# RIC3: Reliability Improvement in UWB Networks Using Enhanced CCA and Complex Channels

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***Abstract*—The usage of ultra-wideband (UWB) radios in different IoT applications has increased in recent years. With the evergrowing traffic of UWB-based applications, delivering reliable communication becomes a challenge due to packet collision. Traditional collision avoidance methods are either not fully compatible with UWB technology or do not have the desired performance. In this work, RIC3, we introduced two approaches to improve the reliability of UWB communications in busy networks. First, we present a UWB-compatible collision avoidance (CA) solution to minimize unwanted collisions among UWB transmitters. Our second approach utilizes complex channels and modifies the configuration of the sender and receiver to isolate the link from other UWB applications' traffic. Using the latest UWB radio chip (DW3000), our real-world evaluation demonstrated link reliability of over 90% in a network with multiple UWB applications, gaining 30-60% improvement in different scenarios compared to previous recommendations.**

***Index Terms*—Ultra-WideBand, Preamble detection, CCA, Frame Filter, Complex channel, Link reliability**

## I. Introduction

UWB enables accurate indoor/outdoor localization and ranging in many IoT applications. Commercial products such as Apple AirTags, iPhones, and the Samsung Galaxy series have already embedded UWB radio chips in their products. In addition, researchers have also recommended UWB radios for other applications such as data communication [1], [2]. With this increase in UWB-enabled devices and applications, multi-application UWB networks and generally higher UWB traffic volume will become common.

As the number of transmitters increases in UWB networks, applications may experience packet losses due to frame collisions with other UWB network traffic. These losses become more frequent without a collision avoidance (CA) mechanism, causing performance reduction in UWB applications. Currently, UWB chips use ALOHA as the Medium Access Control (MAC) protocol that transmits the data without performing any CA, reducing the performance of the applications in large networks [3], [4].

UWB applications commonly use Time Division Multiple Access (TDMA) to prevent contention in the wireless channel. However, in multi-application UWB networks, TDMA is difficult to implement as different platforms may develop their own channel management protocols. Carrier Sense Multiple Access (CSMA) does not tackle the frame collision problem sufficiently due to power level of the UWB signals [5].

The IEEE802.15.4a standard defines complex channels (CC) as a combination of channel and preamble code (PC) to isolate the links within the same channel and mitigate the interference of other UWB senders. However, continuous clock synchronization is required among all transmitters to run the technique that isolates complex channels [6].

In addition to CA methods, another group of solutions focuses on exploiting frame collision and recovering information from collisions. *Capture effect* allows receivers to extract a frame from collided packets under certain circumstances. Many solutions in low-power radios have utilized capture effect to enhance the performance of their applications [7]–[9]. The research community has utilized concurrent transmission in UWB radios in the context of ranging [10], and localization [11], [12] applications. However, these solutions work with limited UWB applications in single-application UWB networks.

In this work, we present RIC3 to improve the reliability of links in multi-application and busy UWB networks. RIC3 consists of two components. First, RIC3-CA (Collision Avoidance) uses concurrent transmission in the UWB networks to avoid destructive packet collisions that lead to frame drop. Second, RIC3-IR (Interference Reduction) uses the complex channels (CC) to develop an Interference Reduction (IR) method that prevents nodes from synchronizing with unwanted UWB frames. In contrast to previous works [11]–[13], we design RIC3 as one of the MAC layer's components that improves link reliability for a wide range of UWB applications. Furthermore, RIC3 can operate without a central manager or a reference clock, simplifying the design of UWB applications. Our evaluation with DW3000 UWB provided more than 90% link reliability, achieving 30-60% improvement compared to traditional CCA in the UWB network. Our contributions are:

- Design and testbed-based evaluation of collision avoidance mechanism for UWB radios to minimize packet corruption and the reception of unwanted frames.
- Design and testbed-based evaluation of enhanced-complex channels, providing more isolation for UWB links.
- Dynamic configuration update process that enables/disables enhanced-complex channels in run-time to gain the highest link reliability.

