Study and Mitigation of Non-Cooperative UWB Interference on Ranging

Hessam Mohammadmoradi, Omprakash Gnawali
University of Houston
{hmoradi,gnawali}@cs.uh.edu

Abstract

UWB localization systems are well known for their accuracy for indoor localization. Recently UWB-based localization systems with less than 5 cm error have been proposed. Since IEEE802.15.4-11 standard only allows UWB signal transmission with very low power (-41.3 dBm/MHz), UWB systems cannot utilize carrier sensing techniques to manage shared access to the wireless channel. In this paper, first, we studied the likelihood of wideband interference in localization applications and also analyzed the impact of interference on ranging performance. Then, we design and evaluate RAPSI (Random Pulse Shape Identification), a simple yet effective technique to detect and mitigate the ranging error caused by interference. Our results show 30% to 40% reduction in ranging errors caused by wideband interference after applying the proposed techniques.

1 Introduction

UWB signals have been utilized to build accurate indoor localization systems to support smart building applications [24, 18]. The large bandwidth (500 MHz) of UWB signals makes them resilient to multipath fading and decreases the error of localization down to few centimeters [9]. IEEE 802.15.4-11 standard [6] regulates the use of UWB signals in low rate wireless networks. It defines 16 frequency channels with the minimum bandwidth of 500 MHz for UWB communication in 0 to 10 GHz range. To avoid interference with existing ISM band signals, the standard limits the maximum transmission power for UWB signals to be -41.3 dBm/MHz.

The transmission power is spread across very large bandwidth of UWB signals which means they can not use standard carrier sensing techniques to access the medium. The 802.15.4-11 standard defines ALOHA as MAC protocol for UWB communication in which interference is considered negligible and nodes use the medium whenever they need to send a message without checking the availability of medium.

If we increase the number of communicating UWB nodes in localization network, ALOHA may not be able to protect UWB communication from interference. In addition, non-cooperative UWB communication may increase ranging errors. Non-cooperative UWB traffic and interference are caused by other UWB nodes in the vicinity but are not necessarily adversarial. As UWB systems become more common, the chances of non-cooperative UWB interference increases. The main question we try to answer in this work is how scalable is the UWB localization?

In our work, we study the likelihood of wideband interference in different localization scenarios with different UWB physical layer setting and network sizes. We also quantified the impact of interference on ranging accuracy and showed performance drop in UWB-based localization due to the existence of non-cooperative UWB interference.

UWB signals are sent as a sequence of short pulses and the accuracy of UWB-based ranging methods is mostly dependent on the ability to identify the time of the first path's arrival. UWB-based ranging techniques use an accurate estimation of the channel impulse response (CIR) to accurately identify the first path. Non-cooperative UWB traffic can change the CIR which may lead to errors in ranging. In this work, we proposed a simple and practical technique called RAPSI (Random Pulse Shape Identification) to detect the ranging error caused by wideband interference and reduce this error by using unique characteristics of UWB signals. We utilize unique shape of UWB pulses to search the distorted CIR to find the best match for the known pulse shape. Overall, RAPSI reduces 30% to 40% ranging error caused by wideband interference in normal indoor localization applications.

Our contributions in this work are:

- Studied the likelihood of wideband interference and its impact on UWB-based ranging
- Designed RAPSI, a simple and practical method to detect and mitigate ranging error caused by wideband interference
- Evaluated the effectiveness of RAPSI in real world scenarios

2 Related Work

Interference is an old research problem in wireless communications including Ultra-wide band signals.

2.1 UWB Interference Detection & Mitigation

Impact of interference from narrow-band signals on UWB receivers has been studied before. Non-linear filters can improve the performance of UWB receivers by canceling out narrowband interference [22, 26, 28, 20]. Recently [25] compressed sampling is also used to estimate and remove narrowband interference (NBI). Creative ideas like using direction of UWB waves to detect and remove NBI showed reduction in the bit error rate in UWB receivers [19].

Multi-user interference (MUI) in UWB systems has also been investigated before. MUI can be modeled with hidden Markov model or Gaussian mixture model [14]. Another work[29], utilizes the received UWB signal cluster sparsity characteristics to mitigate MUI. These efforts improved decoding performance of energy detection based receivers in UWB communication by adding complexity to the receiver.

Studies show [16] adding randomness to modulation schema will improve the performance of ranging and reduces the error to few meters. Using non-linear filters in physical layer also reduces the errors but makes the receiver more complicated and expensive [27]. Perfect autocorrelation characteristic of UWB preambles is used to detect the interference in the physical layer and reduced the ranging error to few meters[15].

One option to prevent MUI is to coordinate medium access, for instance, with carrier sensing. However, the low power signals, the intermittent characteristics of IR-UWB signals and the possible absence of a carrier make it hardly feasible to reliably perform carrier sensing or clear channel assessment (CCA) with a reasonable complexity.

2.2 ALOHA Protocol

The ALOHA mechanism is the suggested channel access method in the IEEE 802.15.4 UWB PHY standard. Performance of Aloha protocol has been evaluated previously and studies[23] showed its performance drops dramatically in dense networks. For ALOHA to work successfully total air utilization has to be less than 18% across all nodes in range of each other [3]. With air utilization above 18% collision probability is high and system performance degrades quickly. Below the 18% air utilization, 97% of transmissions are likely to succeed without collisions. This 18% air utilization comes into play when deploying a group of Tags. Table 1 gives some indications of the blink transmission rates corresponding to some typical data rate/preamble length combinations and with a minimum 12-byte blink frame sending the Tag ID. It is shown in table 1 that due to a comparatively long transmission time of typical ranging packets, collision is very likely in dense networks.

2.3 Commercial UWB-based indoor Localization and Interference

After IEEE802.15.4 standardized the usage of UWB signals in low power wireless networks, there have been lot of efforts to bring inch-level accurate UWB based indoor localization systems to the real world. There are many companies who design and sell the real time localization system (RTLS) solutions. We did a survey on most famous solutions to assess the status of handling interference in commercial solutions and find out the scalability of the solutions. Despite the very accurate results in ranging performance these companies mention in their websites and show in their demos, almost all of them did not evaluate their systems in dense networks. Table 2 summarizes the result of our survey.

Table 2 shows that two-way ranging solutions maximum support 10 nodes in the network since most of them use the time division multiple access (TDMA) protocol to handle the interference. Other solutions suggest using time difference of arrival technique (TDMA) for localization and claim that their solution can support high density networks. TDOA based solutions also have their scalability limitation. First of all, in TDOA, the anchors (nodes with known position) should be synchronized which is a major problem in making these solutions scalable. Also, TDOA solutions are mostly for tracking applications (Localization is done in Anchors) and is not useful for navigation solutions. TDOA requires cooperation between anchors to be able to locate the target which reduces the scalability.

