Department of Mathematics and Computer Science
EIT ICT Masters Embedded Systems

Ultra-wide Band for Vehicle Platooning

Master Thesis

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Abstract

Highly Automated Driving is experiencing a huge interest worldwide from many stakeholders. It holds the promise of increasing safety, comfort, personal productivity or entertainment, traffic efficiency, cost and environmental benefits. One area of investigation is the ability of cars to drive closer together, or even to platoon. Since physical sensors such as radars and cameras do not provide the required system performance, reliable communication between vehicles is a means to achieve this. While the wireless communication standard ITS-G5 is being selected as the technology of choice, ultra - wideband (UWB) as a second independent communication technology may provide additional benefits. UWB physical layer enables accurate ranging at low latency, improved robustness against interference, ultra low power consumption, low power spectral density, low cost, low impact on existing narrowband systems and lower probability of intercept and detection.

In this thesis, we investigate the feasibility of using UWB next to WiFi-p, examine the robustness of UWB communication in platooning mode with respect to differences in velocities, typical inter-vehicle environment, outdoor environment and ascertain the ranging accuracy that can be achieved through UWB. We implemented a test platform, TP-UWB (Test Platform for evaluation and analysis of UWB) using LPCXpresso 4337 and DecaWave DW1000 UWB transceiver. The test platform enables us to measure the UWB link quality and range, perform test automation by varying test parameters that influence UWB behavior such as packets or message, channels, Pulse Repetition Frequency (PRF), preamble lengths, preamble codes, standard or non-standard Start of the Frame Delimiter (SFD) and Smart Power enablement. We conduct experiments in table-top, outdoor and inter-vehicle environments using the test platform. We then perform a behavioral analysis of UWB using different parameters indicated above and determine the best configuration of UWB for platooning such that it operates with least possible interference to WiFi-p.

Conclusion not included for reasons of confidentiality.

Keywords: Platooning, UWB, WiFi -p, Interference, Range, Ranging.

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Nomenclature

Abbrevations

ABS Anti-lock Braking System

ADAS Advanced Driver Assistance Systems

API Application Programming Interface

APTS Advanced Public Transportation Systems

ATIS Advanced Traveler Information Systems

ATMS Advanced Transportation Management Systems

BER Bit Error Rate

BPM Burst Position Modulation

CACC Cooperative Adaptive Cruise Control

CACC Cooperative-Adaptive Cruise Control

CIRP Channel Impulse Response Power

CRC Cyclic Redundancy Check

CSMA Code Division Multiple Access

CSS Chirp Signal Spectrum

DAA Detect and Avoid

DAA Detect and Avoid

DPS Dynamic Preamble Select

DS-TWR Double Sided Two Way Ranging

DS-TWR Double-sided two-way ranging

DSRC Dedicated Short-Range Communications

EIRP Equivalent Isotropically Radiated Power

EIRP Equivalent Isotropically Radiated Power

ESP Electronic Stabilization Program

FEC Forward error correction

GPIO General Purpose Input/Output Pin

GPS Global Positioning Systems

ICT Information and Communication Technology

IRQ Interrupt Request

ISO International Standards Organization

ITS Intelligent Transport System

ITS Intelligent Transportation System

IVC Inter Vehicle Communication

IVC Inter-vehicle Communication

LDC Low Duty Cycle

LOS Line Of Sight

PAC Preamble Accumulation Count

PER Packet Error Ratio

PRF Pulse Repetition Frequency

PRR Packet Reception Ratio = 100 - PER

PSM Platoon Status Message

PSR Preamble Symbol Repetitions

RS Reed-Solomon

SECDED Single-Error-Correct-Double-Error-Detect

SFD Start of the frame Delimiter

SIC Successive Interference Cancellation

SIR Signal to Interference Ratio

SPI Serial Peripheral Interface Bus

SS-TWR Single-sided two-way ranging

TOF Time of Flight

TP-UWB Test Platform for evaluation and analysis of UWB

UMTS Universal Mobile Telecommunication System

UWB Ultra-Wide Band

V2I Vehicle-to-Infrastructure

V2V Vehicle to Vehicle Communication

V2V Vehicle-to-Vehicle

VFM Vehicle Following Message

Listings

Chapter 1

Introduction

1.1 Context

Automated Driving is seen as one of the key innovation areas shaping our future mobility and quality of life. The main drivers for higher levels of automated driving are the following:

- Safety: Reduce accidents caused by human errors.
- Efficiency and environmental objectives: Increase transport system efficiency and reduce time in congested traffic. Smoother traffic will help to decrease the energy consumption and emissions of the vehicles.
- Comfort: Enable user's freedom for other activities when automated systems are active.
- Social inclusion: Ensure mobility for all, including elderly and impaired users.
- Accessibility: Facilitate access to city centers.

In technology terms, the advancement towards highly automated driving is seen as an evolutionary process to ensure that all involved stakeholders can develop and evolve with adequate pace. This process already started with the development of Advanced Driver Assistance Systems (ADAS) like Anti-lock Braking System (ABS) and Electronic Stabilization Program (ESP), and will progressively apply to more functions and environments.

For the domain of commercial vehicles, especially trucks, platooning (based on Cooperative-Adaptive Cruise Control, i.e., C-ACC) is regarded as one of the most promising applications based on automated driving technologies, that improve safety (reduction of human error), efficiency (approx. 10% fuel reduction, transport or labor efficiency), and comfort for the driver. Platooning implies that the platoon is led by a vehicle which is driven by a professional driver. This driver must have a valid license and is assumed to have additional training for leading a platoon. The following vehicles are under automated longitudinal and lateral control. The following vehicle driver must be able to take over control of the vehicle in the event of a controlled or unforeseen dissolving of the platoon. Following are the advantages of platooning for trucks:

- Asset Utilization Optimization: Reduced truck idle time and enhanced efficiency.
- Fuel Consumption: In the Peloton Technology Inc. test with CR England, platooning saved 7% at 65 mph - 10% for the rear truck and 4.5% for the lead truck (Kahaner, 2015). NREL conducted track testing of three vehicles - two platooned trucks and one control truck- at varying speeds (55-70 mph), platooning distances (20-75 feet), and gross vehicle weights (65,000-80,000 pounds), platooning reduced fuel consumption at all test speeds, platooning distances, and payload weights. The lead truck demonstrated fuel savings up to 5.3%; the trailing truck saved up to 9.7%; and together, the platooning pair saved up to 6.4% (Lammert, Duran, Diez, Burton & Nicholson, 2014).

- Driver efficiency optimization: Driving or resting times.

1.2 Motivation

The control strategy for the platoon will be a combination of local control where each vehicle individually senses its environment and global control where the lead vehicle decides set-points e.g. following distance and speed but also being informed about the status and capabilities of all (heterogenous) vehicles in the platoon. Global control may also be required to avoid oscillations in the platoon as these will have a detrimental effect on fuel efficiency, safety and also passenger comfort. To achieve global control over the platoon, a communication system that interconnects the vehicles is needed (V2V Communication). Currently, this communication is only implemented with 5.9 GHz IEEE 802.11p (IEEE802.11p, 2015). In recent two-truck platooning (TPC, 2016) situation, trucks were traveling at 80 Km/hr (22.5 m/sec) with 12.5m distance between the trucks (i.e., 0.5 sec reaction time), wherein messages between the leading truck and the following truck is exchanged at 25 Hz (40 ms). Global control presents significant technical challenges when the safety requirements are considered, and it is important to have a standalone backup communication mechanism to bolster the reliability of the system.

UWB communication may be a suitable standalone backup communication mechanism considering the following advantages and disadvantages:
Advantages

- Larger Bandwidth (>500 MHz) provides enhanced resistance to narrowband interference, multi-path resistance, and more accurate ranging estimates.
- Short time domain pulses (<2 ns) of UWB systems make them ideal for combined communication and positioning.
- Ultra low power consumption, low power spectral density, low cost and lower bit error rate.
- Lower probability of intercept and detection.

Disadvantages
Need to balance:

- Spectrum requirements for applications
- Emission limits for applications
- Interference risk to sensitive radio services

UWB Technology has to fulfill the following objectives to be integrated as a secondary backup communication channel to the existing WiFi-p platooning system:

- UWB communication must not interfere with WiFi-p communication or vice versa.
- Latency requirements of the platooning application need to be met.
- It should be reliable in challenging conditions like varying relative speeds and range.
- ECC requirements should be fulfilled when applied commercially.

In this thesis, we investigate UWB technology to decide if it can be used as a secondary independent backup channel for platooning.

1.3 Problem Statement

We deduce the problem statement for our thesis based on our motivation. Currently, there is no information available to determine the suitability of using UWB as a secondary independent backup channel for platooning. We investigate UWB technology in an inter-vehicle environment to ascertain if it can be used as a secondary independent backup channel for platooning. We define a test approach to evaluate the question and implement a test platform that enables us to investigate the test approach in different test set-ups.

1.4 Research Questions

We break the problem statement into a set of research questions which the thesis answers:

1. Research Question RQ_01: What is the impact on the performance (Packet Error Ratio (PER), Message Error Ratio (MER), message latency, packet latency) of UWB in the presence of WiFi-p and vice-versa?
    - What is the effect of distance between the WiFi-p transceivers and UWB transceivers on interference (MER)?
    - What is the worst case interference of UWB on WiFi-p or vice-versa?
    - What is the effect of Channel, Preamble Length, PRF (Pulse Repetition Frequency), Standard SFD (Start of the Frame Delimiter), Non-standard SFD, Smart Power enablement, Preamble Code on the performance of UWB link in the presence of WiFi-p interference (MER)?
2. Research Question RQ_02: Sensitivity analysis of performance under various conditions:
    - What is the performance of UWB communication between trucks in platooning mode with respect to speed/acceleration differences?
    - Evaluate if range could cause negative interference (nulls) at relative distances?
3. Research Question RQ_03: What is the ranging accuracy that can be achieved through UWB when the trucks are operating in platooning mode?
    - What is the effect of standard SFD and Non-standard SFD on ranging accuracy?
4. Research Question RQ_04: Which configuration is the best configuration of UWB for platooning application?

1.5 Approach

To evaluate the performance of UWB in the presence of WiFi-p and vice-versa, we setup 2 MK5s' (GmbH, 2015) emitting WiFi-p signals at time instant 0, 15, 25 and 30 ms of a 40 ms time slot. The TP-UWB platform is set to transfer and receive four packets per message in a time slot of 40 ms to have maximum overlap between WiFi-p and UWB transmission. We choose the operating channel of WiFi-p such that we get close to the UWB frequency to the maximal extent to measure the maximum effect that interference can have, and measure the performance of UWB link by sweeping various parameters such as channels, Pulse Repetition Frequency (PRF), preamble lengths, preamble codes, Standard or non-standard SFD and Smart Power enablement. We measure the PER or MER induced by the setup with or without interference for both UWB and WiFi-p and analyze the results. We conduct the experiments by keeping the transceivers apart and at very close distance to each other. Also, we evaluate the worst case interference. We choose the best configuration of UWB such that it operates with least possible interference to WiFi-p.

To perform the sensitivity analysis, we evaluate the performance of UWB in a typical inter-vehicle and outdoor environment by sweeping parameters at various distances. For this, we conduct experiments outdoors with zero relative velocity. We determine the ranging accuracy that can be achieved through UWB. Also, we determine the performance of UWB link with respect to speed or acceleration difference for selected priority configuration. For this, we perform experiments by keeping one car stationary and move another car so that speed or acceleration difference can be induced. Analyzing all the results, we determine the best configuration of UWB for platooning application.

To conduct the experiments, we make use of the automated test platform which eases the effort and increases the speed of performing the tests. Using the automated test platform, TP-UWB, several combinations of test cases can be executed for several runs without any manual effort thereby overcoming the need to test each configuration one after the other manually. After the completion of an experiment, we use MATLAB post-processing script to extract useful information out of the logged data during the tests.

1.6 Thesis Overview

The remainder of this thesis is organized as follows. In Chapter 2, we provide a background about Intelligent Transport System (ITS), vehicle platooning, vehicular RF channel, WiFi-p, UWB and UWB ranging. Also, we provide background information about the research tools (LPCXpresso 4337 development board and DecaWave DW1000) that are used to study the UWB technology in an inter-vehicular and outdoor environment. Chapter 3 presents the related work about UWB for Inter-Vehicle Communication (IVC), interference of UWB on narrowband communication and vice-versa, UWB ranging and highlights the novel aspects of the current work. In Chapter 4, we present the set of measurement plans that are designed to study the suitability of UWB as a secondary independent backup channel for platooning. We also describe the requirements of the test platform TP-UWB. In Chapter 5, we discuss the design choices, and the implementation details of our test platform, TP-UWB, that enables us to execute the measurement plans. In Chapter 6, we discuss the duty cycle requirements for UWB. Chapter 7 discusses the experiments and the results of the measurement plans. We explain the different test set-ups that were used to perform experiments and elucidate the results of the tests conducted. Finally, we summarize the conclusions of our work and present the future work in Chapter 8.

Chapter 2

Background

In Section 2.1, we provide a background about Intelligent Transportation System (ITS). In Section 2.2 we discuss vehicle platooning concept and control functions. In Section 2.3, we describe the features of a vehicular RF channel. In Section 2.4, 2.5, and 2.6 we provide a short introduction on WiFi-p, UWB, and UWB ranging, respectively. In Section 2.7 and 2.8, we provide background about LPCXpresso4337 development board and DecaWave DW1000 UWB transceiver respectively.

2.1 Intelligent Transportation System

It is envisioned that Information and Communication Technology (ICT) can increase the efficiency of the current transportation system significantly. This will require a significant investment because embedding transportation systems with sensors, wireless communication technologies, and other electronics will be needed to make them more intelligent. Hence the name Intelligent Transportation System (ITS). According to (Ezell, 2010), ITS applications can bring benefits such as increasing driver and pedestrian safety (Facts, 2008), performance improvement of the transportation network, enhanced convenience (Drane & Rizos, 1998), delivering environmental benefits, and boosting productivity, economic, and employment growth. ITS enables a broad range of ITS applications such as Advanced Traveler Information Systems (ATIS), Advanced Transportation Management Systems (ATMS), ITS-Enabled Transportation Pricing Systems, Advanced Public Transportation Systems (APTS), Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) integration. To support the diverse array of applications, a wide range of technologies are combined by ITS such as Global Positioning Systems (GPS) (El-Rabbany, 2002), cellular technology, Dedicated Short-Range Communications (DSRC), camera recognition, etc.

2.2 Vehicle Platooning

Vehicle platooning is a concept that aims to increase the current road capacity. The key in achieving this goal is the organization of vehicles in tightly controlled groups, also called platoons that operate close together. Several implementations of vehicle platooning concept have been proposed. Some potential implementations of vehicle platooning are described below (Vugts, 2010):

Adaptive Cruise Control(ACC)

Figure 2.1 illustrates a three-vehicle platoon using ACC. Front radar of an ACC system is only able to detect vehicles in line of sight. ACC system is not able to measure the distance and speed of the vehicle driving in front of the immediately preceding vehicle or behind the vehicle or in a different lane as shown in Figure 2.2. Moreover, speed information flows down the platoons with increasing delays potentially leading to unstable platoons and unsafe traffic. To overcome these shortcomings, Cooperative Adaptive Cruise Control (CACC) is implemented in platoons.

Figure 2.1: Vehicle platoon using ACC

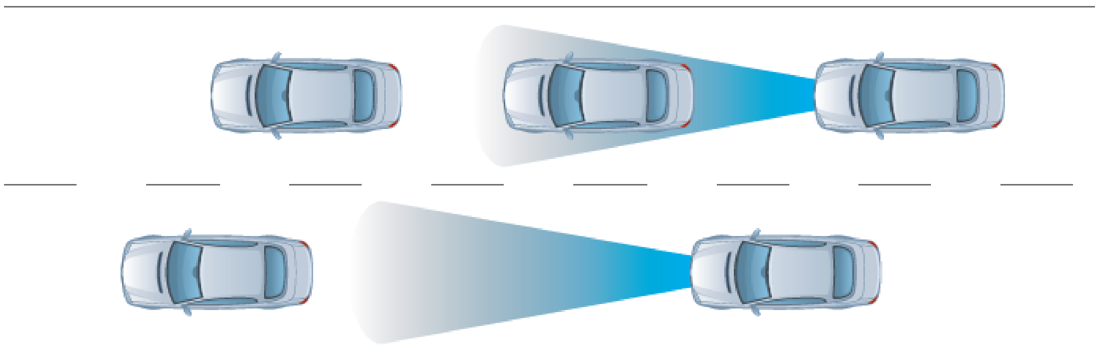

Figure 2.2: A typical view of a front-radar used in ACC

Figure 2.3: Vehicle platoon using CACC

Cooperative Adaptive Cruise Control

CACC augments ACC with wireless communication, new control logic and GPS as illustrated in Figure 2.3. Wireless communication allows vehicles to extend their view beyond the LOS of the radar. With CACC, the third vehicle in the illustration of Figure 2.3 is notified via wireless communication of the behavior of the leading vehicle. The third vehicle can almost instantly react to speed changes of the first vehicle and as a result, a CACC system enables to drive with closer headways.

Automated Highway System (AHS)

With both ACC and CACC, the driver is (partly) responsible for the operation of the vehicle. The driver is for example still responsible for steering the vehicle. The next step in vehicle platooning is a system in which vehicles are fully automated. AHS platoons are similar to CACC platoon as illustrated in Figure 2.3. However, AHS platoons rely heavily on wireless communication to create automated and high cooperative vehicles.

Advantages and Risks of Platooning

The advantages of vehicle platooning include (De Vos, Theeuwes, Hoekstra & Coëmet, 1997) an increase in road capacity, reduction of environmental impacts, improved safety, improved driver comfort, highly cooperative groups, decrease in fuel consumption (reduced air resistance), shorter commutes during peak periods, etc.

The risks of platooning include the driver is less in control being at the hands of computer software or lead driver and the driver is inattentive than usual hence not able to react as quickly to adverse situations if software or hardware fails.

Vehicle Platooning Control Functions

The most basic functionality for automated vehicles in vehicle platoons, being respectively longitudinal control, lateral control and maneuver control (Shladover, 2005).

Longitudinal control of a vehicle is the feature that controls the speed and distance to the preceding vehicle using powertrain and brakes. Implementations of the longitudinal control rely heavily on measurements of headway and the speed of the preceding vehicle. Longitudinal controllers that control the speed of a vehicle, purely based on the vehicle's sensors are classified as autonomous. Autonomous controllers are capable of maintaining string stability i.e. headway errors do not flow down the platoon, under constant time gaps between vehicles. Another type of longitudinal control is cooperative control. These controllers typically complement radar and image-processing sensors with wireless communication to collect state information (position, speed, acceleration, and maneuver information) of close operating vehicles. These type of controllers are not only able to maintain string stability under constant time gap, like autonomous controllers, but also under constant distance gaps.

The primary functionality of lateral control is keeping the vehicle in the center of the lane. Lateral control is also concerned with lane changing wherein lane changing is the feature to steer a vehicle from the current lane to an adjacent lane.

Vehicle platooning involves, apart from longitudinal and lateral control, the coordination of vehicle maneuvers. These maneuvers are typically the formation and splitting of platoons, the merging of traffic streams and coordination of changing lanes.

Additional details on platooning and its implementation can be obtained by referring to SARTRE Report on Fuel Consumption, SARTRE Report on Infrastructure and Environment, (Bergenhem, Huang, Benmimoun & Robinson, 2010), (Chan, Gilhead, Jelinek, Krejci & Robinson, 2012), (Dávila & Nombela, 2010), etc.

