An Overview of Ultra-Wideband Technology and Performance Analysis of UWB-TWR in Simulation and Real Environment

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Abstract

The Ultra-wide band technology (UWB) offers the benefits of robust interference immunity and flexible data rate at low power consumption within the short distance communication area. From a indoor localisation/positioning perspective, UWB also beats other ranging techniques due to its high resolution in time and space, obstacle penetration capability and fine grained ranging/localization accuracy. This paper presents an overview of UWB related technical specifications, applications, two main transmission techniques (i.e., Impulse Radio UWB and Frequency Modulation UWB), relative communication standards, regulated channel distribution and commercially available UWB chips. Then it provides some insights for several popular UWB-based ranging and positioning techniques and their corresponding advantages and disadvantages. Finally, we briefly introduced a simulation model and a real working prototype that highlights the high precision of UWB-TWR in distance based systems.

Keywords

Ultra-WideBand (UWB), Impulse Radio UWB (IR-UWB), Frequency-Modulation UWB (FM-UWB), Time of Flight (TOF), Two Way Ranging (TWR), Time Difference of Arrival (TDOA), indoor positioning, simulation

1. Introduction

As the development of wireless communications for Internet of Things (IoT), the Ultra-wide band (UWB) technology has been recognized as a highly promising technology for short distance communications. Compared with other wireless communication technologies, UWB provides high energy efficiency and flexible data rates [1]. Due to its fine-grained ranging and good obstacle penetration capabilities [2, 3], UWB also plays an important role in the field of indoor positioning and localization services. In fact, UWB represents a wireless communication technology that has no carrier signals. It uses very narrow pulses (i.e., non-sinusoidal pulses at nanosecond or microsecond level) to transmit data bits over extremely wide bandwidths [4]. According to the Federal Communications Commission (FCC) regulations in 2002 [5], UWB has to satisfy one of the following two conditions: the signal bandwidth must be at least 0.2 times

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carrier frequency, or the signal must occupy at least 500 MHz of the spectrum. Further, within the frequency range of 3.1 GHz to 10.6 GHz, the maximum radiation power of UWB signals has been legally stipulated to be -41.3 dBm/MHz which assumes the noise is also integrated within the same bandwidth [6]. This is illustrated by the following Power Spectral Density (PSD) for UWB technology with a spectrum mask limited by FCC [7] included as well, as shown in Fig. 1.

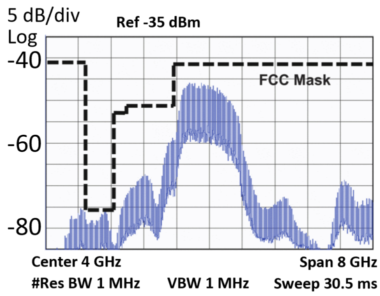

Figure 1: Typical transmitted power spectral density of UWB signal.

With the prevalence of Global Navigation Satellite Systems (GNSS) service and the growth of outdoor positioning and navigation systems [8, 9], there is no universal solution for indoor localization yet, despite numerous ranging/positioning methods being proposed [10]. There are five different types of positioning technologies, ranging based, angle based, Cell ID/approximate, fingerprinting and dead reckoning in general. Notably, ranging and angle based techniques are both rely on precise estimation of the absolute/relative position of the unknown node with respect to a reference node with the given location. There are five widely acceptable distance/angle measurement methods [11, 12], namely Received Signal Strength Indicator (RSSI), Time of Arrival (TOA) or Time Difference of Arrival (TDOA), Angle of Arrival (AOA) and Two Way Ranging (TWR). There are still some other techniques, such as using a centroid algorithm based on the wireless connectivity between nodes [13]. This eliminates the need for fine granularity of localization. The inherent characteristic of UWB signal makes TDOA and TWR become the most suitable ranging approaches for positioning/localization services, particularly in the indoor environments [1, 14], as they can provide high accuracy and robust immunity to multi-path fading effect at low power consumption. Although TOA and TDOA work differently, TDOA can be implemented by two TOA measurements. This paper focused on TWR only and more details are elaborated in section 3.