In summary, the impact of multi-user interference in energy detector receiver in impulse UWB ranging has not been studied and addressed properly in the literature. In our work, we study the likelihood of interference in UWB localization applications and the impact of that interference on ranging performance. We also provide a simple yet effective solution to mitigate the impact of interference.

3 Design

In this section, we describe the basics of UWB communication and ranging, present the results that show UWB interference in different scenarios and their impact on ranging error, and present the design of RAPSI, a technique to detect and mitigate ranging errors caused by interference.

3.1 UWB in IEEE802.15.4-11

3.1.1 Physical Layer Modulation

IEEE802.15.4-11[6] standardized the use of low power UWB signals in personal area networks (PAN). In this standard, a specific format has been defined for UWB packets. It begins with a synchronization header consisting of the preamble and the start of frame delimiter (SFD) after which the PHY header (PHR) defines the length (and data rate) of the data payload part of the frame. The UWB used in 802.15.4 is sometimes called impulse radio UWB because it is based on high speed pulses of RF energy. The PHR and Data parts of the frame, use burst position modulation (BPM) in which position of the burst is utilized to modulate the bits. In addition, binary phase-shift keying (BPSK) is used to shift the phase of the burst by calculating a parity bit.

Forward error correction (FEC) is also included in the PHR and Data parts of the frame. The 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. These features increase the resilience to interference in the receiver.

In contrast to the BPM/BPSK modulation used for the PHR and data, the synchronization header consists of single pulses. Preamble code defines the actual sequence of pulses

Table 1: Maximum Advised Transmissions per Second If ALOHA used as MAC Layer vs datasheet[3]

Channel	PRF	Date rate	Preamble Length	Payload	Transmission Time Time	TX per second at 18% air-utilization
2	64 MHz	110 kbps	2048 symbols	30 bytes	4.684 ms	40
2	64 MHz	6.8 Mpbs	1024 symbols	30 bytes	1.108 ms	180
7	16 MHz	110 Kpbs	256 symbols	30 bytes	2.853 ms	62

Table 2: Scalability and limitations of Commercial UWB Indoor Localization. Supporting evidence for some of these claims are not available and could be incorrect.

Company	Localization Technique	Max number of Tags	Max number of Anchors	Location Update Rate (Hz)	Limitation
Decawave [2]	TWR	6	4	10	TDMA based MAC
CIHOLAS [1]	TDOA	48	10	$\leq$20	not evaluated
UNISET [13]	TWR	Limited Density	10	$\leq$ 20	Density Unknown
UNISET [13]	TDOA	Unlimited (Claimed)	10	$\leq$ 20	Not evaluated
POZYX [10]	TWR	10	10	$\leq$ 40	Not evaluated
RedPoint [11]	TDOA	65000 (Claimed)	1000	Not Specified	Wired Infrastructure
Time Domain [12]	TWR	Unknown	Unknown	Unknown	TDMA based MAC

sent on each symbol interval. The preamble sequence has a property of perfect periodic autocorrelation which helps a coherent receiver to estimate precise impulse response of the radio channel (CIR).

In summary PHR and Data parts of UWB frame are more resilient to interference compared to synchronization header due to difference in modulation schema used in these sections compared to synchronization header.

3.1.2 Physical Layer Parameters

IEEE802.15.4-11 defined several tunable parameters for UWB physical layer which are briefly explained here. It is essential to mention, in this section, we are focused on the parameters which are supported by DW1000 chip [3] which is one of the most popular low cost UWB chips commercially available.

- Center Frequency: Most popular center frequencies for UWB signals are in the range of 3 GHz to 10 GHz and according to IEEE 802.15.4 standard [6], the minimum bandwidth for each channel on UWB signals is 500 MHz.
- Preamble Length: This parameter determines number of times the preamble symbol is repeated in each UWB frame. The UWB receiver calculates the correlation of received signal with the template it generates based on preamble code. Increasing the preamble length, improves the correlation values estimated by the receiver.
- Pulse Reputation Frequency (PRF): In simple terms PRF defines the amount of time interval between sending two consecutive pulses. UWB standard defines 16 MHz and 64 MHz as standard PRF values for communication.
- Preamble Code: Depending on the channel and the PRF the IEEE 802.15.4 standard defines a choice of two or four preamble codes.
- Data Rate: IEEE 802.15.4 standard has defined three different data rates (110 kbps, 850 kbps, and 6.8 Mbps) for UWB communication.

Table 3 summarizes all adjustable UWB physical layer's parameters and their potential values.

3.1.3 Ranging in UWB

Perfect auto-correlation between preamble codes allows UWB receiver accurately estimate channel impulse response. The accurate CIR helps the receiver to resolve the channel in detail and determine the arrival time of the first (most direct) path, even when attenuated.

Accurate ranging using UWB requires the ability to precisely detect first path's time of arrival. The challenging part in time of arrival estimation is proper selection of the threshold for the minimum gap between signal's power and noise. If the gap between the power of the first path and the noise floor is small the chance of misclassification of noise signal as the first path signal increases. On the other hand, higher threshold value increases the chance of not finding the first path signal which is buried in the noise.

The simplest way to estimate the distance between two nodes is two way ranging. In this technique, a pair of nodes exchange at least 3 messages and estimate the time of flight (TOF) for the message which leads to the estimation of distance between the nodes. Since UWB signals are sent as sequence of very short pulses, they are resilient to multipath fading making accurate detection of first path signal possible using simple methods. Researchers have achieved range estimation with less 5 cm error in indoor environments [9].

3.1.4 Network Traffic in Localization Applications

Generally localization applications are considered low traffic applications due to the limited number of messages required for ranging. However, factors like location update rate and the number of neighbor nodes may increase the overall traffic leading to a higher chance of wideband interference. There are three major techniques for UWB indoor localization: Two Way Ranging (TWR), Time Difference of Arrival

Table 3: UWB Physical Layer Parameters (Supported by DW1000)

Parameter	Values
Frequency Channel (MHz)	1(3494.4), 2(3993.6), 3(4492.8), 4(3993.6), 5(6489.6), 7(6489.6)
Bandwidth (MHz)	1(499.2), 2(499.2), 3(499.2), 4(1331.2), 5(499.2), 7(1081.6)
Pulse Repetition Frequency (PRF)	16 MHz, 64 MHz
Preamble Length (symbols)	64, 128, 256, 512, 1024, 2048, 4096
Date Rate	110 Kbps, 850 kbps, 6.8 Mbps

(TDOA), and Direction of Arrival (DOA). Most simple one is TWR since the other two approaches require precise synchronization (with nanosecond granularity) between nodes which decreases the scalability of such approaches.