2.3 Vehicular RF Channel

Key characteristics of vehicular channels are shadowing by other vehicles, high Doppler shifts, and inherent non-stationarity (Mecklenbrauker et al., 2011). All have a major impact on the data packet transmission reliability and latency. For vehicular channels, it is customary to distinguish between V2V and V2I channels. These channels not only differ from each other but also deviate significantly from those in cellular communication. In cellular scenarios, the base station (BS) is fixed, elevated, and located at or above rooftop level, such that its close surroundings are free of scatterers. Furthermore, most of the relevant scatterers are immobile or move relatively slowly. The distance between the BS and the user span roughly from 10 m to 10 km. In a V2V communication scenario, there is neither an access point (AP) nor BS and both the Rx and the Tx may move with high velocities. The antennas are mounted at a the height of 1-2 m, many relevant scatterers (i.e., vehicles) move, and the distances between the Tx, the Rx, and principal scatterers are in the range of a few hundred meters. Depending on whether the scenario includes a the road in an open field or a busy street in an urban environment, the number of relevant scatterers might vary significantly.

The following five properties mainly characterize wireless channels.

- Pathloss: How does the average received power level vary with distance to the transmitter?
- Signal fading: How does the instantaneous signal level fluctuate over time, frequency, and space?
- Delay spread: How is the signal smeared in time by echoes?
- Doppler spread: How is the transmitted signal smeared in frequency due to movements of the Rx, the Tx, and scatterers?
- Angular spread: How is the transmitted signal smeared over directions by antennas and scatterers?

The propagation conditions in particular for V2V communications are influenced by the antennas and their placement on the vehicle. The roof of the vehicle can strongly affect the antenna pattern; if the antenna is placed on a backward-slanted roof, it has difficulties seeing vehicles in front of it.

The region over which the transmitter provides coverage is smaller than the area in which it creates interference. Due to high speeds involved, V2V channels show substantial time variance (the channel state changes) and non-stationarity (the channel statistics change). These effects are more pronounced for cars approaching each other or approaching intersections, while they are less severe for vehicles driving in convoys or V2I communications.

2.4 WiFi-p

An international standard, IEEE 802.11p (Committee et al., 1997), which is part of the WAVE initiative, has gained considerable importance. Based on popular WiFi standard, it is intended for both V2I and V2V traffic telematics applications and operates in the 5.9-GHz band. Its importance is further highlighted by the European decision on the use of the 5875-5905 MHz frequency band for safety-related ITS applications (Reding, 2007). IEEE 802.11p is an amendment to the IEEE 802.11 standard for vehicular networks. Modifications to the original standard were needed as the MAC, and PHY layers were never designed for mobile environments. We note that a 700 MHz band is devoted to advanced driving safety support systems in Japan (Mecklenbrauker et al., 2011). IEEE 802.11p is also one mode of communication access for land mobiles, a framework for heterogeneous packet-switched communication in mobile environments approved by the International Standards Organization (ISO). Summarizing, the IEEE 802.11p standard has established itself as the key technology for V2V and safety-critical V2I communications.

Figure 2.4 shows the DSRC spectrum band and its channels as allocated by the FCC. This allocation consists of 7 channels with a bandwidth of 10 MHz each. Some of these channels are restricted to be used for the transmission of a particular type of information. For instance, channel 178 is the control channel and can only be utilized for the transmission of safety-related data. The outer channels number 172 and 184 are reserved for special purpose communication, and the remaining four channels can be used for both safety and non-safety related communication (Chen, Jiang & Delgrossi, 2009).

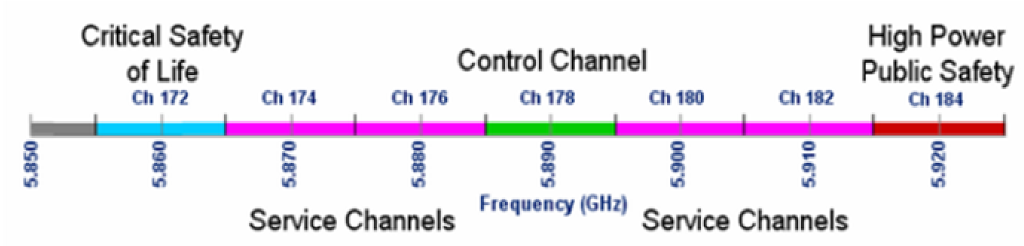

Figure 2.4: DSRC spectrum band and channels (Chen et al., 2009)

2.5 UWB

UWB differs substantially from conventional narrowband radio frequency (RF) and spread spectrum technologies (SS), such as Bluetooth Technology and 802.11 a/g. UWB uses an extremely wide band of RF spectrum to transmit data as shown in Figure 2.5.

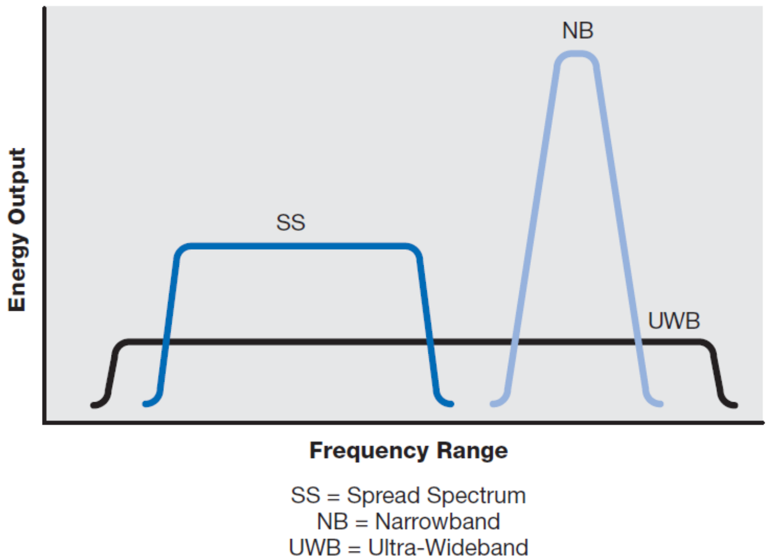

Figure 2.5: Comparision of narrowband, spread spectrum, and ultra-wideband signal concepts (Intel, 2015)

The potential data rate over a given RF link is proportional to the bandwidth of the channel and the logarithm of the signal-to-noise ratio (Shannons Law) (Haykin, 2008). RF design engineers typically have little control over the bandwidth parameter, because this is dictated by FCC regulations that stipulate the allowable bandwidth of the signal for a given radio type and application. Bluetooth technology, 802.11a/g Wi-Fi, cordless phones, and numerous other devices are relegated to the unlicensed frequency bands that are provided at 900 MHz, 2.4 GHz, and 5.1 GHz. Each radio channel is constrained to occupy only a narrow band of frequencies, relative to what is allowed for UWB.

UWB is a unique and new usage of a recently legalized frequency spectrum. UWB radios can use frequencies from 3.1 GHz to 10.6 GHz - a band more than 7 GHz wide. Each radio channel can have a bandwidth of more than 500 MHz, depending on its center frequency. To allow for such a large signal bandwidth, the FCC put in place severe broadcast power restrictions. By doing so, UWB devices can make use of an extremely wide frequency band while not emitting enough energy to be noticed by narrower band devices nearby, such as 802.11a/g radios (Karapistoli, Pavlidou, Gragopoulos & Tsetsinas, 2010). Figure 2.6 denotes the center frequencies and bandwidths of the defined bands, as well as the regulatory domains in which they are admissible. Frequency bands (channel numbers) 4, 7, 11, 15 have the same center frequency as bands 2, 5, 9, 13 respectively. This is due to the fact that bands 4, 7, 11, 15 are all "wide-band" channels whose bandwidth is larger than 1 GHz, and these bands, in fact, overlay the other 500 MHz wide bands.

freq. band	center freq.(MHz)	BW (MHz)	admissible region
0	499.2	499.2	USA,
1	3494.4	499.2	USA,Europe
2	3993.6	499.2	USA,Europe, Japan
3	4492.8	499.2	USA,Europe, Japan
4	3993.6	1331.1	USA, Europe, Japan
5	6489.6	499.2	USA, Europe
6	6988.8	499.2	USA, Europe
7	6489.6	1081.6	USA, Europe
8	7488.0	499.2	USA, Europe, Japan
9	7987.2	499.2	USA, Europe, Japan
10	8486.4	499.2	USA, Japan
11	7987.2	1331.2	USA, Japan
12	8985.6	499.2	USA, Japan
13	9484.8	499.2	USA, Japan
14	9984.0	499.2	USA, Japan
15	9484.8	1354.9	USA, Japan

Figure 2.6: IEEE 802.15.4a UWB Frequency Bands (Zhang et al., 2009)

UWB communications are based on the transmission and reception of frames. Figure 2.7 shows the general structure of the UWB frame. It begins with a synchronization header consisting of the preamble and the Start of the Frame Delimiter (SFD), after which the PHY header (PHR) defines the length (and data rate) of the data payload part of the frame.

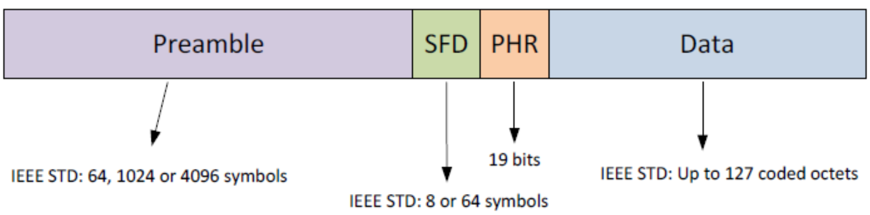

Figure 2.7: UWB PHY Frame structure (Decawave, 2015b)

Figure 2.8 shows the UWB Symbol duration, T_c is the chip (pulse) duration of approximately 2 ns, T_b is the burst-hopping duration, which equals, $T_b = NT_c = 32$ ns, n indexes the N=16

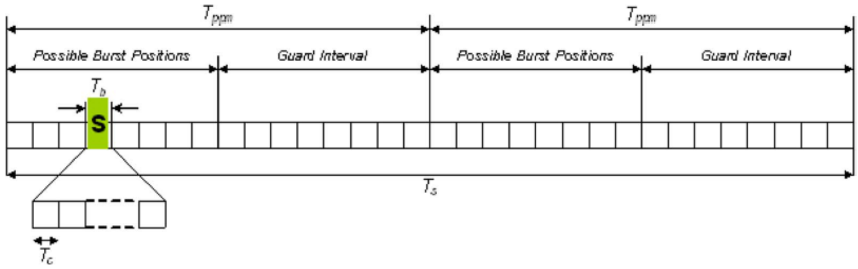

Figure 2.8: UWB Symbol duration (Mirzoev et al., 2014)

pulses that are transmitted during each data burst. T_{ppm} is the modulation interval for the pulse position modulation $T_{ppm} = 16T_b$, and T_s is the symbol duration.

The UWB used in 802.15.4 is also called impulse radio UWB because it is based on high-speed pulses of RF energy. During the PHR and data parts of the frame, information bits are signaled by the position of the burst, in a modulation scheme termed Burst Position Modulation (BPM). Each data bit passes through a convolution encoder to generate a "parity bit" used to set the phase of the burst as either positive or negative, this component of the modulation is termed binary phase-shift keying (BPSK).

Also, the quarter symbol interval is sub-divided into 2, 4, or 8 sub-intervals and a pseudo random sequence used to determine both the burst shape and which of the sub-intervals are used for the burst transmission. This gives more immunity to interference and whitens the output spectrum allowing a higher signal power to be utilized in the transmitter.

To ensure that the signals can still be decoded by noncoherent receivers, a systematic code is used wherein the systematic code is one in which the information bits are transmitted unchanged along with the parity check bits. The systematic bits are used to determine the PPM position of the burst and are visible to both noncoherent and coherent receivers. The parity bits are modulated onto the burst phase and are thus visible only to coherent receivers. Forward error correction (FEC) is also included in the PHR and data parts of the frame. The 19-bit PHR includes a 6-bit Single-Error-Correct-Double-Error-Detect (SECDED) code and the data part of the frame has a Reed-Solomon (RS) code applied. Both SECDED and RS codes are systematic (Zhang et al., 2009).

The synchronization header consists of the preamble sequence and the SFD. In contrast to the BPM/BPSK modulation used for the PHR and data, the synchronization header is made up of single pulses. The symbol is divided into approximately 500 "chip" time intervals, (496/508 depending on 16/64 MHz PRF), in which either a negative or a positive pulse may be sent, or no pulse. The "chip" interval is 499.2 MHz, a fundamental frequency within the UWB PHY, and so the resultant symbol times are thus 496/499.2 us for 16 MHz PRF, 508/499.2 us for 64 MHz PRF. It is to be noted that number of chips per burst change for PRF of 16 or 64 MHz. The number of chips per burst for 64 MHz PRF will be four times greater than the number of chips per burst for 16 MHz PRF (Mirzoev et al., 2014).

The sequence of pulses sent during the symbol interval is determined by preamble code. The standard defines eight different length-31 preamble codes for use at 16 MHz PRF and 16 different length-127 preamble codes for use at 64 MHz PRF.

The standard nominates particular codes for specific channels so that at 16 MHz PRF there are just two to choose from per channel, while at 64 MHz PRF there is a choice of four codes per channel. The length-31 codes are spread by inserting 15 zeros for each code point to give the 496 chip times per symbol while the length-127 codes are spread by adding three zeros for each code point to give the 508 chip times per symbol. The preamble length is defined by how many times (i.e. for how many symbols) the sequence is repeated. This is determined by the configuration of Preamble Symbol Repetitions (PSR).

The standard defines PSR settings of 16, 64, 1024 and 4096. The preamble sequence has a property of perfect periodic autocorrelation (Ipatov, 1979) which in essence allows a coherent receiver to determine the exact impulse response of the RF channel between transmitter and receiver. This brings two significant benefits. Firstly, it allows the receiver to make use of the received energy from multiple paths, turning multipath from an interference source into a positive affect extending operating range. Secondly, it lets the receiver resolve the channel in detail and determine the arrival time of the first (most direct) path, even when attenuated, which brings precision advantages for Real Time Location System (RTLS) applications. The SFD marks the end of the preamble and the precise start of the switch into the BPM/BPSK modulation of the PHR. The time-stamping of this event is very deterministic in terms of symbol times, and it is this in conjunction with determining the first arriving ray within that symbol time that allows the accurate time-stamping needed for precision RTLS applications.

The standard specifies the SFD, which consists of the preamble symbols either not sent, or sent as normal or sent inverted (i.e. positive and negative pulses reversed) in a defined pattern eight symbol times long for data rates other than 110 kbps, and 64 symbols long for the 110 kbps mode.

The PHY header (PHR) is modulated using the BPM/BPSK modulation scheme, but it does not employ the Reed-Solomon code used for data, instead is employs a 6-bit SECDED parity check sequence as part of its 19-bit length.

The preamble codes specified by the standard for use on a particular channel were chosen to have a low cross-correlation factor with each other with the intention that the complex channels could operate independently from each other as separate networks.

The IEEE 802.15.4 UWB PHY standard includes a feature called Dynamic Preamble Select (DPS) intended for use in a security mechanism for two-way ranging, where devices switch to using one of the DPS specific preamble codes for the ranging exchange, and perhaps a different one for each direction of communication. The idea is to make it harder to eavesdrop or spoof, by randomly changing the DPS preamble codes in a mutually agreed sequence only known to the valid participants.

2.6 UWB Ranging

In all of the schemes that follow one node acts as Initiator, initiating a range measurement, while the other node acts as a Responder listening and responding to the initiator, and calculating the range.

Single-sided two-way ranging (SS-TWR) involves a simple measurement of the round trip delay of a single message from one node to another, and a response sent back to the original node.

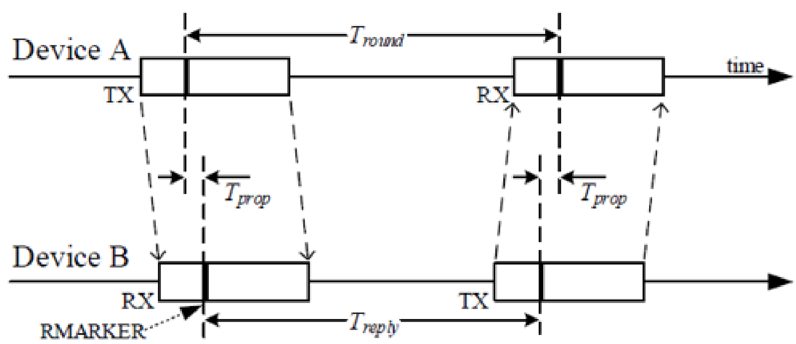

Figure 2.9: Single-sided Two-way ranging (Decawave, 2015b)

The operation of SS-TWR is as shown in Figure 2.9, where device A initiates the exchange and device B responds to complete the exchange and each device precisely timestamps the transmission and reception times of the message frames, and so can calculate times T_{round} and T_{reply} by simple subtraction. And the resultant time-of-flight, T_{prop} may be estimated by the equation:

$$T_{prop} = 0.5(T_{round} - T_{reply}) \tag{2.1}$$

The times T_{round} and T_{reply} are measured independently by device A and B using their respective local clocks, wherein both have some clock offset error eA and eB from their nominal frequency, and so the resulting time-of-flight estimate has a considerable error that increases as T_{reply} increases. Depending on the size of ranging error that is acceptable to the application, SS-TWR may be an appropriate choice for range measurement especially if the reply time T_{reply} is minimized and the clock error is low. It should be noted that the reply time T_{reply} is not just the RX-to-TX turnaround time but also includes the message length.

It can be seen that as T_{reply} increases and as the clock offset increases the error in the time-of-flight estimation increases to the point where the error is such as to render the estimation very inaccurate. For this reason, SS-TWR is not commonly used, but it is worthy of examination for particular use cases where tight tolerance clocks are used, and the communication range is relatively short (Mirzoev et al., 2014).

Double-sided two-way ranging (DS-TWR), is an extension of the basic single-sided two-way ranging in which two round trip time measurements are used and combined to give a time-of-flight result which has a reduced error even for quite long response delays. The operation of DS-TWR is as shown in Figure 2.10, where device A initiates the first round trip measurement to which device B responds, after which device B starts the second round trip measurement to which device A responds completing the full DS-TWR exchange. Each device precisely timestamps the transmission and reception times of the messages. The four messages of DS-TWR, shown in Figure 2.10, can be reduced to three messages by using the reply of the first round-trip measurement as the initiator of the second round-trip measurement. The resultant time-of-flight estimate, T_{prop}, in both the three and four message cases may be calculated using the expression:

$$T_{prop} = (T_{round1} \times T_{round2} - T_{reply1} \times T_{reply2})/(T_{round1} + T_{round2} + T_{reply1} + T_{reply2}) \tag{2.2}$$

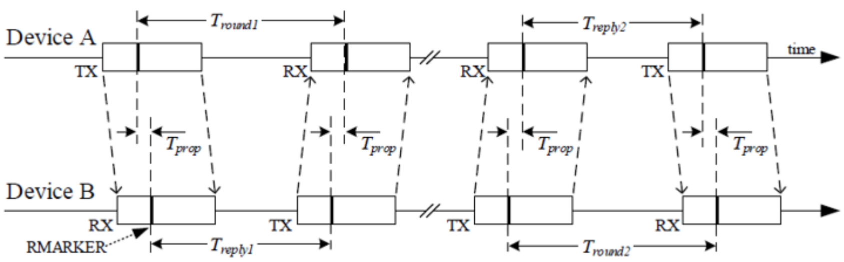

Figure 2.10: Double-sided Two-way ranging (Decawave, 2015b)

Both of the above schemes are denoted ASYMMETRIC because they do not require the reply times from each device to be the same. Using this scheme, the typical clock induced error is in the low picosecond range even with 20 ppm crystals. At these error levels, the precision of determining the arrival time of the messages at each of the receivers is a more significant contributor to overall T_{prop} error than the clock-induced error.

There is a special case of the double sided scheme known as SYMMETRIC Double-sided Two-way ranging in which T_{reply1} and T_{reply2} are restrained to be equal (or as close to equal as possible). In this case:

$$T_{prop} = (T_{round1} - T_{reply2} + T_{round2} + T_{reply1})/4 \tag{2.3}$$

This scheme requires only addition, subtraction, and division by four which is easily achieved in low power microcontrollers however it results in the entire exchange taking longer than necessary.

The sources of error for ranging include Clock drift, Frequency drift, T_{reply} (turnaround time from receiver to transmitter or vice versa, including the time required for creation of message), ranging transaction performed while one of the devices is transitioning through the crystal warm-up phase (during duty cycling) and bias which varies with received signal strength.

