally, MSDU inter-arrival times that are less than the assigned timeslots to each node in two-node scenarios with the the 9-ms superframe durations are explored. In this case, MSDU inter-arrival times like 1, 2, 4 and, 6 are tested. These MSDU inter-arrival times support low-latency control applications, such as semi-trailer and inverted pendulum examples.

The simulation time is set to 20 seconds. According to superframe duration the number of runs in each experiment can be calculated. For instance 1300, 651, 325 and 163 iterations are associated with 15.6, 30.72, 61.44 and 122.88 ms superframe durations in each run of the simulation.

Buffer capacity is 2 Kbits and the condition for satisfying overflow prevention is as follows;

$$(ArrivalDatarate) - (OutgoingDataRate) \leqslant (BufferCapacity) \tag{20}$$

$$ArrivalDataRate = \frac{(PPDUSize)}{(MSDUInterArrival)} \tag{21}$$

$$(OutgoingDataRate) = \frac{(ProtocolDataRate) \times (AssignedTimeslots)}{TotalTimeslots} \tag{22}$$

Thus, by having single sensor which utilizes 1 timeslot or 7 timeslots in a superframe, the MSDU inter-arrival time that does not saturate the buffer should be larger than 0.02 and 0.079 ms respectively.

A screen capture of two- node scenario is exhibited in Figure 8. According to Section 3.1 the following assumptions are made for IEEE 802.15.4 and IEEE 802.15.4e:

- TimeSlotDuration is assigned at least to 0.96, 2.88, 3.84, 6.72 and 14.4 ms for different scenarios.

- SuperFrameDuration is 15.36 ms as the lowest possible superframe duration

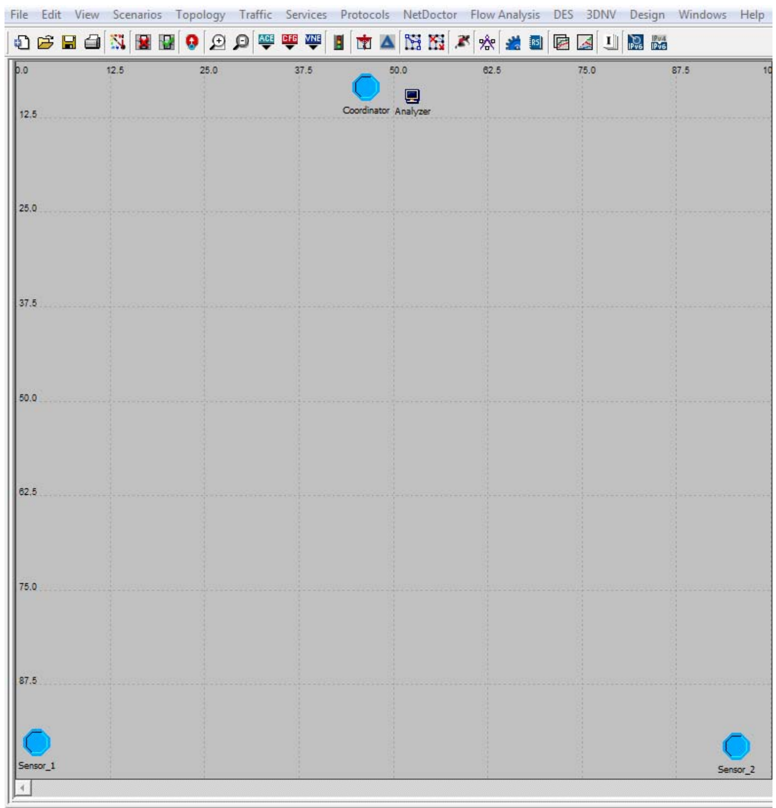

Figure 8: A screen capture of the OPNET scenario 2 showcasing the position of the nodes.

in IEEE 802.15.4, although diverse SO are examined in some sections of this study.

- A sensor and a coordinator are the member of the PAN for the single node scenario. Also two nodes and a coordinator define the two-node scenario.
- The superframe has 16 timeslots according to the IEEE 802.15.4 standard.
- The timeslots of the superframe changes to achieve low delay according to standard IEEE 802.15.4e.
- The buffer capacity is set to 2kbits. Most of the wireless nodes performing IEEE 802.15.4 and IEEE 802.15.4e protocols have at least a 2-Kbits buffer capacity.
- As the energy consumption is not investigated in this thesis, $SO = BO$ is considered. This means that inactive periods are excluded from the assumptions.

Required Parameters that need to be considered for the outcome evaluation are:

- The receiver throughput at the coordinator which is the number of successfully delivered frames which it receives from the sensors.
- End-To-End delay at the Sink module in the application layer of the Coordinator which demonstrate the latency of a packet from creation in the sensor to the time that it is received at the coordinator.

4.3 IEEE 802.15.4 Assessment for Low and High Inter-arrival Times

This section studies the a general behaviour of IEEE802.15.4 with two groups of MSDU inter-arrival times. The role of the MSDU inter-arrival groups is highlighted for low timeslot sizes rather than large timeslot sizes, which introduces the critical borderline MSDU inter-arrival time for the small timeslot duration. The raw data of the coordinator End-To-End delay for different MSDU inter-arrival times is plotted in Figures 9 and 10.

A scenario of a node and coordinator is implemented with a distance of 150 meters. The buffer size is 2 Kbits. The MSDU size attribute is set to 40 bits to prevent the use of LIFS. The CAP is not used in this experiment, since the focus is solely on GTS performance. The superframe is arranged to be 15.36 and timeslot durations are 1.92 and 6.72 ms as shown in Figures 9 and 10 respectively. In order to have a perspective on the End-To-End delay behaviour a simulation of the scenario was executed for a 20-second time and the results are illustrated in Figures 9 and 10.

The figures show how much frame delay the coordinator experiences during the simulation. Each run consisted of 1300 iterations.

The MSDU inter-arrival times are grouped into two main specific levels: higher than 15.36 (equal to superframe duration) and lower than 15.36, shown in Figures 9 and 10 for two different timeslot sizes. The experiment is conducted for varied MSDU inter-arrival times.

The End-To-End coordinator delay is compared for different values of MSDU inter-arrival time in Figures 9 and 10. The results how that there is a huge difference between the two groups of MSDU inter-arrival for a low timeslot size. These groups can be organized into low and high sensor inter-arrival times. A low inter-arrival group contains values less than a superframe duration, such as 4, 8 and, 14 ms as in Figure 9. A high inter-arrival group includes the interval times higher than the superframe duration, such as 16, 18 and, 20 ms as shown in Figure 9. High incoming rates (from 1 to 15 ms inter-arrival times) introduce more End-To-End coordinator delays especially for lower timeslot duration as exhibited in Figure 9. Both MSDU inter-arrival groups are plotted in Figure 9 to show the large gap delay between high and low MSDU inter-arrival times introduced by small timeslot size. The End-To-End Coordinator delay quickly increases during the first few seconds of the simulation for those cases where the inter-arrival time is less than or equal to 14 ms. The End-To-End coordinator delay oscillates around 7.5 ms for low inter-arrival times 190 ms for higher inter-arrival times. The delay jump at the beginning of the simulation time for the low inter-arrival times is caused by the saturation of the output buffer with the gradual increase in the data load. Unlike the low inter-arrival times, the higher sensor intervals do not saturate the buffer, since the incoming sensor data rate is less than the outgoing data rates from the buffer. For this reason the volume of data that needs to be stored in the buffer increases for low MSDU inter-arrival times due to the high arrival data rates. If the number of sensor data updates increases in a superframe, a higher delay is imposed which explains the large gap between the first and second groups. The fluctuation of the End-To-End delay is caused by the impact of different parameters, such as the starting time of the MSDU creation, the buffer capacity, MSDU inter-arrival time, the superframe duration and the timeslot duration. The combination of these parameters for different MSDU inter-arrival values produces diversity in the MAC buffer status.

Hence the MSDU inter-arrival that is lower than the superframe duration introduces the higher delay to the control systems which assigns small timeslot sizes. Figure 10 evaluates the performance of IEEE 802.15.4 for a 6.72-ms timeslot with both MSDU inter-arrival groups. As can be seen, the delay gap between two groups of MSDU inter-arrival is decreased. Comparing Figures 10 and 9 shows that increasing timeslot size from 1.92 to 6.72 ms has a remarkable enhancement on End-To-End delay. Moreover, the MSDU inter-arrival times which are close to the superframe duration (14 and 16 ms) introduce more delay variation (jitter) represented as am-

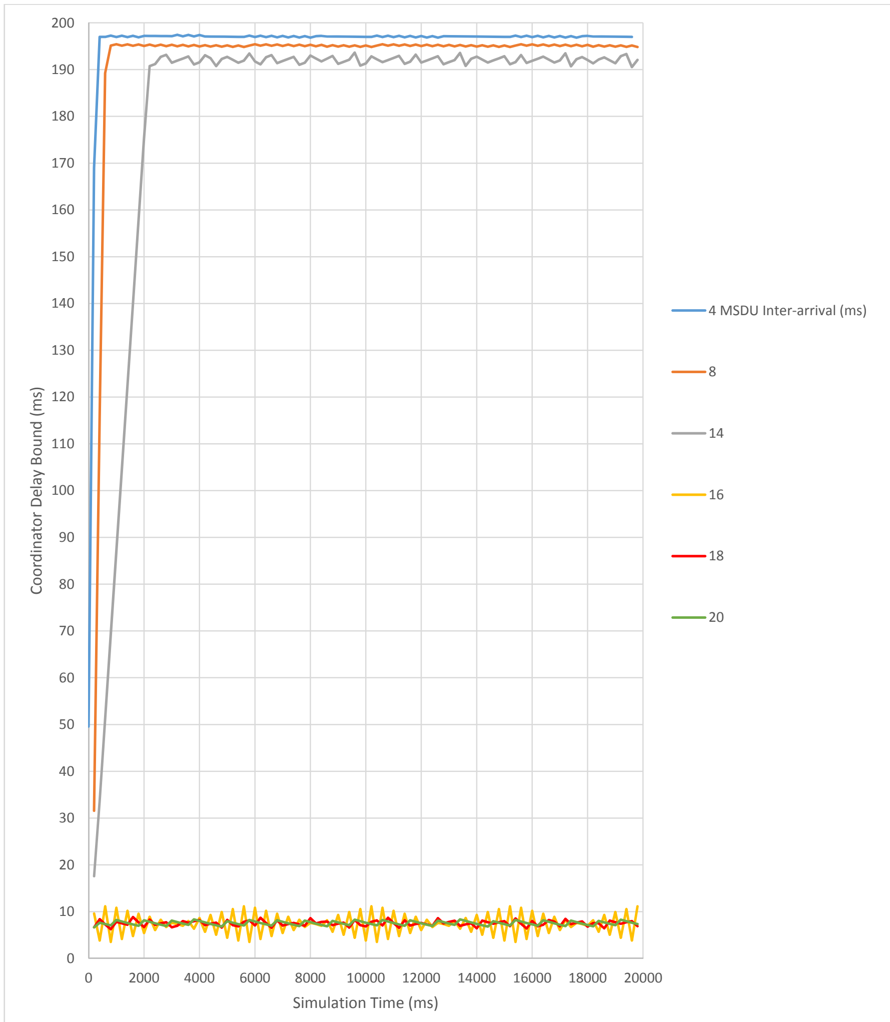

Figure 9: End-To-End coordinator delay vs. simulation time for larger and low MSDU inter-arrival with small timeslot duration (single node scenario).

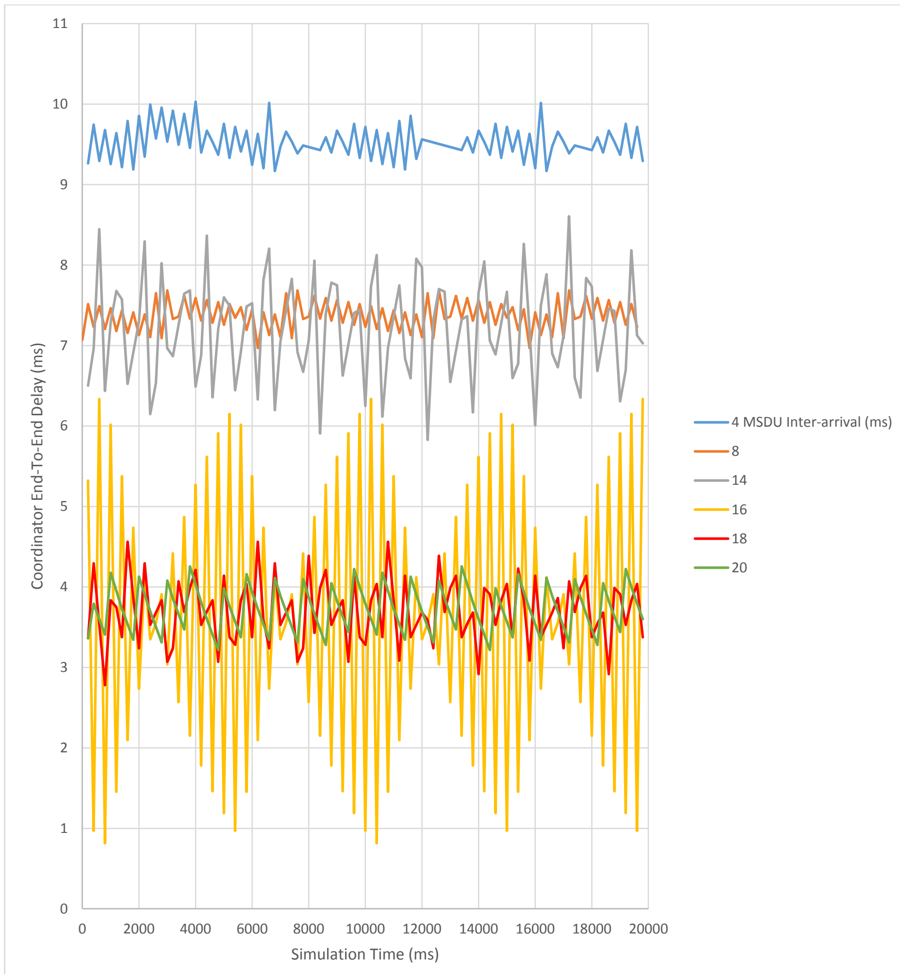

Figure 10: End-To-End coordinator delay vs. simulation time for larger and low MSDU inter-arrival with a 6.72-ms timeslot duration (single node scenario).

plitude in the delay oscillation. The next chapter assesses the behaviour of IEEE 802.15.4 and IEEE 802.15.4e for one and two sensor scenarios.

5 Simulation Results and Analysis

5.1 Performance Evaluation of IEEE 802.15.4 with Diverse Timeslot Duration and Different Inter-Arrival Data Rates

The simulation parameters are presented in Table 1 for this scenario. The inter-arrival rate is set to a specific value for each timeslot during each run of the simulation. A maximum delay value for the captured data is calculated. For each timeslot duration, 13 simulation runs were performed corresponding to the different inter-arrival times, and 6 timeslots sizes were chosen for the evaluation of the IEEE 802.15.4. The timeslot sizes were calculated based on the number of *aBaseSlotDuration* which is defined to be 0.96 ms in the standard. The maximum values for End-To-End delay are assessed to give a sense of the worst case scenarios for each run in this scenario.

Number of Nodes	Distance	Buffer size (Kbits)	MSDU size (bits)	Timeslot duration (ms)	Superframe duration (ms)	MSDU inter-arrival (ms)
Sensor-1	150	2	40	1.92-6.72	15.36	1-30

Table 1: Timeslot variation for single sensor

Short MSDU inter-arrival times such as 1 and 2 ms show a downward trends for the End-To-End delay, meaning that the network does not respond much differently between those arrival rates. For very short MSDU arrival times, such as 1 and 2 ms, the trend approaches the 30 ms delay value with the highest possible 7.68 timeslot duration in a superframe. The outcomes generally specify that increasing timeslot duration within a superframe reduces the delay for MSDU inter-arrival less than superframe duration value. inter-arrival times 4, 6 and, 8 ms settle down and maintain stable values with different timeslot durations corresponding to 4.8, 3.84 and, 2.8 ms respectively which shows increasing MSDU inter-arrival times decreases the need for larger timeslots. As can be seen in Figure 11, increasing the timeslot duration does not impact the maximum End-To-End delay for MSDU inter-arrival values more than the superframe duration. Higher inter-arrival times than 8 and less than 14 ms specify very similar delay-response values and End-To-End delay stabilizes on roughly 10 ms for larger timeslots than 2.8 ms. In other words, increasing timeslots duration more than 2.8 ms does not affect the delay reduction for inter-arrival times 8 ms to 15 ms, since the data load is minor enough that the node transmits all the buffered data during its assigned timeslot.

Figure 12 presents the average throughput for different MSDU inter-arrival times with diverse timeslot durations. Increasing the timeslot results in increasing throughput for low inter-arrival times. However, increasing the MSDU inter-arrival decreases the throughput as the timeslot duration increases, since more timeslots are empty.