## II. Related Work

The impact of packet collision in low-power wireless networks has been the topic of discussion across all radio technologies. Studies have cited that when the channel utilization exceeds 18%, MAC protocols that do not possess a CA mechanism (such as ALOHA) start experiencing frame loss

[14]. For UWB networks that use ALOHA as its default MAC layer, researchers have also cited approximately 50 % packet drop for a network of 4 or more transmitters [4]. To reduce packet drops caused by collisions, majority of wireless applications and MAC protocols seek to avoid, mitigate, or exploit packet collisions.

### A. Collision Avoidance

Clear channel assessment (CCA) is a widely used collision avoidance method in wireless technologies. However, it does not work well in UWB networks since the power level of UWB signals is close to the noise level [5]. To avoid collisions in UWB networks, implementations commonly use Time Division Multiple Access (TDMA). TDMA avoids packet collision by scheduling the transmission time of all senders. Despite the high reliability, challenges such as resource orchestration and centralized management make TDMA unsuitable for networks with many nodes and applications [12]. Researchers have also recommended channel hopping for isolating the UWB links [15]. However, channel hopping is not always feasible since different implementations support different UWB channels. For example, DW3000 only supports channels 5 and 9, providing two choices for dynamic channel selection.

### B. Collision Mitigation

Collision mitigation approaches reduce the impact of interfering frames by isolating the communication. The standard introduced complex channels (CC) to isolate links within the same channel. Although complex channels have low cross-correlations, they still interfere [16]. To isolate the complex channels, researchers designed a mechanism that modifies the clock offset of transmitters [6]. However, this solution requires constant synchronization of all the transmitters in the network.

### C. Collision Exploitation

In collision exploitation solutions, not all collisions lead into frame loss or frame corruption. In some low-power radios, *capture effect* enables receivers to capture and extract one packet out of two or more collided packets. This phenomenon led researchers to design protocols that enhanced the performance of wireless applications compared to their collision avoidance design [17]. FlashFlood [8] and Glossy [7] used capture effect for flooding and synchronization. Researchers have also developed a Message-In-Message (MIM) MAC layer for low-power radios that supports unicast communication [9]. In this solution, the transmitter performs a CCA to measure the level of interference in the air. Based on the results of CCA and the concurrency map, the sender decides to transmit or defer the transmission.

The UWB research community developed the idea of concurrent transmission to improve the scalability of localization and ranging applications [13]. In that context, researchers did a detailed study on UWB frame reception in concurrent transmission [16]. Both these studies claim that independent of the received signal power of the collided frames, the UWB receiver could usually extract one of the frames from collided packets. This finding differs from the capture effect, which is the building block for opportunistic MAC protocols. The UWB researcher community has exploited UWB concurrent transmission in localization systems [11], [12], [18] and message flooding [2].