In TWR, each target node (Tag) needs to estimate its distance to at least three other nodes with known locations (Anchor) and finally, use trilateration to estimate its location. To estimate the distance to each Anchor, at least three messages (double-sided two way ranging [21]) have to be exchanged. Thus, each location estimation requires at least 8 packet transmissions in localization applications and 5 packets in tracking applications even with an optimization: Tag talks with all 3 anchors with one message through broadcast which reduces the total number of packets.

Based on the values reported in table 1, if on average each packet occupies the channel for 2 ms, and each Tag updates its location 10 times per second, overall each Tag occupies for 160 ms per second. Such a network with just five Tags would result in 80% channel utilization. Thus, a relatively simple localization application in a small network could lead to high channel contention and interference.

In non-cooperative UWB networks, the probability of packet collision can be surprisingly high as we found from testbed experiments and also quantified under simplifying assumptions: $1 - e^{-2G}$ (G is number of attempts to send packets during twice the time it takes to send one packet). A 10-node network with 10 Hz broadcast of 12 bytes/pkt can lead to collision probability of 46%. Empirically we found this probability to be about 54%.

3.2 Wideband Interference & Ranging

In this section, we analyze the impact of wideband interference from non-cooperative UWB nodes on the ranging performance.

3.2.1 Interference Measurement Setup

Our testbed consists of Radino32 (Figure 1a) and EVB1000 (Figure 1b) boards which both have DW1000 RF Transceiver , which is IEEE802.15.4-2011 UWB compliant. Radino32, uses STM32L151CC with 32-bit ARM Cortex-M3 CPU with 256 KB Flash, 32 KB RAM, 8 KB EEPROM and 12 bit ADC and DAC [7]. EVB1000 boards use STM32F105 ARM Cortex M3 processor with 12 MHz external crystal and 32.768 kHz RTC crystal [4].

We deployed 15 Radino32 nodes in a corridor ($6m \times 14m$) (Figure 2) while two Decawave EVB1000 nodes are placed 12 meters apart. In all the experiments, EVB1000 nodes are used for distance measurements and we refer to them as ranging nodes. Ranging nodes are placed in constant locations and run two way ranging with 10 Hz.

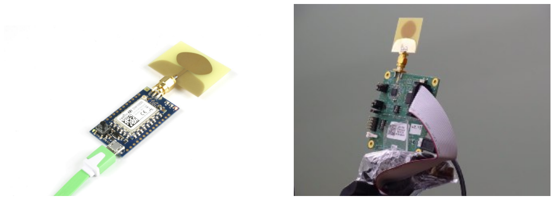

(a) Radino32 (b) EVB1000

Figure 1: UWB Nodes used in Data Collection

Figure 2: Experiment Set up

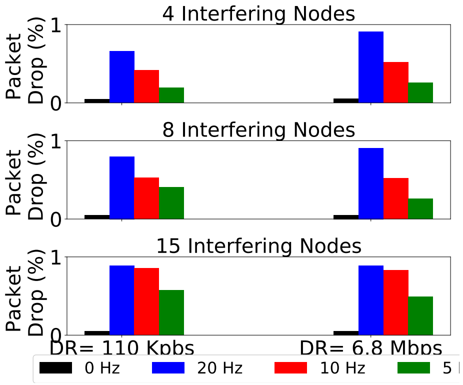
To create non-cooperative UWB network traffic, we setup Radino32 nodes to periodically send packets with 30 bytes payload. The sending rate can be configured to 20 Hz, 10 Hz or 5 Hz. Each node uses a random delay value before sending its packet. This random value is selected between 0 up to maximum possible delay based on configured sending intervals (for instance 0 to 50 ms for 20 Hz frequency).

In each experiment, we collect at least 2000 packets and results are averaged over all the collected packets. In total, during our experiments, we collected more than 200000 ranging packets.

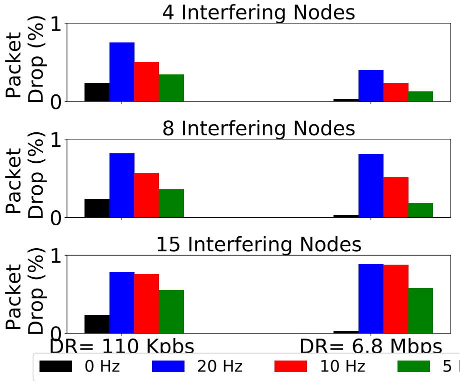
Last but not least, in order to improve the visibility of figures and claimed assumptions, in all the experiments, CIR samples are 10 times up-sampled using Fourier method [5].

3.2.2 Likelihood of Wideband Interference

We first study the impact of the non-cooperative wideband interference on communication. We want to know if the nodes can decode messages under interference. How do the changing the parameters of UWB physical layer impact the packet drop rates? In this section, we use different settings (Number of Nodes, Physical Layer Setting and Packet

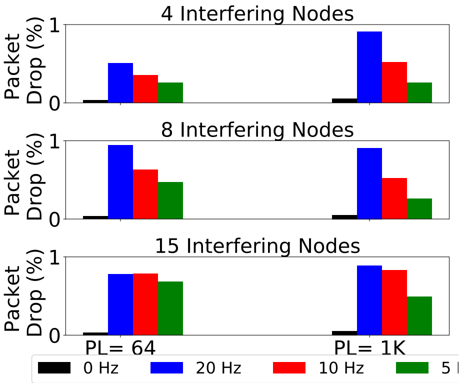


(a) Channel 2, PRF = 64 MHz, Preamble Len = 1024

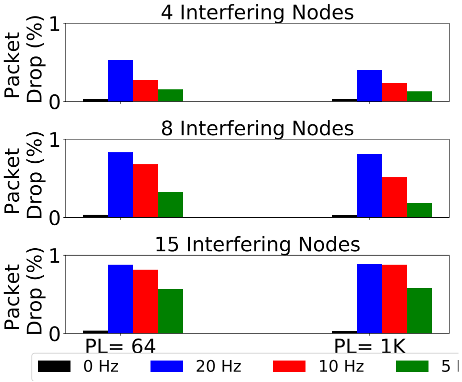


(b) Channel 7, PRF = 64 MHz, Preamble Len = 1024

Figure 3: Packet drop caused by Wideband Interference under different Data rates (110 Kbps and 6.8 Mbps)



(a) Channel 2, PRF = 64 MHz, Data Rate = 110 Kbps



(b) channel 7, PRF = 64 MHz, Data Rate = 110 Kbps

Figure 4: Packet drop caused by Wideband Interference under different Preamble Length (64 and 1024 symbols)

Transmission Rate) of UWB nodes and measure packet drop rates in each of those settings. Unless otherwise mentioned, in each experiments, all the interfering nodes (Radino32) and ranging nodes (EWB1000) are configured using the same parameters.