2.7 LPCXpresso4337 development board

The LPCXpresso4337 board (NXP, 2015) has been developed by NXP to enable evaluation of and prototyping with the LPC4300 family of MCUs and features the LPC4337 in its 100 PIN BGA package option. LPCXpresso is a low-cost development platform available from NXP supporting NXP's ARM-based microcontrollers. The platform is comprised of a simplified Eclipse-based IDE and low-cost target boards which include an attached SWD debugger. LPC4337 has a dual core (M4 and M0) MCU running at up to 208 MHz. It includes up to 264 KB of SRAM. The LPCXpresso4337 board includes the following features:

- On-board, high-speed USB based, Link2 debug probe with support for ARMs CMSIS-DAP, LPCXpresso IDE Redlink and SEGGER J-Link protocol options
- Link2 probe can be used with on-board Target MCU or external target
- Support for external debug probes
- Tri-color LED
- Target Reset, ISP and WAKE buttons
- Expansion options based on Arduino UNO and PMod, plus additional expansion port pins
- UART, I2C, and SPI port bridging from Target MCU to USB via the on-board debug probe
- UART connector

More information about the peripherals available on the chip can be found in the user manual (NXP, 2015).

2.8 DecaWave DW1000

DW1000 (Decawave, 2015b) is an IEEE 802.15.4-2011 UWB compliant wireless transceiver module. Its features include high data rate communications, low power consumption, small physical size, highly immune to fading, etc. The DecaWave DW1000 transceiver is embedded on to the LPCXpresso4337 board. It spans 6 RF bands from 3.5 GHz to 6.5 GHz and supports data rates of 110 kbps, 850 kbps, and 6.8 Mbps.

The DW1000 consists of an analog front-end (both RF and baseband) containing a receiver and transmitter and a digital backend that interfaces to a host processor, controls the analog front-end, accepts data from the host processor for transmission and provides received data to the host processor over an industry standard SPI interface.

The DW1000 provides capabilities to take accurate transmission timestamp, supports delayed transmission, extended length data frames, cyclic redundancy check, frame filtering, automatic acknowledgment, automatic receiver re-enable, etc.

DW1000 supports Smart transmit power control. The power output regulations typically specify limits as -41 dBm in each 1 MHz bandwidth and generally measure this using a 1 ms dwell time in each 1 MHz segment. When sending short frames at 6.8 Mbps, it is possible for a single frame to be transmitted in a fraction of a millisecond. So long as the transmitter does not transmit again within that same millisecond, the power of that transmission can be increased while complying with the regulations. This power increase will increase the transmission range. Smart TX power control acts at the 6.8 Mbps data rate. DW1000 allows operating using different channels, preamble codes, preamble lengths, with Standard SFD or non-standard SFD, PRF, etc.

More information about DW1000 can be found in the datasheet (Decawave, 2015a) and user manual (Decawave, 2015b).

Chapter 3

Related Work

In Section 3.1, we present the related work about the use of UWB for inter-vehicle communication, interference of UWB to other narrowband communication protocols and vice-versa, and UWB Ranging. In Section 3.2, we highlight the novel aspects of the current work.

3.1 Summary

There have been several studies conducted on UWB radars for inter-vehicle communication, interference of UWB on other narrowband communication protocols and vice-versa, the coexistence of UWB with other narrowband communication protocols and UWB ranging as indicated below.

3.1.1 UWB for inter-vehicle communication

The authors of (Kohno, 2008) state that UWB is a promising technology for both communications and ranging in highly reliable systems such as ITS and medical healthcare. The authors of (Sakkila et al., 2008) propose a road radar to be embedded on the vehicles based on UWB technology which provides good resolution and increased precision for detection and localization of obstacles, attributed to the high degree of accuracy that UWB provides and its capability to differentiate between various obstacles like cars, plates, pedestrians, etc. The authors of (Doi et al., 2004) propose an inter-vehicle UWB radar system using chirp waveforms instead of the conventional UWB-IR system that uses a modulated Gaussian pulse wherein the transmitted signal consists of a linear combination of chirp signals with the same time duration but different frequency bands. They show that this system has a lower non-detected rate than the conventional UWB-IR system, and hence suitable for ITS applications.

The authors of (Takahara, Ohno & Itami, 2012) propose a UWB radar system assisted by communication to improve safety by obtaining additional information of the target vehicle by communication. They show that it is possible to improve the precision of ranging against the distant vehicles by following this approach through computer simulations. In the proposed scheme, the data for communication is appended to the UWB radar signal and the preceding target vehicle that receives the radar signal obtains information of the following vehicle. Moreover, the target vehicle transmits its driving information to the following vehicle after specific time duration. The following vehicle receives not only the reflected radar signal but also the following communication signal from the target vehicle. By using these two signals, more precise ranging and information collection can be performed. They indicate that in a conventional UWB radar, the precision of ranging usually degrades against distant targets because of degradation of the signal to noise ratio of the reflected signal from the target vehicle. However, using the proposed scheme, it is possible to improve ranging precision by detecting the communication signal that is transmitted just after the reflected signal from the target vehicle.

In (Takahara, Ohno & Itami, 2013), the authors discuss the problems encountered as a result of the proposed system presented above. They state that near-far problem due to the difference of signal power from each vehicle and inter-symbol interference while communicating with multiple devices was encountered and propose an iterative detection system using Successive Interference Cancellation (SIC) to improve the detection rate of the signal and the bit error rate (BER) performance. In the iterative detection system, the signals except the desired signal detected by SIC is subtracted from the original received signal leading to improved performance in simulations. The authors of (Takahara, Kurosu, Namakura, Ohno & Itami, 2014) determine that the data to be transmitted through communication should include vehicle ID and the transmission time of the signal.

The authors of (Elbahhar, Rivenq, Heddebaut & Rouvaen, 2005) propose an inter-vehicle communication system based on UWB. They study two types of UWB waveforms: coded Gaussian and monocycle pulses and state that Gaussian pulses waveform was the better of the two since the obtained BER was lower than that for monocycle pulses during simulations.

3.1.2 Interference of UWB on narrowband communication and vice-versa

In (Hämäläinen, Saloranta, Mäkelä, Oppermann & Patana, 2003), the authors investigated the level of impact of UWB devices on IEEE 802.11b and Bluetooth networks using a UWB device corresponding to hundreds of FCC-compliant UWB devices because of its high transmitted power level, in the 2.4-GHz ISM band. They state that under the extreme interference conditions examined, the UWB devices can have an impact on both IEEE 802.11b and Bluetooth networks, depending on the separation from the victim system. For interference distances of less than 50 cm, the UWB interferers affected the reported SNR for both LOS and NLOS cases. The worst case degradation of the received SNR in the IEEE 802.11b was less than 15 dB for 20 UWB devices (equivalent to several thousand FCC-complaint UWB devices) at 10 cm distance. A corresponding drop in the network throughput was observed only for the NLOS case and only for distances of less than 35 cm. In the LOS case, the impact of the UWB devices was insignificant. With respect to the Bluetooth connection, they state that it does not suffer significantly from the UWB interferers. The resulting decrease in throughput was approximately 20 Kbps in the worst case.

The authors of (Sadowski & Sadowski, 2011) measured the narrowband transmission quality in the presence of impulse radio UWB interference with unmodified IEEE 802.15.4a and modified IEEE 802.15.4a IR UWB signal. They state that selective reduction of UWB power spectral density at the frequency of narrowband transmission allowed to reduce bit error rate without the need to decrease the power of UWB interferer.

In (Fındıklı, Erküçük & Çelebi, 2011), the authors assess the UWB-IR system performance in the presence of an active narrow-band system. They show that while the BER performances of coherent and non-coherent receiving structures may be slightly degraded with the use of a linear combination of pulses when there is no active narrow-band system, the performances can be significantly improved with appropriate filtering techniques at the receiver when a narrow-band system is active. The authors of (Taha & Chugg, 2002) state that interference coming from external sources degrade the UWB radio performance and depending on the frequency of narrowband interferers, they degrade the performance differently. They state that those narrow band interferers with frequencies concentrated at regions where the UWB radio pulse has stronger frequency contents, degrade the performance more severely. Moreover, they state that careful design of UWB pulse shape can mitigate the narrowband interference.

In (Ahmed & Ramon, 2008), the authors assess the effect of UWB on the Universal Mobile Telecommunication System (UMTS) and Code Division Multiple Access systems (CSMA-450). They show that, for the case of a single UWB transmitter, the UMTS can easily tolerate UWB interference when the UWB Equivalent Isotropically Radiated Power (EIRP) is -92.5 dBm/MHz or less for a distance between the UWB transmitter and the UMTS mobile of 1 m or higher. Also, they show that, for the case of multi-UWB transmitters, the UMTS can easily tolerate the UWB interference when the UWB EIRP is -94.5 dBm/MHz. For the single UWB transmitter case, the CDMA-450 downlink can tolerate UWB interference when the UWB power density is in the order of -106 dBm/MHz. For the case of multi-UWB transmitters, the power density that can be tolerated by the downlink of the CDMA-450 system is in the order of -108 dBm/MHz.

In (Chiani & Giorgetti, 2009), the authors assess the coexistence between UWB and narrowband wireless communication systems. Concerning UWB systems affected by narrowband interference, they show that the impact of narrowband interference strongly depends on, for a UWB-IR coherent receiver, on the carrier frequency of the interferer, the UWB pulse shape, and the spreading code adopted. They found that there was no significant performance degradation in the UWB link for Signal to Interference Ratio (SIR) on the order of -20 dB or greater. However, they state that the low transmitted power level currently allowed for UWB systems, which is typically much lower than that for narrowband transmitters could lead to a scenario wherein strong narrowband interferers could produce very small SIR at the UWB receiver. Similarly, for the dual case of narrowband systems affected by UWB interference, they show that the effects of a single UWB interferer are almost negligible, and the performance of the narrowband links are practically unchanged for sufficiently large SIR values. However, they state that in situations where the narrowband receiver is much closer to the UWB transmitter than to narrowband transmitter, can lead to very low SIR, with a consequent performance degradation in the narrowband link.

The authors of (Lewandowski, Putzke, Koster & Wietfeld, 2010) examine the coexistence of 802.11b and 802.15.4a-CSS through simulations and show that an error free coexistence of IEEE 802.11b and IEEE 802.15.4a-CSS is not feasible. The authors of (Mishra, Brodersen, ten Brink & Mahadevappa, 2007) show that in their UWB/WiMax coexistence experiments conducted by using a single UWB device with WiMax system, it is indeed feasible for UWB and WiMax system to co-exist by using Detect and Avoid (DAA) mechanism.

3.1.3 UWB Ranging

In (Soganci, Gezici & Poor, 2011), the authors observe that time-based ranging is well suited for UWB systems. In (Lanzisera & Pister, 2009), the authors tested outdoor ranging using two Waldo nodes in a parking lot with some cars but mostly open space. The environment was providing a baseline for ranging performance in an atmosphere where there is relatively little multipath interference. The method of communication between the nodes was through a wireless link. Range estimates were taken at distances ranging from 1 m to 45 m, and the received signal strength estimates were considered as well. They found that the received signal strength range estimates did not provide good range estimates compared to the time of flight estimates even in a mild multipath environment, but the time of flight measurements performed much better. They found that approximately 80% of the time of the flight measurements were accurate to within 1 m, but not even 20% of the received signal strength based estimates were within 1m. The authors of (Kristem, Niranjayan, Sangodoyin & Molisch, 2014) carried out UWB ranging measurement in a dense urban environment at distances of 20 m,30 m, and 40 m, with two different antenna heights. They observed that the root mean square error in the range increased from 0.12 m to 0.14 m for LOS measurements and from 7.9 m to 9.8 m in NLOS measurements when the antenna height reduced from 100 cm to 10 cm.

The authors of (Petovello et al., 2012) propose the concept of differential GPS relative navigation augmented with UWB and bearing measurements. They found that combining GPS pseudo range, UWB range, and bearing measurements can significantly improve horizontal positioning accuracy, particularly in environments where GPS availability is reduced. The UWB measurements contributed to an improved along-track relative position while the bearing measurements improved the across-track position.

The authors of (Ye, Walsh, Haigh, Barton & O'Flynn, 2011) examine the effect of LOS and NLOS ranging in indoor and outdoor environments using IEEE 802.15.4a impulse UWB transceiver. They found that the average ranging error was less than 20 cm when measured outdoors for a distance of 10 m in LOS. In the NLOS case, they found that the ranging error varied from 6 cm (Glass) to 29 cm (Door) when measured with a 3 m testing point.

3.2 Novelty

In this Section, we describe the limitations of the existing work and the novel aspects of our work in the field of inter-vehicle communication.

Limitations

1. Interference of UWB to WiFi-p or vice-versa has not been studied.
2. The influence of Channel, Preamble length, PRF, Standard SFD, Non-standard SFD, Smart Power enablement, Preamble code on UWB link in the presence of WiFi-p interference has not been studied.
3. The feasibility of using UWB as a secondary independent backup channel for platooning has not been studied.
4. The performance of IR-UWB link in the presence of speed or acceleration difference has not been documented.
5. Effect of speed or acceleration on ranging accuracy with respect to platooning has not been documented.
6. Existence of UWB Nulls has not been documented.
7. Effect of Standard SFD and Non-standard SFD on ranging accuracy has not been documented.
8. UWB for Inter-Vehicle Communication (IVC) has been evaluated only through UWB radars and simulations. UWB communication for IVC through actual experiments has not been documented.

IEEE 802.15.4a is a relatively new standard, which has not been tested in an inter-vehicle and outdoor environment for platooning. This thesis focuses on handling all the above limitations except limitation 5. We design a set of measurement goals in Chapter 4 to study the feasibility of using UWB as a secondary independent backup channel for platooning. We implement a test platform (Chapter 5) to study the measurement goals in different test set-ups. We study the LDC requirements of UWB in (Chapter 6). We conduct experiments (Chapter 7) in various test set-ups under different experimental scenarios and analyze the outcomes to study the above-mentioned measurement goals.

Chapter 4

Test Platform Requirements

In Section 4.1, we define the link quality metrics used for our experimental analysis. In Section 4.2, we list the set of goals to determine the suitability of using UWB as a secondary independent backup channel for platooning derived from our research questions. In Section 4.3, we explain the role of both the nodes in the network. In Section 4.4, we describe the data communication primitive that will be used to study the link quality. In Section 4.5, we design measurement plans. In Section 4.6, we list the set of requirements of the test platform TP-UWB that enables us to execute the developed measurement plans. In Section 4.7, we list the set of post-processing requirements.

4.1 Communication Performance Metrics

Below we define the various metrics that we use to perform the comparative analysis of different configurations.

4.1.1 Packet Error Ratio

The Packet Error Ratio gives a measure of the relative number of packets lost in a link. We define the following variables:

- A = Total number of packets transmitted by the leading truck during the data communication state at the link layer.

- B = Total number of packets received by the following truck during the data communication state at the link layer.

- C = Total number of packets transmitted by the following truck during the data communication state at the link layer

- D = Total number of packets received by the leading truck during the data communication state at the link layer.

  We define the packet error ratio (PER) of the leading truck and the following truck using the above variables.

$$PER_{LeadingTruck} = (C - D)/C \tag{4.1}$$

$$PER_{FollowingTruck} = (A - B)/A \tag{4.2}$$

4.1.2 Message Error Ratio

The Message Error Ratio gives a measure of the relative number of messages lost in a link wherein a message is a combination of several packets. We define the following variables:

- A = Total number of messages transmitted by the leading truck during data communication state at the application layer.
- B = Total number of messages received by the following truck during data communication state at the application layer.
- C = Total number of messages transmitted by the following truck during data communication state at the application layer
- D = Total number of messages received by the leading truck during data communication state at the application layer.

  We define the Message Error Ratio (MER) of the leading truck and the following truck using the above variables.

$$MER_{LeadingTruck} = (C - D)/C \tag{4.3}$$

$$MER_{FollowingTruck} = (A - B)/A \tag{4.4}$$

4.1.3 Packet Latency

It is to be noted that in this thesis, we do not retransmit the packets in the communication state. Hence the message latency and the packet latency provide an indication about the typical latencies involved when this system is integrated with any other system, the number of packets that can be transmitted and received in a given time slot, and an indication about the proper functioning of the system. A message comprises of several packets. Packet latency is the time taken to transfer a packet from the link layer of leading truck to the link layer of following truck or vice versa. We define the following variables:

- Buffer time at the leading truck when transmitting a packet, B_{LTX}: In the case of a packet sent from the leading truck to the following truck, the time required to copy the payload of a packet to the broadcast packet along with the time taken to write it to the transfer buffer.
- Buffer time at the leading truck when receiving a packet, B_{LRX}: In the case of a packet sent from the following truck to the leading truck, the time required to read the received buffer.
- Buffer time at the following truck when receiving a packet, B_{FRX}: In the case of a packet sent from the leading truck to the following truck, the time required to read the received buffer.
- Buffer time at the following truck when transmitting a packet, B_{FTX}: In the case of a packet sent from the following truck to the leading truck, the time required to copy the payload of a packet to the broadcast packet along with the time taken to write it to the transfer buffer.
- Propagation time + Transmission time, P_t = Time taken for a packet to travel from the the leading truck to following truck or vice versa.

As shown in Figure 4.1 and Figure 4.2, the packet latency for the leading truck transmitting a packet and following truck transmitting a packet can be calculated using the Equation 4.5 and 4.6 respectively.

$$Packet\_Latency_{LTX} = B_{LTX} + P_t + B_{FRX} \tag{4.5}$$

$$Packet\_Latency_{FTX} = B_{FTX} + P_t + B_{LRX} \tag{4.6}$$

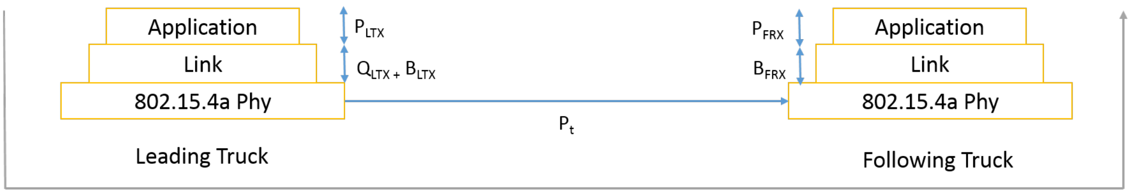

Figure 4.1: End to End latency when a message is transmitted from leading truck to the following truck

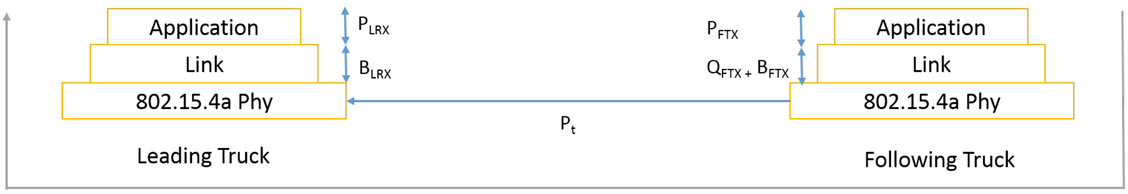

Figure 4.2: End to End latency when a message is transmitted from following truck to the leading truck

4.1.4 End-to-End Latency/Message Latency

The end-to-end latency/Message Latency is the time taken for a message to travel from the application layer of the leading truck to the application layer of the following truck or vice versa. We define the following variables:

- Processing time at the leading truck when transmitting a message, P_{LTX}: In case of a message sent from the leading truck to the following truck,the time taken to split a message into several packets and push it to the link layer of the leading truck.
- Processing time at the leading truck when receiving a packet, P_{LRX}: In the case of a message sent from the following truck to the leading truck, the time taken for the received message to be completely processed by the application layer of the leading truck after the reception interrupt.
- Queuing time at the leading truck when transmitting a packet, Q_{LTX}: When packets of a message are transmitted from the leading truck to the following truck, the time spent between transmission of each packet in the link layer of the leading truck.
- Queuing time at the following truck when transmitting a packet, Q_{FTX}: When packets of a message are transmitted from the following truck to the leading truck, the time spent between transmissions of each packet in the link layer of the following truck.
- Processing time at the following truck when transmitting a message, P_{FTX}: In the case of a message sent from the following truck to leading truck, time taken to split a message into several packets and push it to the link layer of the leading truck.
- Processing time at the following truck when receiving a packet, P_{FRX}: In the case of a message sent from leading truck to the following truck, the time taken for the received message to be completely processed by the application layer of the following truck after the reception interrupt.