For MSDU inter-arrival times 4, 6, 8, 10, 12, 14 and, 16, throughput raises with the increasing timeslot duration and then stabilizes at the specific timeslot related to each inter-arrival time. The throughput then drops with timeslots greater than 5.76 ms. This result shows that the number of free unused timeslots are increasing with decreasing arrival data rate. Larger timeslot sizes does not impact the average throughput for MSDU inter-arrival times which are more than the superframe durations.

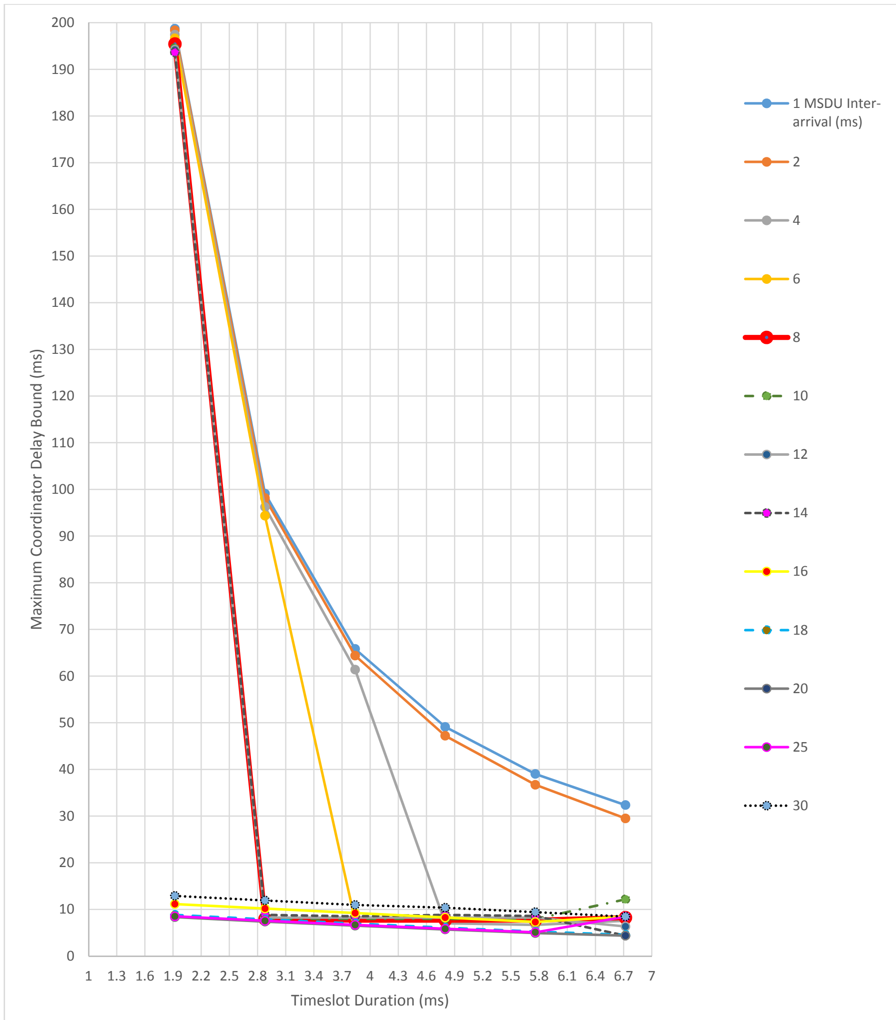

Figure 11: Maximum coordinator End-To-End delay as a function of timeslot duration for different MSDU inter-arrival with 15.35 ms superframe duration.

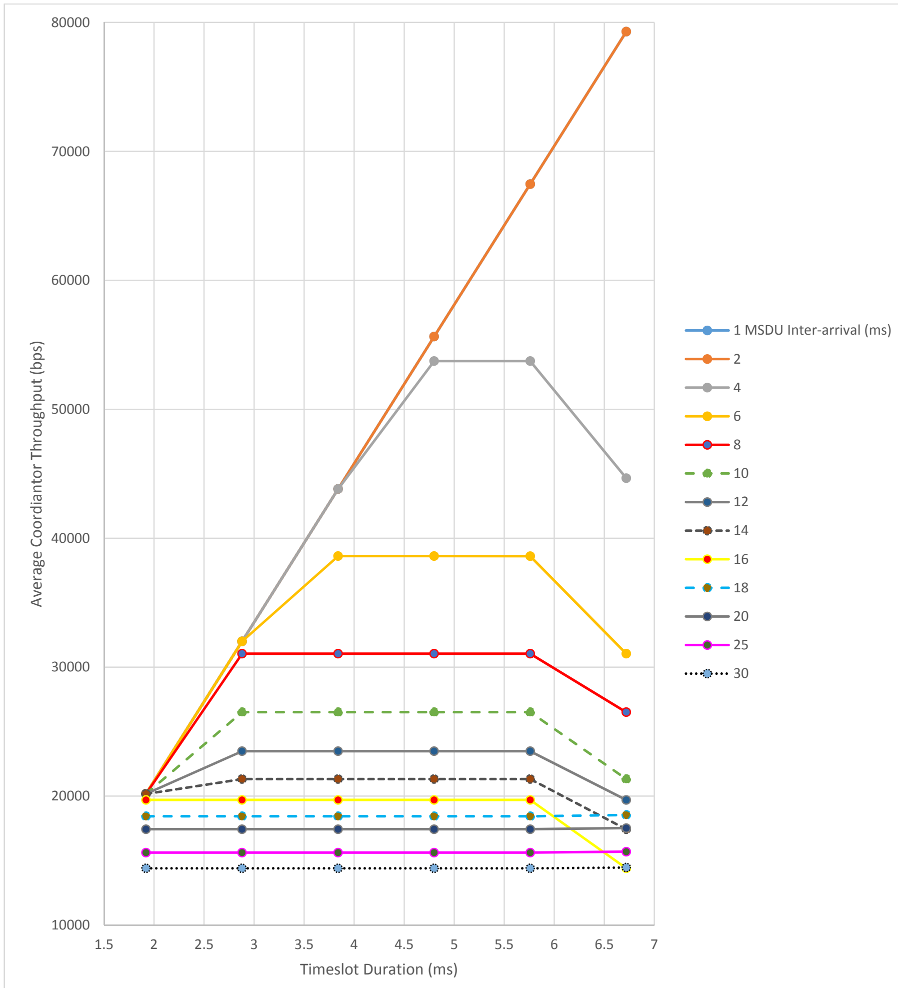

Figure 12: Average coordinator throughput as a function of timeslot duration for different MSDU inter-arrival with 15.35 ms superframe duration.

5.1.1 Observations

The maximum End-To-End delay and average throughput for each MSDU inter-arrival time which is more than 2 ms would settle after a distinct timeslot size which illustrates the optimum timeslot value for that MSDU inter-arrival. The suitable timeslot size introduces the lowest delay and highest throughput for that specific MSDU inter-arrival time. The delay stabilizes for the larger inter-arrival times with the lower timeslot duration. Additionally, Figure 11 elaborates that adding more timeslots to the superframe does not impact the delay, although it has an adverse influence on the throughput. For this reason, if an adaptive timeslot modification is not possible, then the complete usage of the bandwidth of the CFP is suggested for a single node scenario to reduce the delay for all types of MSDU inter-arrival times in time constrained control applications. The next section considers all 7 timeslots for transmission of a node.

5.2 Best Design for IEEE 802.15.4 with Single Sensor and Full CFP Communication

An end-node and a coordinator node located 150 meters apart operating with IEEE 802.15.4 beacon-enabled mode, with 250 Kbps data rate. Eight-first timeslots are designated to CAP which is intact for this experiment and the remaining (7 timeslots) belong to CFP based on the IEEE 802.15.4 standard definition. The simulation settings are presented in Table 2. The end-node uses all the GTS duration to reach a lower delay. The first slot is assigned to the beacon for synchronization, the superframe information, and GTS allocation commands from the coordinator.

In each run of the simulation, the MSDU inter-arrival and timeslot duration is changed

Number of Nodes	Distance	Buffer size (Kbits)	MSDU size (bits)	Timeslot duration (ms)	Superframe duration (ms)	MSDU inter-arrival (ms)
Sensor-1	150	2	40	6.72	15.36	1-30

Table 2: MSDU inter-arrival time variation for single sensor

to explore the throughput and End-To-End delay values. In this section, each run consists of 1300 repeats with imposed simulation parameters on each superframe. In order to have an acceptable representation of the simulated data, a mean value was calculated for the throughput evaluation of each experiment. For the delay, the maximum delay is more critical, since for hard control problems, no frame should arrive after a specified delay bound of the control system application. Hence maximum latency represents a more accurate constraint, while the average value is provided to observe the highest frame delay range with such parameter settings. The confidence interval is set to be 95 percent in all average calculations.

Figure 13 shows the bandwidth usage of a single node related to the the MSDU inter-arrival of the sensor. Using a single sensor, which starves the entire dedicated CFP bandwidth and leaves the rest of the slots vacant in CAP, shows the required throughput performances for that range of inter-arrival times. The throughput trend follows a downward approach. In other words, longer inter-arrival times results in more empty timeslots that could be used for transmission and drops the throughput. The small range of confidence for each inter-arrival time is included in each graph around the average amounts. The steady state throughput value falls between the for 1 and 2-ms inter-arrival times illustrates that the high usage of bandwidth for both MSDU inter-arrival times is the same.

The average range of End-To-End delay falls between the range between 3 and 8 ms for the MSDU inter-arrival times excluding 1 and 2 ms. As the inter-arrival

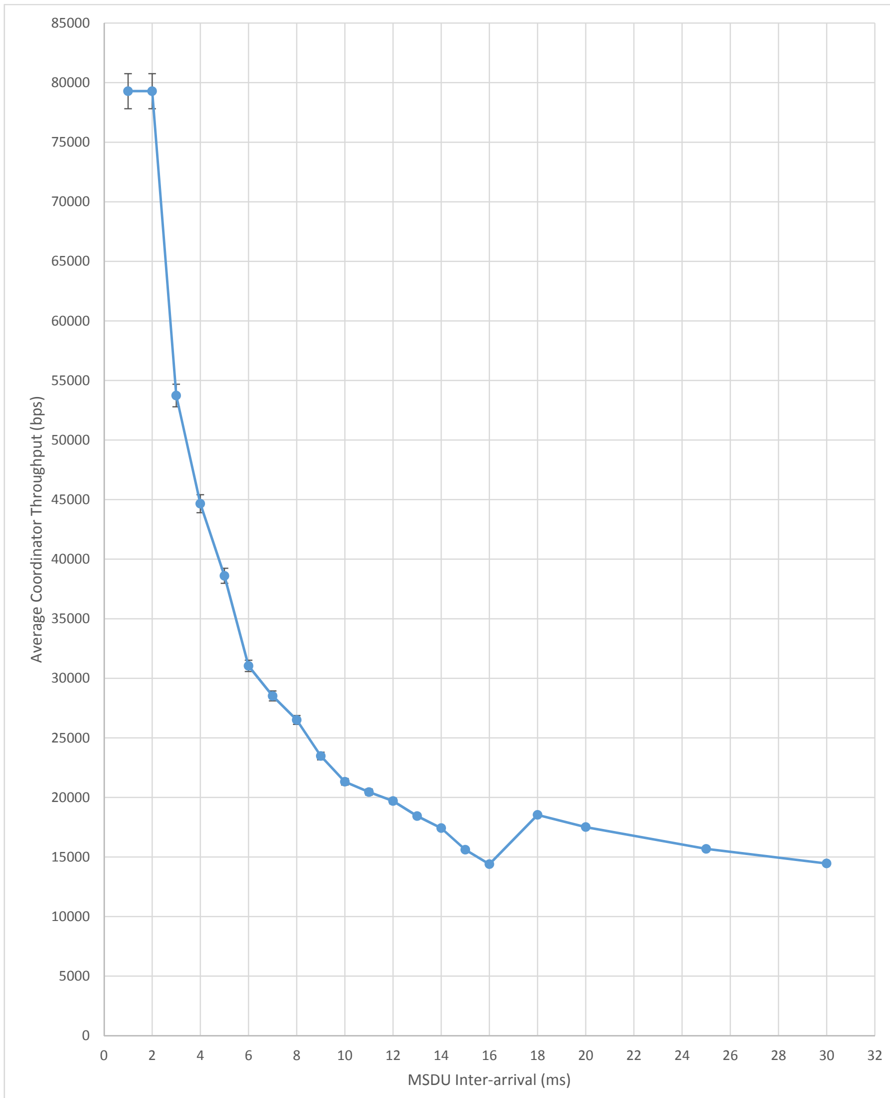

Figure 13: Average coordinator throughput vs. MSDU inter-arrival for 15.36 superframe and 6.72 ms timeslot durations (single node scenario).

time increases, the End-to-End delay decreases for both the average and maximum amounts. Both average and maximum latency drops substantially after a 2-ms inter-arrival time which represent a high arrival data load. The average latency is stable from 3 to 11 ms inter-arrival and is followed by a step down at 12 ms. To explain further, a frame generation occurs at every two superframes and the average delay is the superframe duration.

According to Figure 14, the average delay is not affected by the data load at higher sensor inter-arrival times. The maximum delay trend peaks at 10 and 15 ms which are close to the superframe duration value. The MSDU inter-arrival time equivalent to the superframe duration is a critical point for every superframe, since this borderline inter-arrival time introduces the maximum point for the worst case delay caused by the MAC sub-layer. The Maximum End-To-End delay hump at 15 ms can be explained in a way that the generated MSDU can be transmitted whether the generated frame falls in that superframe or the next superframe depending on the start of the data generation by the application layer. The increment in the maximum End-To-End delay for 25 and 30-ms inter-arrival times is produced by a long time gap between the data generation (higher data inter-arrival times) and the time frames needed to wait for the next superframe in the MAC queue. This means that increasing data generation time for every two superframe increases the worst case delay, although the average delay maintains the same amounts. As can be seen from Figure 14, the 95-percentage confidence interval increases for 11, 16 and 30-ms MSDU inter-arrival times due to the larger jitter and delay amplitudes between different sets of data.

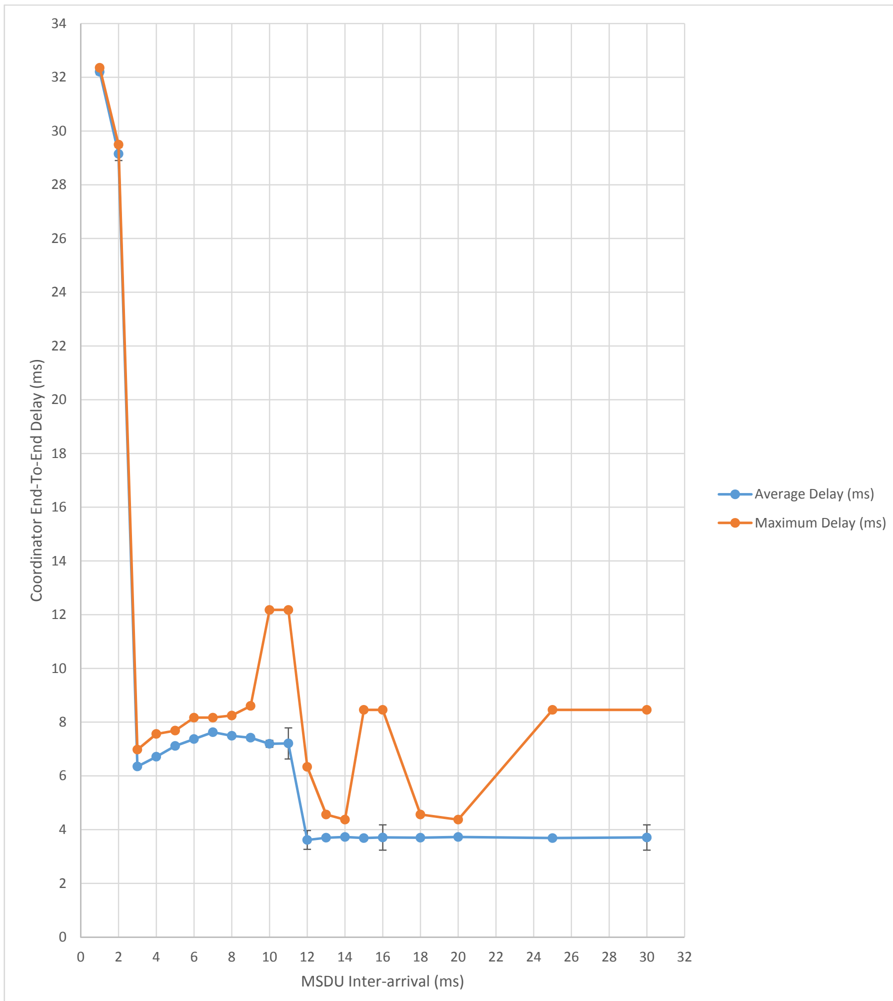

Figure 14: Average and maximum coordinator End-To-End delay vs. MSDU inter-arrival for 15.36 superframe and 6.72 ms timeslot durations (single node scenario) with a 95-percent confidence.