The ranging performance and positioning accuracy of UWB technology have been analyzed in a plethora of works. However to the best of our knowledge, these studies have not been exposed to a comprehensive performance analysis and comparison of a UWB based working prototype and a simulation model at the same time. In our work, we do this using a TWR based UWB positioning system. The remainder of the paper is structured as follows, we explore the inherent signal characteristic of two transmission techniques (i.e., Impulse-Radio UWB and Frequency-Modulation UWB) used by UWB signals in section 2. In addition, several IEEE standards that are specified for UWB communications particularly, channel distribution regulated by FCC and most commercially available UWB chips and their manufacturers are also included in this section. A technical overview of two ranging based techniques (i.e., TDOA and TWR) performed by UWB technology and corresponding applications in positioning systems can be found in section 3. Section 4 is dedicated to evaluate the system performance of a simulation model and a real working prototype that are both using UWB nodes as a range finder and TWR mechanism to perform distance measurement. In the end, we wrap up with some conclusions in section 5.

2. Overview of UWB transmission techniques

2.1. Impulse Radio UWB

Impulse Radio UWB (IR-UWB) replies on the impulse radio signal generated within an extremely short duration (i.e., sub-nanosecond level) to transmit data packets continuously. Typically, the impulse radio signal is a high-order Gaussian pulse that occupies an ultra wide frequency spectrum [7, 15]. This is a particular type of transmission using carrierless modulation as the radio signal usually propagates in the originally allocated channel. There are several different modulation schemes that can be applied to this type of baseband signal, namely Pulse Amplitude Modulation (PAM), On-OffKeying (OOK), Pulse Position Modulation (PPM) and Pulse Shape Modulation (PSM), Pulse Width Modulation (PWM), etc. In fact, the first four modulation methods mentioned before are the most popular ones to be employed in the IR-UWB system. In order to increase the interference immunity and multiple access feature to the UWB signal, the randomising technique would be necessary to be applied and it can be categorised into two different types, i.e., time-hopping and direct-sequence [16].

Due to the inherent signal characteristic of IR-UWB system, this transmission technique can provide high resolution in time and space. Therefore, it can also be used by a range finder to perform localisation with high accuracy [17]. The duty cycle of this type of UWB pulse is normally very low and even less than 1% sometimes, which improves the energy efficiency profoundly via intermittent operation [18]. Because of the capabilities of fine-grained ranging and low power consumption, the IR-UWB technique has been recognised as revolutionary advance in the area of radio communications. However, the problem of time synchronisation between different nodes within the same wireless sensor network would be significantly affected by its low duty cycle as well [19]. In addition, in terms of the UWB pulse generation, it is critical to consider the balance between the peak value of the provided voltage and the signal coverage. In details, the higher peak voltage results in the higher bit energy and the lower communication range [20]. Due to the challenge of time synchronisation and very restrictive UWB power limitations, the modulation approach of frequency hopping was introduced.

2.2. Frequency-Modulation UWB

The FM-UWB technique is inspired by the double frequency modulation scheme [21] that can be divided into two different steps. One is called subcarrier generation that applies Binary Frequency Shift Keying (BFSK) modulation method to transfer the baseband signal into an analog triangle wave with two different carrier frequencies. The other step which is also called radio frequency modulation is to have this triangle waveform achieve the control voltage of a Voltage-Controlled Oscillator (VCO). The control voltage spreads out widely which makes the output signal across a very wide frequency spectrum after modulation. Due to the feature of constant envelop modulation, the peak value of voltage would not be very high which suits for low-voltage applications. Unfortunately, the FM-UWB system always generates a continuous waveform which means the duty cycle cannot be as low as IR-UWB. Thus, the energy efficiency would be decreased significantly compared with the IR-UWB system. In order to resolve this issue, Chen et al. [22] proposed a novel modulation scheme for UWB signal so that the frequency modulation can be operated at certain time intervals. In addition, the data rate of FM-UWB system is restrictedly limited because of the short duration of modulation and corresponding low modulation index.

2.3. Comparison of IR-UWB and FM-UWB

Due to highly accurate ranging capability and good energy efficiency feature, IR-UWB has a wider range of applications in secure mobile IoT networks. The comparison between IR-UWB and FM-UWB has been summarised in Table 1.