Data rate & Wideband Interference UWB nodes can communicate with three different data rates: 110 Kbps, 850 Kbps and 6.8 Mbps [6]. Generally, lower data rates are preferred for better ranging performance, but decreasing the data rate will increase the packet transmission time which leads to higher chance of collisions. Figure 3 shows the impact of changing the data rate on packet drop rates.

In less dense networks with less traffic, the lower data rate causes more packet drop rates in crowded scenarios. Higher data rates are preferred on more dense networks.

Preamble Length & Interference Another parameter in UWB physical layer which impacts ranging performance is preamble length. Figure 4 shows the impact of changing the preamble length on the likelihood of collision and dropping the packet.

In most cases, changing the preamble length does not cause a noticeable increase in packet drop rates.

Center Frequency & Interference IEEE standard defines 16 different channels for UWB communication which are in the range of 3 GHz to 7 GHz but DW1000 only supports 6 of them (Table 3). In this experiment, we kept all the UWB physical layer configurations same (PRF = 64 MHz, Preamble Length = 1024 and Data rate = 110 Kbps) and only changed the center frequency. The results are summarized in Figure 5. Channel 7 has higher bandwidth ($\approx$1.3 GHz) compared to channel 2 ($\approx$500 MHz) and that is why the packet drop rates are higher in channel 7.

Results from Figure 5 show that wideband interference is a real problem across all the frequency channels and increasing the bandwidth will not significantly improve the ranging performance under interference.

3.2.3 Ranging Errors Under Wideband Interference

In previous sections, we showed that even in high density and high traffic networks, nodes still receive some ranging packets. Now, if a node receives a packet under interference, what happens to the ranging performance. Figure 6 shows the CDF of ranging errors under interference happening in different channels.

We find that ranging done with the packets retrieved under interference leads to large errors.

Regardless of frequency channel, in average the chance of ranging error of more than 40 cm is more than 50%. The error is worse in 2D localizations: at least 3 range estimations are required to locate the target thus leading to higher chances of not being able to locate the target.

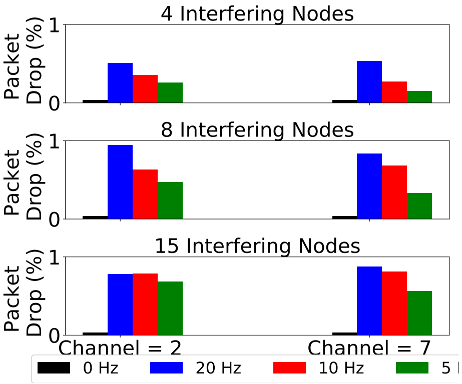


Figure 5: Packet drop caused by Wideband Interference under different Frequency Channels (Channel 2 and 7)

3.3 Design of RAPSI for UWB Interference Detection and Mitigation

In this section, we describe the design of RAPSI, Random Pulse Shape Identification, a technique to detect and mitigate the impact of interference on UWB-based ranging.

3.3.1 *Pulse Shape*

UWB signals are sent as a sequence of pulses. There is a parameter in DW1000 settings called pulse generator delay (PGDelay). PGDelay sets the width of transmitted pulses which changes the output bandwidth. Previous studies showed that changing the pulse width will not impact the ranging performance but it changes the pulse shape and unique pulse shape can be used as unique identifier for sender nodes[17].

Our hypothesis is if nodes use different pulse shapes, these unique pulse shapes can be extracted from distorted CIR using matched filters (key idea of our proposed random pulse ranging). In order to validate our hypothesis, we put two EWB1000 nodes in an anechoic chamber (Figure 7a) and collected CIR information while nodes were communicating with different PGDelay values. We also created a reflection path by using a reflective surface (Figure 7b) to make sure the data we use to extract the pulse shape is from the first path and not from a reflected path.

Figure 8 shows pulse shapes extracted from the first path in CIR data collected in the chamber. As expected, the width of pulse is different using different PGDelays in both channel 2 and channel 7.

Pulse Shape Adjustment Even though Figure 8 shows the different width of pulses, the amplitudes of pulses are approximately equal which makes them not practical to be used as templates in matched filter. To mitigate this problem, we adjust those pulse shapes to make sure the area under each pulse is equal while the width of them different (adjusted pulse shape). We change the amplitude of pulses to make pulses equal in the area. Figure 8 shows the pulse templates after the adjustment. In summary, the core of RAPSI is to utilize different pulse shapes during transmission and utilizing these pulses as templates for standard matched filtering to detect distorted CIR and also extract the first path from it.

Algorithm 1 Proposed Interference Detection Technique

```
$Th_{Detection} \leftarrow$ Interference Detection Threshold
$CIR \leftarrow$ Channel Impulse Response Extracted from Received Packet
$PGDelay_{target} \leftarrow$ Sender's PGDelay Encoded in the Payload
$PulseShape \leftarrow$ Pulse shape based on $PGDelay_{target}$
$MatchedCIR \leftarrow$ Call MatchFilter($CIR$,$PulseShape$)
$MaxCorIndex \leftarrow$ Index of Maximum Value in $(MatchedCIR)$
$FPIndex \leftarrow$ Index of First Path in $(CIR)$
if $abs(MaxCorIndex - FPIndex) \geq Th_{Detection}$ then
    Return $True$
else
    Return $False$
end if
```

3.3.2 *Using Random Pulse Shapes*

UWB nodes can communicate with each other using different pulse shapes. In other words, different pulse shapes typically do not have much impact on the ranging or communication capabilities of UWB nodes. Our proposed interference avoidance technique (RAPSI) is the combination of adding random delays and also random pulse shapes in UWB ranging. Since pulse shapes do not need to match between sender and receiver of UWB message, the sender can randomly choose a pulse shape and send its data using that pulse shape. The sender should include the pulse shape code (1 Byte) in its message. The receiver upon receiving this pulse shape code can both detect and also mitigate the ranging error caused by interference.