5.2.1 Observations

Larger inter-arrival times generally results in lower throughput and lower delay. Also the average delay stabilizes after 12 ms due to high inter-arrival times. For MSDU inter-arrival times greater than the superframe duration, the maximum delay experiences a drop at 18 ms and an increase at 30 ms. Provided the time sensitive control applications requires no more than a 9-10 ms frame and has MSDU inter-arrivals from 3 to 30 ms excluding 10 and 11 ms, the desired delays are facilitated by a single node transmission utilizing the original IEEE 802.15.4. On the other hand, if the controller can tolerate higher wireless communication time delays, it is worth using the entire bandwidth of the CFP with low inter-arrival times (except 1 and 2 ms inter-arrivals) which result in higher throughputs.

5.3 Superframe Evaluation in original IEEE 802.15.4 with Single Sensor and Full CFP Communication

The same single node scenario with full utilizing CFP is implemented in this section to assess the impact of superframe duration by determining SO values. According to the calculation in Section 3.3, the worst case upper bound $QDelay$ amount is 8.64, 17.28 and 34.56 ms for 0, 1 and 2 values of SO respectively. The results of such a scenario for different superframe duration and MSDU inter-arrival time are shown in Figures 15 and 16. The MSDU inter-arrival time varies from 1 to 30 ms for diverse $SO = BO = 0, 1$ and 2. The settings of the simulation scenario are presented in Table 3.

The throughput illustrates a downward trend in Figure 15. The throughput starts with a steady state for 15.36 and 30.72 ms superframes which justifies high data

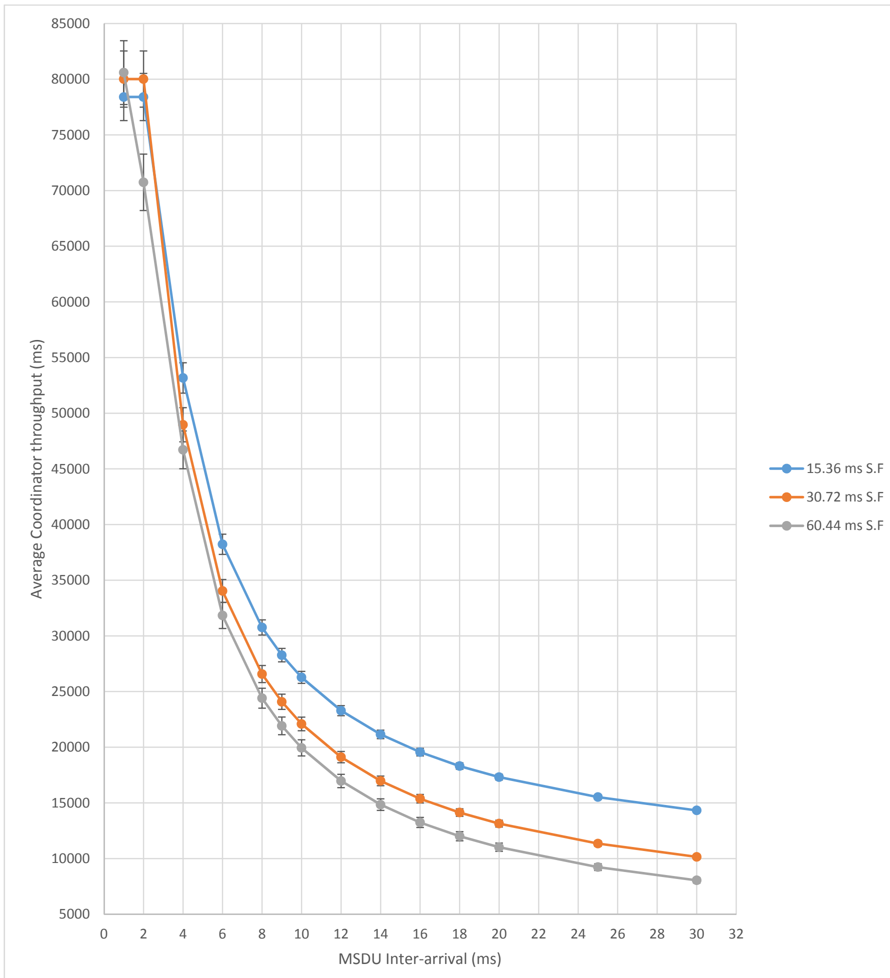

Figure 15: Average coordinator throughput vs. MSDU inter-arrival times for different superframe and 7 timeslots durations (single node scenario).

Number of Nodes	Distance	Buffer size (Kbits)	MSDU size (bits)	Timeslot duration (ms)	Superframe duration (ms)	MSDU inter-arrival time (ms)
Sensor-1	150	2	40	7 times-lot	15.36-60.44	1-30

Table 3: Superframe variation for single sensor

load for MSDU inter-arrival times from 1 to 2 ms. A 30.72-ms superframe performs better than 15.36 for very small MSDU inter-arrival times like 1 and 2 ms. However, for MSDU inter-arrival larger than 2 ms, a 15.36-ms superframe duration shows a greater throughput in comparison with the two other superframe sizes; 30.72 and 60.44 ms. The throughput decreases with increasing MSDU inter-arrival times. A sample can be transmitted every two and three superframe for higher MSDU inter-arrival times than 16 ms. Therefore, there are some superframes that contain no information and data in CFP. Diverse superframe durations or SO do not show a huge difference in throughput results, since the throughput depends on the number of $aBaseSlotDuration$ to use the entire assigned bandwidth in the CFP.

As illustrated in Figure 16, the End-To-End delay drops significantly at a 2-ms MSDU inter-arrival time for both 15.36 and 30.72 ms superframe. In other words, the arrival data rate is higher than the outgoing data rate. Therefore, the data is accumulated by each superframe and the maximum delay is defined by the status of the buffer and generation time of the data. A 61.44-ms superframe size reaches a trough in 2 ms and after that the trend shows an increase, since the gap between the data generation has increased and increasing the CAP influences the delay. The 15.36 ms superframe shows a better performance in delay rather than 30.72 and 60.44 ms superframes for more than the 2-ms inter-arrival times. In other words, the larger superframe duration increases the End-To-End delay. However, for 1 and 2-ms inter-

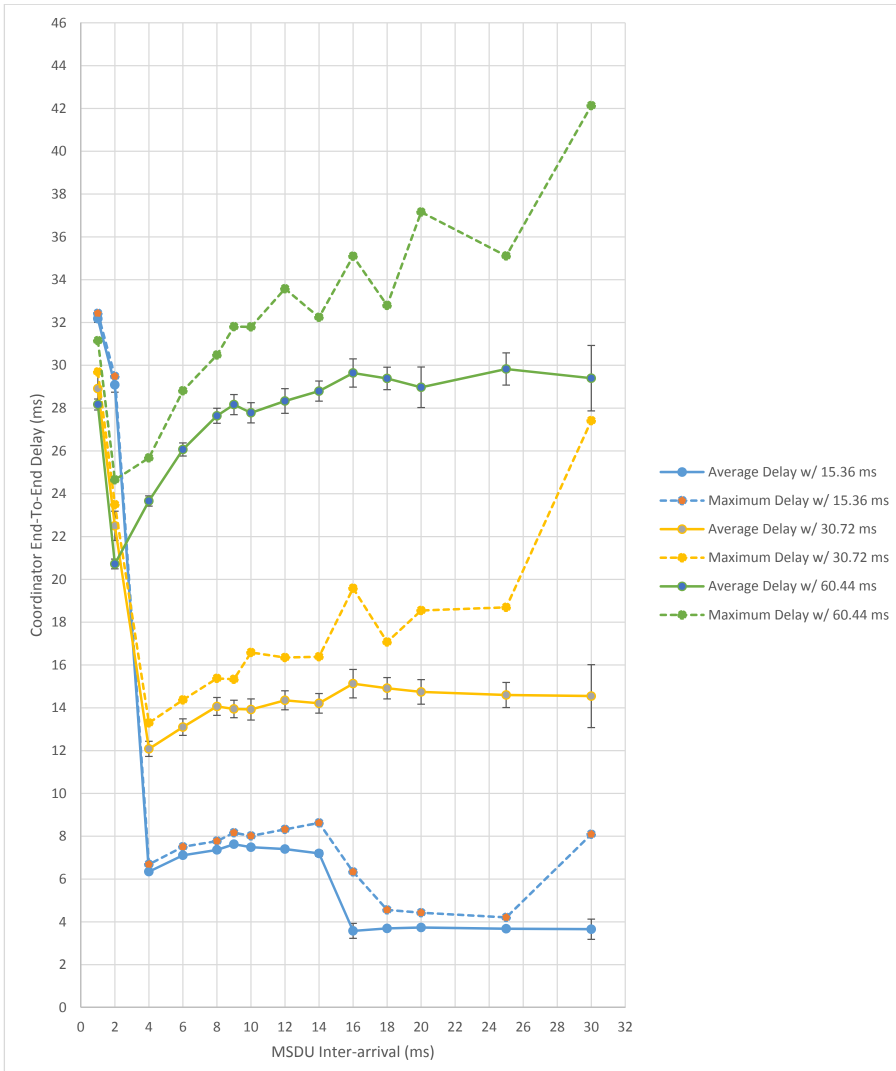

Figure 16: Average and maximum coordinator End-To-End delay vs. MSDU inter-arrival times for different superframe and 7 timeslots duration (single node scenario).

arrival times, 30.72 ms superframe duration performs better rather than 15.36 and 60.44 ms durations.

A MSDU inter-arrival time of 16 ms experiences a jump for 30.72 and 60.44 ms superframes, although it shows a steep down trend for 15.36 ms superframe, because the inter-arrival times are higher than the superframe duration. The maximum End-To-End delay increases for the 30-ms inter-arrival times and higher in all graphs due to long CAP, albeit average End-To-End delay stabilises from 16 ms inter-arrival time because of the lower arrival data rate. The jitter increases for 30 ms inter-arrival time in the large superframe durations, such as 30.72 and 60.44 ms, since the CAP duration increases with the increment of the superframe duration and the frame needs to wait longer time to be transmitted.

5.3.1 Observations

Increasing superframe size does not affect the throughput remarkably. The average coordinator throughput declines by increasing the MSDU inter-arrival times. In $SO = 2$ and 3, the superframe size is large enough to waste more time in CAP for the inter-arrival that transmits every two superframes. Therefore, 30.72 and 60.44 ms superframes show a small decrease in the throughput results comparing to 15.36 ms superframe. For MSDU inter-arrival times less than 1 and 2 ms, the delay illustrates a 2-ms difference between the 15.36 and 60.44 ms superframe durations. However, the results in Figure 16 show that the decreasing amount of generated data in one superframe enhances the delay due to low load of data for more than 2 ms inter-arrival. Unlike delay responds in $SO = 0$ and 1, the delay follows a increasing trend with a very large superframe duration (higher than 60.44 ms)for more than the 2-ms inter-arrival times. The delay generally increases with increasing superframe durations, since the MAC layer is required to wait for the next assigned timeslot longer, located at the next superframe in order to transmit the last generated frames. As the CAP duration increases with increasing the superframe duration, the queue delay would be increased too. As evident, the 15.36-ms superframe duration can result in less than 9 ms desired latency for semi-trailer application, although 30.72 and 60.44 ms are not able to satisfy that delay.

5.4 Best Design for IEEE 802.15.4 with Two Sensors and Full CFP Communication

This scenario evaluates the communication of two nodes with a coordinator. The complete duration of CFP is absorbed by two nodes with equal portions of timeslots. Thus 7 remaining slots are divided by 2 sensors and each has 2.88 (3×0.96) ms timeslot duration in a 15.36 ms-duration superframe.

Number of Nodes	Distance	Buffer size (Kbits)	MSDU size (bits)	Timeslot duration (ms)	Superframe duration (ms)	MSDU inter-arrival time (ms)
Sensor-2	150	2	40	2.88	15.36	1-30

Table 4: MSDU inter-arrival time variation for two sensors

The throughput illustrates a minor enhancement in contrast with the one slot per sensor scenario. Figure 17 explains when the creation of MSDU data is every two superframe after 20 ms, some superframes do not have data to deliver. Table 4 illustrates the simulation settings for this section. The steady commencement of throughput shows the maximum number of bits that can be transferred per second is stable between 1 to 6 ms inter-arrival time for this scenario, since the buffer is full.

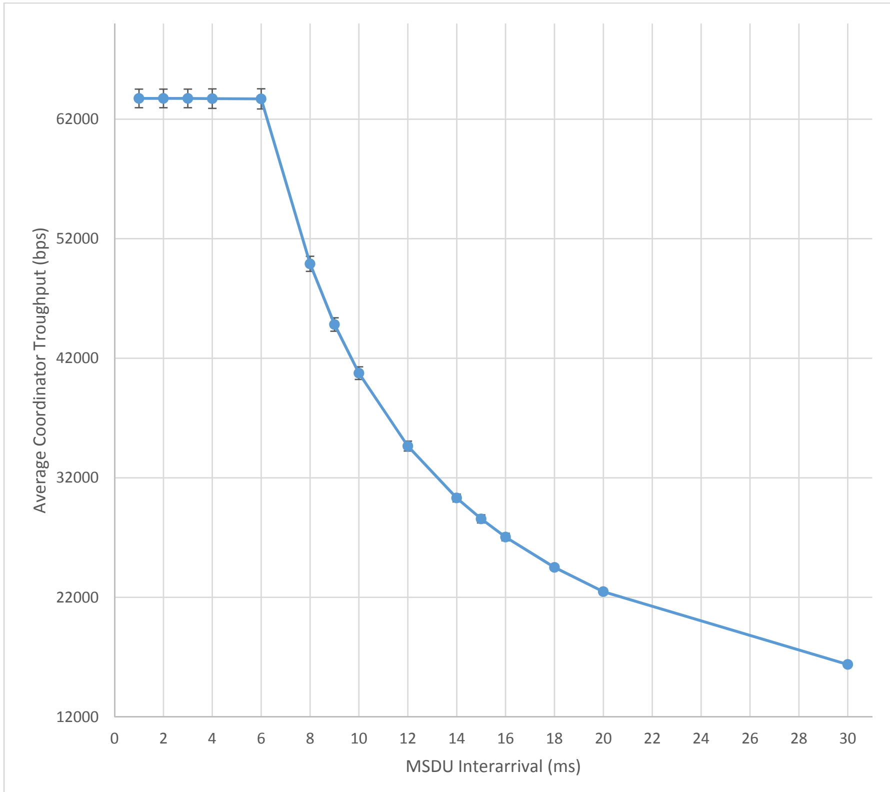

Figure 17: Average coordinator throughput vs. MSDU inter-arrival time for 15.36 superframe and 2.88 ms timeslot durations per node (two-node scenario).

The result shows that the bandwidth reduces for inter-arrival times greater than 6 ms, as shown in Figure 17.

The delay performance of the protocol exhibits poor results for low inter-arrival rates due to abundant data load as shown in Figure 18. The coordinator End-To-End delay reaches a trough at 8 ms which equals the assigned timeslot durations for both nodes. It states that the maximum amount of traffic is handled by 2.88 ms timeslot duration to reach 15 ms delay. The maximum coordinator End-To-End latency fluctuates between 9 to 18 ms MSDU inter-arrival due to changes in arrival data rate over different experiments. The larger value of the maximum coordinator End-To-End delay is caused by low arrival data rates. The confidence interval is smaller than the confidence interval computed for the single node scenario in the original IEEE 802.15.4.

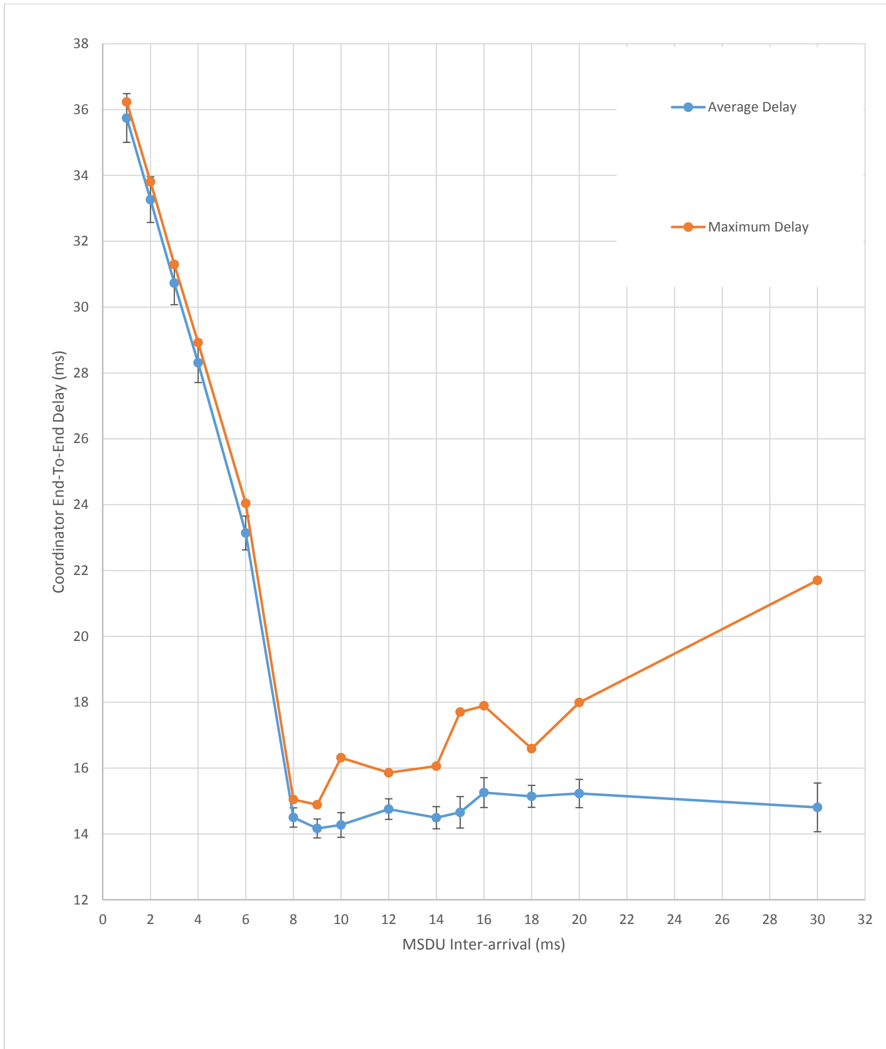

Figure 18: Average and maximum coordinator End-To-End delay vs. MSDU inter-arrival time for 15.36 superframe and 2.88 ms timeslot durations per node (two-node scenario).