As shown in Figure 4.1 and Figure 4.2, the end-to-end/message latency for the leading truck transmitting a message and the following truck transmitting a message can be calculated using the Equation 4.7 and 4.8 respectively wherein No_of_packets_per_message indicates the number of packets to be transmitted in a message.

$$Message\_Latency_{LTX} = P_{LTX} + Q_{LTX} + No\_of\_packets\_per\_message * (B_{LTX} + P_t + B_{FRX}) + P_{FRX} \tag{4.7}$$

$$Message\_Latency_{FTX} = P_{FTX} + Q_{FTX} + No\_of\_packets\_per\_message * (B_{FTX} + P_t + B_{LRX}) + P_{LRX} \tag{4.8}$$

4.1.5 Reliable and Unreliable link

We consider the links with MER less than 1% as a reliable link because we are speaking about a secondary independent channel, wherein a loss of ten message for every thousand messages is acceptable for platooning.

4.2 Measurement Goals

To answer each of our research questions introduced in Section 1.4, we design a set of measurement goals corresponding to each question.

4.2.1 Research Question RQ_01

What is the impact on the performance (Packet Error Ratio, Message Error Ratio, message latency, packet latency) of UWB in the presence of WiFi-p and vice-versa?

Measurement Goal MG_Interference

In the measurement goal MG_Interference, we investigate the performance of the UWB link in the presence of WiFi-p and vice versa based on link quality metrics PER, MER, message latency, and packet latency. Besides, we investigate the effect of Channel, Preamble Length, PRF (Pulse Repetition Frequency), Standard SFD, Non-standard SFD, Smart Power enablement, Preamble code on the performance of the UWB link in the presence of interference.

Measurement Goal MG_Distance_Between_Transceivers

In the measurement goal MG_Distance_Between_Transceivers, we study the influence of distance between UWB transceiver and WiFi-p transceiver on the links based on link quality metrics.

Measurement Goal MG_Worst_Case_Interference

In the measurement goal MG_Worst_Case_Interference, we investigate the performance of UWB link in the presence of WiFi-p and vice versa, by maximizing the time domain overlap of transmission instants, based on link quality metrics.

4.2.2 Research Question RQ_02

Sensitivity analysis of performance under various conditions:

Measurement Goal MG_Speed_Or_Acceleration_Difference

In the measurement goal MG_Speed_Or_Acceleration_Difference, we investigate the performance of UWB link in the presence of speed or acceleration difference, based on link quality metrics.

Measurement Goal MG_Nulls

In the measurement goal MG_Nulls, we investigate the performance of UWB link at a distance of 20-30 m, based on link quality metrics. A null could arise because of negative interference from different multipaths. If the Line Of Sight (LOS) signal and the multipath signal, arrive at the destination at the same instant of time, negative interference could lead to no signal being received resulting in a null.

4.2.3 Research Question RQ_03

What is the ranging accuracy that can be achieved through UWB when the trucks are operating in platooning mode?

Measurement Goal MG_Ranging_Accuracy

In the measurement goal MG_Ranging_Accuracy, we investigate the static ranging accuracy that can be achieved through UWB based on the difference between calculated distance and actual distance. Besides, we also examine the effect of Standard SFD and Non-Standard SFD on ranging accuracy.

4.2.4 Research Question RQ_04

Which is the best configuration of UWB for platooning application?

Analyzing all the results, we determine the best configuration of UWB for platooning application.

4.3 Network Topology

We use point to point topology (Figure: 4.3), wherein we have two nodes, namely the leading truck and the following truck. We use point to point topology as we consider platooning between two trucks as the situation under test and the existing EcoTwin Platooning project (project collaboratively developed by NXP, DAF Trucks and TNO) operates on the same topology (TPC, 2016).

Below we describe the functions of each component present in our network topology (shown in Figure: 4.3):

- **Leading Truck**: In the communication state, the Vehicle Following Message (VFM) is sent from the leading truck to the following truck every 40 milliseconds starting from the instant of 0 millisecond. Also, it receives the Platoon Status Message (PSM) from the following truck. The node is an LPCXpresso 4337 board with DecaWave DW1000 transceiver.

- **Following Truck**: In the communication state, the PSM is sent from the following truck to the leading truck every 40 milliseconds starting from the instant of 20 milliseconds. Also, it receives the VFM from the leading truck. The node is an LPCXpresso 4337 board with DecaWave DW1000 transceiver.

- **Laptop/PC**: Laptop/PC is used as the human interface to log the data exported by the leading truck via the serial interface. The leading truck is interfaced to a laptop/PC through a USB port.

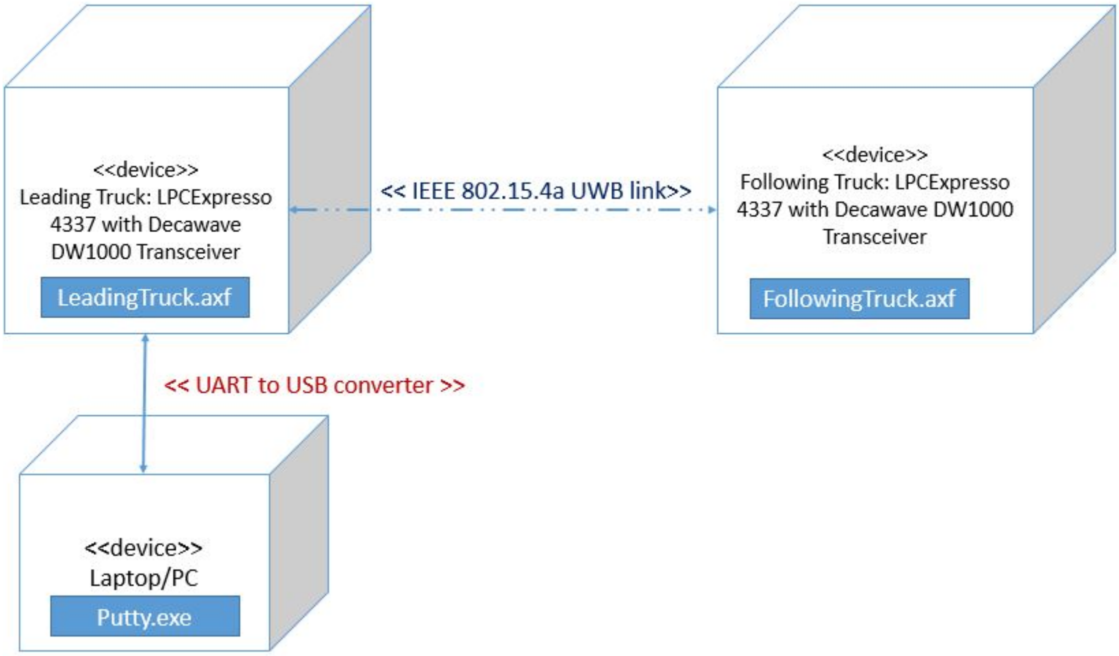

Figure 4.3: Point to Point topology deployment diagram

4.4 Data Communication Primitive

We consider the data communication primitive to quantify the link characteristics in both directions: i. Uplink: leading truck to the following truck, and ii. Downlink: following truck to the leading truck.

Data Communication: In the case of data communication state, VFM is sent from leading truck to the following truck every 40 milliseconds starting from the instant of 0 millisecond, PSM is sent from the following truck to leading truck every 40 milliseconds starting from the instant of 20 milliseconds. This communication primitive is designed to mimic the actual exchange of messages that occurs during platooning as shown in Figure 4.4.

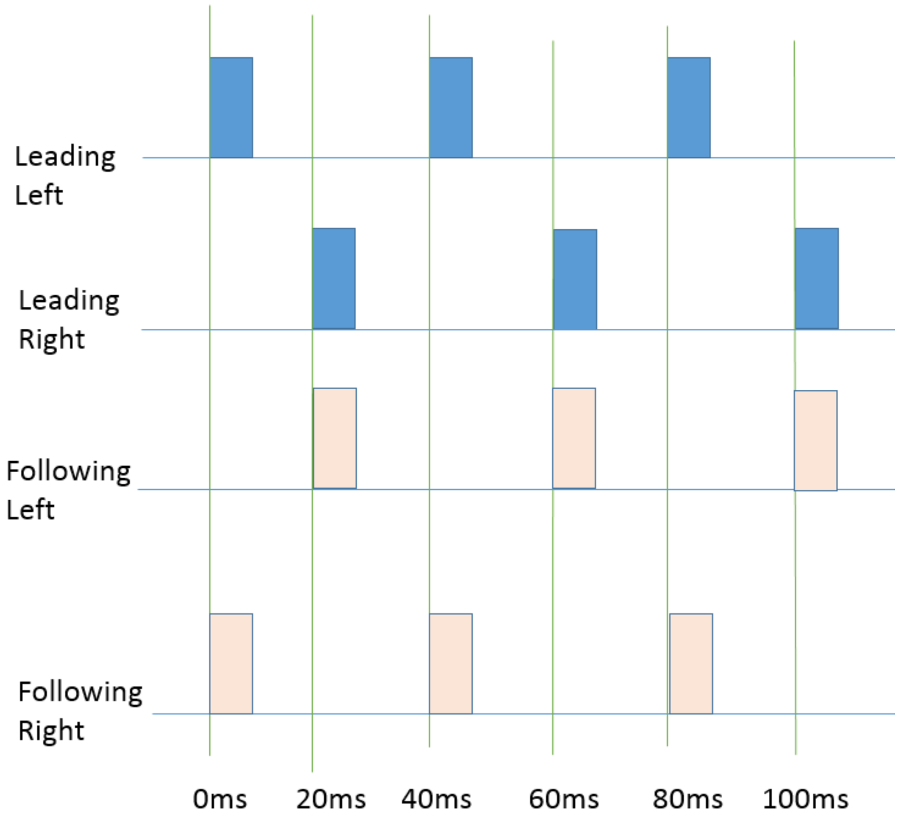

Figure 4.4: Message Exchange in Platooning Application

4.5 Measurement Plan

The measurement goals defined in Section 4.2 necessitate the need for varying different parameters such as packets per message, channels, PRF, preamble lengths, preamble codes, Standard or non-standard SFD, Smart Power enablement, distance, speed or acceleration, etc. to study their influence on the link quality. We design three measurement plans, to explore these measurement goals by sweeping a parameter over a range of values while keeping the other parameters constant. We use the measurement plan as a tool to perform experiments with/without vehicles and on the table top. Below we describe the measurement plans in detail.

4.5.1 Measurement Plan MP_Interference

In measurement plan MP_Interference, we investigate the performance of UWB in the presence of WiFi-p and vice versa based on link quality metrics. This measurement plan helps us to study measurement goals MG_Interference, MG_Distance_Between_Transceivers, and MG_Worst_Case_Interference.

To introduce WiFi-p signals, we use equipment from Cohda wireless. Python scripts are used to monitor the sent and received messages. We operate WiFi-p in channel 184 corresponding to 5.920 GHz so that we get closest to channel 7 of UWB.

UWB transceivers are placed at an appropriate distance (0cm and 80cm) to the WiFi-p antennas, and we sweep several parameters as shown in Table 4.1. UWB transceiver - leading truck transmits every 40 ms starting at the 0 ms instant, and the UWB transceiver - following truck transmits every 40 ms starting at the 20 ms instant. We run a total of 44 configurations (A.1) in this measurement plan varying several parameters as indicated in the Table 4.1.

We conduct this measurement plan keeping the distance between UWB transceivers and WiFi-p Antenna at 80 cm and 0 cm to evaluate measurement goal MG_Distance_Between_Transceivers. To assess MG_Worst_Case_Interference, we transmit as quickly as possible (one message every 8 ms) from the UWB transceiver-leading truck and receive them at the UWB transceiver-following truck without adhering to the 40 ms constraint, so that we increase the time domain overlap between WiFi-p transmission and UWB transmission.

4.5.2 Measurement Plan MP_Speed_Or_Acceleration_Difference

In measurement plan MP_Speed_Or_Acceleration_Difference, we mount the UWB transceivers on the mirrors of two cars. We make static measurements, following which we move one of the cars at 5-15 Km/hr to determine the influence of speed or acceleration difference on the performance of UWB link based on the link quality metrics. In this measurement plan, we vary parameters according to Table 4.2. To overcome the major drawback of short range when using 6.8 Mbps data rate, we make use of 110 Kbps as the data rate in this measurement plan. This measurement plan helps us to study the measurement goals MG_Nulls and MG_Speed_Or_Acceleration_Difference.

4.5.3 Measurement Plan MP_Distance

In measurement plan MP_Distance, we investigate the influence of distance on UWB link, based on the link quality metrics. Here, we keep the UWB transceivers at various distances and measure the link quality. In this measurement plan, we vary parameters according to the Table 4.3. This measurement plan helps us to study the measurement goals MG_Ranging_Accuracy and MG_Nulls. We also determine the effect of antenna position on the link quality.

Table 4.1: Configurations for measurement plan MP_Interference

Sweep Parameter	**Value**
Channels	Channel 1, Channel 3, Channel 5 and Channel 7
PRF	16Mhz and 64 MHz
Data Rate	6.8 Mbps
Preamble Lengths	256, 128 and 64
SFD	Standard or Non-Standard SFD
Distance between WiFi-p antenna and UWB transceiver	80 cm and 0 cm
Smart Power Enablement	With and Without Smart Power Enablement
Preamble Code	According to the Channel

Table 4.2: Configurations for measurement plan MP_Speed_Or_Acceleration_Difference

Sweep Parameter	**Value**
Channel	Channel 1
PRF	64 MHz
Data Rate	110 Kbps
Preamble Lengths	2048, 4096
SFD	Standard or Non-Standard SFD
Preamble Code	According to the Channel

Table 4.3: Configurations for measurement plan MP_Distance

Sweep Parameter	**Value**
Channel	Channel 1, Channel 4
PRF	16 MHz, 64 MHz
Smart Power	Enabled or Not Enabled
Data Rate	110 Kbps, 850 Kbps, 6.8 Mbps
Preamble Lengths	2048, 4096, 1024, 256
SFD	Standard or Non-Standard SFD
Preamble Code	According to the Channel
Antenna Position	0, 45, 90, 135, 180, 225, 270, 315 (degrees)
Distance	10, 15, 20, 25, 30, 35, 40, 45, 50 (meters)

4.6 Test Platform Requirements

The test platform implements the necessary functionalities to execute the measurement plans discussed in Section 4.5. Based on our measurement plans and measurement goals defined in the previous Sections, we develop the following set of requirements for our test platform.

1. It must support point to point topology with one transceiver-leading truck and another transceiver-following truck.
2. It must implement data communication workload and transmit/receive according to the 40 ms schedule.
3. It must enable us to vary parameters such as packets per message, channels, PRF, preamble lengths, preamble codes, Standard or non-standard SFD and Smart Power enablement.
4. It must capture physical layer metrics such as Channel Impulse Response Power (CIRP), Preamble Accumulation Count (PAC), accurate time stamps for ranging, and sequence numbers of the test payload, at both transceivers.
5. It must enable the following truck to store the logging information and communicate this information to the leading truck.
6. It must allow the transceivers to send the logging information and print the log via the serial interface connection to the laptop/PC.
7. It should run autonomously without human intervention and execute all possible test combinations of parameters based on the selected measurement plan so that the manual effort required for the same can be significantly reduced.

4.7 Post Processing Requirements

The task of the post-processing scripts is to parse and extract useful information from the logs created during the experiments.

For the post processing we have the following requirements:

1. It must be able to process logs resulting from a full night test.
2. It should parse the log files and store the data appropriately so that desired kind of graphs such as PER vs. Channel, MER vs. Channel, MER vs. Distance, Measured Distance vs. Calculated Distance, etc. can be created.

Chapter 5

Test Platform Implementation

In this chapter, we describe in detail the design (Section 5.1), key design choices (Section 5.2), and the implementation details (Section 5.3) of the Test Platform for evaluation and analysis of UWB (TP-UWB).

5.1 Test Platform Design

The test platform as shown in Figure 5.1 consists of five phases:

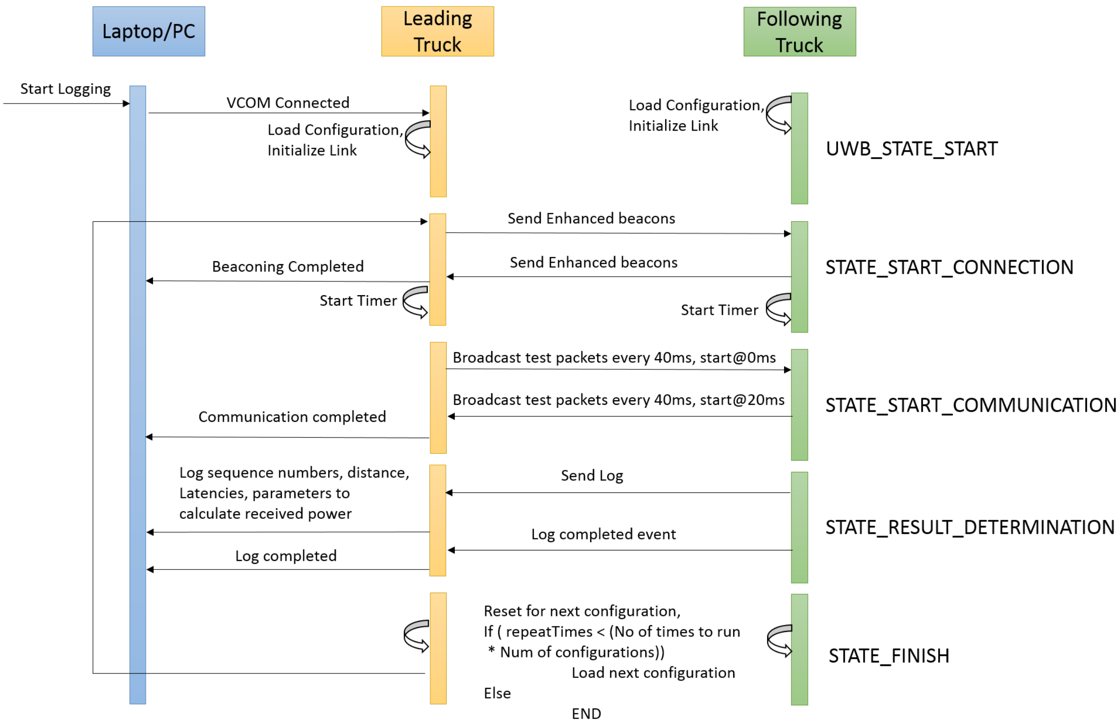

Figure 5.1: Phases of test platform

1. **UWB_STATE_START**: In this phase, the leading truck will be waiting for the VCOM connected event from the laptop/PC to start execution. Once it receives this event, the first configuration is loaded, and the link is initialized. The following truck does not wait for the

VCOM connected event and starts execution on power-up wherein the first configuration is loaded, and the link is initialized. In link initialization, we set the MAC address of the node, configure event counters, set the receiver to infinite timeout, set preamble detect to infinite timeout, enable frame filtering only to accept acknowledgment, data and beacon frames destined to that particular node. Also, we enable interrupts for frame sent, frame received with good CRC, receiver PHY header error, receiver CRC error, receiver sync loss error, frame wait timeout, preamble detect timeout, SFD timeout and frame rejected. Moreover, we set the pointer to the TX callback function that gets executed after the transfer of a packet and set the pointer to the RX callback function that gets executed after the reception of a packet.

2. **STATE_START_CONNECTION**: In this phase, the following truck will be waiting infinitely for the first beacon. The leading truck will transmit a beacon every 10 ms starting at 0 ms instant and wait for the reception of a beacon from the following truck until the next transmission. In each beacon, it transmits the remaining number of beacons it requires to go to next state. Similarly, the following truck sends a beacon (indicating the required remaining number of beacons) every 5 ms and waits for the reception of a beacon from the leading truck until next transmission. Once a defined number of beacons are received sequentially, the leading truck and the following truck go into the next state respectively.