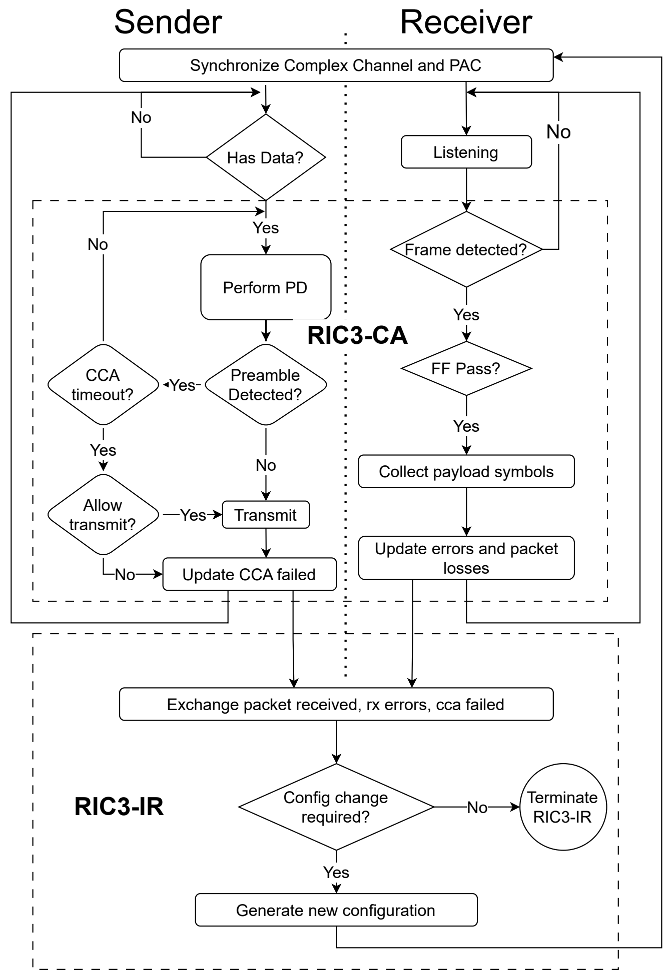



Fig. 1: The design of RIC3 consists of two components: RIC3-CA and RIC3-IR. RIC3-CA prevents destructive collisions via preamble detection (PD) and frame filtering (FF). RIC3-IR mitigates the effect of unwanted frames by dynamically adjusting the radio configuration as needed.

Our work utilizes concurrent transmission outside its core application in localization and flooding to improve communication reliability in multi-application UWB networks. We also introduce an interference reduction (IR) technique that prevents nodes from synchronizing with frames that use different CC without the need for clock synchronization. The former technique is beneficial for improving reliability in congested UWB networks.

## III. Design

To mitigate the impact of collisions, RIC3 proposes a solution for UWB radios by utilizing the UWB packet reception process to synchronize the receivers with their wanted frames.

Fig. 1 illustrates RIC3's design, composed of two sub-systems: RIC3-CA and RIC3-IR. RIC3-CA aims to avoid destructive frame collisions that result in synchronization with unwanted frames. RIC3-IR isolates the communication link, preventing the receiver from sensing unwanted frames and synchronizing only with the wanted frames.

Section III-A provides background about the frame structure and frame reception process in UWB radios. Section III-B describes types of packet collisions in the UWB radio network. Sections III-C and III-D describe the components of the RIC3. Finally, section IV, validates the enhancement of RIC3 in link reliability of multi-application UWB networks.

### *A. Background: Frame reception in UWB network*

Fig. 2 displays the structure of the UWB frame. The frame starts with a preamble which is variable in length. After the preamble, the Start of Frame Delimiter (SFD) indicates the end of the preamble. The physical Header (PHR) comes after SFD containing data about the preamble and the payload. Finally, the transmitter transmits the payload that ends with a two-bytes checksum.

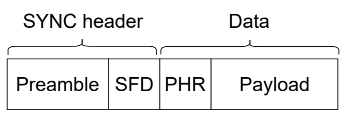


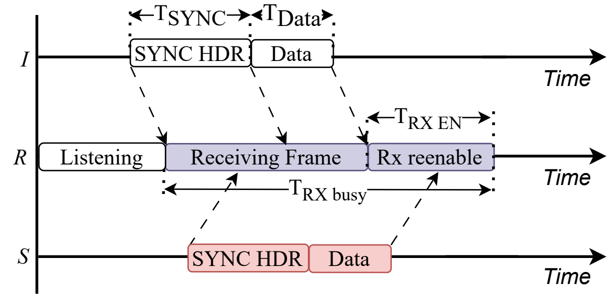

Fig. 2: UWB frame structure [19]. SYNC HDR refers to the preamble and SFD, while Data represents PHR and frame payload.

Reception starts by enabling its radio and looking for preamble symbols. The receiver detects the preamble by cross-correlating the received symbols with a chunk of preamble symbols. The number of preamble symbols in the chunk is controlled by a parameter called PAC size. Upon detecting the preamble, the receiver starts looking for SFD while accumulating the symbols. If the receiver does not find the SFD after a period, it reports an SFD timeout. After obtaining the SFD, the receiver collects the PHR and the payload. At the end of the payload reception, the receiver calculates the checksum of the payload and compares it with the two-byte checksum.