5.4.1 Observations

The throughput is the receiver coordinator throughput and the delay is the End-To-End frame delay received at the coordinator. The throughput declines with increasing MSDU inter-arrival time. The End-To-End delay is high for low MSDU inter-arrival time. The optimum inter-arrival time is equal to the CFP duration. The maximum delay increases for higher inter-arrival times due to the long wait time until the next assigned timeslot. Consequently, two-node scenarios with the original IEEE 802.15.4 protocol cannot accommodate the desired delay for low-latency control applications, such as usual recognized pendulum and semi-trailer applications due to a latency greater than 10 ms. For delay tolerant applications which have less than a 15 ms threshold, it can be one of the options with 8 to 10 ms sampling times.

5.5 Performance Evaluation of IEEE 802.15.4e LLDN with Single Node

A scenarios with the same configurations as implemented in IEEE 802.15.4 were run to investigate the performance of the Adaptive IEEE 802.15.4e LLDN MAC protocol in comparison to the IEEE 802.15.4e protocol. The MSDU inter-arrival, superframe and, timeslot durations have been set manually for this simulation scenario. The performance of the IEEE 802.15.4e LLDN with diverse MSDU inter-arrival times is illustrated in Figure 19.

The first scenario begins with single sensor and a coordinator in a PAN. The same configuration of 15.36 ms superframe duration is set in IEEE 802.15.4e LLDN for comparison purposes (according to IEEE 802.15.4 superframe standard duration). The entire superframe except the beacon slot belongs to a node. Thus the timeslot duration is 14.4 ms and 0.96 ms is reserved for beacon and management frames. A confidence range of 95 percent is utilized around the mean values to show a more specific measurement ranges. The settings for this section are shown in Table 5.

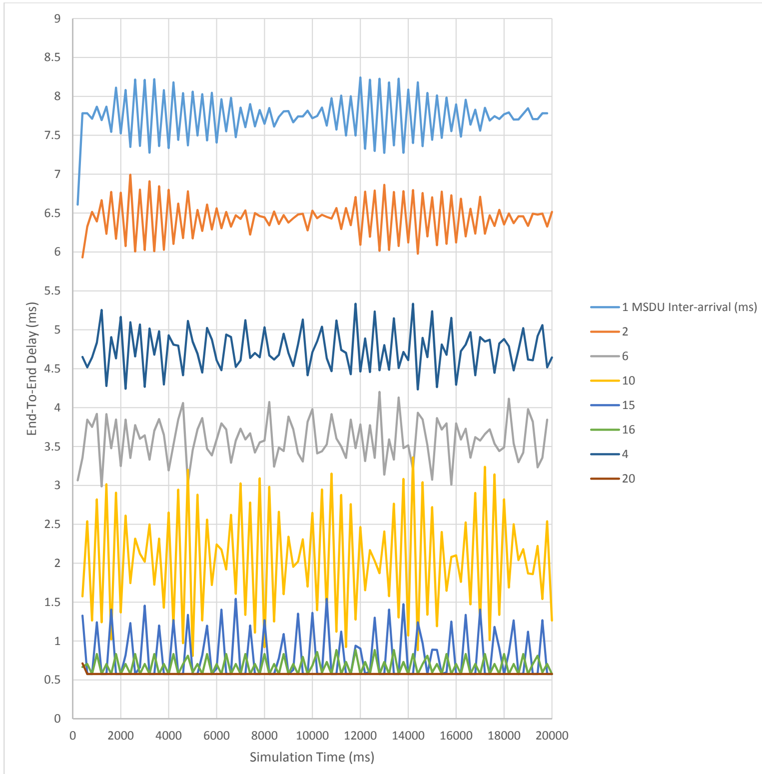

Figure 19: End-To-End delay results vs simulation time for diverse MSDU inter-arrival times and $MSDUSize = 40$ bits with 15.38 ms superframe and 14.4 ms timeslot duration.

Number of Nodes	Distance	Buffer size (Kbits)	MSDU size (bits)	Timeslot duration (ms)	Superframe duration (ms)	MSDU inter-arrival time (ms)
Sensor-1	150	2	40	14.4	15.36	1-20

Table 5: MSDU inter-arrival time variation for single sensor

The throughput illustrates a downward trend with increasing MSDU inter-arrival times in Figure 20. Increasing the sensor data inter-arrival times keeps more timeslots empty from data transmission and consequently reduces throughput. Therefore the implementation of one sensor per superframe is suitable for low sensor rates with 15.36 ms superframe size.

The maximum and average End-To-End delays are computed and the average with a 95-percent confidence is shown in Figure 21. It displays a slight downward trend as MSDU inter-arrival times increase. Also it illustrates that data load has a crucial influence on the latency of both average and maximum values.

The average and Maximum Coordinator End-To-End Delay both settle to 0.7 ms delay for upper than 16 ms MSDU inter-arrival times (equals to superframe duration). The response of the IEEE 802.15.4e LLDN for the entire MSDU inter-arrival seems to be applicable for time sensitive pendulum and semi-trailer applications. In contrast to the original IEEE 802.15.4, this protocol enhances the delay and throughput, since it uses the entire bandwidth for transmission of single node.

Comparing IEEE 802.15.4 single node utilizing 6.72 timeslot duration with IEEE 802.15.4e LLDN single node scenario using 14.4 ms, Figure 21 demonstrates that End-To-End delay improves significantly with different gaps for diverse MSDU inter-arrival times. IEEE 802.15.4 shows the worst case delay for 1 and 2 ms inter-arrival times, while IEEE 802.15.4e LLDN can facilitate the entire range of MSDU inter-arrival times for the semi-trailer application. The throughput outcomes are close between the two protocols, although IEEE 802.15.4e LLDN performs better for 1 and 2 ms MSDU inter-arrival times. Thus IEEE 802.15.4e LLDN satisfies single node transmission for the entire examined MSDU inter-arrival times with the close throughput response compared to the original IEEE 802.15.4.

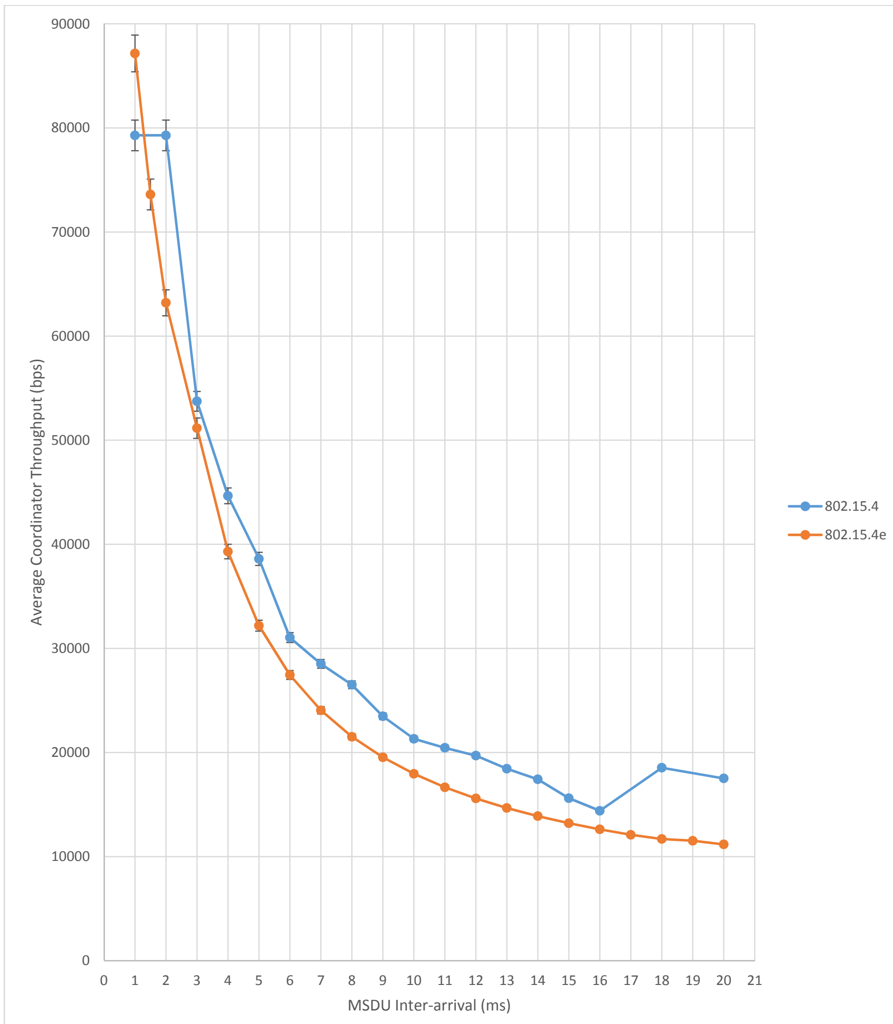

Figure 20: Average coordinator throughput vs. MSDU inter-arrival time for 14.4 ms in IEEE 802.15.4e LLDN and for 6.72 ms in IEEE 802.15.4 timeslot duration with a 95-percent confidence.

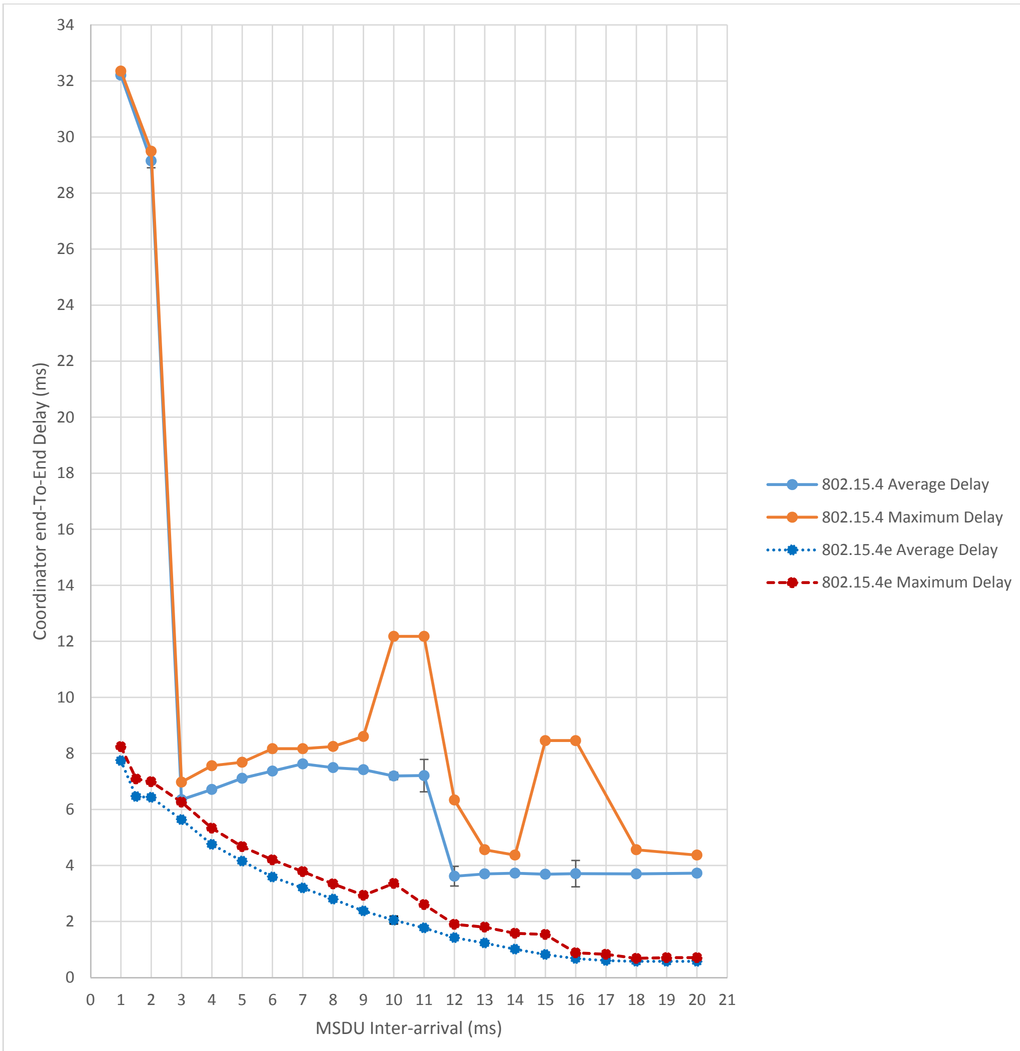

Figure 21: Average and maximum coordinator End-To-End delay vs. MSDU inter-arrival time for 14.4 ms in IEEE 802.15.4e LLDN and for 6.72 ms in IEEE 802.15.4 timeslot with 15.36 superframe duration in single node scenario with a 95-percent confidence.

Number of Nodes	Distance	Buffer size (Kbits)	MSDU size (bits)	Timeslot duration (ms)	Superframe duration (ms)	MSDU inter-arrival time (ms)
Sensor-1	150	2	40	6.72	15.36	1-20

Table 6: MSDU inter-arrival time variation for single sensor

The next experiment evaluates the throughput and End-To-End delay for single node scenario utilizing a 6.72 ms timeslot in 15.36-ms superframe with IEEE 802.15.4e shown in Table 6. For a performance evaluation of the same timeslot and superframe size, as the original IEEE 802.15.4 in a single node scenario, the same criteria are implemented in IEEE 802.15.4e LLDN in Figures 22 and 23. Therefore superframe duration is 15.36 ms and less than half of the superframe is used by a node transmission. The throughput shows a more gradual decrease than the 14.4 ms timeslot, although total throughput values for different MSDU inter-arrival times is less than the throughput amount for a 14.4 ms timeslot case.