3. **STATE_START_COMMUNICATION**: In this phase, the leading truck broadcasts test messages every 40 ms starting at 0 ms time instant and the following truck broadcasts text messages every 40 ms starting at 20 ms time instant. We synchronize on the reception of the first packet from the leading truck to the following truck. The following truck stores the log information (sequence numbers, message latency, packet latency, distance and values for calculation of received power level) of the test packet received from the leading truck.

4. **STATE_RESULT_DETERMINATION**: In this phase, the following truck sends the stored log information of the received test packets to the leading truck. The leading truck on receiving this log information, sends it serially to the laptop, along with its log information of the received test packets from the following truck.

5. **STATE_FINISH**: During this phase, we reset for execution of the next configuration, if (repeatTimes <(No of times to run * Number of configurations)), we load the next configuration and go to the STATE_START_CONNECTION phase, else the test is stopped.

5.2 Important Design Choices

Below we list the key design choices of the test platform:

1. Suitable ranging method: We have three different ways, the pros and cons of each method are provided in Table 5.1. We choose Double Sided Two Way Ranging (DS-TWR) as the method for implementing ranging attributed to the facts that the number of packets required for ranging is small when the application is considered for a large number of following trucks, reply times can be asymmetric, and error in calculated TOF is minimized. Also, the processor on LPCXpresso4337 can easily handle multiplication and division operations in a short duration of time.

2. Compliance to standards or non-compliance to standards: This question arises due to the additional 39 bytes (maximum value) of MAC header for each packet. The pros and cons of these two options are indicated in the Table 5.3. We choose to comply to the IEEE 802.15.4 standard so as to support interoperability, and hence break messages (>127 bytes) into several 127 byte packets.

3. Choice of data rate: The pros and cons for all the available three data rates are provided in the table 5.5. We make use of all the three data rates in different measurement plans attributed to their respective advantages.

Design Choice	Pros	Cons
Single Sided Two way Ranging	• Only one message exchange required which saves time & power (within approx. 40 ms + delta time, the ranging value can be determined).	• Time of Flight (TOF) estimate error increases as Treply increases (turn around time) and as clock offset increases. • If tight tolerance clocks are used, Treply is short & communication range is relatively short then it might be worthy of examination.
Double Sided Two way Ranging	• Reply times need not be the same. • Error in calculated TOF is minimized. • In case of platooning, the number of packets required to determine the range = N+2 (N=Number of following trucks).	• Requires multiplication and division operations. • Requires 4 messages to determine the range • Within approx. 80 ms + delta time, the ranging value can be determined.
Symmetric Double-Sided Two way Ranging	• Requires only simple math operations to derive a result.	• Does not seem suitable for platooning when the number of trucks in the platoon is increased as the number of packets required for ranging = 3N (N= Number of following trucks). • Reply times must be the same - difficult to achieve. • Error induced is proportional to difference between the reply times. • The ranging exchange is longer than necessary because all reply times must be as long as the longest reply time. • Increase in latency.

Table 5.1: Design Choice - Ranging

Design Choice	**Pros**	**Cons**
Compliance to Standards	• Interoperability: Ability of devices to work together relies on products and services complying with standards. • Reliability & Safety: More dependable. • Foundation for new features • Business benefits: Market access, awareness, etc.	• Additional latency during communication. • Increase in coding complexity as messages (>127 bytes) need to be broken down into several 127 byte packets
Non Compliance to Standards	• Decrease in latency during communication. • Decrease in coding complexity.	• Incompatibility with other equipment. • Restricted to one manufacturer or supplier

Table 5.3: Compliance to Standards vs Non Compliance

Data Rate Parameter	**Pros**	**Cons**
110 Kbps	• Range of signal increases. • Ideal for better ranging results and high multipath environments.	• Very high latency (13.5424 ms).
850 Kbps	• Latency better than that of 110 kbps (2.2430 ms). • Ranging accuracy better than that of 6.8 Mbps.	• Latency more than that of 6.8 Mbps. • Ranging accuracy less than that of 110 Kbps.
6.8 Mbps	• Low latency (0.4404 ms). • Data rate similar to that of 802.11p. • Shortened Tx and Rx times, better battery & appropriate for burst interference environments.	• Ranging accuracy will be reduced, • Range/distance reduces

Table 5.5: Pros/Cons - Data Rate

4. Choice of Preamble Length and SFD or Non-standard SFD:
   - **Shorter preamble length**: Reduces transmission and reception time.
   - **Longer preamble length**: Guarantees higher security, improves range and ranging accuracy.
   - **Non-standard SFD sequence**: More robust than IEEE 802.15.4 standard, improved performance and improved ranging accuracy because of more accurate time stamps.
   - **Standard SFD sequence**: If we use non-standard SFD, it will be impossible to inter-work with a device expecting a standard SFD sequence.

   From the above facts, instead of choosing a single preamble length or Standard SFD or non-standard SFD, we use them as a sweep parameter to determine the influence of these factors on the performance of UWB.

5. The test platform consists of two application binaries which will be flashed into the respective devices (leading truck and the following truck). One application implements the functions of the leading truck and will be flashed to the leading truck and other implements the functions of the following truck and will be flashed into the following truck.

6. We send data communication packets from the leading truck to the following truck and vice-versa every 40 ms according to the typical platooning application requirement.

7. We log the values onto the laptop/computer only at the end of configuration execution because printing the logs serially during communication causes deviation from the desired schedule when the COM port is busy. Hence we store the required values until the end of configuration execution.

8. Limited by the logging information that can be stored in RAM, we send 250 messages when we have three or four packets per message and 500 messages when we have two or one packet per message.

9. There exist state transitions in the leading truck and the following truck. We make use of the timeout mechanism in both leading truck and the following truck to come out of a phase if it does not receive within the maximum time window. For example, in the communication state, both nodes transmit messages at their respective time instants irrespective of whether a message is received or not and move into the next state as designed.

10. We operate in two settings: reliable and test settings. We make use of 110 Kbps data rate in the reliable settings. We are in reliable settings during the STATE RESULT DETERMINATION. We use test settings during the STATE START COMMUNICATION. The test settings are based on the current test case.

11. There are four types of messages exchanged between the nodes namely: MSG ID TEST DATA, MSG ID COMMUNICATION RESULT, ACK, BEACON in states STATE START COMMUNICATION, STATE RESULT DETERMINATION, STATE RESULT DETERMINATION, STATE START CONNECTION respectively.

12. The following truck synchronizes on the first communication packet received in the STATE START COMMUNICATION. We do not use beacons to synchronize every message considering the additional packet that needs to be transmitted. The additional packet for every message plays a significant role considering the latency and LDC requirements of the system, and operation of the platooning application.

5.3 Architecture

The system is designed to operate as a UWB subsystem in the platooning system as shown in Figure 5.2 wherein UWB acts as a secondary independent back up channel. The software overview of TP_UWB is shown in Figure 5.3. We use NXP LPCXpresso4337 development board, which has a dual-core: Cortex M4 and M0 MCU. The DW1000 UWB transceiver is connected to LPCXpresso4337. TP_UWB software is organized as two files namely application and link. The link file makes use of DecaWave device Application Programming Interface (API) to interact with the transceiver. 'DW1000' file ports the DecaWave device API to the LPCXpresso4337. The interface between LPCXpresso4337 and DW1000 is through the DecaWave device API, which internally makes use of a Serial Peripheral Interface Bus (SPI), an Interrupt Request (IRQ) and a General Purpose Input/Output pin (GPIO).

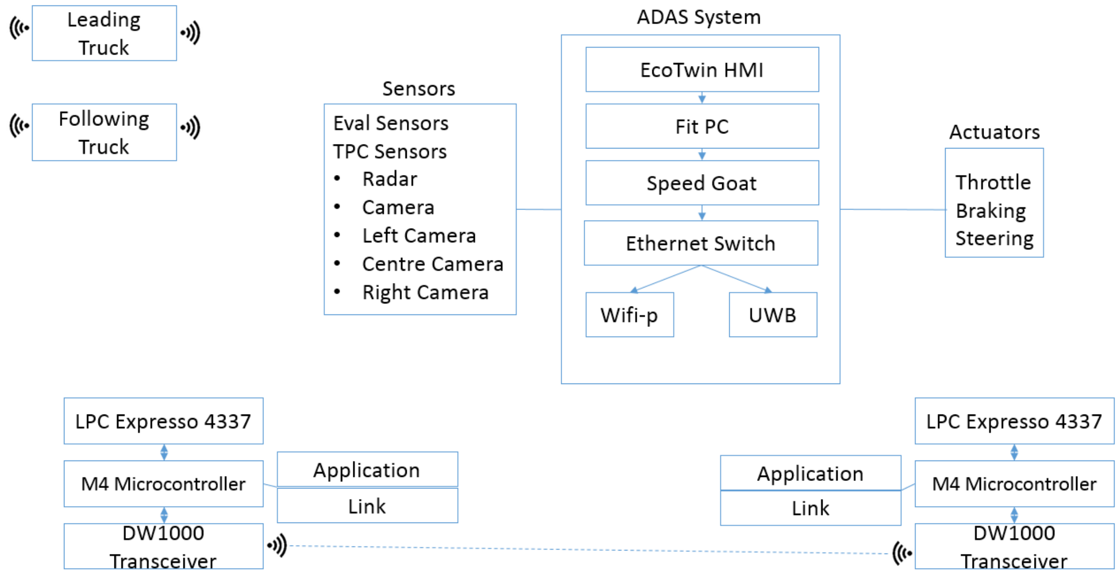

Figure 5.2: Wifi-p + UWB in platooning system

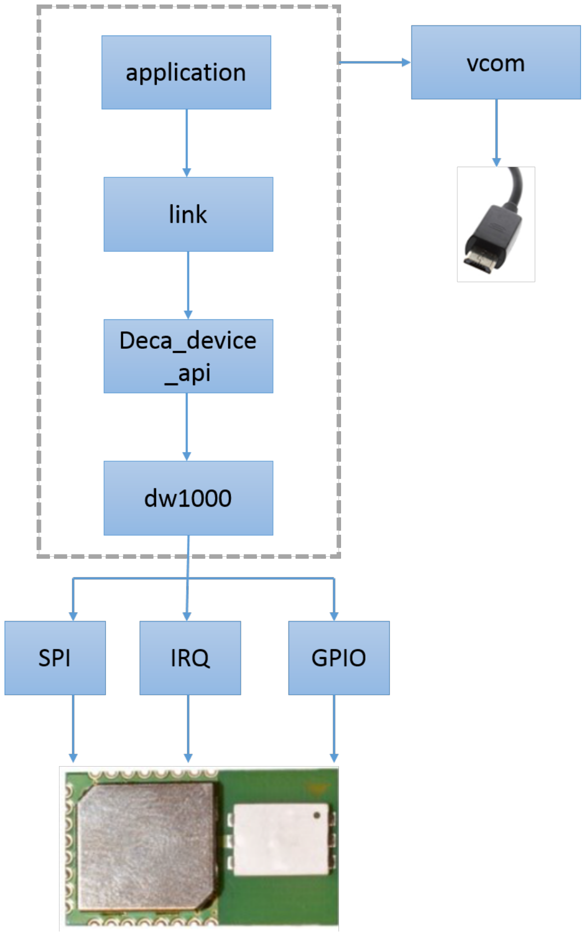

Figure 5.3: Software Overview

5.4 Implementation

Below we explain the set of actions executed in each state and the events which cause state transitions in detail.

5.4.1 State Connection

For this phase, several methods were tried. In the first method, the desired number of beacons were sent from the leading truck to the following truck, and the same number of desired beacons were sent from the following truck to the leading truck. In the latter case, the number of beacons received from the leading truck is sent in the beacons from the following truck to the leading truck. Finally, the number of beacons received from the following truck is sent in the beacons from leading to the following truck. The timeout for this phase was set to 300 ms and even on successful completion of all the above three transmissions and receptions, we wait for the elapse of this 300 ms. So that both the devices enter the next state at the same time. If the number of beacons received is more than the desired number, then the node goes to the next state, else repeat. This method did not work in all circumstances, in few special cases, the code went into infinite trials. Another method that was tried was to have 200 ms and 300 ms as respective timeout durations for leading truck and the following truck respectively. This method was also not effective.

Next method was to transmit a beacon every 10 ms from the leading truck to the following truck with the remaining number of beacons to be received to move to the next state and wait for reception of a beacon until its next transmission. Here, the following truck transmits a beacon every 5 ms to the leading truck with the remaining number of beacons to be received to move to the next state. The respective nodes were to receive a desired number of beacons to go to the next stage. This method of beaconing failed if the last beacon was received in the following truck but not in the leading truck.

The method that worked appropriately was to synchronize on the first packet that is received in the following truck from the leading truck in STATE_COMMUNICATION.

5.4.2 State Communication

The working of state communication phase is given in Figure 5.4. On entering this phase, we set a variable *communicationMode* to 1 and on leaving this phase, we set it back to 0. This ensures that a part of the interrupt handler is executed only when executing in this particular phase. We set *autorxreenable* to 1, so that in a case of an error during a reception, the receiver is re-enabled quickly. We set default antenna delay values for transmission and reception.

In the case of the following truck, we set Timer2 to interrupt after 20 ms, Timer1 to interrupt every 40 ms and Timer 3 to tick every 1 μs. It is to be noted that we only set the three timers but do not enable them immediately. We enable reception for the first message. The following truck waits indefinitely for the first packet. On reception of the first packet, we enable Timer3 and Timer2. While waiting for the other packets of a message, if the Timer2 interrupt occurs then we go ahead and transmit the next message according to the schedule of every 40 ms with an offset of 20 ms from the leading truck. Even on the successful reception of the first message, we wait for Timer2 interrupt to occur. We enable Timer1, and if the messageCounter is less than or equal to *NO_OF_MESSAGES*, then we transmit and enable reception. On the occurrence of every Timer1 interrupt, we enable Timer2 for reception timeout duration. Hence for the first instant when Timer1 is enabled, we define reception timeout for this instant using software defined timeout (Timer3). After successful/unsuccessful reception of this second message, we wait for the Timer1 interrupt to occur. It is to be noted that Timer2 is enabled in the interrupt handler of Timer1 interrupt, hence the occurrence of Timer1 interrupt indicates Timer2 is enabled for reception timeout duration. We transmit a message if messageCounter is less than or equal to *NO_OF_MESSAGES* at this instant and enable the receiver until Timer2 interrupt. As a consequence of the successful/unsuccessful reception, we wait for Timer1 interrupt, transmit a message if messageCounter is less than or equal to *NO_OF_MESSAGES*, and enable reception. This process continues until messageCounter is equal to the *NO_OF_MESSAGES*.

In the case of the leading truck, we set Timer1 to interrupt every 40 ms, Timer3 to tick every 1 μs. On transmission of the first packet, we enable Timer3 and Timer1. Similar to the case of the following truck, on the occurrence of every Timer1 interrupt, we enable Timer2 for the reception timeout duration. Hence for the first instant when Timer1 is enabled, we define reception timeout for this instant using software defined timeout (Timer3). After successful/unsuccessful reception of this message, we wait for the Timer1 interrupt to occur. This process now continues very similar to that of the following truck indicated above. The test data structure data type is shown in Listing 5.1.

```c
typedef struct {
uint8 type;
uint8 timeStamp[4];
uint8 rangingMessage[32];
uint8 transferPayload[PAYLOAD_SIZE_CAN_TRANSMIT];
} msg_app_test_data;
```

Listing 5.1: Test data structure definition

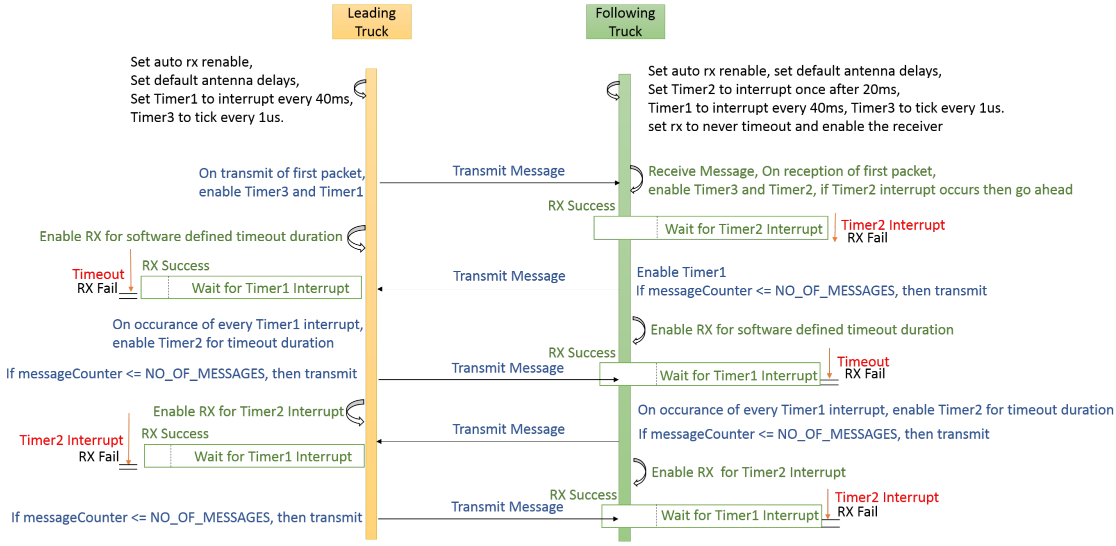

Figure 5.4: Process flow in State Communication

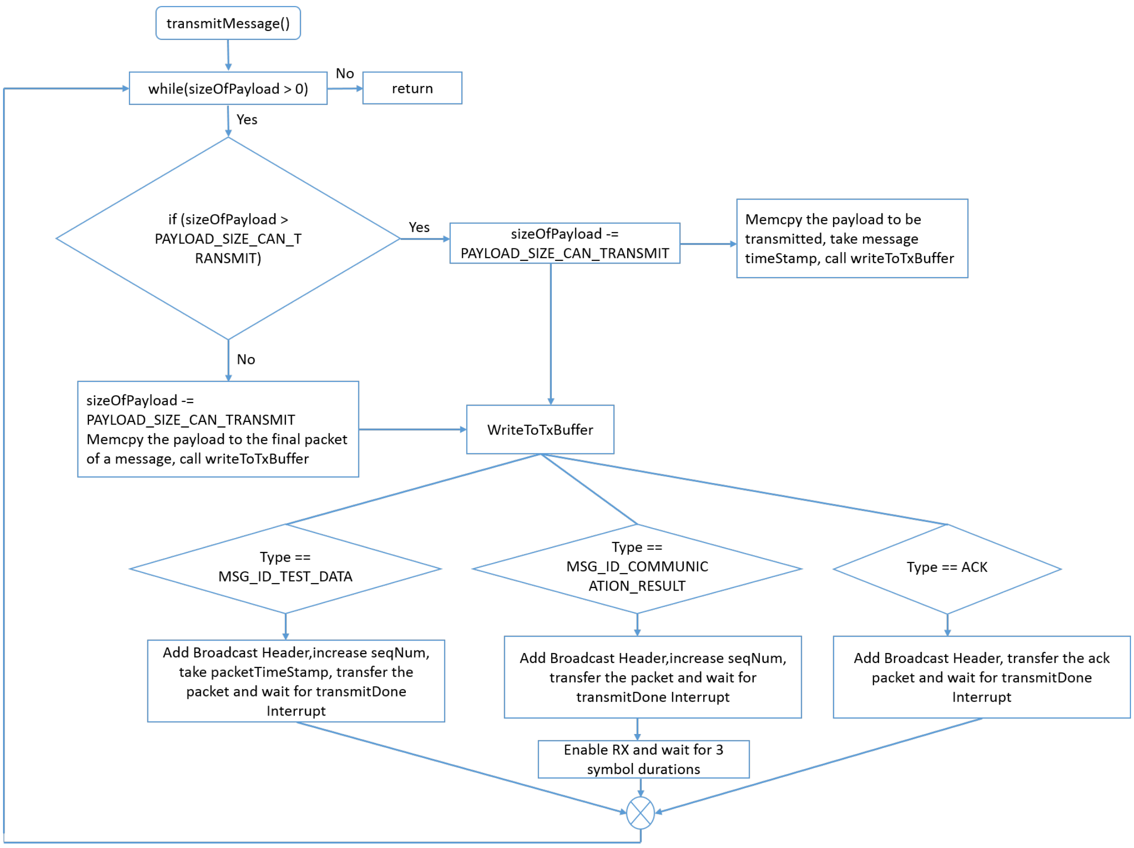

Figure 5.5: Process of transmission of a message

Transmission

Now, let's consider in detail how the transmission works in the leading truck and the following truck which is indicated in the Figure 5.5. Inside a while loop, we check if the size of the payload