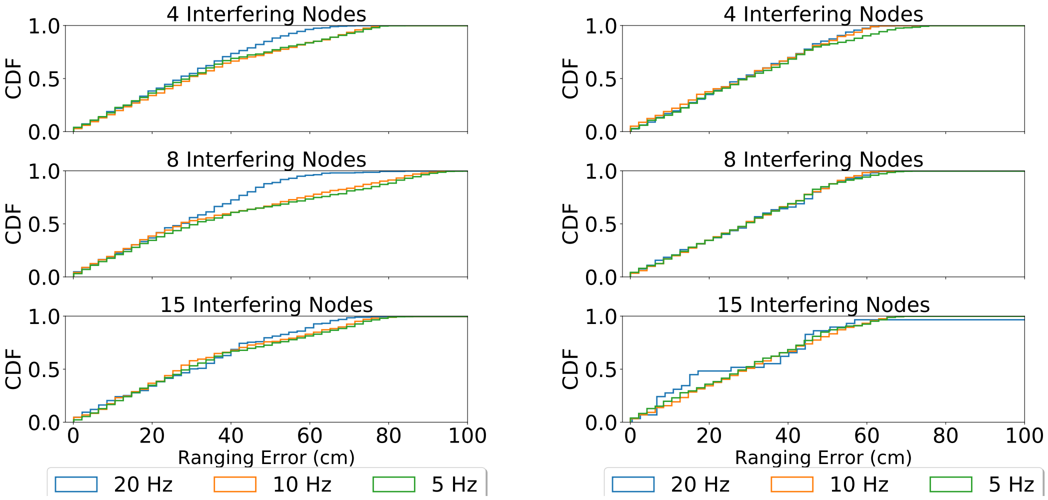
3.3.3 *Detect the Existence of Interference*

Our technique for detection of interference is based on the hypothesis that match filter output will not match with the first path from CIR in the packets retrieved under interference.

To verify our hypothesis, we conducted a simple experiment. We placed one EVB1000 board as initiator node and two other EVB1000 boards as responders (Figure 9). The initiator node sends a broadcast message and each responder upon the reception, replies after a constant time (190 μs) using DW1000's delayed send functionality. In delayed send mode, DW1000 copies the data to its internal buffer and on the designated time ($\pm 8ns$) it just sends the data. Since two responders are 15 cm away from each other, two arriving paths should be visible at receiver as two consecutive pulses.

Following above mentioned setup, we are able to create an interference scenario. We conducted this experiment on both channel 2 and 7 while two responders were using different PGDelay values then we applied our interference detection technique on the collected CIR (Average of 1000 Packets). Figure 10 shows the matched filter result after applying the filter on the retrieved CIR.

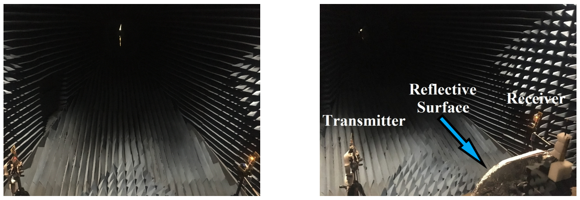
On both channels, there is a gap between the first path of CIR and the peak of matched filter output. We utilize this difference as an indicator of wideband interference impact on the UWB packet which causes the ranging error. Basically,



(a) Channel 2, Preamble Length = 1024, PRF=64 MHz

(b) Channel 7, Preamble Length = 1024, PRF=64 MHz

Figure 6: CDF of Observed Ranging Errors across different number of Interfering Nodes and with different Traffic



(a) Line of Sight

(b) Line of Sight with Controlled Reflection

Figure 7: Using Anechoic Chamber to Extract Pulse Shape

if captured packets are infected by wideband interference, interfering signals overlap with original first path signal and increase the width of the first path pulse. Figure 11 shows validity of our hypothesis. Figure 11 shows the first path pulse width with and without interference on channel 7. This observation is the building block of our interference detection and mitigation technique.

Our interference detection solution is described in Algorithm 1. The detection threshold value has been measured using trial and error technique to be 5 which means if the difference between path with maximum CIR value and index of maximum output of matched filter is bigger than the detection threshold (5), it can be classified as distorted CIR and range estimation which used that packet has been done under interference. As mentioned earlier, the CIR has been up-sampled to 10 times before calling interference detection algorithm.

3.3.4 Mitigate Impact of Interference

After detecting the packets which are infected by noise which if used as-is for ranging could result in incorrect time of flight measurement; we adjust the measured distance for those packets. Our hypothesis here is if nodes use different pulse shapes, the location of the first path can be adjusted using matched filter technique. To evaluate the feasibility of this idea, we used the same set up as previous experiment (Figure 9). In this experiment, we collected data on two channels (2,7). On channel 2, one of the responders (target) used 0xC2 (194) as PGDelay value while the other one (interferer) used 0xD6 (214) and on channel 7, the target node used 0x93 (147) as PGDelay and interferer used 0xA7 (167). Figure 12 shows the result of applying matched filter with different templates (pulse shapes) on the captured CIR (Average of 500 Packets).

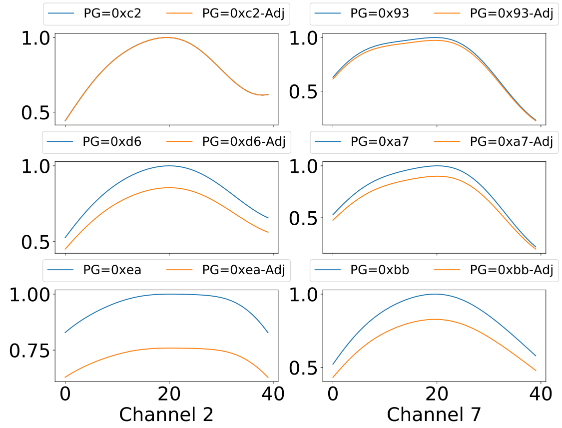
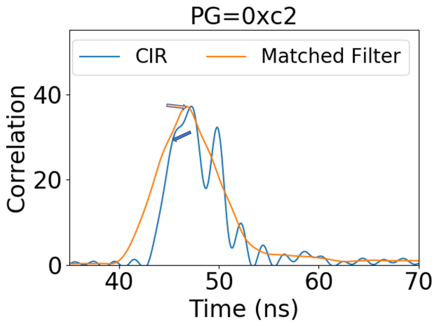


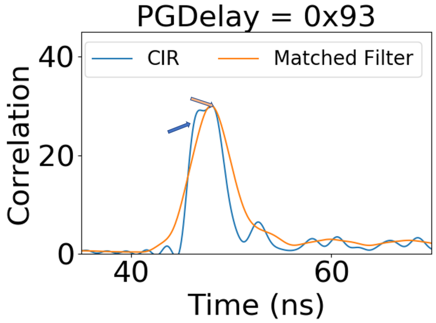
Figure 8: Pulse Shapes across different PGDelay Values