Table 1
Comparison of IR-UWB and FM-UWB

Type	IR-UWB	FM-UWB
Signal	short duration pulse	Wideband FM
Energy efficiency	better	worse
Sensitivity	worse	better
Operation range	better	worse
Obstacle penetration capability	better	worse
Anti-interference feature	multiple IR nodes work better	worse
Application	Low data rate, high data rate, fine ranging	Low data rate

2.4. UWB standards

Based on these two different modulation schemes mentioned before, the IEEE 802.15.4a standard proposed in 2015 defines operation mode of the physical layer for UWB signal transmission and it integrates the benefits of fine ranging, certain penetration capability and high energy efficiency [23, 24]. Later in 2020, the standard was upgraded to IEEE 802.15.4z to enhance some existing functions (i.e., alleviate the time synchronisation problem) and also support more undiscovered features, such as simultaneous ranging and encrypted communication with high security protection via adding a Scrambled Time Sequence (STS) sequence [25, 26].

2.5. Channel distribution for UWB signal

Since UWB signal usually occupies a very broad frequency spectrum, the bandwidth must be shared between UWB devices and other wireless technologies. Given that, UWB signal operates in the industrial, scientific and medical (ISM) radio bands. In order to immune the signal interference from other technologies, the FCC limits the maximum radiation power for UWB transmission which directly affects the signal coverage or operation range that can still achieve high resolution in localisation services. According to the legally regulated maximum transmitted PSD, the typical UWB signal coverage is ranging from 30 to 120 metres [27, 28].

In general, the frequency spectrums allocated for UWB transmission and the maximum transmission power vary with different countries. Fig. 2 briefly shows the UWB operation range in several different countries [29]. Since the higher frequency aggravates the attenuation effect of wireless signal, channel distributed over a relatively low frequency spectrum would be preferred.

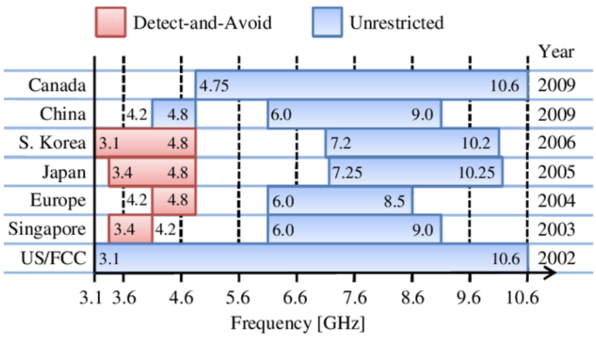

Figure 2: Frequency spectrum allowed in several different countries [29].

2.6. Commercially available UWB radio chips

Most commercially available UWB radio chips from industrial manufacturers are briefly summarised in Table 2.

3. Overview of UWB ranging and positioning techniques

3.1. TWR

Essentially, UWB performs distance measurement by leveraging the Time of Flight (ToF) mechanism. It can be achieved by calculating the time difference of two timestamps captured separately, before and after the UWB signal travels from one transceiver to another [30]. To be specific, the anchor sends out the first poll message to initiate the ranging request at t_{tAB}. When it is received by a tag, the reply message will be generated and sent back after a period of time from the signal reception to the generation of a new signal i.e.,t_{min}. The anchor receives the reply message at t_{rBA}. Then, ToF can be calculated by using this equation,

Table 2
An overview of UWB radio chips from different manufacturers

Supplier	Product name	Band	Standard	Released Date
Decawave	DW1000	3.5-6.5 GHz	HRP	Nov 7, 2013
Decawave	DW3000	6–8.5 GHz	HRP	Jan 2019
NXP	NCJ29D5	6–8.5 GHz	HRP	Nov 12, 2019
NXP	SR100T	6–9 GHz	HRP	Sept 17, 2019
Apple	U1	6–8.5 GHz	HRP	Sept 11, 2019
TSINGOAL	TSG5162	6–8.5 GHz	HRP	2019
Bespoon	B-UWB-MEK1	3.25-4.75 GHz	HRP	Mar 2021
3 dB	3DB6830	6-8 GHz	LRP	N/A
Zebra	UWH-1100-A-00AA	6.35-6.75 GHz	LRP	Jan 2018
Imec	ULP IR-UWB radio	6.2-8.2 GHz	HRP	N/A
Microchip	ATA8350	6.2-7.8 GHz	LRP	Feb 2021
Microchip	ATA8352	6.2-8.3 GHz	LRP	Feb 2021
CEVA	RivieraWaves UWB	3.1-10.6 GHz (depending on radio)	HRP	Jun 2021

$t_{TOF} = \frac{(t_{rBA} - t_{tAB}) - t_{min}}{2}$. Assume that the UWB signal transmits at the speed of light, so that the distance between two UWB transceivers can be computed directly using the following formula, $distance = t_{TOF} * c_{speed\,of\,light}$.