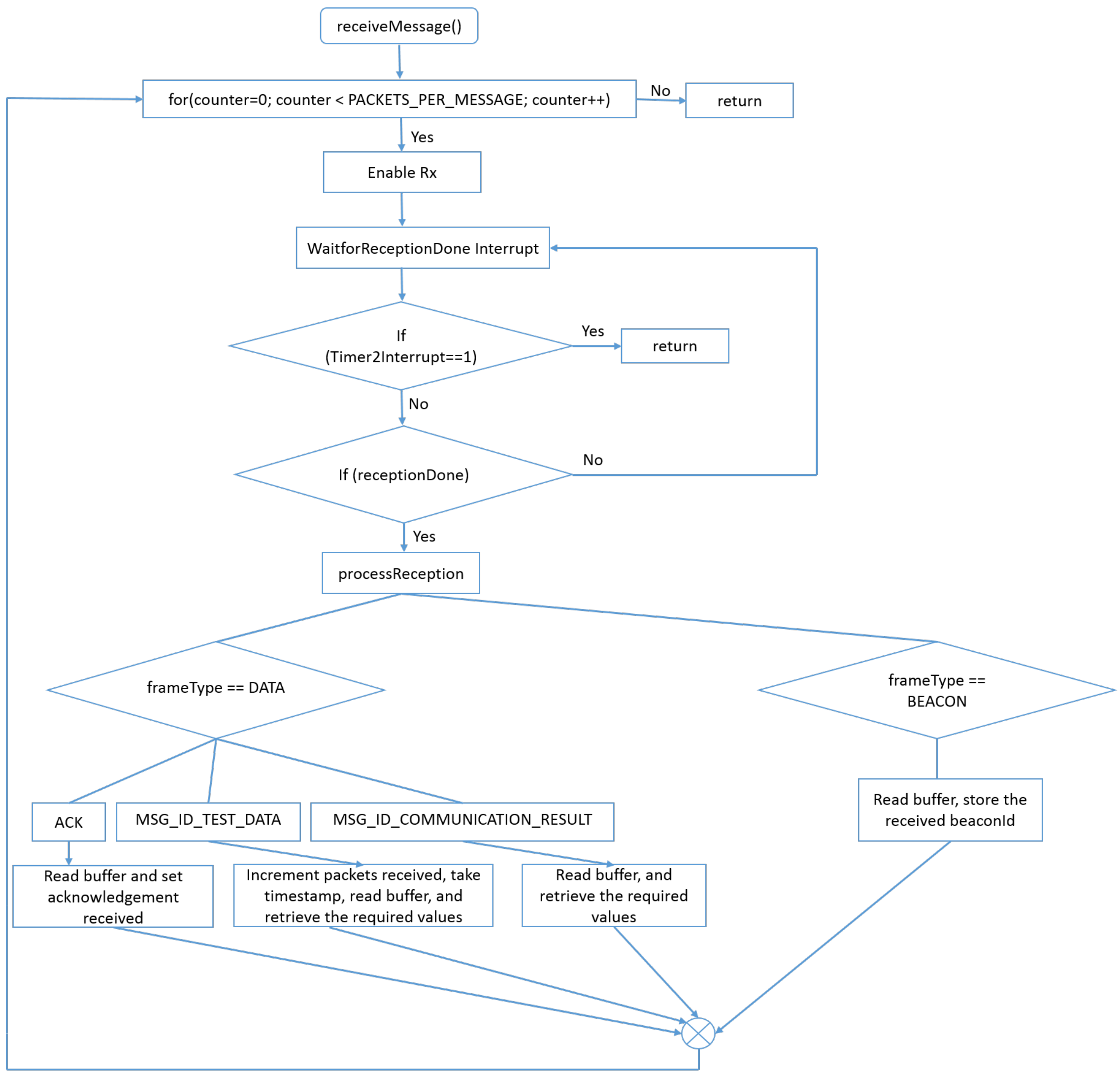

Figure 5.6: Process of reception of a message

is greater than 0. If so, we split the message into several 127-byte packets according to the IEEE 802.15.4 standard, copy the parts of a message appropriately to individual packets, take message timestamp and call *writeToTxBuffer*. In *writeToTxBuffer*, the transmission of MSG ID TEST DATA, MSG ID COMMUNICATION RESULT, and acknowledgment are handled in different ways. In the case of MSG ID TEST DATA we add the broadcast header, increase the sequence number, take the packet timestamp, transfer the packet and wait for the trasmitDone interrupt. In the case of MSG ID COMMUNICATION RESULT we add the broadcast header, increase the sequence number, transfer the packet and wait for the transmitDone Interrupt. Consequently, we enable RX and wait for three symbol durations for the reception of the acknowledgment. In the case of ACK, we add the broadcast header, transfer the acknowledgment packet and wait for the transmitDone interrupt. Once the size of the payload becomes 0, we exit from the while loop. In between two transmissions, we wait for 2 ms for successful reception of a packet at the receiver.

Reception

Figure 5.6 shows how the reception is implemented. When the *receiveMessage()* function is called, we enable the receiver for the first packet of a message and wait for the receptionDone interrupt.

While waiting for the receptionDone interrupt, if the Timer2 interrupt occurs which indicates the reception timeout for that particular slot, we return and wait for the Timer1 interrupt, following which we transmit the next message according to the schedule. On the successful reception of the first packet of the message, we process the reception according to the type of the packet received. Since we can only differentiate between the BEACON and DATA message type, we identify the acknowledgment packet, test data and result communication packets based on the global volatile variables: acknow, final=false and final=true respectively. On reception of an acknowledgment packet, we read the buffer and set acknowledgment received to one. On the reception of a test data packet, we increment the number of packets received, take the time stamp, read the buffer and retrieve the required values. On the reception of communication result packet, we read the buffer and retrieve the required values. In the case of reception of a beacon packet, we read the buffer and store the received *beaconId*. Once the reception of the first packet is processed, we enable reception for the second packet of a message, and the process repeats for all packets of a message and returns once all packets of a message are received or if the Timer2 interrupt occurs.

Latency Calculation

We make use of Timer3 for the latency calculation. Figure 5.7 and Figure 5.8 show the latency calculation for the leading truck and following truck respectively. In order to obtain the message latency, we take the timestamp of the first packet of a message in the application layer before *writeToTxBuffer* function is called and we take the timestamp of the last packet of a message in the application layer after obtaining its payloads, and take the difference between them.

For packet latency, we take the timestamp in the link layer for every packet, in the function *writeToTxBuffer* before copying the payload to the broadcast payload, following which it is written to the transfer buffer and transmission started. We take the timestamp in the link layer once the same packet has reached the other node, in the function *processReception* that is called after a reception interrupt is handled.

In Figure 5.7, the x-axis denotes the time, the top part of the figure indicates the leading truck and the bottom part of the figure indicates the following truck. The figure depicts the scenario of two packets per message being sent from the leading truck to the following truck. The message latency is the difference of timestamp $t6$ in the following truck and timestamp $t1$ in the leading truck. The packet latency is the difference of timestamp $t4$ in the following truck and timestamp $t2$ in the leading truck or difference of timestamp $t5$ in the following truck and timestamp $t3$ in the leading truck.

Similarly, the calculation of message latency and packet latency for the following truck is shown in the Figure 5.8 wherein a message is transmitted from the following truck to the leading truck.

5.4.3 State Result Communication

The working of State Result Communication is indicated in the Figure 5.9. If messageCounter >*NO_OF_MESSAGES*, we set final=true and enter State Result Communication in both nodes. It is to be noted that the leading truck enters this state earlier than the following truck because of the 20 ms offset in the following truck. We set Timer2 for the timeout duration for the entire phase and enable timer2. We make use of the reliable settings in this phase, wherein we use the lowest data rate of 110 kbps and make use of acknowledgment for each log sent in this phase.

In the case of the following truck, for a particular log, we define *MAX_ATTEMPTS* as the number of times to repeat sending that particular log until an acknowledgment is received. If the number of attempts is less than or equal to the *MAX_ATTEMPTS*, we transmit that particular log. Following which, we set Timer1 to timeout after three symbol durations, enable Timer1 and enable receiver for the reception of acknowledgment. On the occurrence of Timer1 interrupt, we increment the number of attempts, go back and transmit that particular log again if the number of attempts is less than or equal to the *MAX_ATTEMPTS*. On the reception of acknowledgment, we set the number of attempts to 0 and transmit the next result log if the number of attempts

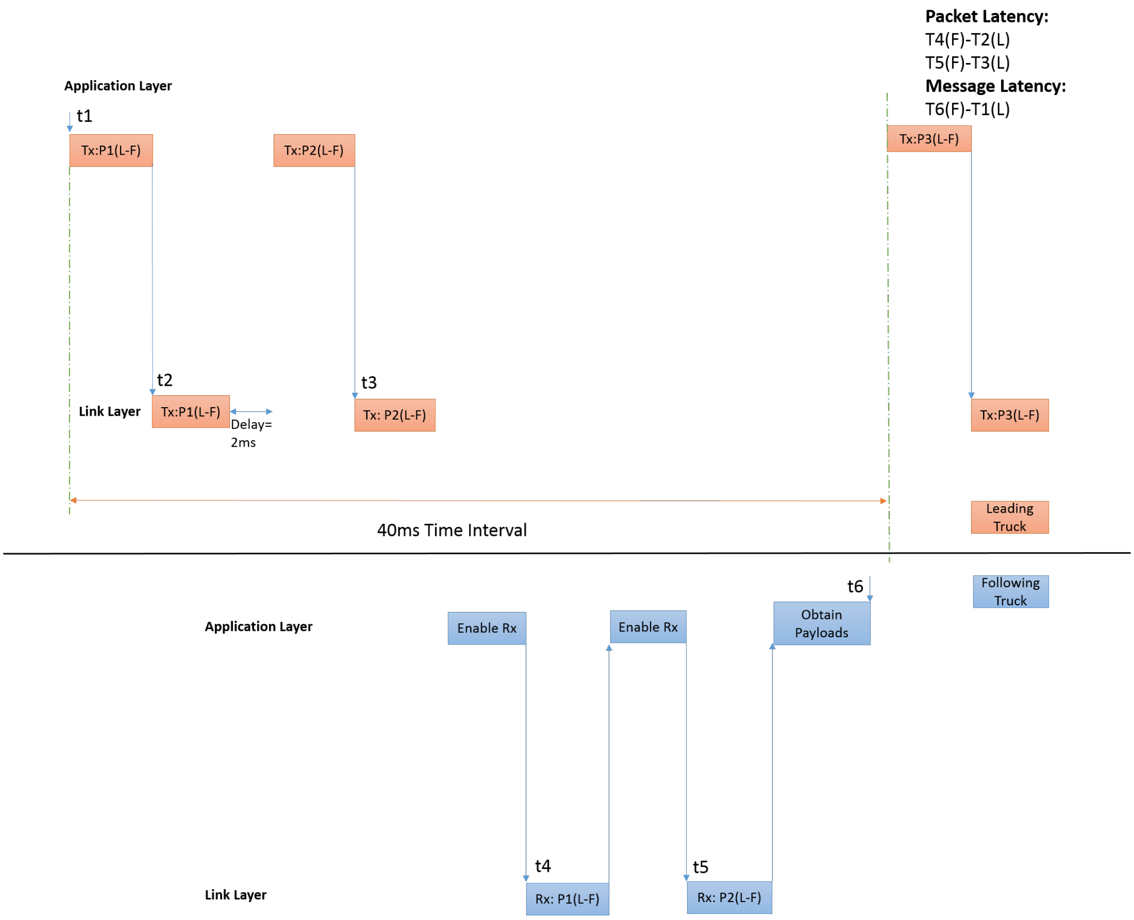

Figure 5.7: Latency Calculation - Leading Truck

is less than or equal to *MAX_ATTEMPTS*. This process continues for all the result logs, and it enters the next phase STATE FINISH after transmission of all logs or if Timer2 interrupt occurs.

In the case of the leading truck, if the number of logs received is less than *DesiredNo* we set *autorxreenable* and enable the receiver. If the result log is received, we process that particular log and send an acknowledgment back. Following which we set *autorxreenable* and enable the receiver if the number of messages received is less than *DesiredNo*. This process continues for the reception of all the logs and it enters the next phase STATE FINISH after the reception of all logs or if Timer2 interrupt occurs. The test log structure definition is shown in Listing 5.3. Using the stored values of this structure for each log, a comma separated string is created as shown in Listing 5.2 and printed on the laptop/computer using serial communication, which is further processed in MATLAB.

```
Log,tseqno1,0,tseqno2,1,tseqno3,2,tseqno4,3,rseqno1,0,rseqno2,1,rseqno3,2,rseqno4
    ,3,messageLatency,8.950,packetLatency1,0.843,packetLatency2,0.843,
    packetLatency3,0.843,packetLatency4,0.829,distance,0.00,C1,955,C2,1015,C3,1028,
    C4,925,N1,236,N2,236,N3,235,N4,229,F11,2716,F12,2385,F13,2883,F14,2420,F21
    ,3033,F22,3369,F23,3040,F24,3099,F31,2971,F32,2439,F33,2869,F34,2290
```

Listing 5.2: Logging Format

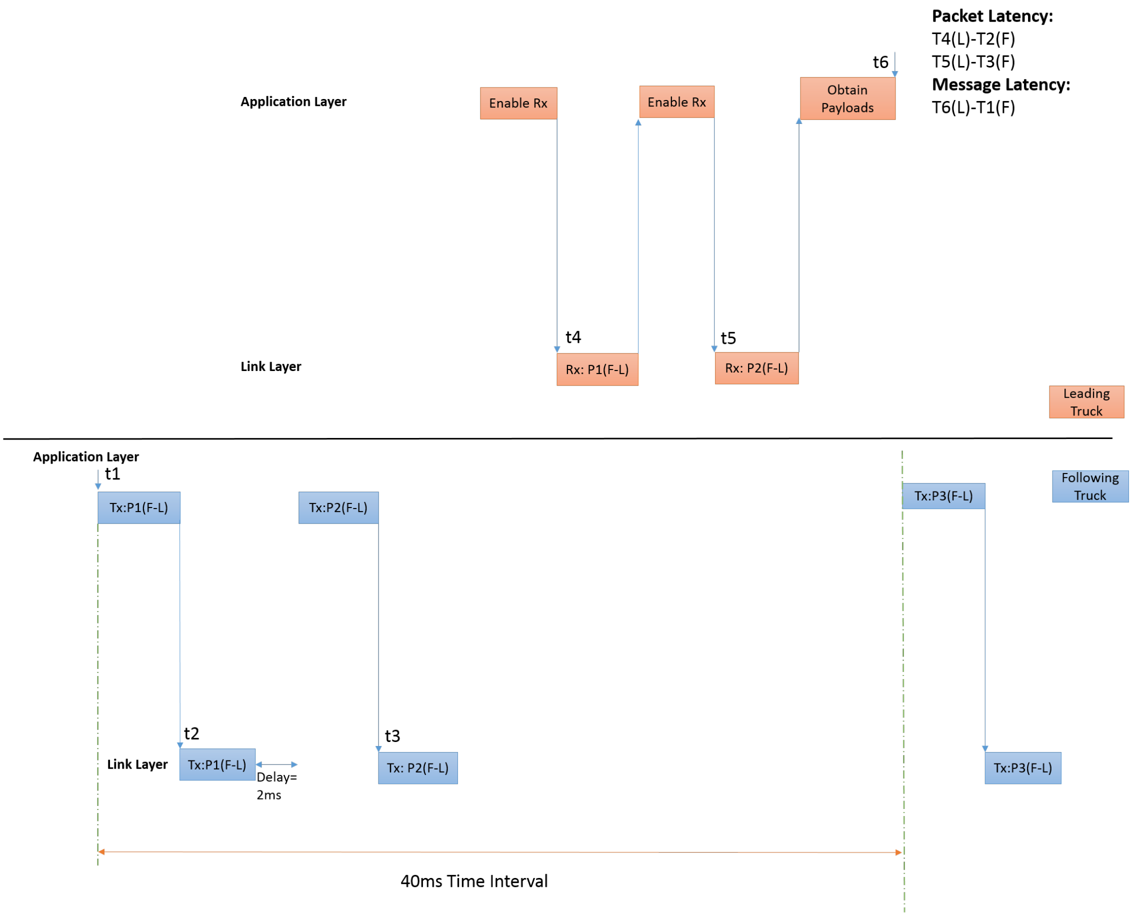

Figure 5.8: Latency Calculation - Following Truck

```
typedef struct {
uint16_t tseqNo[PACKETS_PER_MESSAGE];
uint16_t rseqNo[PACKETS_PER_MESSAGE];
uint32_t messageLatency;
uint32_t packetLatency[PACKETS_PER_MESSAGE];
double distance;
uint16_t stdNoise[PACKETS_PER_MESSAGE];
uint16_t C[PACKETS_PER_MESSAGE];
uint16_t N[PACKETS_PER_MESSAGE];
uint16_t F1[PACKETS_PER_MESSAGE];
uint16_t F2[PACKETS_PER_MESSAGE];
uint16_t F3[PACKETS_PER_MESSAGE];
}logging;
```

Listing 5.3: Test Log structure definition

5.4.4 State Finish

In the phase STATE FINISH, we reset for the next configuration and stop the link. Wherein we disable all interrupts which were set in STATE START, disable all the three timers, reset them and reset the transceiver. If the number of times to repeat is less than (NO OF TIMES TO RUN * NUM OF DW1000 CONFIGS) we load the next configuration ((configuration + 1) % NUM OF DW1000 CONFIGS) and return to STATE START, else we stop the execution.