Figure 9: Experiment Setup to Verify Interference Detection Technique

The correlation values on the intended pulse shape (0xc2 on channel 2 and 0x93 on channel 7) are significantly higher



(a) Channel 2



(b) Channel 7

Figure 10: Detect the Wideband Interference from CIR - Peak of Matched Filter Output (Orange Arrow) $\neq$ First Path of CIR (Blue Arrow)

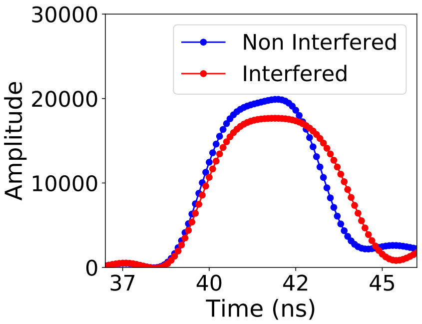


Figure 11: Wider First Path under Interference

Algorithm 2 Proposed Interference Mitigation Technique

```
$Th_{mitigate} \leftarrow$ Interference Mitigation Threshold
$FP_{Org} \leftarrow$ Original First Path
$FP_{Adj} \leftarrow$ Adjusted First Path
$CIR \leftarrow$ Channel Impulse Response from Received Packet
$PGDelay_{target} \leftarrow$ Sender's PGDelay from the Payload
$PulseShape \leftarrow$ Pulse shape based on $PGDelay_{target}$
$MatchedCIR \leftarrow$ Call MatchFilter($CIR$,$PulseShape$)
if $InterferenceExists$ then
    $AdjustedFirstPath \leftarrow$ Index of first path in $MatchedCIR \geq Th_{mitigate} * max(MatchedCIR)$
    Return $FP_{Adj}$
else
    Return $FP_{Org}$
end if
```

than ($\approx 10\% - 17\%$) the correlation values for other templates. If the receiver knows the PGDaley value used by sender, instead of searching inside the CIR, it can search the output of matched filter and extract the first path.

Overall, our experiments support the feasibility of using different pulse shapes to detect and mitigate the impact of non-cooperative UWB interference on UWB-based ranging. Algorithm 2 summarizes our mitigation algorithm. Using trial and error, we found that the suitable value for mitigation threshold in algorithm 2 is 0.85 which means after calculating the match filter output from CIR, the adjusted path is the first path whose correlation value is higher than 85% of peak of correlation values.

4 Evaluation

In this section, through extensive data collection from real world scenarios, we evaluate the effectiveness of our proposed approach to detect wideband interference and also remove its impact on the range estimation (first path detection)

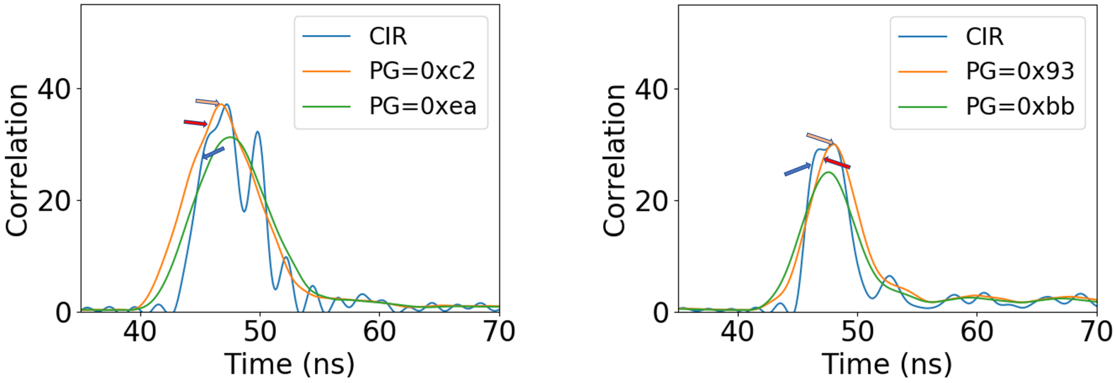
4.1 Performance of Interference Avoidance Techniques in IEEE802.15.4-11

The IEEE802.15.4-11 standard defines a few adjustable parameters (table 3) in UWB physical layer aiming to avoid wideband interference in UWB communication. In this section, we evaluate the effectiveness of utilizing UWB physical layer settings to avoid interference.

Reducing Transmission Power to Avoid Interference In this experiment, we placed two EVB1000 nodes (ranging nodes) 12 m apart while different number (4, 8, 15) of Radino32 nodes (interfering nodes) broadcast messages with different (5 Hz, 10 Hz, 20 Hz) rates but with the same physical layer configurations as ranging nodes. Ranging nodes transmit with maximum possible transmission power(-30 dBm) and interfering nodes transmit with different levels of transmission power (-14 dBm, -30 dBm and -40 dBm). We want to study the impact of lowering interfering nodes' transmission power on avoiding the interference.

Figure 13 shows that lowering the transmission power is not a reliable way to avoid the interference in dense networks. In addition, in general localization/tracking applications, long range performance is desired and lowering transmission power decreases the ranging performance.

Utilizing Random Delay to Avoid Interference Carrier sensing techniques are considered challenging in UWB due to the limited maximum transmission power in UWB signals (To avoid interfering with narrow-band devices). IEEE802.15.4-11 suggests ALOHA as the main technique for UWB MAC layer which sends data without checking the availability of medium. One potential improvement to pure ALOHA could be adding random delays before sending data. In this section, we evaluate the effectiveness of adding random delays to UWB transmissions to avoid the wideband interference. The experiment setup is as those in previous section, but this time we change the maximum possible random delay before sending packets and measure the packet



(a) Channel 2 - Intended PGDelay = 0xc2

(b) Channel 7 - Intended PGDelay = 0x93

Figure 12: Intended pulse template has higher correlation values & First path can be adjusted from Matched Filter output
Blue arrow = First path detected by DW1000, Orange arrow = Matched filter output peak- Red Arrow = Adjusted first path