However, this method has a very restrictive requirement that the clocks of the transmitter and receiver device must be synchronised which becomes a huge challenge in terms of the real implementations. Since the UWB pulse usually takes an extremely short duration (i.e., within the sub-nanosecond regime) to transmit, the time synchronisation obviously can hardly achieve the same time resolution as the UWB pulse generation does. In that case, the measurement accuracy would be sacrificed significantly (i.e.,1 nanosecond of time deviation leads to 30 cm distance error).

To cope with the preceding time synchronisation error, TWR method with no need of time synchronisation was proposed. TWR is almost the most common distance estimation method that needs two UWB devices (i.e., one is the transmitter and the other one is the receiver) to communicate with each other. Obviously, the data packets can be transmitted in both direction, as the name suggests (i.e., Two Way Ranging). Assume we have two UWB devices and they can be called 'anchor' and 'tag' respectively. Initially, TWR was achieved by a round trip of travelling which means the anchor sends out the poll message and the tag replies after the signal is successfully received, as shown in Fig. 3. Thus, ToF can be calculated by, $t_{TOF} = \frac{t_{roundA} - t_{replyB}}{2}$.

However, the clock drift caused by device B may lead to a large ranging error in the end. An alternative method was proposed to mitigate the effect of clock drift via leveraging one more message to be transmitted from anchor to tag again, as presented in Fig. 4. It is called

Symmetric double-sided two-way ranging (SDS-TWR) scheme.

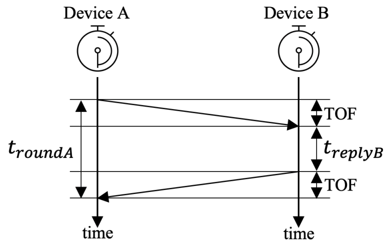

Figure 3: TWR mechanism [31].

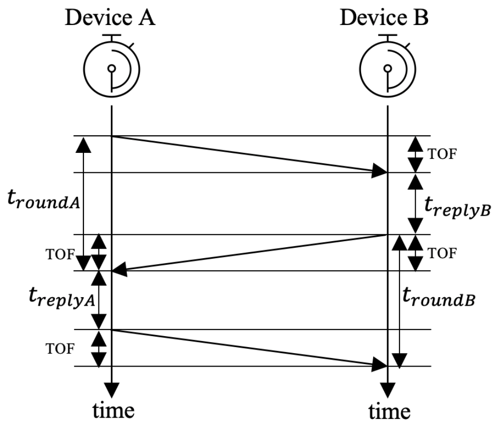

Figure 4: Symmetric TWR mechanism [31].

Unfortunately, the performance of SDS-TWR is still affected by clock drift sometimes, and it may also be impacted by the frequency drift occur during the crystal warm-up phase and this potential error mainly depends on the UWB device itself. An Alternative double-sided two-way ranging (AltDS-TWR) can be used to resolve this issue and improve the accuracy performance [32]. In fact, the clock offset between the transmitter and receiver can also be estimated based on the measurement of carrier frequency offset. Therefore, another approach of Single Sided Two-Way Ranging (SS-TWR) was recommended by Decawave and it can achieve the same accuracy as AltDS-TWR scheme [33]. The benefit of TWR mechanism is it does not require time synchronisation but at the cost of more energy consumption for extra message exchange compared.

Overall, all different version of TWR mechanisms can be employed for distance estimation only. If the tag device is always moving with an unknown location and a few anchors are deployed at fixed but different locations, the anchor can be considered as a reference node, so that the distance between the tag and anchors can be measured respectively using the TWR technique. Finally, the mobile tag can be localised using the trilateration algorithms.