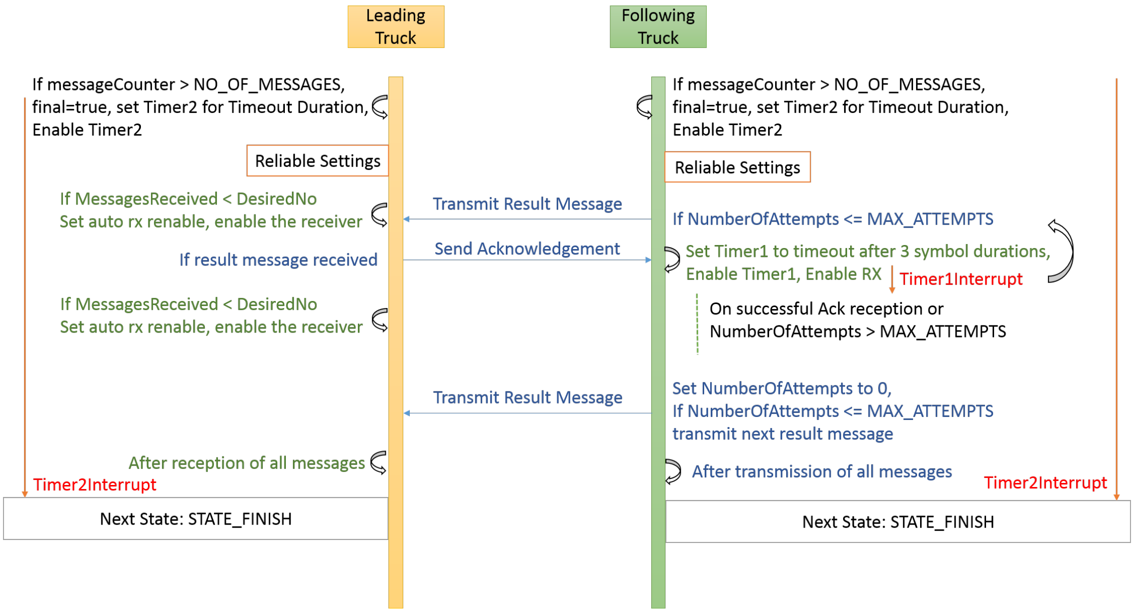

Figure 5.9: State Result Determination

5.4.5 Ranging Method

For the implementation of ranging, we make use of Double-Sided Two-Way Ranging (DS-TWR), which is an extension of the basic single-sided two-way ranging in which two round trip time measurements are used and combined to give a time-of-flight result which has a reduced error even for quite long response delays. The operation of DS-TWR used in our implementation is shown in Figure 5.10. The leading truck sends a POLL packet to the following truck, for which the following truck sends a response packet to the leading truck. Consequently, the leading truck sends a final packet to the following truck. Lastly, the following truck sends the result packet to the leading truck with all the required time stamps from the following truck (POLL RX time stamp, RESPONSE TX time stamp and FINAL RX time stamp). The leading truck makes use of the time stamps sent in the result packet and its own time stamps (POLL TX time stamp, RESPONSE RX time stamp and FINAL TX time stamp) to calculate the time-of-flight estimate according to Equation 5.1. Using this time-of-flight estimate, distance is calculated according to Equation 5.2.

$$T_{prop} = \frac{T_{round1} * T_{round2} - T_{reply1} * T_{reply2}}{T_{round1} + T_{round2} + T_{reply1} + T_{reply2}} \tag{5.1}$$

$$Distance = T_{prop} * SPEED\_OF\_LIGHT \tag{5.2}$$

5.4.6 Ranging Implementation

Figure 5.11 shows how we integrate ranging along with communication. We refer to the last packet of a message to send/receive ranging related information. Initially, we reset the parameters for range calculation in both the leading truck and the following truck.

In the case of the following truck, on the reception of ranging POLL information, it resets the parameters and gets the POLL RX time stamp. It sends the ranging RESPONSE information when *rangeType*%2==0. On the reception of the ranging FINAL information, it gets the RESPONSE TX time stamp and the FINAL RX time stamp. It sends the ranging RESULT information along with the POLL RX time stamp, the RESPONSE TX time stamp and the FINAL RX time stamp when *rangeType*%2==1.

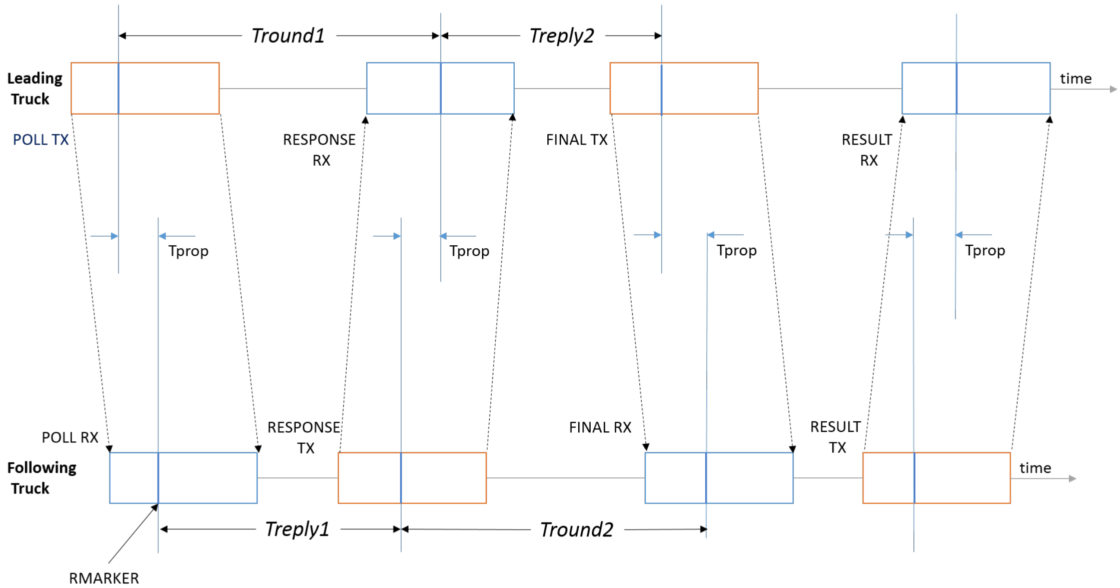

Figure 5.10: Ranging Method

In the case of the leading truck, it sends the Ranging POLL information when $rangeType\%2{=}{=}0$. On reception of the ranging RESPONSE information from the following truck, it resets the parameters and gets the POLL TX time stamp and the RESPONSE RX time stamp. It sends the ranging FINAL information when $rangeType\%2{=}{=}1$. On reception of the ranging RESULT information from the following truck, it gets the FINAL TX time stamp, retrieves the POLL RX time stamp, the RESPONSE TX time stamp and the FINAL RX time stamp from the ranging RESULT information and calculates the distance between the trucks. The reset of the parameters is done to ensure the distance is calculated appropriately even in the case of packet loss. To calculate the distance, the time-of-flight estimate calculated according to the equation 5.1 is multiplied by DWT TIME UNITS since these time stamps are given by the DecaWave device and finally the distance is calculated according to the equation 5.2.

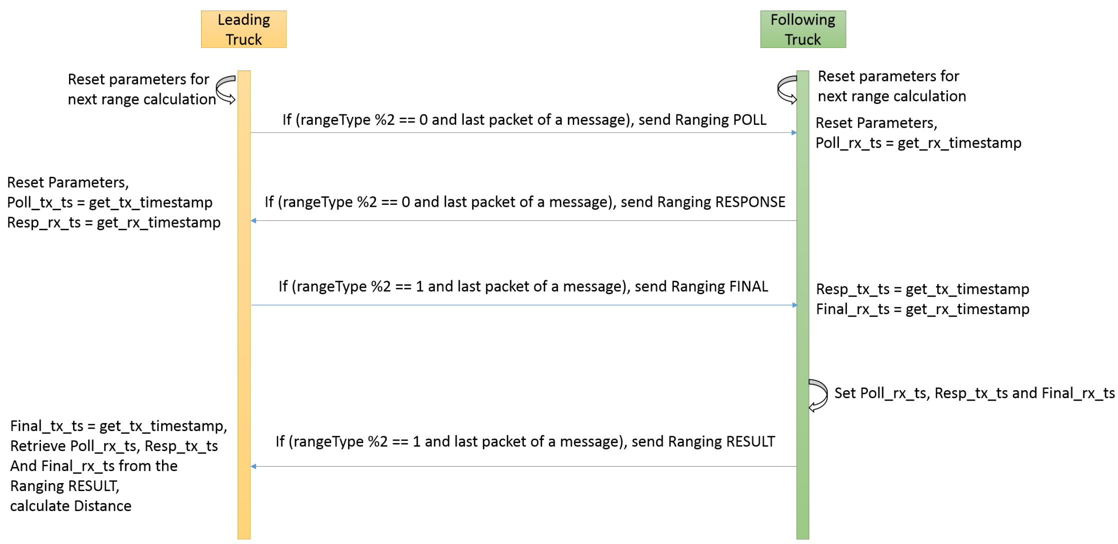

Figure 5.11: Implementation of Ranging

5.4.7 Cross Verification of Design

To cross verify if the system is designed accurately, additional parameters were logged for the packets as shown in Listing 5.4 in the unit testing phase. An indication of the parameters logged is provided in Figure 5.12.

```
typedef struct {
uint16_t tseqNo[PACKETS_PER_MESSAGE];
uint16_t rseqNo[PACKETS_PER_MESSAGE];
uint32_t tonTimePacket[4];
uint32_t ronTimePacket[4];
uint32_t tcompletiontimePacket[4];
uint32_t rcompletiontimePacket[4];
uint32_t messageLatency;
uint32_t packetLatency[PACKETS_PER_MESSAGE];
uint8_t timeout[PACKETS_PER_MESSAGE];
uint32_t errorcompletiontimePacket[4];
double distance;
uint16_t stdNoise[PACKETS_PER_MESSAGE];
uint16_t C[PACKETS_PER_MESSAGE];
uint16_t N[PACKETS_PER_MESSAGE];
uint16_t F1[PACKETS_PER_MESSAGE];
uint16_t F2[PACKETS_PER_MESSAGE];
uint16_t F3[PACKETS_PER_MESSAGE];
} logging;
```

Listing 5.4: Test Log structure for verification of design

Here the parameter 'timeout' indicates if a timeout occurred during the reception of a packet and 'errorcompletiontimePacket' indicates the timestamp if any errors like Rx Frame timeout, Rx SFD timeout, Rx Preamble timeout, RX PHR error, Rx Reed-Solomon error (Sync loss),or Rx Bad CRC occur. Using these parameters we checked if the receiver of the following truck is turned on before the transmission from the leading truck for every packet of a message and similarly we checked if the receiver of the leading truck is turned on before the transmission from the following truck for every packet of a message. We also checked if the time between the transmission of packets was 2 ms and the time between the reception completion of one packet and enablement of reception for the next packet is less than 2 ms. We verified if the system worked as designed during timeouts or when errors occurred. We also verified that the nodes are synchronized when they enter the communication phase through an oscilloscope by creating a pulse on the GPIO Pin on entering the communication phase. It was observed that the difference in synchronization was less than 200 μs, which is ok for our application.

During the cross verification of the design, two major issues were found when the code was run for long durations of time. The first issue was that the schedule of transmission was getting affected in few cases wherein the receiver of the following truck was not getting turned on before the transmission of a packet from the leading truck and vice versa. This error was not reproducible and hence it was tough to identify the source of the problem. To solve this problem, flags were used to identify in what phase the node was when Timer1 interrupt of 40 ms occurred. It was observed that the node was always in the logging state when Timer1 occurred. At that point of time when this error occurred, the sequence of the code was to transmit a message, receive a message, log that particular message and then go to the next transmission. Having identified that the issue was associated with logging, we turned off all logging and printed an error only if a packet reception was missed. We found that the code worked as desired. Digging deep into the issue we found that the issue was associated with the COM port interrupts interfering with the Timer1 and Timer2 Interrupts. To solve this issue, we stored all the logging information in a structure array and handled the printing of the log after the communication phase.

Another issue that was identified is that the code crashed at times. This error too was not reproducible. The approach used to solve this issue was to store values of certain variables in RAM and print the values of these variables on pressing reset after the crash occurred. To do this, we changed the settings in LPCXpresso IDE to trick the microcontroller to believe that there is lesser memory space available while creating the makefile and used that part of memory for storing the values of these variables. It was identified that the issue was caused due to the reception of an unexpected packet which could occur if the reception and timeout interrupt occurred at the same point in time. This exception was handled to solve this problem, and the system was cross-verified for the designed functioning before going into the experimentation.

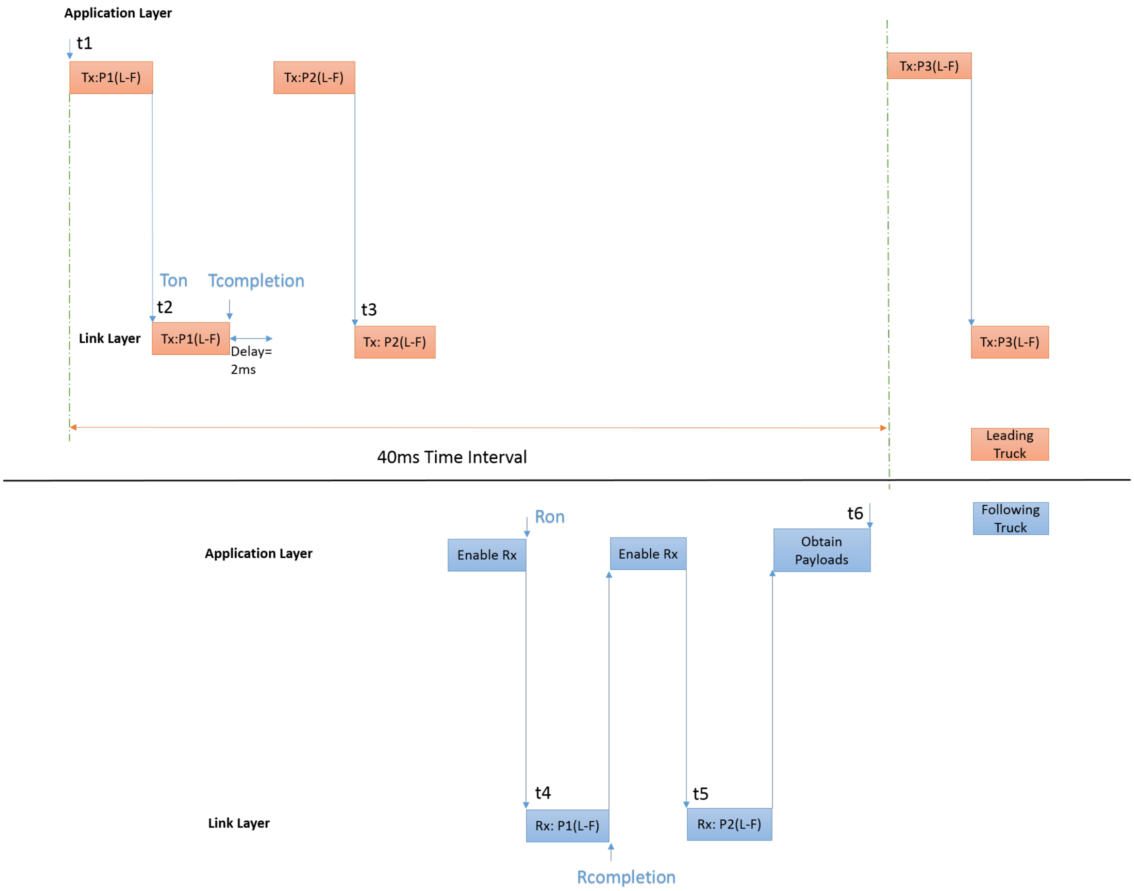

Figure 5.12: Logged parameters to determine appropriate working of the system

5.4.8 MATLAB Implementation

To process large data files created in the format as shown in Listing 5.2, we handle the log specific to each configuration at a time, on processing the log unique to that configuration completely; we go ahead with processing the log unique to the following configuration. Following this approach helps us to avoid storing significant amounts of data in memory which could lead to a MATLAB crash. On processing all the logs, we store the information appropriately so as to create desired graphs such as PER vs. Channel, MER vs. Channel, PER vs. Distance, Measured Distance vs. Calculated Distance, etc.

The parsing is implemented by obtaining the lines containing the string "messageLatency" from the log and stored in a cell array. A single row is created for each message with columns representing the parameter and its corresponding values. Depending on the number of messages and packets per message tested, appropriate number of lines are read that are specific to each configuration. The parameters packets per message, the number of messages, actual measured distance and the number of configurations tested and paths to the log files need to be input before running the post processing script.

The obtained cell array after parsing the log files is used for further processing. Based on the required results like PER, MER, message latency, packet latency, the accuracy of ranging, etc. the obtained cell array is traversed for the desired parameters and after applying the desired modifications on the data, it is stored in separate arrays corresponding to each result. Each row in these separate arrays corresponds to an average of all the values for the desired parameter in that specific configuration, and the column in these separate arrays corresponds to each run. It is to be noted that the cell array obtained by parsing the log files needs to be converted to numbers from strings to process them as indicated above. This process continues for all the configurations across all runs.

From these separate arrays, we obtain data and classify them based on channel, data rate, Preamble length, etc. by correlating with the configuration number. Consequently, the data is further processed based on the required result and the classification, and corresponding graphs created. The MATLAB implementation is such that it can process logs for up to four packets per message and any desired number of configurations and runs.

It is to be noted that based on the configurations that are tested, the code for classification needs to be modified because classification is performed by correlating with the configuration number. The MATLAB implementation currently calculates PER at leading truck, PER at following truck, MER at leading truck, MER at following truck, packet latency for leading truck (mean, min, max and standard deviation), packet latency for following truck (mean, min, max and standard deviation), message latency in leading truck (mean, min, max and standard deviation), message latency in following truck (mean, min, max and standard deviation), range accuracy, RX level at leading truck for each packet of a message (mean, min, max and standard deviation) and RX level at following truck for each packet of a message (mean, min, max and standard deviation). The MATLAB implementation allows creation of graphs with respect to the parameters stated above.

Chapter 6

Duty Cycle Requirements for UWB

In this chapter, we discuss the duty cycle requirements for UWB and determine if platooning application requirements meet the duty cycle requirements for UWB.

To permit the use of Ultra Wide Band (UWB) but mitigate the possibility/effect of interference with other systems, two main approaches have been adopted which include Low Duty Cycle (LDC), and Detect and Avoid (DAA). LDC in which UWB equipment must limit the relative time for which it is transmitting. Detect and Avoid (DAA) in which UWB systems listen for other UWB transmissions before they transmit. The LDC requirement needs to be met when using Band 3 of UWB wherein the center frequency is 4488 MHz. LDC and DAA requirements have to be met when using Band 1, Band 2 and Band 11 of UWB wherein the center frequencies are 3432 MHz, 3960 MHz, and 8712 MHz respectively as shown in Figure 6.2. It is to be noted that Detect and Avoid is not supported by DecaWave DW1000, the hardware used for the implementation of the thesis. The channels supported by DecaWave DW1000 are as shown in the Figure 6.1. From the Figure 6.2 and Figure 6.1, we can infer that LDC regulations need to be met when using Channels 1, 2, 3 and 4 of DecaWave DW1000, and the same is not required when operating in Channels 5 and 7.

Channel number	Centre frequency (MHz)	Bandwidth (MHz)	Preamble Codes (16 MHz PRF)	Preamble Codes (64 MHz PRF)
1	3494.4	499.2	1, 2	9, 10, 11, 12
2	3993.6	499.2	3, 4	9, 10, 11, 12
3	4492.8	499.2	5, 6	9, 10, 11, 12
4	3993.6	1331.2 *	7, 8	17, 18, 19, 20
5	6489.6	499.2	3, 4	9, 10, 11, 12
7	6489.6	1081.6 *	7, 8	17, 18, 19, 20
N.B.	For correct operation of the DW1000 the software must take care to only allow selection of those preamble codes appropriate for the configured PRF.			

* The DW1000 has a maximum receive bandwidth of 900 MHz

Figure 6.1: Channels supported by DecaWave DW1000 (Decawave, 2015b)

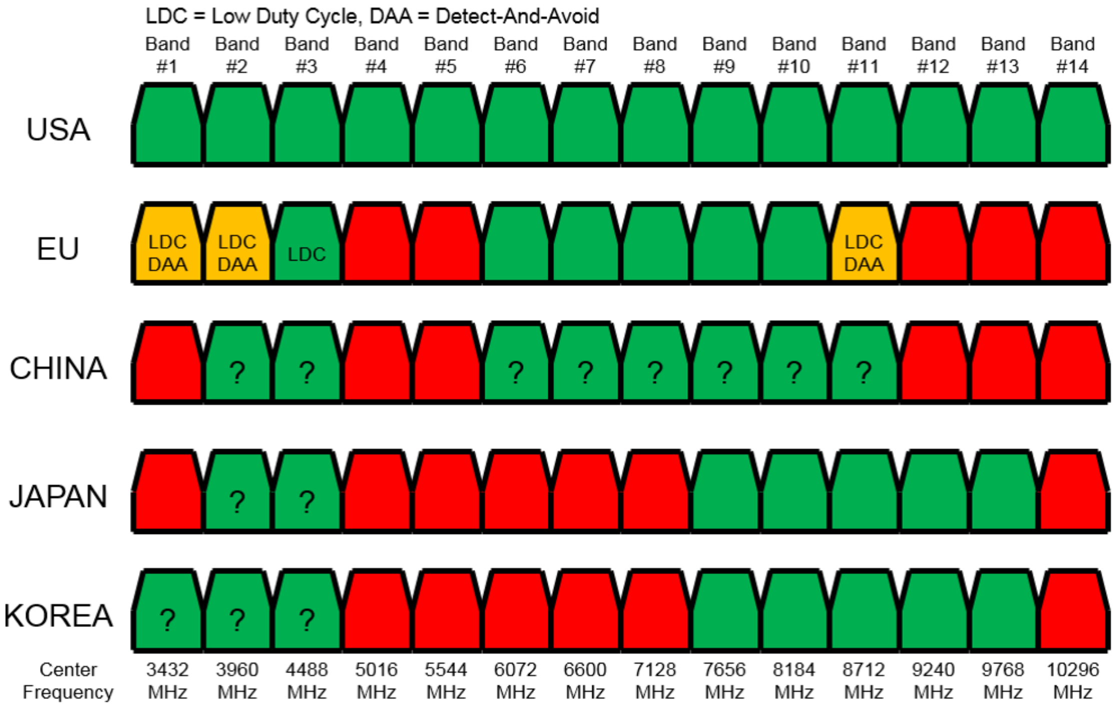

Figure 6.2: UWB Regulations, Source: F.Leong, NXP Semiconductors

6.1 Low Duty Cycle

In Europe, the Electronic Communications Committee - one of CEPT's (European Conference of Postal and Telecommunications Administrations) working committees dealing with radio spectrum use and telecommunications numbering addressing, specifies technical requirements for LDC mitigation technique, enabling operation at -41.3 dBm /MHz Equivalent Isotropically Radiated Power (EIRP) within the band 3.4 - 4.8 GHz (ECC, 2006). A device implementing LDC is a UWB device that meets the requirements as shown in Table 6.1.