The IEEE 802.15.4e with 6.72 timeslot duration performs adversely in comparison with the two previous scenarios shown in Figure 22. The End-To-End delay bound illustrates a downward trend for 15.36 ms superframe and 6.72 ms timeslot. The maximum End-To-End delay has a jump for 15 ms MSDU inter-arrival time, since it is a critical inter-arrival point where the inter-arrival time is equal to the superframe duration and usually needs to wait for another superframe after the beacon interval time for transmission. Upper inter-arrival times greater than 16 ms, the node needs to transmit within every two superframes. Thus the delay decreases and the throughput drops drastically. In other words, the data load is not so large to be held in the MAC buffer in order to access the network. Such a configuration imposes higher delay bound rather than using the entire superframe by a node (Figure 23). The MSDU inter-arrival times of higher than 6 ms fall in the low delay category for semi-trailer

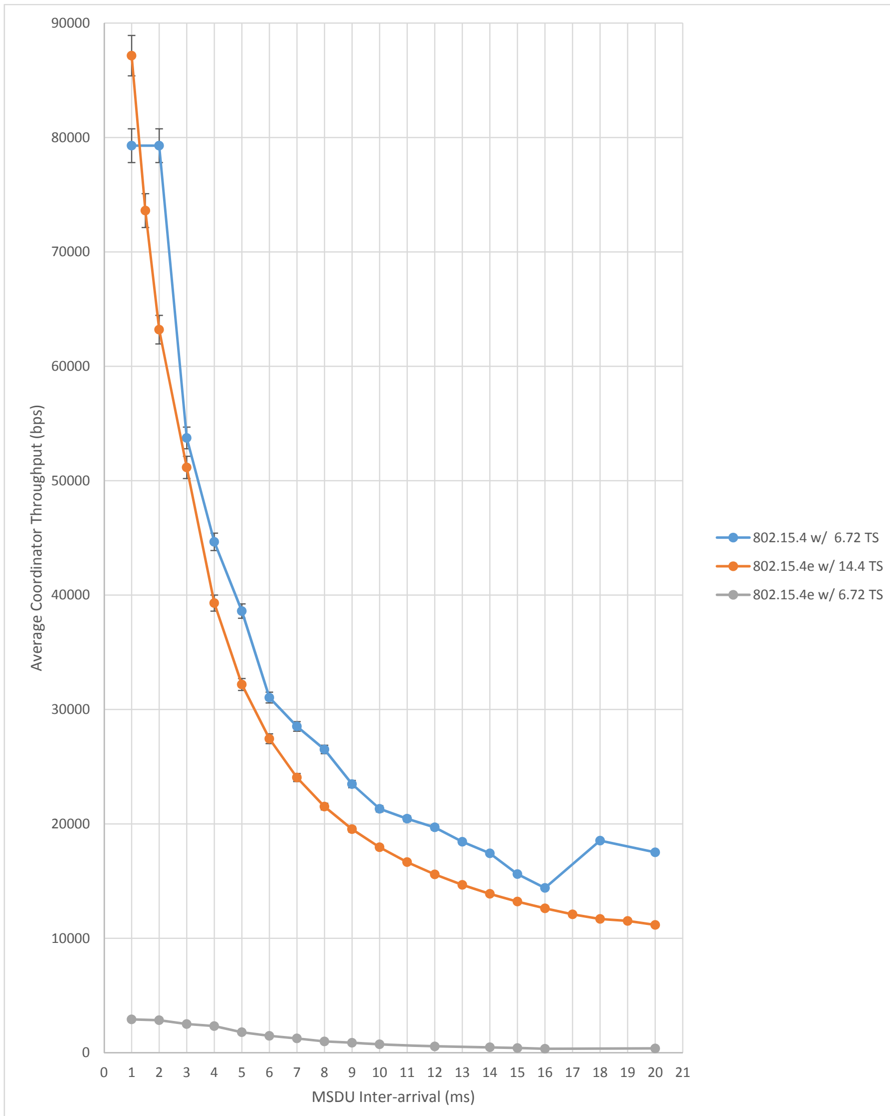

Figure 22: Average coordinator throughput vs. MSDU inter-arrival time for 14.4 and 6.72 ms in IEEE 802.15.4e LLDN and for 6.72 ms in IEEE 802.15.4 timeslot duration with a 95-percent confidence.

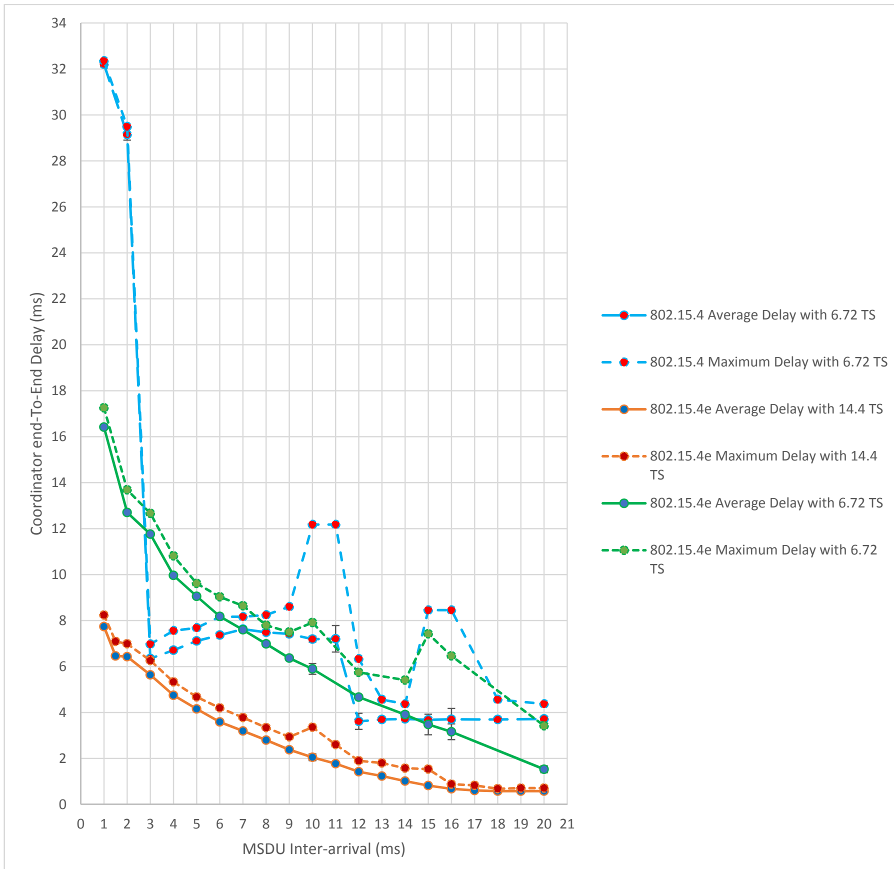

Figure 23: Average and maximum coordinator End-To-End delay vs. MSDU inter-arrival time for 14.4 and 6.72 ms in IEEE 802.15.4e LLDN and for 6.72 ms in IEEE 802.15.4 timeslot with 15.36 superframe duration with a 95-percent confidence (single node scenario).

and pendulum control problems. This means that the normal 10 ms sensor rates fulfil the requirements of delay constrains within a single node scenario, although the throughput is not as large in comparison with a 14.4 ms timeslot.

Comparing IEEE 802.15.4 and IEEE 802.15.4e LLDN with the exact same conditions and parameters for timeslot and superframe illustrates that for 3 to 7 ms inter-arrival times, IEEE 802.15.4 introduces less delay along with higher throughput due to full usage of its bandwidth. However, IEEE 802.15.4e responds better for the ranges of 8 to 20 ms and 1 to 2 ms inter-arrival times.

5.5.1 Observations

The End-To-End delay has a decreasing trend followed by the stabilized delay values after the inter-arrival time equals to superframe duration for the full usage of the superframe in IEEE 802.15.4e. Provided the control applications need less than a 9 ms End-To-End delay for a single node and coordinator in a PAN, the 14.4 ms timeslot will do especially for low sensor rates, which provides increased throughput in such a scenario. The performance of the protocol is mitigated drastically in terms of throughput with partial use of superframe by a node. The low delay is satisfied by the MSDU inter-arrival times which are greater than the timeslot duration due to regulated data load. Therefore using the entire bandwidth plays a crucial role in throughput response.

As can be seen from the results, two main factors play substantial roles in delay and throughput including the load of arrival data and timeslot allocation of the node which defines the duration of the transmission. The timeslot allocation can be regulated by both the timeslot and the superframe durations for each node.

5.6 Performance Evaluation of IEEE 802.15.4e LLDN with Two Nodes

The experiment continues with two node and a coordinator in a PAN in presence of diverse MSDU inter-arrival times. The superframe duration is set to 15.36 and timeslot is arranged to 6.72 ms for each node.

The throughput begins with a steady state for 1, 2 and 3 ms input sampling times due to high arrival data rate and it shows the highest values compared to the rest of the inter-arrival times in Figure 24. The throughput rate decreases more rapidly for lower inter-arrival times rather than longer inter-arrival times. Comparing one and two node setups using the entire bandwidth shows that single node performs better for low sensor inter-arrival times, while throughput for larger sensor inter-arrival times matches in both cases due to the low traffic load. Figure 24 explains that two-node scenarios in IEEE 802.15.4 gives better results from 3 to 20 ms inter-arrival times in contrast to IEEE 802.15.4e one and two-node scenarios using full bandwidth. The setting information is included in Table 7.

Number of Nodes	Distance	Buffer size (Kbits)	MSDU size (bits)	Timeslot duration (ms)	Superframe duration (ms)	MSDU inter-arrival time (ms)
Sensor-2	150	2K	40	6.72	15.36	1-20

Table 7: MSDU inter-arrival time variation for two sensors

Figure 25 compares two-node scenarios in IEEE 802.15.4 and IEEE 802.15.4e LLDN. The performance IEEE 802.15.4e LLDN presents an enhancement over the entire inter-arrival times, although the Maximum delay IEEE 802.15.4e LLDN does not satisfy the semi-trailer application until the 18-ms inter-arrival time. Apparently

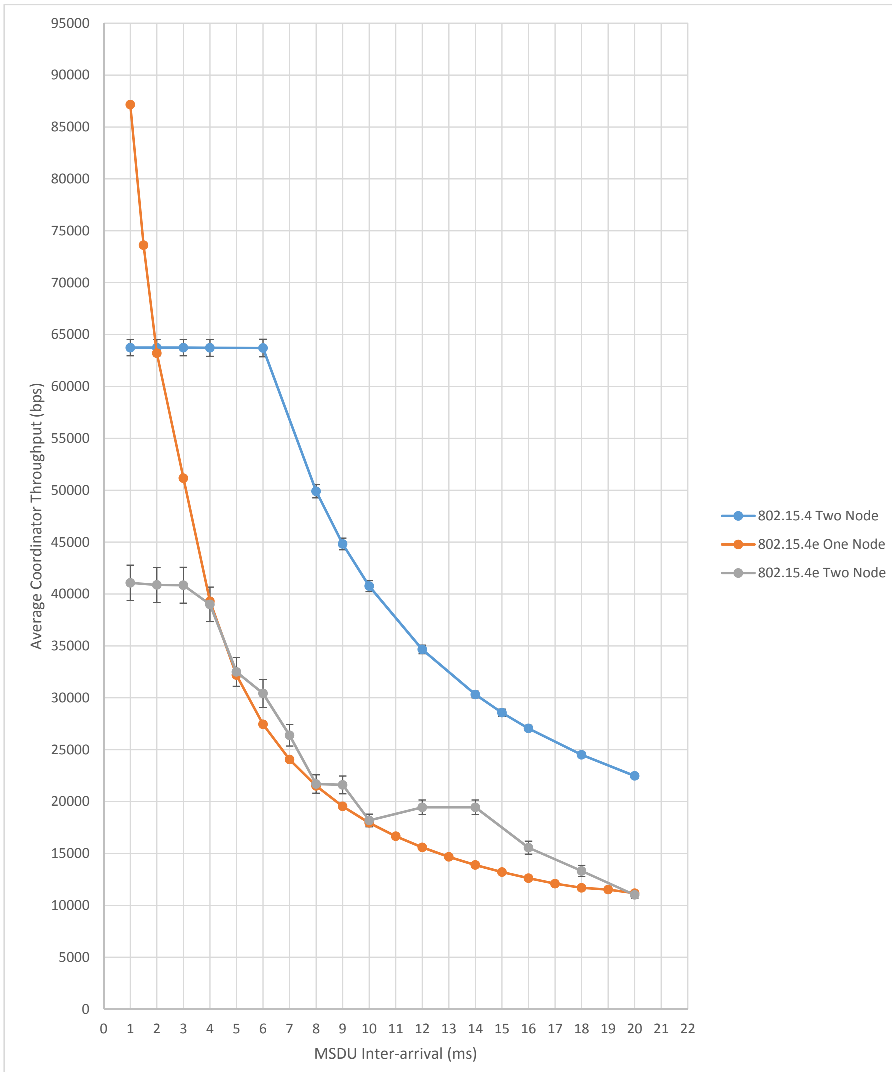

Figure 24: Average coordinator throughput vs. MSDU inter-arrival time for full timeslot usage with two-node scenario in IEEE 802.15.4 and IEEE 802.15.4e LLDN and with single node scenario in IEEE 802.15.4e LLDN with a 95-percent confidence.

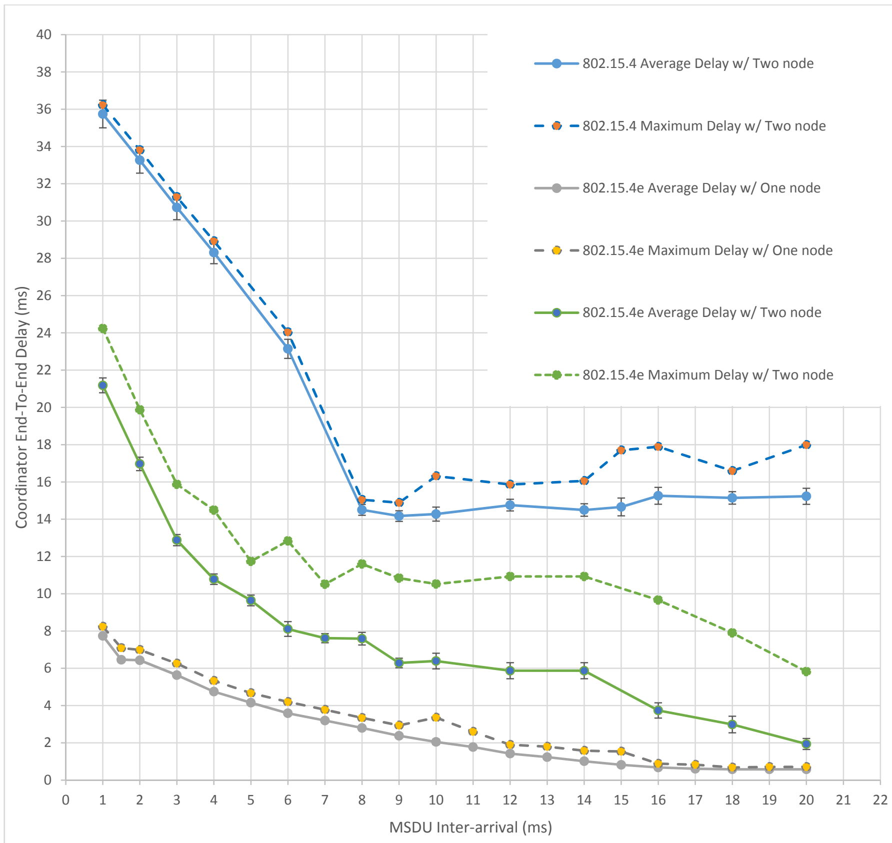

Figure 25: Coordinator End-To-End delay vs. MSDU inter-arrival time for full timeslot usage with two-node scenario in IEEE 802.15.4 and IEEE 802.15.4e LLDN and with single node scenario in IEEE 802.15.4e LLDN with a 95-percent confidence.

single node scenario encounters less End-To-End delay than two-node setup because of more bandwidth usage by a node. The different gaps between average and maximum End-To-End delay for a two-node setup increases compared to a single node setup for all inter-arrival times, which stipulates a rise in the amplitude of the jitter for higher data inter-arrival times. The generated data stored in the buffer requires more time to wait to access the network in the next superframe, since it should wait for another assigned timeslot to be finished. Therefore the worst case scenarios represent larger differences from the average delay values for larger input inter-arrival times.

As mentioned in Chapter 4, the pendulum and semi-trailer control applications require 10 and 9 ms End-To-End delay respectively [64, 65]. The maximum End-To-End delay shows that time sensitive delay applications (semi-trailer and pendulum control cases) are not guaranteed with two node, 6.27 ms timeslot for each node, 15.36 ms superframe and sensor sampling less than 17 ms. The confidence 95 percentage range shows that this configuration is supportive of higher sampling times than 6 ms, if a reliability greater than 5 percent can be tolerated in the control application.

5.6.1 Observations

According to Figure 25 results, the two-node scenario with 6.72 ms timeslot using the entire superframe does not assure the delay less than 9 ms. In this case, the delay is not guaranteed for low-latency applications with sampling rates less than 17 ms. Unless the 5-percent packet loss can be suported by the control application, the desired delay bound is achieved by sensor arrival rates less than 6 ms with high throughput. Consequently, the role of timeslot and superframe duration impacts the delay response and it is evident that CAP is not the only parameter that increases the delay.

5.7 Performance Evaluation of IEEE 802.15.4e LLDN with Superframe Duration Equivalent to the Desired Latency in Two Node Scenarios

Considering the results of the last two scenarios, the significance of timeslot allocation and superframe duration are highlighted in the delay reduction. For this reason, the two-node scenario is examined with 8.64 ms superframe and 3.84 ms timeslot durations for each node. The buffer capacity stays the same as the last value, 2 Kbits. The beacon frames and management frames have 0.96 ms times for transmission and the beacon Interval is set to equivalent of the superframe duration. The 9-ms superframe duration is chosen based on the calculations for the delay bounds which are conducted in Sections 3.3 and 3.4 with varied timeslot durations. The configuration parameters are shown in Table 8.

Number of Nodes	Distance	Buffer size (Kbits)	MSDU size (bits)	Timeslot duration (ms)	Superframe duration (ms)	MSDU inter-arrival time (ms)
Sensor-2	150	2	40	3.84	8.64	1-16

Table 8: MSDU inter-arrival time variation for modified superframe two sensors

As Figure 26 demonstrates, the throughput maintains a downward trend similar to previous simulation experiments when sensor data rates increase. The term SD refers to the superframe duration in this thesis. The results illustrate a remarkable enhancement compared with 15.36 ms superframe duration for two sensors in IEEE 802.15.4e LLDN; nevertheless, the two-node set up in original IEEE 802.15.4 with 15.36 ms still presents superior throughput over the other two-node scenarios.