3.2. TDOA

Unlike TWR technique that can only be used for ranging, Time Difference of Arrival (TDOA) is a very popular positioning/localization technique [34]. TDOA is severely affected by the time synchronisation problem of the anchors, while it has no requirement for the synchronisation of mobile tags. TDOA technique can remain low power consumption compared with TWR technique, since it is a one way communication approach. Assume we also have one moving tag and four fixed anchors with reference location this time, the message sent from the mobile tag will be received by all anchors within the communication range. The alternative way is the anchors send the request to the mobile tag but at different time instant so that the tag can successfully receive all these messages and obtain the location of itself. TDOA highly relies on the fine granularity of time which implies that the clock between the anchors must be strictly synchronised. Another advantage of this technique is the latency of a TDOA base system would be lower than that of a TWR based system.

3.3. AoA

The Angle of Arrival (AoA) positioning technique is based on the direction of UWB signal propagation and there are several AoA algorithms that can be compatible with this angle based solution [35, 36, 37, 38]. The angle measurement replies on multiple antennas (i.e., antenna array) or rotation of a single antenna, for example, Beta Phase Difference of Arrival (PDoA) Kit provided by Decawave. We need at least two referenced nodes in the 2D domain to obtain the intersection angle at the moving target lying in between two reference nodes. In fact, there are two different ways to perform AoA measurement using UWB signal, and one of them is to infer the direction of the UWB tag based on distance difference measured by the base stations, which is similar with the TWR technique. The other one is two joint base stations share the same time clock to calculate the arrival time difference of the same transmitted signal. Then, the AoA of source signal can be also computed based on the relative position between two antennas embedded on two base stations respectively. This can be regarded as a special TDOA scheme, to some extent.

Given the inherent UWB signal characteristic of high timing resolution, it is more efficient to incorporate the AoA measurement with ToF or other timing based localisation techniques than using AoA only. The reason for that is AoA based UWB localization systems require pairwised devices to make a difference.

3.4. TWR vs TDOA vs AoA

An overview of all these techniques in terms of positioning/localization service has been presented in Table 3. Particularly, the out-of-area positioning capability can be reflected by the positioning accuracy out of the area enclosed by the preset UWB anchors.

Table 3
Overview and comparison of positioning methods

Method	TWR	TDOA	AOA
Accuracy	High	High	Low
Power consumption	High	Low	Low
System capacity	Low	High	High
Synchronisation requirement	No	Yes	No
Out-of-area positioning	No	Yes	Yes

3.5. Accuracy performance analysis

The accuracy performance of all the previous ranging/positioning techniques can be affected by several different aspects and all potential errors are summarised and organised in Fig. 5.

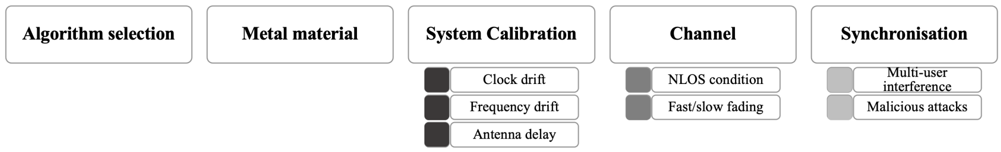

Figure 5: Overview of all potential ranging/positioning error in terms of the TOF, TDOA and AOA technique performed by UWB.

- With respect to the algorithm selection, it is better to choose AltDS-TWR rather than simple TWR scheme to optimise the accuracy performance.
- The ranging/positioning accuracy would normally be severely affected when metals are close enough to the UWB target device.
- Typically, the system calibration error is determined by the quality of the UWB device [39].
- During the signal propagation phase, non line of sight (NLOS) condition and fast/slow fading might occur which depends on the actual environment [40].
- The synchronisation error caused by multi-user interference and malicious attacks are usually not immutable and can be reduced via Time-Division Multiple Access (TDMA) [41, 42], etc.

4. Performance evaluation using simulation model and physical implementations

4.1. Functional description for the simulation model

In order to evaluate the simulation performance without going through a time-consuming process of physical implementations, we developed a OMNET++ based network simulator which emulates the real activity of physical UWB devices that might be moving or remain stationary. The initial motivation to create this simulation model is to provide an easier way to evaluate the accuracy performance of TWR and the delay performance under different system capacities, therefore it can be used to detect obstacles and avoid collisions in the end. It is hard to be done in reality since physical implementations usually take such a long time and need much more efforts than simulates a network model. All essential parameters that are manually configured in the model have been listed in Table 4. The data rate, packet size, data slot duration and maximum transmission range are set according to the datasheet of Decawave 1000. While the update interval is expected to be as short as possible, in order to reduce the end-to-end delay between the transmitter and receiver nodes.