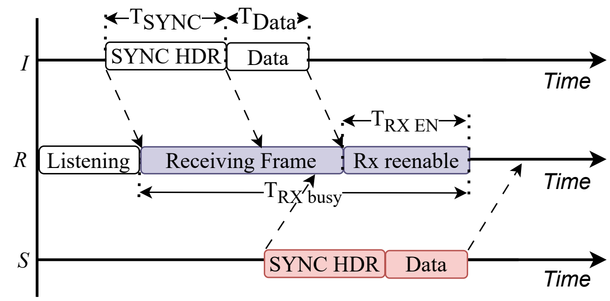
### *B. Packet collision in UWB radio network*

The literature on concurrent transmission in UWB radios suggests that not all UWB collisions result in frame reception errors [10], [16]. In a similar spirit, we categorize frame collisions into two main groups: synchronization phase and payload phase collision.

To study the impact of each collision, we demonstrate a straightforward communication scenario involving a sender ($S$), an interrupter node ($I$) and a receiver ($R$). Fig. 3 illustrates the two categories of packet collisions that occur in UWB networks. $T_{SYNC}$ represents the transmission time of synchronization header and $T_{Data}$ refers to the transmission time of the data for $I$'s frame. $R$ starts receiving $I$'s frame when detecting its preamble. $T_{RXEN}$ refers to the time $R$ takes to restart its radio when completing the packet reception.




(a) Synchronization phase collision




(b) Payload phase collision

Fig. 3: Frame collisions in UWB networks with interferer $I$, sender $S$ and receiver $R$. In both collisions, $R$ will likely capture the earliest frame it is synchronized.

Synchronization phase collision occurs when $S$ starts transmitting while $R$ is capturing $I$'s preamble. Studies have used this type of collision for localization [11], [12] and ranging [13] applications. Payload phase collision occurs when $R$ has captured the SFD of $I$'s frame, and $S$ starts the transmission while $I$ transmits the data symbols.

Earlier findings regarding UWB concurrent transmission noted that the receiver captures the earliest packet regardless of the distance between the receivers and senders in payload phase collision. However, during synchronization phase collision, if the later signal has higher reception power than the first one, there is a probability ($\sim 14\%$) that the receiver switches to capturing the later frame [16].

### *C. Collision Avoidance using Preamble detection (PD) and Frame Filtering (FF)*

Considering the scenario in section III-B, if $R$ aims to capture $S$'s frame, collisions cause $S$'s frame to drop, leading to lower reliability of link $S \rightarrow R$. The goal of RIC3-CA is to maximize the number of $S$'s frames that $R$ can successfully receive. To maximize successful packet delivery of $S \rightarrow R$, $R$ needs to synchronize with $S$'s preamble outside of $T_{RXbusy}$. For this to happen, $S$ needs to detect $T_{RXbusy}$ and schedule its preamble transmission so that it does not completely overlap with $T_{RXbusy}$. According to Fig. 3, $T_{RXbusy} = T_{SYNC} + T_{Data} + T_{RXEN}$.

Fig. 4 describes how RIC3-CA utilizes preamble detection (PD) and frame filtering (FF) to avoid transmissions of $S$'s

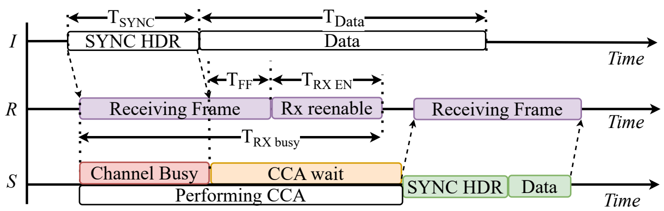



Fig. 4: RIC3-CA leverages FF and PD to prevent sender $S$'s preamble from overlapping with $T_{RXbusy}$. PD prevents $S$ from transmitting while receiver $R$ captures interferer $I$'s preamble. FF allows $R$ to stop capturing the entire payload of the unwanted frame and look for preamble symbols. $R$ can still synchronize with $S$'s preamble during $I$'s payload transmission.

packets during $T_{RXbusy}$. UWB transmitters can detect the presence of preambles on the channel by enabling the radio and listening for preamble symbols. Without a hidden terminal, preamble detection (PD) can avoid synchronization phase collisions by sensing $I$'s preamble and preventing $S$ from transmitting packets during $T_{SYNC}$, when $I$'s preamble is occupying the channel. PD also ensures that $S$'s preamble is the first preamble that synchronizes with $R$ as there are no preambles on the channel when $S$ starts the transmission.