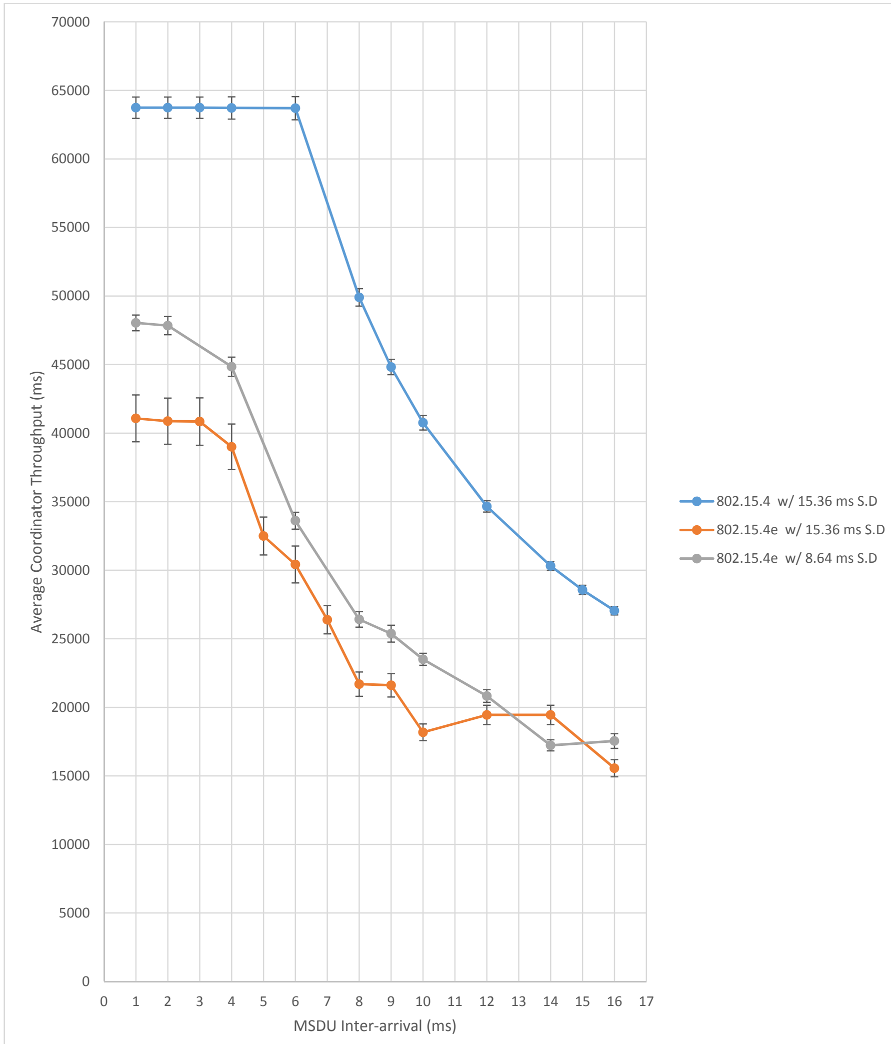

Figure 26: Average Coordinator throughput vs. MSDU inter-arrival time for 3.84 and 6.72 ms timeslot duration in IEEE 802.15.4e and 6.72 ms timeslot in IEEE 802.15.4 with a 95-percent confidence (two-node scenario).

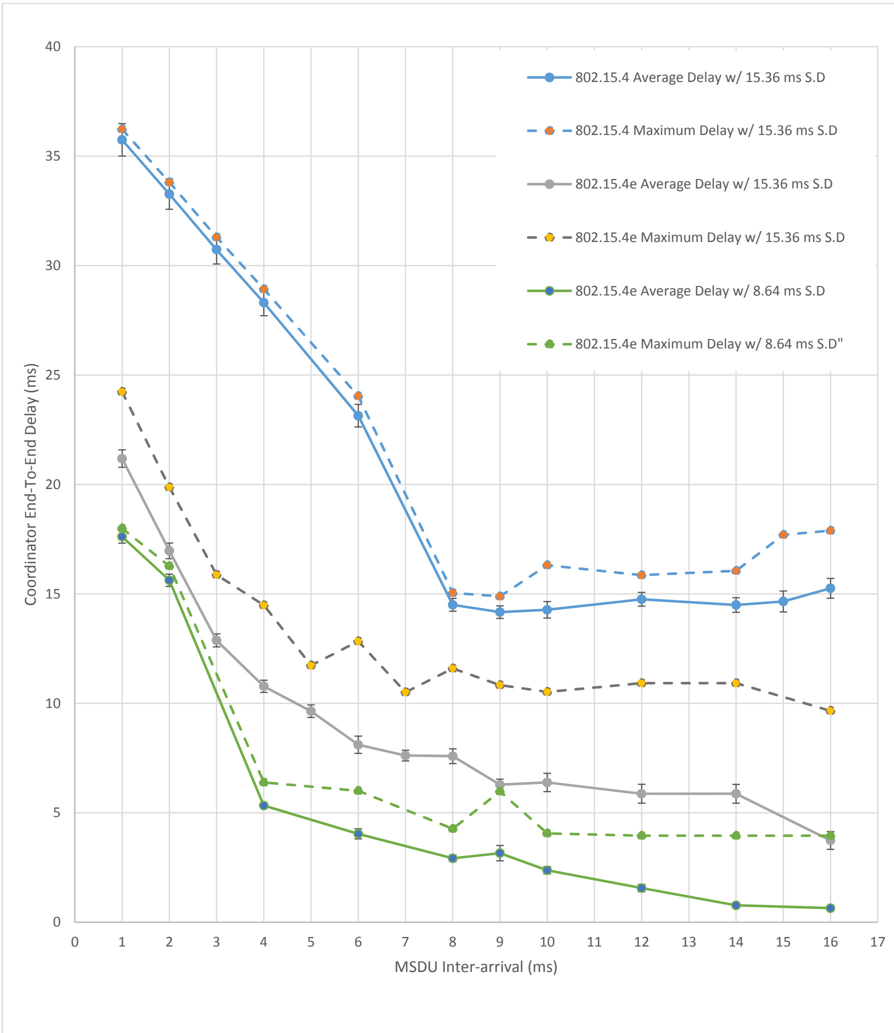

Figure 27: Coordinator End-To-End delay vs. MSDU inter-arrival time for 3.84 and 6.72 ms timeslot duration in IEEE 802.15.4e and 6.72 ms timeslot in IEEE 802.15.4 with a 95-percent confidence (two-node scenario).

The End-To-End delay improves dramatically for MSDU inter-arrival rates larger than 4 ms. Moreover, the variation of sensor inter-arrival times from 2 to 4 ms shows a significantly steep drop to delay values which can be employed in time-sensitive applications, such as semi-trailer and pendulum control categories. The reason for high delay with 1 ms arrival sensor sampling times is that a sensor produces 8 frames roughly during each superframe and transmits approximately 3 frames. Considering each frame is transmitted during every 0.96 ms, 5 generated frames in each superframe wait for another superframe to be transmitted which leads to the elevation of the delay bounds. Traffic load increase, with the accumulated waited data in the MAC buffer. However, 4 ms MSDU inter-arrival generates 4 frames during each superframe which can be transmitted in the next superframe in the worst case scenario and the load representing the arrival data rate equals to the outgoing transmission data rate. This observation is the trigger of the use of an adaptive IEEE 802.15.4e LLDN algorithm that changes the superframe duration to be equivalent to the MSDU inter-arrival times so as to have the same number of transmissions and generation of the packet within a superframe.

The maximum delay trend has a significant difference with average delay which introduces the larger amplitude of jitter (delay variation) in greater MSDU inter-arrival. When the period of generation of data is long, transmission of data can be complete in the same superframe that is generated which produces a short delay bound. Otherwise if the data is generated and the access to the network is not possible, the packet needs to wait for a long superframe period for successful transmission (considering having small timeslot duration in proportion to the superframe size). The maximum End-To-End delay has an escalation in 9 ms sensor rate at the equivalent time duration of the superframe which presents a critical point of this superframe (the critical point is equals to MSDU inter-arrival time). After 4 ms MSDU inter-arrival, the average delay bound has a slight decreasing trend from 5 to 0.6 ms, although maximum End-To-End delay reaches a stabilized value for upper than 10 ms sensor sampling time due to a low arrival data rate.

This Implementation introduces the smaller delay bounds for the entire MSDU inter-arrival times in contrast to IEEE 802.15.4e with 6.72 ms and IEEE 802.15.4 with 2.88 ms timeslots. This occurs due to balancing the superframe with the desired delay and shows that this technique is effective to reduce the End-To-End delay.

5.7.1 Observations

Consequently, this design is one of the suitable designs for the application experiencing MSDU inter-arrival time equal and more than 4 ms. It also facilitates the requirements of low-latency applications like pendulum and semi-trailer LCV applications, since it provides an End-To-End delay of less than 9 ms. Other applications which need more accurate and more frequent arrival data than 4 ms sample rate should refer to further protocol design options. Larger inter-arrival times more than 10 ms data experiences the same maximum delay bound.

The observation of the results for IEEE 802.15.4e LLDN carries on utilizing the same value of superframe duration time as large as MSDU inter-arrival times. Hence the MSDU inter-arrival rate is arranged to 4 ms in next section. the superframe duration is changed to 3.84 ms which is directly proportional to minimum standard timeslot duration (0.96 ms) and it is close to 4 ms.

5.8 Performance Evaluation of IEEE 802.15.4e LLDN with Superframe Duration Equivalent to MSDU Inter-arrival in the Two Node Scenario

The configuration settings of $SO = 0$, 3.84-ms superframe, 0.512-ms beacon and 1.67-ms timeslot durations are created for each node. If the SO increases by one, then the superframe and timeslot durations are doubled. The rest of the time is reserved for beacon and management frames. The settings are presented in Table 9.

Number of Nodes	Distance	Buffer size (Kbits)	MSDU size (bits)	Timeslot duration (ms)	Superframe duration (ms)	MSDU inter-arrival time (ms)
Sensor-2	150	2	40	1.66	3.84	1-16

Table 9: MSDU inter-arrival time variation for modified superframe two sensors

The reason that there are no results for inter-arrival times greater than 7 ms is the deallocation of the timeslots by the coordinator that are assigned further than 8 ms sampling rate (more than double the amount of the superframe size).

The throughput result shows better performance as compared to the previous cases except for the two-node IEEE 802.15.4 simulation test. There is a break point which determines how many data frames can be handled in a superframe with 3.84 ms duration case. The IEEE 802.15.4e with 1.66 ms timeslot for each node performs better with high throughput for low arrival times; nonetheless, this superframe duration in IEEE 802.15.4e results in the deallocation procedure being activated and is not able to serve higher MSDU inter-arrival times.

The average and maximum coordinator End-To-End delays have the same performance in the 3.84-ms superframe duration for less than 4 ms sampling inter-arrival

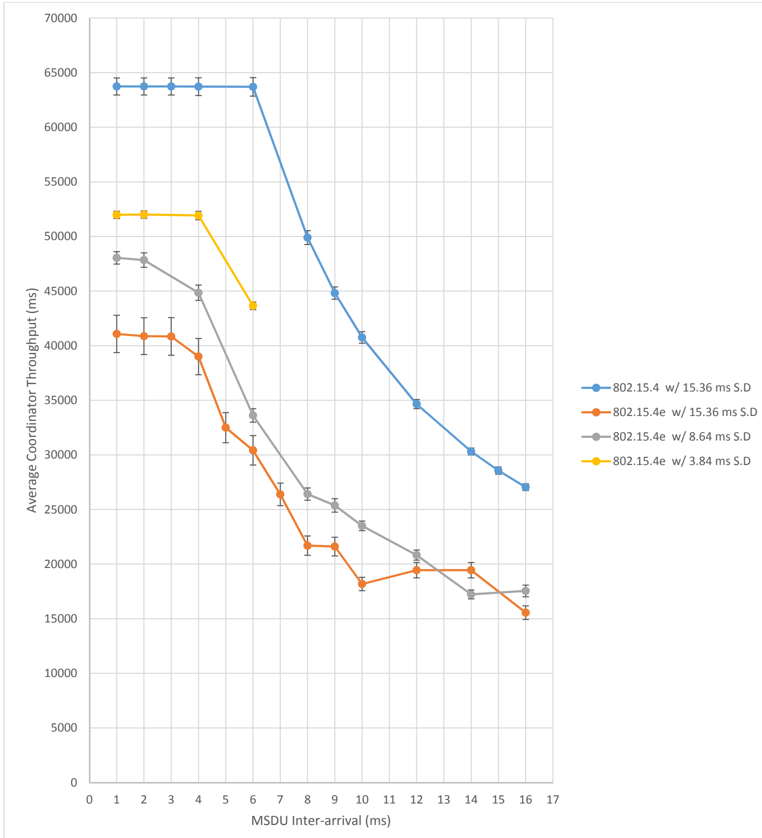

Figure 28: Average coordinator throughput vs. MSDU inter-arrival time for 3.84, 1.66 and, 6.72 ms timeslot duration in IEEE 802.15.4e and 6.72 ms timeslot in IEEE 802.15.4 with a 95-percent confidence (two-node scenario).

times, albeit it shows a minor difference for 1 and 2 ms inter-arrival compared to a 9-ms superframe duration in IEEE 802.15.4e LLDN. Furthermore, for $SD = 3.84$ there is a small enhanced performance for MSDU inter-arrival times for more than 4 ms compared to the last scenario with 8.64 ms superframe. Thus it is a suitable superframe duration for a range of 4 to 6 ms inter-arrival but is not able to achieve the desired delay of 9 ms for inter-arrival times greater than 6 ms. As evident in Figure 29, this superframe configuration gives the lowest delay compared to all other two-node scenarios.

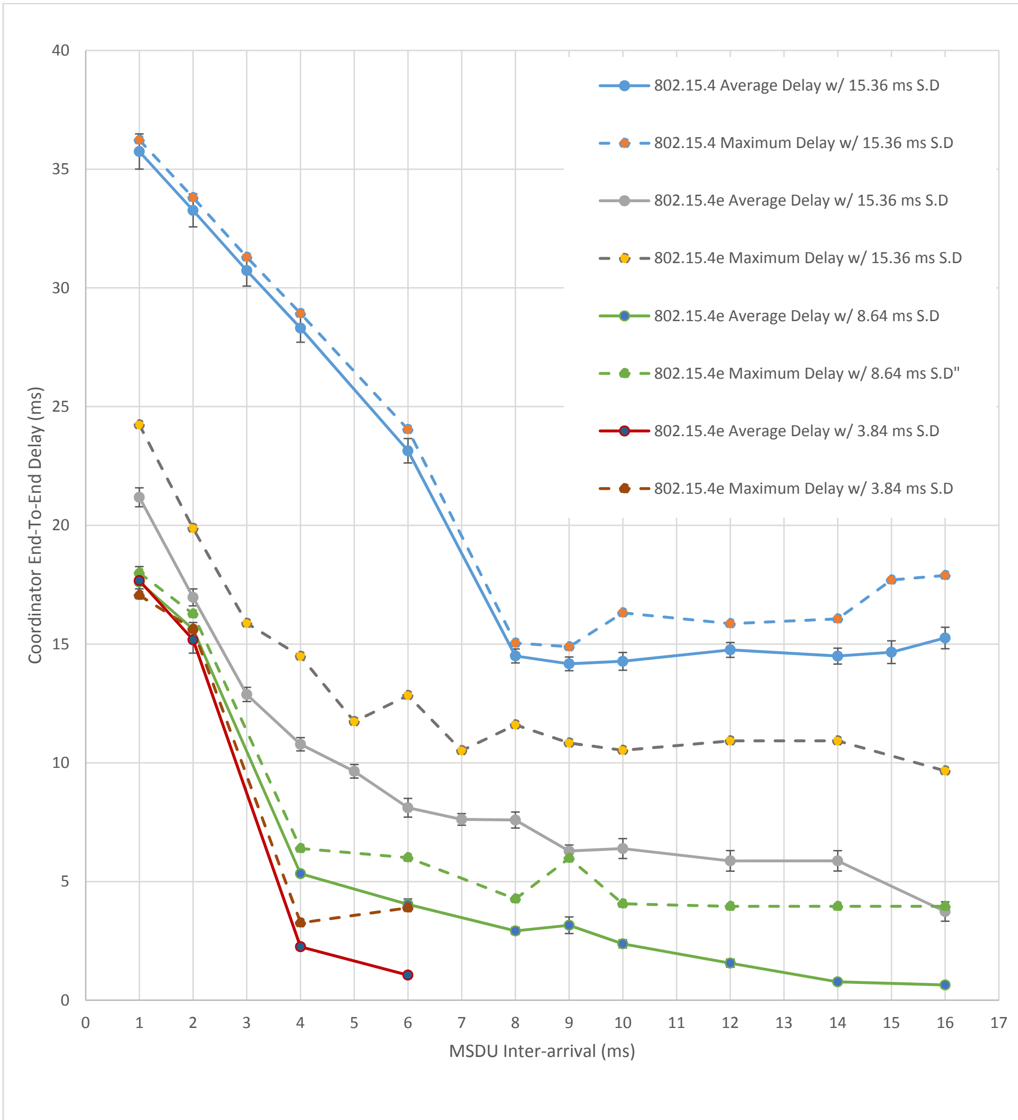

Figure 29: Coordinator End-To-End delay vs. MSDU inter-arrival time for 3.84, 1.66 and, 6.72 ms timeslot duration in IEEE 802.15.4e and 6.72 ms timeslot in IEEE 802.15.4 with a 95-percent confidence (two-node scenario).