Parameter	Value	Definition
T_{on} max	5 ms	T_{on} is defined as the duration of a burst irrespective of the number of pulses contained
T_{off} mean	38 ms (averaged over 1 s)	T_{off} is defined as the time interval between two consecutive bursts when the UWB emission is kept idle.
$\sum T_{off}$	> 950 ms per second	
$\sum T_{on}$	< 5% per second and 0.5% per hour	

Table 6.1: ECC Definition of Low Duty Cycle Operation (ECC, 2006)

To determine if LDC requirement can be met by truck platooning application, let's consider the UWB PHY frame structure and the application requirements.

6.2 UWB PHY and Platooning Application

UWB PHY frame structure is as shown in Figure 6.3. According to the IEEE 802.15.4a UWB standard, the mandatory SHR Preamble base rate is 1.01 Msymbols/s and 0.25 Msymbol/s. The PHR is sent at 850 kb/s for all data rates greater than or equal to 850 kb/s and at 110 kb/s for the data rate of 110 kb/s. The data field is transferred in MAC format as shown in Figure 6.4 at the data rate defined experimentally.

In truck platooning application, if we consider leading truck and the following truck, VFM (leading truck to the following truck) and PSM (following truck to the leading truck) are exchanged every 40 ms with a particular offset as shown in Figure 4.4.

Figure 6.5 shows the symbol durations for various configurations of PRF and data rate, which are used to calculate the LDC requirement for the truck platooning application.

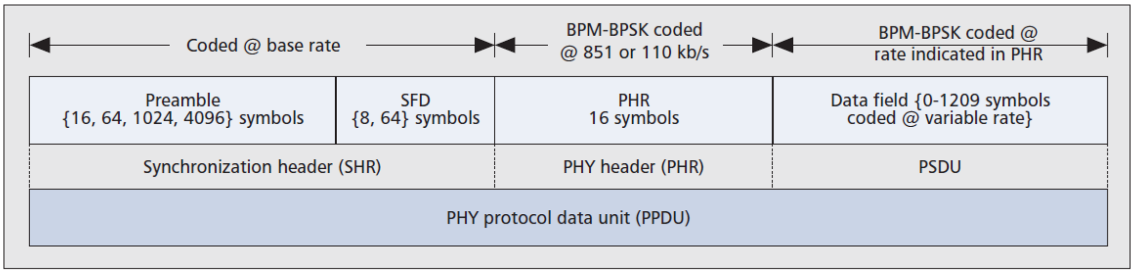

Figure 6.3: UWB PHY Frame Structure (Karapistoli et al., 2010)

MAC Header (MHR)							MAC Payload	MAC Footer (MFR)
Frame Control	Sequence Number	Destination PAN Identifier	Destination Address	Source PAN Identifier	Source Address	Aux Security Header	Frame Payload	FCS
2 octets	1 octet	0 or 2 octets	0, 2 or 8 octets	0 or 2 octets	0, 2 or 8 octets	0, 5, 6 10 or 14 octets	Variable number of octets	2 octets

Figure 6.4: 802.15.4 - MAC Message Format (Decawave, 2015b)

PRF (MHz)	Data Rate (Mbps)	SHR (ns)	PHR (ns)	Data (ns)
16	0.11	993.59	8205.13	8205.13
16	0.85	993.59	1025.64	1025.64
16	6.81	993.59	1025.64	128.21
64	0.11	1017.63	8205.13	8205.13
64	0.85	1017.63	1025.64	1025.64
64	6.81	1017.63	1025.64	128.21

Figure 6.5: DW1000 Symbol Durations (Decawave, 2015a)

6.3 LDC Calculation for the Truck Platooning Application

According to the LDC requirement as specified in Table 6.1, the transmitter can be on for 50 ms of a second and 18000 ms of an hour. To check if the truck platooning application meets the LDC requirement, let's consider the typical platooning payloads of 60 bytes (1 packet/message) and 160 bytes (2 packets/message). Here, 60 bytes and 160 bytes corresponds to the minimum and maximum platooning payload of the current Eco-Twin Truck platooning implementation (TPC, 2016).

For the calculation of the Ton times for 6.8 Mbps, following values are used for various parameters.

Preamble Length = 256 Symbols
Data Rate = 6.8 Mbps
Bit Rate = 6800
PHR Rate = 850
PHR = 19 bits
SFD length = 8 Symbols
PRF = 16 MHz (Symbol Duration = 993.59 ns) or 64 MHz(Symbol Duration = 1017.63 ns)

Let us calculate the respective Ton times for the following scenarios using Equation 6.1 and Equation 6.2.

$$PreambleDuration = (preambleLength + sfdLength) * preambleSymbolDuration \tag{6.1}$$

$$maxFrameDuration = preambleDuration + 19/phrRate + packetSize * 8/bitRate \tag{6.2}$$

- **Scenario 1: 60 bytes payload, 64 MHz PRF** For Scenario 1, we can determine that the maximum frame duration is 0.3616 ms. Considering only two mirrors, 49 exchanges of messages take place in a second because of the platooning application requirement of 25 Hz. For 1 second, the total Ton time is 17.7184 ms out of the available 50 ms and for 1 hour, the total Ton time is 1063.104 ms out of the available 18000 ms. Since the max duration of a burst is always less than 5 ms. LDC requirement is met in this scenario.

- **Scenario 2: 60 bytes payload, 16 MHz PRF** For Scenario 2, we can determine that the maximum frame duration is 0.3552 ms. For 1 second, the total Ton time is 17.4048 ms out of the available 50 ms and for 1 hour, the total Ton time is 1044.288 ms out of the available 18000 ms. Since the max duration of a burst is always less than 5 ms. LDC requirement is met in this scenario too.

- **Scenario 3: 160 bytes payload, 64 MHz PRF** For Scenario 3, we can determine that the maximum frame duration is 0.7702 ms if we transmit two packets each of 80 bytes. For 1 second, the total Ton time is 37.7398 ms out of the available 50 ms and for 1 hour, the total Ton time is 2264.388 ms out of the available 18000 ms. Since the max duration of a burst is always less than 5 ms. LDC requirement is met in this scenario too.

- **Scenario 4: 160 bytes payload, 16 MHz PRF** For Scenario 4, we can determine that the maximum frame duration is 0.7576 ms if we transmit two packets each of 80 bytes. For 1 second, the total Ton time is 37.1224 ms out of the available 50 ms and for 1 hour, the total Ton time is 2227.344 ms out of the available 18000 ms. Since the max duration of a pulse is always less than 5 ms. LDC requirement is met in this scenario too.

From the above scenarios, we can conclude that the LDC requirement is fulfilled in all of the scenarios. Hence the UWB system for truck platooning will meet the LDC requirement according to the regulations when 6.8 Mbps data rate is used.

Similarly, we can calculate Ton times for 850 Kbps using Equation 6.1 and Equation 6.2. For the calculation of Ton times for 850 Kbps, following values are used for various parameters.

Preamble Length = 1024 Symbols
Data Rate = 850 Kbps
Bit Rate = 850
PHR Rate = 850
PHR = 19 bits
SFD length = 8 Symbols
PRF = 16 MHz (Symbol Duration = 993.59 ns) or 64 MHz(Symbol Duration = 1017.63 ns)

Table 6.2: Ton with respect to data rates for Platooning application

Data Rate	**Ton Duration in milliseconds**			
	60 bytes, 64 MHz PRF	**60 bytes, 16 MHz PRF**	**160 bytes, 64 MHz PRF**	**160 bytes, 16 MHz PRF**
6.8 Mbps	17.7184	17.4048	37.739	37.1224
850 Kbps	80.2277	79.0076	178.8990	176.4686

Table 6.2 summarizes the Ton durations with respect to data rates 6.8 Mbps and 850 Kbps for Platooning application. It is to be noted that the LDC requirement is not fulfilled when 850 Kbps is used because, for 1 second, the total Ton time must be within 50 ms. In the case of 110 Kbps, the LDC requirement is not met because the duration of a burst (8.6697 ms) is greater than 5 ms even for 60 bytes payload.

Chapter 7

Experiments and Results

Content is not included for reasons of confidentiality.

Chapter 8

Conclusion and Future work

Content is not included for reasons of confidentiality.

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Appendix A

Configurations for Measurement Plan MP_Interference

```
Log,configModes,0,channel,1,dataRate,2,PRF,1,preambleLength,36,preambleCodes,1,
    smartPower,0,nonStandardSFD,0
Log,configModes,1,channel,1,dataRate,2,PRF,1,preambleLength,20,preambleCodes,2,
    smartPower,0,nonStandardSFD,0
Log,configModes,2,channel,1,dataRate,2,PRF,1,preambleLength,4,preambleCodes,1,
    smartPower,0,nonStandardSFD,0
Log,configModes,3,channel,1,dataRate,2,PRF,2,preambleLength,36,preambleCodes,9,
    smartPower,0,nonStandardSFD,1
Log,configModes,4,channel,1,dataRate,2,PRF,2,preambleLength,20,preambleCodes,10,
    smartPower,0,nonStandardSFD,1
Log,configModes,5,channel,1,dataRate,2,PRF,2,preambleLength,4,preambleCodes,11,
    smartPower,0,nonStandardSFD,1
Log,configModes,6,channel,1,dataRate,2,PRF,2,preambleLength,36,preambleCodes,12,
    smartPower,1,nonStandardSFD,1
Log,configModes,7,channel,1,dataRate,2,PRF,2,preambleLength,20,preambleCodes,9,
    smartPower,1,nonStandardSFD,0
Log,configModes,8,channel,1,dataRate,2,PRF,2,preambleLength,4,preambleCodes,10,
    smartPower,1,nonStandardSFD,0
Log,configModes,9,channel,3,dataRate,2,PRF,1,preambleLength,36,preambleCodes,5,
    smartPower,0,nonStandardSFD,1
Log,configModes,10,channel,3,dataRate,2,PRF,1,preambleLength,20,preambleCodes,6,
    smartPower,0,nonStandardSFD,1
Log,configModes,11,channel,3,dataRate,2,PRF,1,preambleLength,4,preambleCodes,5,
    smartPower,0,nonStandardSFD,1
Log,configModes,12,channel,3,dataRate,2,PRF,1,preambleLength,36,preambleCodes,6,
    smartPower,0,nonStandardSFD,0
Log,configModes,13,channel,3,dataRate,2,PRF,1,preambleLength,20,preambleCodes,5,
    smartPower,0,nonStandardSFD,0
Log,configModes,14,channel,3,dataRate,2,PRF,1,preambleLength,4,preambleCodes,6,
    smartPower,0,nonStandardSFD,0
Log,configModes,15,channel,3,dataRate,2,PRF,2,preambleLength,36,preambleCodes,9,
    smartPower,0,nonStandardSFD,1
Log,configModes,16,channel,3,dataRate,2,PRF,2,preambleLength,20,preambleCodes,10,
    smartPower,0,nonStandardSFD,1
Log,configModes,17,channel,3,dataRate,2,PRF,2,preambleLength,4,preambleCodes,11,
    smartPower,0,nonStandardSFD,1
Log,configModes,18,channel,3,dataRate,2,PRF,2,preambleLength,36,preambleCodes,12,
    smartPower,1,nonStandardSFD,1
Log,configModes,19,channel,3,dataRate,2,PRF,2,preambleLength,20,preambleCodes,9,
    smartPower,1,nonStandardSFD,0
Log,configModes,20,channel,3,dataRate,2,PRF,2,preambleLength,4,preambleCodes,10,
    smartPower,1,nonStandardSFD,0
Log,configModes,21,channel,5,dataRate,2,PRF,1,preambleLength,36,preambleCodes,3,
    smartPower,0,nonStandardSFD,1
```

```
Log,configModes,22,channel,5,dataRate,2,PRF,1,preambleLength,20,preambleCodes,4,
    smartPower,0,nonStandardSFD,1
Log,configModes,23,channel,5,dataRate,2,PRF,1,preambleLength,4,preambleCodes,3,
    smartPower,0,nonStandardSFD,1
Log,configModes,24,channel,5,dataRate,2,PRF,1,preambleLength,36,preambleCodes,4,
    smartPower,0,nonStandardSFD,0
Log,configModes,25,channel,5,dataRate,2,PRF,1,preambleLength,20,preambleCodes,3,
    smartPower,0,nonStandardSFD,0
Log,configModes,26,channel,5,dataRate,2,PRF,1,preambleLength,4,preambleCodes,4,
    smartPower,0,nonStandardSFD,0
Log,configModes,27,channel,5,dataRate,2,PRF,2,preambleLength,36,preambleCodes,9,
    smartPower,0,nonStandardSFD,1
Log,configModes,28,channel,5,dataRate,2,PRF,2,preambleLength,20,preambleCodes,10,
    smartPower,0,nonStandardSFD,1
Log,configModes,29,channel,5,dataRate,2,PRF,2,preambleLength,4,preambleCodes,11,
    smartPower,0,nonStandardSFD,1
Log,configModes,30,channel,5,dataRate,2,PRF,2,preambleLength,36,preambleCodes,12,
    smartPower,1,nonStandardSFD,1
Log,configModes,31,channel,5,dataRate,2,PRF,2,preambleLength,20,preambleCodes,9,
    smartPower,1,nonStandardSFD,0
Log,configModes,32,channel,5,dataRate,2,PRF,2,preambleLength,4,preambleCodes,10,
    smartPower,1,nonStandardSFD,0
Log,configModes,33,channel,7,dataRate,2,PRF,1,preambleLength,20,preambleCodes,7,
    smartPower,0,nonStandardSFD,1
Log,configModes,34,channel,7,dataRate,2,PRF,1,preambleLength,4,preambleCodes,7,
    smartPower,0,nonStandardSFD,1
Log,configModes,35,channel,7,dataRate,2,PRF,1,preambleLength,36,preambleCodes,7,
    smartPower,0,nonStandardSFD,0
Log,configModes,36,channel,7,dataRate,2,PRF,1,preambleLength,20,preambleCodes,8,
    smartPower,0,nonStandardSFD,0
Log,configModes,37,channel,7,dataRate,2,PRF,1,preambleLength,4,preambleCodes,8,
    smartPower,0,nonStandardSFD,0
Log,configModes,38,channel,7,dataRate,2,PRF,2,preambleLength,36,preambleCodes,17,
    smartPower,0,nonStandardSFD,1
Log,configModes,39,channel,7,dataRate,2,PRF,2,preambleLength,20,preambleCodes,17,
    smartPower,0,nonStandardSFD,1
Log,configModes,40,channel,7,dataRate,2,PRF,2,preambleLength,4,preambleCodes,17,
    smartPower,0,nonStandardSFD,1
Log,configModes,41,channel,7,dataRate,2,PRF,2,preambleLength,36,preambleCodes,18,
    smartPower,1,nonStandardSFD,1
Log,configModes,42,channel,7,dataRate,2,PRF,2,preambleLength,20,preambleCodes,18,
    smartPower,1,nonStandardSFD,0
Log,configModes,43,channel,7,dataRate,2,PRF,2,preambleLength,4,preambleCodes,19,
    smartPower,1,nonStandardSFD,0
```

Listing A.1: Configurations for Measurement Plan MP_Interference

Appendix B

Configurations for Measurement Plan MP_Speed_Or_Acceleration_Difference

```
Log,configModes,0,channel,1,dataRate,0,PRF,2,preambleLength,40,preambleCodes,9,
    smartPower,0,nonStandardSFD,0
Log,configModes,1,channel,1,dataRate,0,PRF,2,preambleLength,12,preambleCodes,9,
    smartPower,0,nonStandardSFD,0
Log,configModes,2,channel,1,dataRate,0,PRF,2,preambleLength,40,preambleCodes,9,
    smartPower,0,nonStandardSFD,1
Log,configModes,3,channel,1,dataRate,0,PRF,2,preambleLength,12,preambleCodes,9,
    smartPower,0,nonStandardSFD,1
```

Listing B.1: Configurations for Measurement Plan MP_Speed_Or_Acceleration_Difference

Appendix C

Configurations for Measurement Plan MP_Distance

C.1 110 Kbps

```
Log,configModes,0,channel,1,dataRate,0,PRF,2,preambleLength,12,preambleCodes,9,
    smartPower,0,nonStandardSFD,0
```

Listing C.1: Configurations for Measurement Plan MP_Distance, 110 Kbps

C.2 850 Kbps

```
Log,configModes,0,channel,1,dataRate,1,PRF,2,preambleLength,8,preambleCodes,9,
    smartPower,0,nonStandardSFD,0

Log,configModes,1,channel,1,dataRate,1,PRF,2,preambleLength,8,preambleCodes,9,
    smartPower,0,nonStandardSFD,1
```

Listing C.2: Configurations for Measurement Plan MP_Distance, 850 Kbps

C.3 6.8 Mbps

```
Log,configModes,0,channel,4,dataRate,2,PRF,1,preambleLength,36,preambleCodes,7,
    smartPower,1,nonStandardSFD,0

Log,configModes,1,channel,4,dataRate,2,PRF,2,preambleLength,36,preambleCodes,17,
    smartPower,1,nonStandardSFD,1

Log,configModes,2,channel,4,dataRate,2,PRF,2,preambleLength,36,preambleCodes,18,
    smartPower,1,nonStandardSFD,1

Log,configModes,3,channel,1,dataRate,2,PRF,1,preambleLength,36,preambleCodes,1,
    smartPower,1,nonStandardSFD,0

Log,configModes,4,channel,1,dataRate,2,PRF,2,preambleLength,36,preambleCodes,9,
    smartPower,1,nonStandardSFD,1

Log,configModes,5,channel,1,dataRate,2,PRF,2,preambleLength,36,preambleCodes,12,
    smartPower,1,nonStandardSFD,1
```

Listing C.3: Configurations for Measurement Plan MP_Distance, 6.8 Mbps

C.4 Antenna Rotation

```
Log,configModes,0,channel,1,dataRate,0,PRF,2,preambleLength,12,preambleCodes,9,
    smartPower,0,nonStandardSFD,0
```

Listing C.4: Configurations for Measurement Plan MP_Distance, Antenna Rotation

Appendix D

Parameter encodings for configurations

Table D.1: Data Rate, PRF and Preamble length encodings

Parameter	**Encoding**	**Actual Value**
Data Rate	0	110 Kbps
Data Rate	1	850 Kbps
Data Rate	2	6.8 Mbps
PRF	1	16 MHz
PRF	2	64 MHz
Preamble Length	12	4096
Preamble Length	40	2048
Preamble Length	8	1024
Preamble Length	52	512
Preamble Length	36	256
Preamble Length	20	128
Preamble Length	4	64