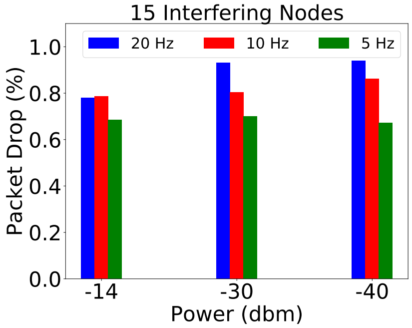


Figure 13: Impact of Changing Transmission Power to Avoid Interference

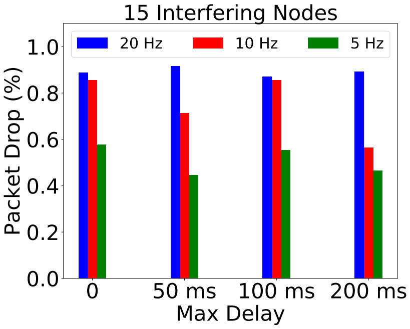


Figure 14: Impact of Adding Random Delay to Avoid Wideband Interference

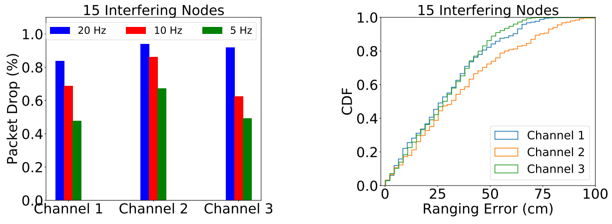
drop rates. Each node selects a random value between 0 to max delay value and sends its data after that time interval. The maximum delay is determined by the packet sending rate. For example, for 20 Hz packet sending rate maximum random delay is 50 ms, for 5 Hz packet sending rate the maximum random delay can go up to 200 ms. Figure 14 shows the packet drop rates under different delays.

As shown in Figure 14, in some cases, adding a random delay decreases the packet drop rates but at the cost of increasing total delay of ranging application. Overall, our results indicate that nodes can utilize the maximum possible random delay to decrease the chance of interference but the improvements come at the cost of the total delay added to ranging applications.

Channel Hopping to Avoid Interference One of the standard ways in interference avoidance techniques is using different settings at physical layer to minimize or avoid collision between packets transmissions. In this section, we evaluate the impact of changing the UWB physical layer setting to avoid the collision. Easiest parameter to change and keep the ranging performance the same, is changing the communication channel (center frequency) of UWB signals. IEEE standard defines 16 channels for UWB communication and DW1000 chip support 6 of them. Figure 15 shows the drop rates and ranging errors in the experiment in which two nodes that are 12 meters apart are running ranging algorithm on channel 2, while 15 other nodes are creating traffic on other channels (channel 1 and channel 3). We kept other parameters of UWB physical layer the same in all the experiments.

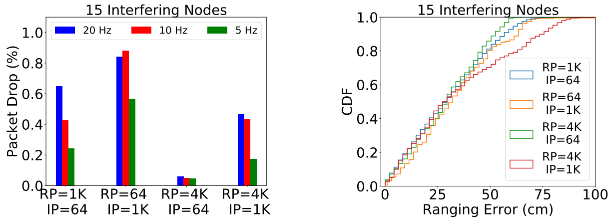
Figure 15a shows that, changing the channel does not reduce the drop rate significantly and also as Figure 15b reports, ranging errors are high even when the interfering nodes are communicating on different channels. This could be due to inter-channel interference between UWB channels as reported in previous studies [8]

Changing the Preamble Length to Avoid Interference Other UWB physical layer setting which can be changed to increase the resilience to interference is preamble length. In this experiment, we changed the length of preamble on ranging nodes and also interfering nodes and measured the performance of ranging. The results are reported in Figure 16. Generally increasing the length of preamble in ranging nodes compared to interfering nodes increases the resilience to interference. Specially 4096 symbols as preamble length for ranging and 64 samples as preamble length for interfering



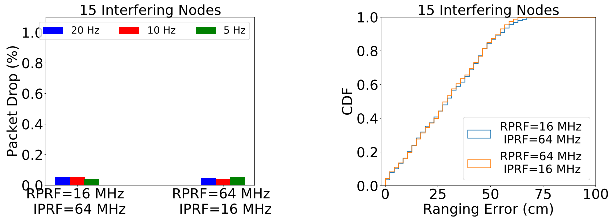
(a) Drop Rates (b) Ranging Error

Figure 15: Packet drop and ranging error with ranging nodes and interfering nodes using different frequency channels. (Channel 1=3494.4 MHz, Channel 2= 3993.6 MHz, Channel 3= 4492.8 MHz)



(a) Drop Rates (b) Ranging Error

Figure 16: Packet drop and ranging error with ranging nodes and interfering nodes using different preamble lengths. RP=ranging node's preamble length. IP=interfering node's preamble length.



(a) Drop Rates (b) Ranging Error

Figure 17: Packet drop and ranging error with ranging nodes and interfering nodes using different PRF values. RPRF=ranging node's PRF. IPRF=interfering node's PRF.(maximum drop rate of 6%)

nodes achieved the lowest packet drop rate. Although longer preamble increases the performance of ranging, it increases the power consumption and transmission time which leads to higher chances of interference.

Changing the PRF to Avoid Interference Pulse repetition frequency is another parameter in the UWB physical layer. In this experiment, we evaluate two scenarios. In the first scenario, the ranging nodes use PRF 64 MHz while interfering nodes use 16 MHz PRF. In the second experiment, ranging nodes switch to 16 MHz and interfering nodes use PRF 64 MHz.

This is one of our most interesting findings. As shown in Figure 17, using different PRFs significantly reduces the likelihood of collision between nodes (Maximum packet drop of 6%). Figure 17 also supports the fact that higher PRF improves the ranging performance and resilience to interference.

Changing the Preamble Code to Avoid Interference IEEE802.15.4 defined different preamble codes per channel to avoid the interference. Figure 18 shows the packet drop rates while ranging nodes and interfering nodes use different preamble codes.

As expected, using different preamble codes reduces the chance of interference.

Overall, based on our experiments, using different PRFs and Preamble codes seems to be the most effective way to avoid the interference but DW1000 only supports two different PRF values (16 MHz and 64 MHz) and maximum of 4 different preamble codes per channel per PRF which limits the scalability of above interference avoidance techniques. In addition, for successful UWB communication, PRF and preamble code between sender and receiver should match. Otherwise the receiver is not able to decode the received messages. This fact significantly limits the applicability of these kinds of techniques in real world localization/tracking applications since in normal localization technique, all the Tags use the same set of Anchor nodes and they all should use the same PRF and preamble code to be able to communicate.

4.2 Accuracy of RAPSI for Interference Detection

In this section, we evaluate the accuracy of RAPSI in detecting wideband interference. In this experiment, 2 EVB1000 nodes are placed 12 m apart and run two way ranging algorithm and another 15 Radino32 nodes generate traffic using the same physical layer setting but using random delays and also random pulse shapes. One of our assumption here is since the location of ranging nodes are constant during the experiments, additional ranging error after activating interfering nodes, is due to the interference. To evaluate the accuracy of the proposed interference detection technique, we used amount of ranging error as an indicator of interference existence. If the ranging error estimated using a packet is higher than normal error(error when all the interfering nodes are off), we mark the packet as interfered packet. We calculated minimum and maximum of ranging error observed in our dataset and divided the error range into 10 equal size bands. Next, in each error band, we walked through all the interfered packets with error range in that specific band and measured the probability of classifying an interfered packet (ranging packet impacted by interference) as correct packet (False Negative) by our interference detection algorithm. The results are summarized in Figure 19. In most cases, our proposed solution (RAPSI) is able to detect the packets which are received under interference with very small false negative rates. We achieved almost the same results with 6.8 Mbps data rate. On average on more than 75% of the cases, our technique accurately classifies corrupted ranging packets by investigating CIR and looking for the best match for designated pulse shape.