5.8.1 Observations

Long waiting time in a buffer is caused by choosing inappropriate superframe duration, which leads to the increases in jitter. Hence the scenario of 3.84 ms superframe duration is optimum for 4, 5 and 6 ms inter-arrival times. In contrast to other two-node setups, this 3.84-ms superframe duration represents a better approach all the inter-arrival times considering both delay and throughput. Additionally, selecting 3.84 ms superframe and 1.66 timeslots for two nodes, leads to low delays for 4, 5 and 6 ms sensor sampling inter-arrival times. However, the worst drawback of this configuration is that it is not capable of serving for higher MSDU inter-arrival times. For this reason, an adaptive superframe and timeslot duration comes to mind to facilitate the entire MSDU inter-arrival times automatically which is the subject of the next section.

5.9 Adaptive IEEE 802.15.4e LLDN scheduler algorithm Evaluation with Different MSDU Inter-arrival

The concept of adjusting superframe duration based on MSDU inter-arrival times was introduced in Section 5.3. The investigation of this design is implemented in OPNET following the same program that used for previous sections. For this reason, the codes of Open-ZB [5] are changed to create a new protocol IEEE 802.15.4e LLDN with adaptive timeslot and superframe duration MAC sub-layer. It means that the consideration and changes of arrival data rates are applied in the superframe and timeslot duration selection according to the Adaptive IEEE 802.15.4e LLDN algorithm which was presented in Section 3.5. The simulation settings are included in Table 10 for this section.

Number of Nodes	Distance	Buffer size (Kbits)	MSDU size (bits)	Timeslot duration (ms)	Superframe duration (ms)	MSDU inter-arrival time (ms)
Sensor-2	150	2	40	Adaptive	Adaptive	4-30

Table 10: MSDU inter-arrival time variation for Adaptive IEEE 802.15.4e LLDN algorithm two sensors

At each run of the simulation the MSDU inter-arrival time is selected through a user interface in OPNET Modeler. The superframe is scheduled by the coordinator. The coordinator realizes the MSDU inter-arrival time of each sensor during the first level, Discovery state. The desired latency is defined by the user, for example 9 ms is set for desired latency in this experiment. It then transmits the allocation and duration of timeslots for each sensor in the beacon. In the simulator codes, the value of MSDU inter-arrival time is set to superframe duration and it is subtracted by the beacon duration (0.5 ms). The attained amount is divided to the number of nodes considering all nodes have the same MSDU inter-arrival times in each simulation run. An average with confidence of 95 percent and maximum for captured measurements in each run is calculated to make it comparable with different delay and throughput amounts for varied input MSDU inter-arrival times. The sensor sampling inter-arrival time does not change during online state of the protocol, since sensor sampling times are one of the specifications of the sensor types. In other words, the sensor is not required to be altered after installation, although at the commencement, formation of each PAN can be changed.

The results of such improvements are illustrated in Figure 30 and 31. The average coordinator throughput follows a downward trend due to the increase in the number of vacant timeslots with increasing sensor inter-arrival times. The enhancement of throughput is clear through the comparison between the Adaptive IEEE 802.15.4e

LLDN algorithm and other examined scenarios for two nodes except the original IEEE 802.15.4 which has a high delay.

The first version of $SO = 0$ is preferred for two node WNCS communication until the MSDU inter-arrival times are equal to double the superframe duration, since from that point the deallocation mechanism takes effect.

For this case, a MSDU inter-arrival time equal to 18 is double the superframe duration and hence $SO = 1$ is applied from 18 ms inter-arrival time and greater. As evident in Figure 30, the throughput has the same behaviour as other IEEE.802.15.4e scenarios.

The simulation results of the average and maximum End-To-End delay with varied MSDU inter-arrival times are shown in Figure 31. The 95 percentage confidence range is added to the trends. The average End-To-End latency demonstrates a slight variation and can be bound between 0.5 and 4 ms. The maximum End-To-End delay for the entire sensor inter-arrival ranges from 0.8 to 4 ms. As the sensor sampling time decreases, the period between the generations of samples increases and the maximum End-To-End delay bound stabilizes. This stabilization is due to the slow rate of generation of data. The worst case scenario is when the frame is generated at the last moments of the node's assigned slot where the frame is required to be stored and wait for the next timeslot for transmission.

Comparing the new Adaptive IEEE 802.15.4e LLDN algorithm with the previous studied two-node scenarios, it is apparent that the End-To-End delay introduces an enhancement over the entire MSDU inter-arrival times. Moreover, the Adaptive IEEE 802.15.4e LLDN algorithm can continue for higher MSDU inter-arrival times like 30 ms.

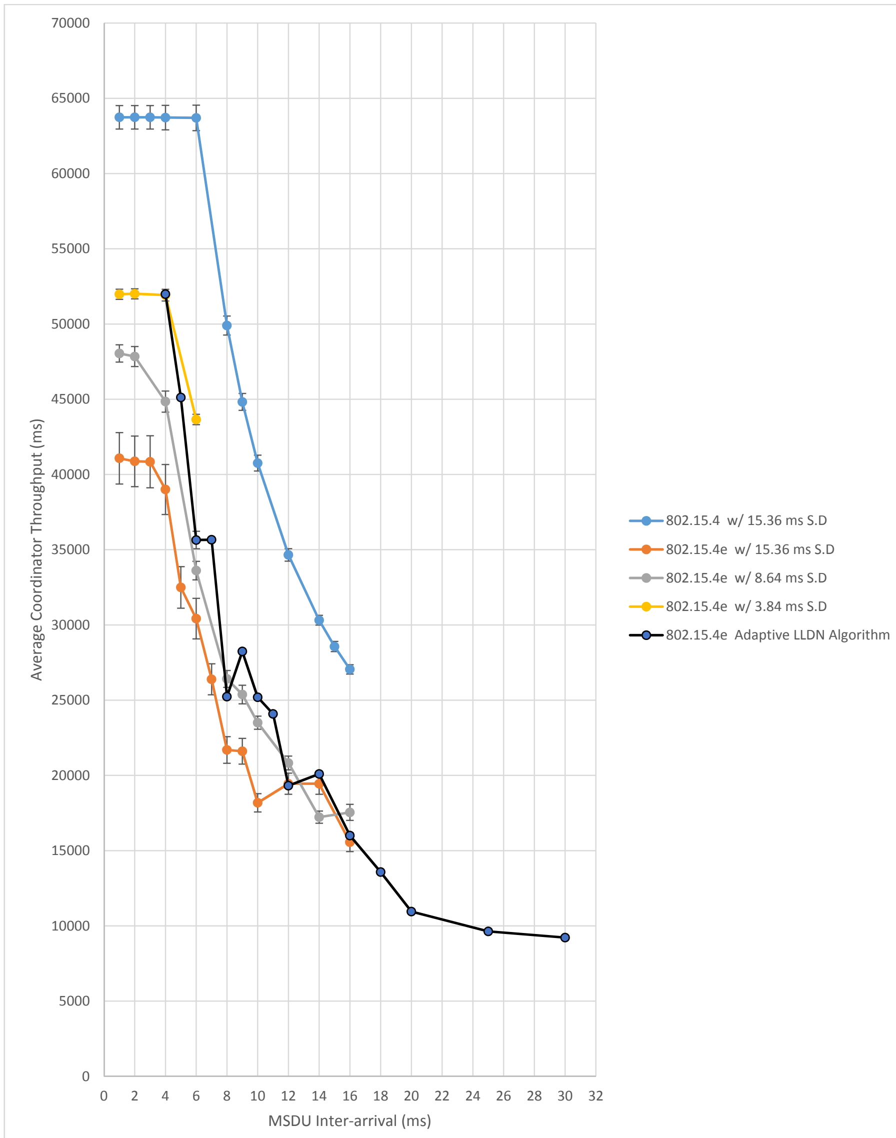

Figure 30: Average coordinator throughput vs. MSDU inter-arrival time comparing 3.84, 1.66, 6.72 ms and, adaptive timeslot duration in IEEE 802.15.4e and 6.72 ms timeslot in IEEE 802.15.4 with a 95-percent confidence (two-node scenario).

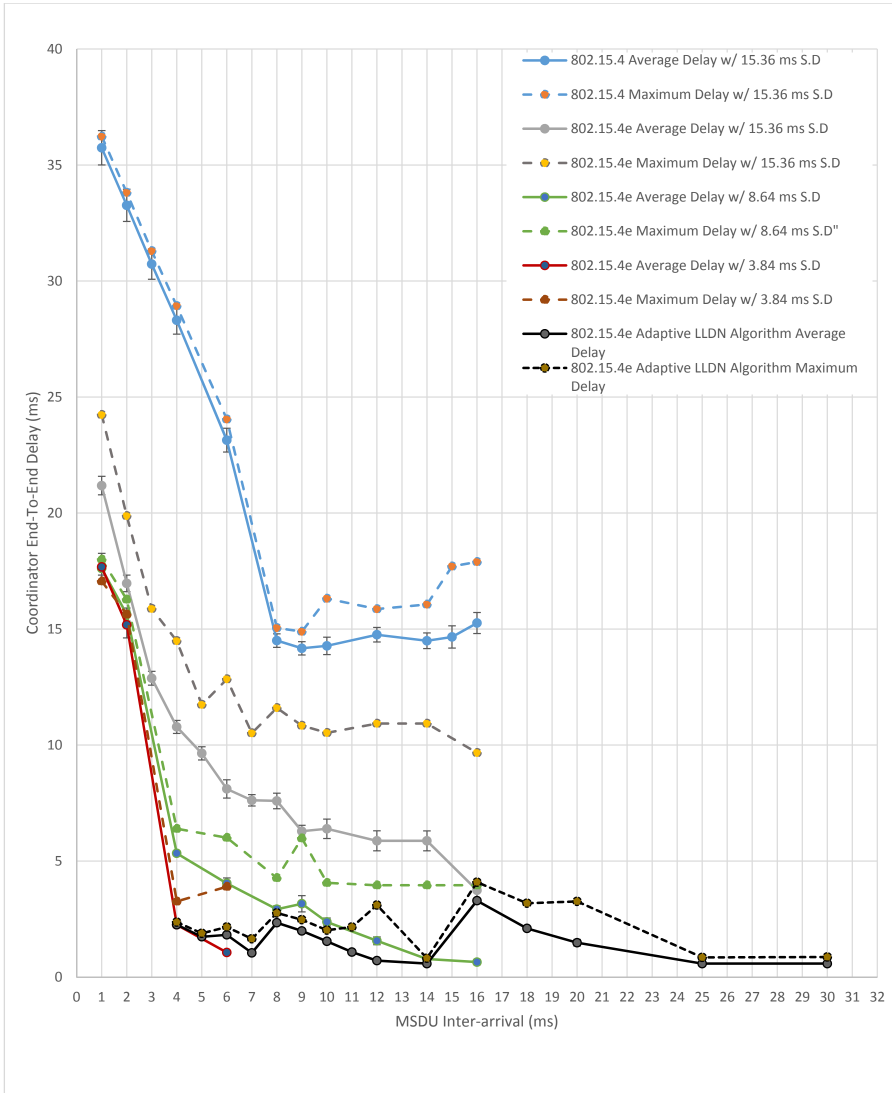

Figure 31: Average and maximum coordinator End-To-End delay vs. MSDU inter-arrival time comparing 3.84, 1.66, 6.72 ms and, adaptive timeslot duration in IEEE 802.15.4e and 6.72 ms timeslot in IEEE 802.15.4 with a 95-percent confidence (two-node scenario).

5.9.1 Observations

The Adaptive IEEE 802.15.4e LLDN algorithm regulates the timeslot and superframe duration between two variables, MSDU inter-arrival times and desired latency. The results in Figure 31 and 30 illustrate the improved performance of MAC sublayer protocol in comparison with IEEE 802.15.4 and IEEE 802.15.4e LLDN scheduling mechanisms. The average delay hovers about 3 ms for the entire MSDU inter-arrival times and Maximum delay does not exceed the desired latency. Furthermore, throughput has the same trend as other scenarios in IEEE 802.15.4.

6 Conclusion

6.1 Summary

This thesis presented the conditions and concept of application wireless communication protocol IEEE 802.15.4 and IEEE 802.15.4e in low-latency requirement control scenarios. Moreover, it endeavored to provide the reader the functionality of the working mechanism of both protocols and the challenges involved in wireless communication for achievement of low latency bounds. The problems of wireless communication in control stabilization were reviewed through two major application categories which were known as Platooning and Cooperative Adaptive Cruise Control (CACC). Several related works in protocol MAC design for IEEE 802.15.4 and IEEE 802.15.4e LLDN and their constraints were assessed. Both IEEE 802.15.4 beacon-enabled mode and IEEE 802.15.4e LLDN were elaborated and the reason for choosing the IEEE 802.15.4e LLDN was justified. The evaluation of two protocols was conducted in terms of theoretical calculation and simulation scenarios to provide some guidelines for control application criteria. The optimal designs according to the number of sensors and diverse MSDU inter-arrival cases were studied and examined with OPNET Modeler simulation.

The existing IEEE 802.15.4 beacon-enabled protocol in OPNET Modeler was modified to design the IEEE 802.15.4e LLDN MAC sub-layer mechanism. The superframe duration in IEEE 802.15.4e LLDN was changed in two scenarios (single node and two -node) which were exposed to different arrival rates and the outcome delay was assessed for semi-trailer and pendulum control applications.

The goal of this thesis was to provide a suitable MAC sub-layer for the wireless communication protocol to access the network and transmit each frame with minimum possible End-To-end delay. It attempted not only make the IEEE 802.15.4

beacon-enable and IEEE 802.15.4e LLDN work based on the custom designs, but also presented a novel superframe and timeslot allocation in accordance to arrival sensor sampling rates and desired latency titled in this thesis an Adaptive 802.15.4e LLDN algorithm.

Two major scenarios with different cases of protocols, timeslot allocations and superframe allocations were implemented. Using the fact that the equivalent number of incoming frame to outgoing frame produces the best End-to-End delay reduction with high throughput, so the number of timeslots all nodes in the superframe was tailored according to both desired latency and sensor inter-arrival times.

The summary of the simulation results is illustrated in Table 11. As evident, only two scenarios could provide the desired latency for the entire MSDU inter-arrival times; single node scenario using IEEE 802.15.4e LLDN with 14.4 ms timeslot and two-node scenario using IEEE 802.15.4e Adaptive IEEE 802.15.4e LLDN algorithm.

6.2 Future Work

There are some areas of research that have not been covered in this work. First, this thesis just concentrated on effect of MAC sub-layer on the delay and throughput for WNCS applications. More realistic channel models results in more packet loss and delayed frames due to shadowing and Doppler impact. An example of this is that the nodes and controller positions where the communication between some nodes can be blocked due to the metal body of the trailers or vehicles. Thus the antenna repeater selections enforce the cooperation of other field of wireless communication.

Further works can involve priority transmission of the frames or nodes with different sampling rates. Different sampling rates of nodes in a PAN naturally leads

Protocol	Number of end-node	Superframe duration (ms)	Timeslot duration per node (ms)	Possible MSDU inter-arrivals for LCV stability (ms)	Possible MSDU inter-arrivals for pendulum stability (ms)
802.15.4	1	15.36	6.72	3-9, 12-30	3-9, 12-30
802.15.4	2	15.36	2.88	N/A	N/A
802.15.4	1	30.72	13.44	N/A	N/A
802.15.4	1	60.44	26.88	N/A	N/A
802.15.4e LLDN	1	15.36	14.4	1-30	1-30
802.15.4e LLDN	1	15.36	6.72	6-20	5-20
802.15.4e LLDN	2	15.36	6.72	18-20	16-20
802.15.4e LLDN	2	8.36	3.84	4-20	4-20
802.15.4e LLDN	2	3.84	1.66	4-6	4-6
Adaptive 802.15.4e LLDN	2	3.84-17.28	1.66-8.38	4-30	4-30

Table 11: Summary of experiments

to the thought of assigning varied timeslots to regulate the End-To-End delay of frames for both nodes. Evaluation of different packet size according to variety of the sensors opens another research subject. Additionally, the reliability of frame reception comes into attention for time-sensitive cases. A mesh network and other protocols facilitating multi routes make the possibility for questioning the reliability of the protocol.

Moreover, scalability is another concern for vehicular applications which requires diverse sensor data to transmit from different locations to the controller. The response of the WNCS can be investigate in terms of delay and throughput over a vast range of

MSDU inter-arrival times and number of nodes can be investigated for each scenario. Also, The most optimum co-simulator can be utilized which models both control and estimation strategies with wireless protocols in vehicular environment. For example, a dynamic model of LCVs associated with a controller would be implemented and a wireless network protocol transmits the actual messages from the sensors to the controller.