Table 4
Configurable parameters used in the simulation model

Parameter description	Values
Map size	200 x 200 m
Moving speed of the vehicle node	8.3 m/s
Walking speed for the tag on worker	1.5 m/s
Update interval	10 ms
Max transmission range	100 m
Data rate	110 kbps
Radio model	802.14.5 UWB impulse radio
Processing delay	0.25 ms
Packet size	96 bits
Data slot duration	2.084 ms
Control slot duration	0.2 ms

This model is developed on the Omnet++ platform to get higher flexibility of module design. In general, this model emulates the real behaviour of UWB devices including time slot reservation and distribution, and ranging data transmission when performing TWR in the practical use.

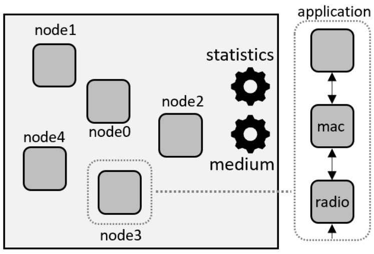

Figure 6: Structure of the network simulation model and node constitution.

As shown in Fig. 6, the simulator constructs a 2D scene with configurable length and width, including five UWB nodes and each of these so called application nodes contains three different layers of implementation according to UWB TWR technique. They are application layer, mac layer and radio layer respectively. The application layer is used to generate ranging packets to perform TWR mechanism. The mac layer is mainly for data packet encapsulation and timeframe distribution and time slot allocation, to be more specific, a TDMA-based medium access control protocol is used in this work. The last one is the radio layer and it is designed to convert the message from bit by bit values to radio frequency signal. It also limits the signal transmission and reception scheme (i.e., imposing the restriction of communication range). Overall, each layer is represented by a compound module comprising abundant of nested submodules that are encapsulated one by one to become the upper level module. The same principle applies to the statistics and medium module as well. The statistics module is dedicated to capture all timing-related data so that the overall delay can be calculated after each run of simulation activity. In addition, the medium module gives some necessary restrictions on the signal propagation which makes it behave like real transmission through the channel.

In terms of the timeframe structure, each frame has five control slots to be used for making reservations for five nodes respectively and ten data slots in total. The data transmission scheme is the all the packets that need to be transmitted have to queue in the mac layer, in which case, an empty queue in the mac layer means there is no need of transmission at all. Oppositely, as long as the message queue comes up with any information that needs to be sent out, the reservation request will be made and the corresponding control slot representing the specific node will be filled out intuitively. This helps the data slot allocation for later ranging packets to be forwarded without interruptions.

4.2. Simulation result

As specified in the configuration file, node 0 is the anchor and the rest four nodes are considered as tags within this application scenario. Two of the four nodes represent one moving vehicle with a constant speed of 8.3 m/s and the rest two nodes represent two walking workers with another constant speed of 1.5 m/s. The vehicle and the other two workers are moving towards different directions, whereas node 0 remains stationary. The distance should be measured between node 0 and the rest four nodes intermittently (with the update interval of 10 ms). The ranging performance is depicted in Fig. 7.

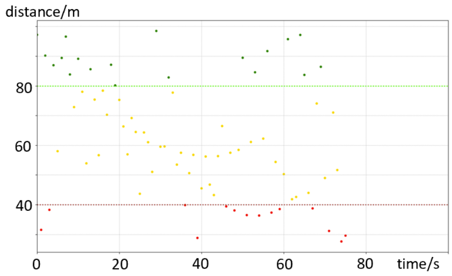

Figure 7: Distance between node 0 and the rest 4 moving nodes.

Y-axis represents the distance result and has the unit of metre. While X-axis represents the simulation time which starts from 0 every time when we run the simulation. The running time is set to be 100 seconds. To obtain a clear and organised view of all measurements, we set two different threshold to discern the 'Critical Zone', 'Warning Zone' and 'Safe Zone' in terms of the node 0 surroundings. The brown dotted line forms the boundary between the critical zone and warning zone, which has the distance value of 40 m. Similarly, another horizontal line in the color of lime is set to be 80 m to separate the warning zone and safe zone. In general, the variation of distance result entirely conforms with our expectation.