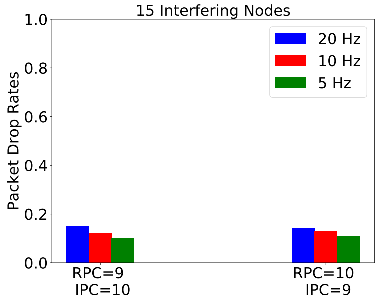


Figure 18: Packet drop and ranging error with ranging nodes and interfering nodes using different preamble codes. RPC= ranging node's preamble code. IPC=interfering node's preamble code

4.3 Effectiveness of RAPSI for Interference Mitigation

Next we evaluate the effectiveness of RAPSI to mitigate the impact of interference on ranging errors. We used the data collected from previous section and used our proposed technique to adjust ranging errors due to the existence of wideband interference. The results are summarized in Figure 20. Regardless of bandwidth (channel 2 with 500 MHz and channel 7 with 1 GHz), our proposed interference mitigation technique is able to significantly reduce the ranging error caused by wideband interference. Based on our extensive data collection results the proposed method in average reduces the ranging error by 30% to 40% depending on the bandwidth of the channel. Higher bandwidth channels show better interference detection and mitigation on average.

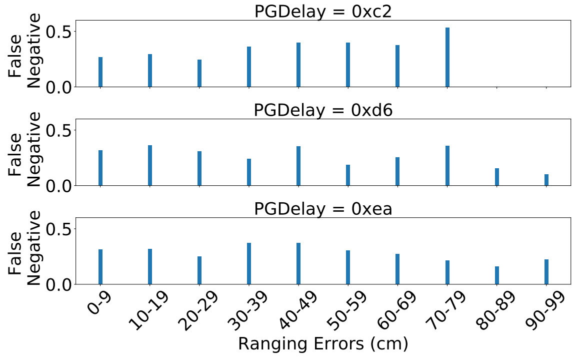
5 Discussion

Time Difference of Arrival (TDOA) and Angle of Arrival (AOA) techniques reduce the localization traffic since the Tag can send one blink message for each location estimation but the chance of interference still is high in more dense networks in low data rates like 110 Kpbs. In these approaches the localization is happening in Anchor side which means these techniques are usually suitable for tracking applications and not the navigation applications. Both TDOA and AOA techniques require very accurate synchronization between anchors which may increase network traffic and chances of interference.

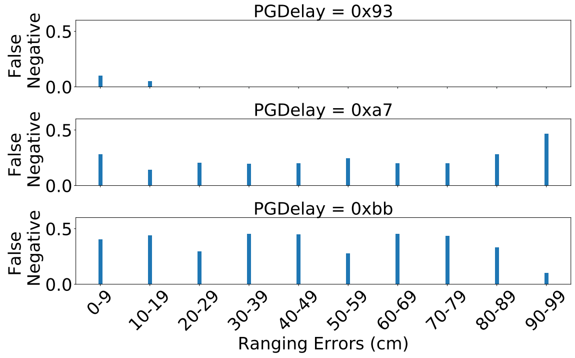
Changing the value of PGDelay alters the output pulse shape. Our experiments in different real world scenarios show that to be able to reliably differentiate pulse shapes, the minimum difference between two selected PGDelay values should be 5. Since PGDelay is a one byte register, on each frequency channel (DW1000 supports 6 frequency channels), $255 \div 5 = 51$ distinguishable PGDelay values are available. To make sure the output signal does not violate regulatory restrictions, the TX power is tuned based on the PGDelay value.

6 Conclusions & Future Work

In this work, we studied the likelihood of wideband interference from non-cooperative UWB nodes in ranging applications. We showed, in applications with low location update rates, there is a high chance of UWB interference. We also measured the impact of this wideband interference on UWB-based ranging applications. Finally, we proposed a simple yet effective technique to detect and mitigate the impact of wideband interference on ranging. Our extensive experiments in real world scenarios show the effectiveness of our proposed technique to both detect and mitigate the error caused by non-cooperative UWB nodes.



(a) Channel 2, PRF = 64 MHz, Preamble Len = 1024, Data rate = 110 Kbps



(b) Channel 7 ,PRF = 64 MHz, Preamble Len = 1024, Data rate = 110 Kbps

Figure 19: False negative values for distinguishing interfered packets from correct packets using RAPSI

In future, we plan to extend this work by studying the impact of narrow-band interference on ranging performance also, evaluate the effectiveness of our proposed method in harsh environments like construction sites and factories.

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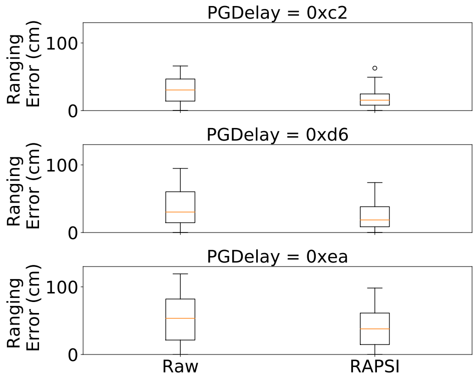
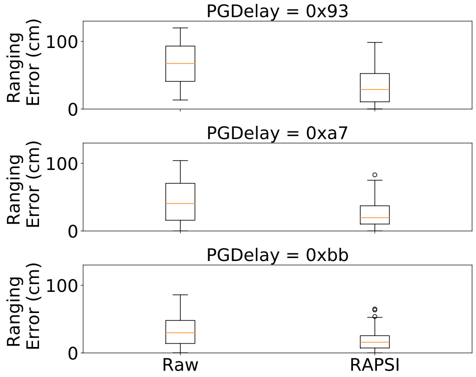


(a) Channel 2, PRF = 64 MHz, Preamble Len = 1024, Data rate = 110 Kbps



(b) Channel 7 ,PRF = 64 MHz, Preamble Len = 1024, Data rate = 110 Kbps

Figure 20: Ranging error without (raw) and with RAPSI. With RAPSI, the error is lower because RAPSI adjusts the first path using match filter

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