References

[1] D. Pape, M. Arant, W. Brock, D. Delorenzis, T. LaClair, A. Lim, J. Petrolino, and A. Spezia, *U31: Vehicle Stability and Dynamics Electronic Stability Control Final Report*. National Transportation Research Center, Incorporated University Transportation Center, sep 2011.

[2] R. Shamim, M. Islam, and Y. He, *A Comparative Study of Active Control strategies for Improving Lateral Stability of Car-Trailer Systems*. SAE Technical Paper, April 2011.

[3] T. Sun, E. Esmailzadeh, J. Ren, and Y. He, *Lateral Stability Improvement of Car-Trailer Systems Using Active Trailer Braking Control*. Proceedings of the CSME International Congress 2012, Winnipeg, Manitoba, Canada, 2012.

[4] X. Ding, Y. He, J. Ren, and T. Sun, "A comparative study of control algorithms for active trailer steering systems of articulated heavy vehicles," in *American Control Conference (ACC), 2012*, pp. 3617–3622, June 2012.

[5] P. Jurcik, A. Koubaa, M. Alves, E. Tovar, and Z. Hanzalek, "A simulation model for the ieee 802.15.4 protocol: Delay/throughput evaluation of the gts

mechanism," in *Modeling, Analysis, and Simulation of Computer and Telecommunication Systems, 2007. MASCOTS '07. 15th International Symposium on*, pp. 109–116, Oct 2007.

[6] T. ElBatt, C. Saraydar, M. Ames, and T. Talty, "Potential for intra-vehicle wireless automotive sensor networks," in *Sarnoff Symposium, 2006 IEEE*, pp. 1–4, March 2006.

[7] A. Goldsmith, *Wireless Communications*. New York, NY, USA: Cambridge University Press, 2005.

[8] J. P. Hespanha, P. Naghshtabrizi, and Y. Xu, "A survey of recent results in networked control systems," *Proceedings of the IEEE*, vol. 95, Jan 2007.

[9] D. Goswami, R. Schneider, A. Masrur, M. Lukasiewycz, S. Chakraborty, H. Voit, and A. Annaswamy, "Challenges in automotive cyber-physical systems design," in *Embedded Computer Systems (SAMOS), 2012 International Conference on*, pp. 346–354, July 2012.

[10] G. Patti, G. Alderisi, and L. Bello, "Introducing multi-level communication in the ieee 802.15.4e protocol: The multichannel-lldn," in *Emerging Technology and Factory Automation (ETFA), 2014 IEEE*, pp. 1–8, 2014.

[11] C. Wang and J. Thompson, "Apparatus and method for motion detection and tracking of objects in a region for collision avoidance utilizing a real-time adaptive probabilistic neural network," Mar. 18 1997. US Patent 5,613,039.

[12] X. Yang, J. Liu, N. Vaidya, and F. Zhao, "A vehicle-to-vehicle communication protocol for cooperative collision warning," in *Mobile and Ubiquitous Systems: Networking and Services, 2004. MOBIQUITOUS 2004. The First Annual International Conference on*, pp. 114–123, Aug 2004.

[13] J. Blum and A. Eskandarian, "Adaptive space division multiplexing: an improved link layer protocol for inter-vehicle communications," in *Intelligent Transportation Systems, 2005. Proceedings. 2005 IEEE*, pp. 455–460, Sept 2005.

[14] L. Chisalita and N. Shahmehri, "A peer-to-peer approach to vehicular communication for the support of traffic safety applications," in *Intelligent Transportation Systems, 2002. Proceedings. The IEEE 5th International Conference on*, pp. 336–341, 2002.

[15] P. Fernandes and U. Nunes, "Platooning with dsrc-based ivc-enabled autonomous vehicles: Adding infrared communications for ivc reliability improvement," in *Intelligent Vehicles Symposium (IV), 2012 IEEE*, pp. 517–522, June 2012.

[16] Z. Taysi and A. Yavuz, "Etsi compliant geonetworking protocol layer implementation for ivc simulations," in *Computer, Information and Telecommunication Systems (CITS), 2012 International Conference on*, pp. 1–5, May 2012.

[17] J. Blum and A. Eskandarian, "Adaptive space division multiplexing: an improved link layer protocol for inter-vehicle communications," in *Intelligent Transportation Systems, 2005. Proceedings. 2005 IEEE*, pp. 455–460, Sept 2005.

[18] J. Blum and A. Eskandarian, "Adaptive space division multiplexing: an improved link layer protocol for inter-vehicle communications," in *Intelligent Transportation Systems, 2005. Proceedings. 2005 IEEE*, pp. 455–460, Sept 2005.

[19] S. Shladover, C. Desoer, J. Hedrick, M. Tomizuka, J. Walrand, W.-B. Zhang, D. McMahon, H. Peng, S. Sheikholeslam, and N. McKeown, "Automated vehicle control developments in the path program," *Vehicular Technology, IEEE Transactions on*, vol. 40, pp. 114–130, Feb 1991.

[20] C. E. J. R. Bergenhem, C. and A. Tehrani, "V2v communication quality: Measurements in a cooperative automotive platooning application," *SAE Int J. Passeng. Cars Electron. Electr. Syst.*, 2014.

[21] A. Davila and M. Nombela, "Sartre - safe road trains for the environment reducing fuel consumption through lower aerodynamic drag coefficient," *SAE Technical Paper*, 2011-36-0060, 2011.

[22] S. C. E. E. C. T. S. Bergenhem, C.; Shladover, "Overview of platooning system," *Proceedings of the 19th ITS World Congress*, Oct 22-26, Vienna, Austria (2012).

[23] M. Manz and H.-J. Wuensche, "Autonomes Konvoi-Fahren in unstrukturierter Umgebung," in *Tagungsband DWT-SGW Forum Unmanned Vehicles III*, (Bonn, Germany), Feb. 2011.

[24] S. Tsugawa, S. Kato, and K. Aoki, "An automated truck platoon for energy saving," in *Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on*, pp. 4109–4114, Sept 2011.

[25] G. D. L. J. S. R. Michael, J.B., "Capacity analysis of traffic flow over a single-lane automated highway system," *ITS Journal*, vol. 4, pp. 49–80, August 1998.

[26] X. Yang, J. Liu, N. Vaidya, and F. Zhao, "A vehicle-to-vehicle communication protocol for cooperative collision warning," in *Mobile and Ubiquitous Systems: Networking and Services, 2004. MOBIQUITOUS 2004. The First Annual International Conference on*, pp. 114–123, Aug 2004.

[27] I. S. y.-. I. S. n.-. IEEE Std 802.11p-2010 (Amendment to IEEE Std 802.11-2007 as amended by IEEE Std 802.11k 2008, IEEE Std 802.11r-2008 and I. S. 802.11w 2009, *IEEE Standard for Information technology– Local and metropolitan area*

networks– Specific requirements–Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments, July 15 2010.

[28] P. Fernandes and U. Nunes, "Platooning with ivc-enabled autonomous vehicles: Strategies to mitigate communication delays, improve safety and traffic flow," *Intelligent Transportation Systems, IEEE Transactions on*, vol. 13, pp. 91–106, March 2012.

[29] M. Segata, B. Bloessl, S. Joerer, C. Sommer, M. Gerla, R. Cigno, and F. Dressler, "Towards inter-vehicle communication strategies for platooning support," in *Communication Technologies for Vehicles (Nets4Cars-Fall), 2014 7th International Workshop on*, pp. 1–6, Oct 2014.

[30] S. Bana and P. Varaiya, "Space division multiple access (sdma) for robust ad hoc vehicle communication networks," in *Intelligent Transportation Systems, 2001. Proceedings. 2001 IEEE*, pp. 962–967, 2001.

[31] J. Blum and A. Eskandarian, "Adaptive space division multiplexing: an improved link layer protocol for inter-vehicle communications," in *Intelligent Transportation Systems, 2005. Proceedings. 2005 IEEE*, pp. 455–460, Sept 2005.

[32] R. Rajamani, *Vehicle Dynamics and Control*. Mechanical Engineering Series, Springer US, 2011.

[33] S. Oncu, N. van de Wouw, and H. Nijmeijer, "Cooperative adaptive cruise control: Tradeoffs between control and network specifications," in *Intelligent Transportation Systems (ITSC), 2011 14th International IEEE Conference on*, pp. 2051–2056, Oct 2011.

[34] X. Yang, J. Liu, N. Vaidya, and F. Zhao, "A vehicle-to-vehicle communication protocol for cooperative collision warning," in *Mobile and Ubiquitous Systems: Networking and Services, 2004. MOBIQUITOUS 2004. The First Annual International Conference on*, pp. 114–123, Aug 2004.

[35] C. Bergenhem, E. Hedin, and D. Skarin, "Vehicle-to-vehicle communication for a platooning system," *Procedia - Social and Behavioral Sciences*, vol. 48, pp. 1222 – 1233, 2012. Transport Research Arena 2012.

[36] F. Chen, R. German, and F. Dressler, "Towards ieee 802.15.4e: A study of performance aspects," in *Pervasive Computing and Communications Workshops (PERCOM Workshops), 2010 8th IEEE International Conference on*, pp. 68–73, March 2010.

[37] D. Rodenas-Herraiz, A.-J. Garcia-Sanchez, F. Garcia-Sanchez, and J. Garcia-Haro, "Current trends in wireless mesh sensor networks: A review of competing approaches," *Sensors*, vol. 13, no. 5, p. 5958, 2013.

[38] L. Cheng, A. Bourgeois, and X. Zhang, "A new gts allocation scheme for ieee 802.15.4 networks with improved bandwidth utilization," in *Communications and Information Technologies, 2007. ISCIT '07. International Symposium on*, pp. 1143–1148, Oct 2007.

[39] S.-E. Yoo, P. K. Chong, D. Kim, Y. Doh, M.-L. Pham, E. Choi, and J. Huh, "Guaranteeing real-time services for industrial wireless sensor networks with ieee 802.15.4," *Industrial Electronics, IEEE Transactions on*, vol. 57, pp. 3868–3876, Nov 2010.

[40] Y.-K. Huang, A.-C. Pang, and H.-N. Hung, "An adaptive gts allocation scheme for ieee 802.15.4," *Parallel and Distributed Systems, IEEE Transactions on*, vol. 19, pp. 641–651, May 2008.

[41] A. Koubaa, M. Alves, and E. Tovar, "i-game: an implicit gts allocation mechanism in ieee 802.15.4 for time-sensitive wireless sensor networks," in *Real-Time Systems, 2006. 18th Euromicro Conference on*, pp. 10 pp.–192, 2006.

[42] G. Sharma, R. Paulus, A. K. Jaiswal, and V. Sahu, "Article: Impact of bo and so on beacon-enabled ieee 802.15.4," *International Journal of Computer Applications*, vol. 66, pp. 34–38, March 2013. Full text available.

[43] M. Kohvakka, M. Kuorilehto, M. Hännikäinen, and T. D. Hämäläinen, "Performance analysis of ieee 802.15.4 and zigbee for large-scale wireless sensor network applications," in *Proceedings of the 3rd ACM International Workshop on Performance Evaluation of Wireless Ad Hoc, Sensor and Ubiquitous Networks*, PE-WASUN '06, (New York, NY, USA), pp. 48–57, ACM, 2006.

[44] M. Anwar and X. Yuanqing, "Ieee 802.15.4e lldn: Superframe configuration for networked control systems," in *Control Conference (CCC), 2014 33rd Chinese*, pp. 5568–5573, July 2014.

[45] A. Koubaa, M. Alves, and E. Tovar, "Gts allocation analysis in ieee 802.15.4 for real-time wireless sensor networks," in *Parallel and Distributed Processing Symposium, 2006. IPDPS 2006. 20th International*, pp. 8 pp.–, April 2006.

[46] F. Xia, R. Hao, J. Li, N. Xiong, L. T. Yang, and Y. Zhang, "Adaptive gts allocation in ieee 802.15.4 for real-time wireless sensor networks," *J. Syst. Archit.*, vol. 59, pp. 1231–1242, Nov. 2013.

[47] S. Oncu, N. van de Wouw, and H. Nijmeijer, "Cooperative adaptive cruise control: Tradeoffs between control and network specifications," in *Intelligent Transportation Systems (ITSC), 2011 14th International IEEE Conference on*, pp. 2051–2056, Oct 2011.

[48] T. ElBatt, C. Saraydar, M. Ames, and T. Talty, "Potential for intra-vehicle wireless automotive sensor networks," in *Sarnoff Symposium, 2006 IEEE*, pp. 1–4, March 2006.

[49] R. Naja., *Wireless Vehicular Networks for Car Collision Avoidance*. New York: SpringerLink (Online service), london: springer ed., 2013.

[50] K. Sjoberg, E. Uhlemann, and E. Strom, "Delay and interference comparison of csma and self-organizing tdma when used in vanets," in *Wireless Communications and Mobile Computing Conference (IWCMC), 2011 7th International*, pp. 1488–1493, July 2011.

[51] D. Reichardt, M. Miglietta, L. Moretti, P. Morsink, and W. Schulz, "Cartalk 2000: safe and comfortable driving based upon inter-vehicle-communication," in *Intelligent Vehicle Symposium, 2002. IEEE*, vol. 2, pp. 545–550 vol.2, June 2002.

[52] L. Chisalita and N. Shahmehri, "A peer-to-peer approach to vehicular communication for the support of traffic safety applications," in *Intelligent Transportation Systems, 2002. Proceedings. The IEEE 5th International Conference on*, pp. 336–341, 2002.

[53] B. X. Yen, D. T. Hop, and M. Yoo, "Redundant transmission in wireless networked control system over ieee 802.15.4e," in *Information Networking (ICOIN), 2013 International Conference on*, pp. 628–631, Jan 2013.

[54] S. Oncu, J. Ploeg, N. van de Wouw, and H. Nijmeijer, "Cooperative adaptive cruise control: Network-aware analysis of string stability," *IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS*, vol. 15, pp. 1527 – 1537, Aug 2014.

[55] "Ieee draft amendment to ieee standard for information technology–telecommunications and information exchange between systems–local and metropolitan area networks–specific requirements–part 15.4:wireless medium access control (mac) and physical layer (phy) specifications for low-rate wireless personal area networks (lr-wpans): Amendment 3: Alternative physical layer extension to support the japanese 950 mhz band," *IEEE Unapproved Draft Std P802.15.4d/D3, Jan 2009*, 2008.

[56] T. ElBatt, C. Saraydar, M. Ames, and T. Talty, "Potential for intra-vehicle wireless automotive sensor networks," in *Sarnoff Symposium, 2006 IEEE*, pp. 1–4, March 2006.

[57] S. Wang, A. Huang, and T. Zhang, "Performance evaluation of ieee 802.15.4 for v2v communication in vanet," in *Computational and Information Sciences (ICCIS), 2013 Fifth International Conference on*, pp. 1603–1606, June 2013.

[58] A. S. G. Anastasi, D. De Guglielmo, "From ieee 802.15.4 to ieee 802.15.4e: a step towards the internet of things," vol. Chapter 10 in Advances onto the Internet of Things (S. Gaglio, G. Lo Re, Editors), pp. 135–152, January 2014.

[59] J.-H. Park, K.-N. Ha, S. Lee, and K.-C. Lee, "Performance evaluation of wireless networked control system via ieee 802.15.4 with time-triggered csma/ca algorithm," *International Journal of Precision Engineering and Manufacturing*, vol. 11, no. 6, pp. 857–864, 2010.

[60] A. Ulusoy, A. Onat, and O. Gurbuz, "Wireless model based predictive networked control system over ieee 802.15.4," in *Distributed Computing in Sensor Systems (DCOSS), 2013 IEEE International Conference on*, pp. 382–387, May 2013.

[61] C. K. Singh, A. Kumar, and P. M. Ameer, "Performance evaluation of an ieee 802.15.4 sensor network with a star topology," *Wirel. Netw.*, vol. 14, pp. 543–568, Aug. 2008.

[62] M. M. Chandane, S. G. Bhirud, and S. V. Bonde, "Article: Performance analysis of ieee 802.15.4," *International Journal of Computer Applications*, vol. 40, pp. 23–29, February 2012. Full text available.

[63] "Ieee standard for local and metropolitan area networks–part 15.4: Low-rate wireless personal area networks (lr-wpans) amendment 1: Mac sublayer," *IEEE Std 802.15.4e-2012 (Amendment to IEEE Std 802.15.4-2011)*, pp. 1–225, April 2012.

[64] T. Mirfakhraie, Y. He, and R. Liscano, *Wireless Networked Control for Active Trailer Steering Systems of Articulated Vehicles*. ASME 2014, Montreal, Canada, 2014.

[65] B. X. Yen, D. T. Hop, and M. Yoo, "Redundant transmission in wireless networked control system over ieee 802.15.4e," in *Information Networking (ICOIN), 2013 International Conference on*, pp. 628–631, Jan 2013.