4.3. Experimental setup for the physical implementations

To scrutinise ranging accuracy of UWB based system that performs TWR mechanisms as the distance measurement technique, Decawave 1000 was selected with an antenna embedded inside. We developed our own UWB anchor and tags using DW1000 chipset. The aim of this experiment is to verify the ranging performance of UWB chips in collision avoidance systems. After detailed manual configuration, each of these device can be treated as the anchor during the TWR process, and the other one or two devices can work as the tag.

In this work, we conducted two experiments, the only difference is the number of the tags which can be called 'Target' as well. In the first experiment, there is only one target device, so called 'Target'; however, there are two targets in the second experiment and they are 'Target 1' and 'Target 2' respectively. In both experiments, the same ranging mechanism, SDS-TWR was adopted by all related UWB nodes. Also, the vehicle with four nodes included always remains stationary in both experiments, but the workers are walking around the vehicle all the time. In that case, the tag device will be always moving.

In the real working prototype, each worker carries one UWB device, which can be called 'tag'. It is installed on the top of the head. However, each vehicle has four UWB anchors installed at four corners of vehicle which is nearly in the shape of a rectangular. Every time of message exchange, the ranging result to be obtained is the distance measured between the tag and one of the anchor on the vehicle. Within each run, the tag device will take turn to connect with the four anchors embedded on the vehicle one by one and carry out the distance measurement separately but in an organised way.

4.4. Experimental result

The result of the first experiment is shown in Fig. 8. In the second experiment, the distance between Target 1 and one of the vehicle anchor is illustrated in Fig. 9. Another distance which is measured between Target 2 and one of the vehicle anchor is depicted in Fig. 10.

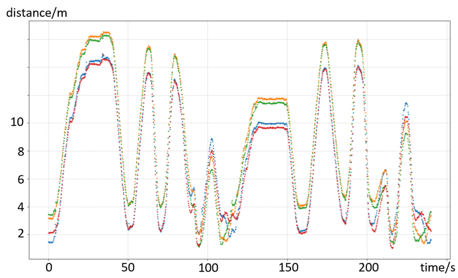

Figure 8: Distance between the target and one of the vehicle anchors (1st experiment).

In all the above Figures (i.e., Figures 8 to 10), Y-axis means the measured distance intuitively with the unit of metre and the X-axis represents the simulation running time which is reset to 0 whenever we rebuild the network. Same as the previous result section, two threshold values of 3 m and 5 m are set to separate the critical zone and warning zone, the warning zone and safe zone respectively. The final distance results are exactly shown as we expected in both

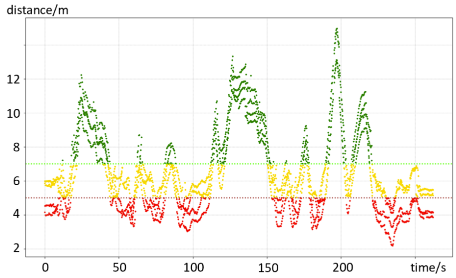

Figure 9: Distance between the Target 1 and one of the vehicle anchor (2nd experiment).

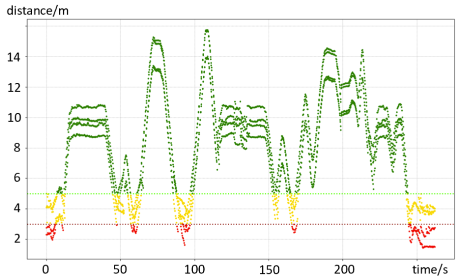

Figure 10: Distance between the Target 2 and one of the vehicle anchor (2nd experiment).

experiments.

5. Conclusion

In this paper, we presented an evaluation of a UWB system using TWR, through simulation and and compared it with a prototype system. It also includes an overview of UWB related technical information and the positioning techniques.The initial results show that UWB/TWR definitely occupies significant superiority, both in terms of high accuracy, ease of implementation and good energy efficiency, when tested with a widely available UWB chip-set. We believe that it will be true for most other UWB chips. Based on these observations, it can be concluded that, the use of UWB really provides a practical solution for indoor positioning and contributes to a comprehensive quantum leap. In the future we intend to investigate the scalability of the ranging based UWB system and it's viability in the harsh environment such as underground mines.

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