In contrast to preamble symbols, UWB radios cannot detect payload symbols if they do not synchronize with the preamble symbols. If $S$ activates PD during $T_{Data}$, it will start transmitting preamble symbols. This causes payload phase collision resulting in a packet drop for $S \to R$. To avoid this, $S$ can delay the transmission for $T_{Data}$ to avoid the collision. As payload transmission time varies significantly across different payload sizes and data rates, assuming a maximum value for $T_{Data}$ might cause unnecessary delays, reducing the application's performance. Frame filtering (FF) is a common approach in radio implementations that allows receivers to interrupt the reception process when synchronizing with an unwanted frame. In FF, the receiver scans the beginning of the payload for a pattern and continues collecting the packet if the initial bytes match the pattern. Otherwise, it terminates the reception process before entirely capturing the payload. With FF, instead of waiting for $T_{Data}$, $S$ can assume a deterministic payload processing time ($T_{FF}$) for processing $I$'s frames. Note that $T_{FF} < T_{Data}$ since $R$ only requires a portion of the frame for FF. Our empirical study cited that this value is $500\mu s$ for DW3000.

With FF enabled, the receiver's unavailability after the synchronization phase is $T_{FF} + T_{RXEN}$. Waiting for this period prevents the sender from starting the preamble transmission during $T_{RXbusy}$. Regardless of $I$'s payload symbols, $R$ can synchronize with $S$'s preamble symbols after restarting the reception process. We evaluated this claim in section IV-B.

To accommodate the transmission delay in our design, RIC3 introduces $CCA\_wait$, determining sender's wait time before transmission. To avoid simultaneous transmission after PD, we used the similar backoff method used in the IEEE802.11 standard. In addition to initial wait ($T_{FF} + T_{RXEN}$), we also included a random wait ($\delta_{random}$) which increases with unit of time slot. With this, the sender with the smallest $\delta_{random}$ will start transmitting the preamble, and other transmitters will postpone their transmission when sensing the preamble. To detect the preamble, UWB radio must collect some symbols, determined by PAC size. We refer to this period as $T_{Detect}$. According to Fig. 5, if the difference between $\delta_1$ and $\delta_2$ ($\Delta$) is shorter than $T_{Detect}$, $T_1$ cannot accumulate enough symbols to detect $T_2$'s preamble. $T_{Detect}$ depends on the PAC size; thus, it can be different for senders in the network. RIC3 limits senders to select PAC sizes smaller than PAC 32 for PD to tackle this inconsistency. It also sets the duration of a time slot ($T_{Detect}$) to the transmission time for 32 preamble symbols. With this limitation, $T_1$ will collect a sufficient number of symbols to detect $T_2$'s preamble, which started transmitting earlier.

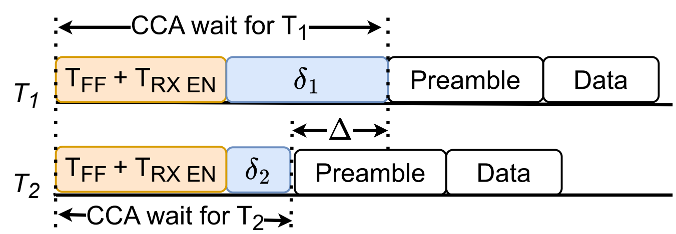



Fig. 5: CCA_wait for transmitters $T_1$ and $T_2$. The value of $\Delta$ has to be greater than $T_{Detect}$ for transmitter $T_1$ to sense the preamble of $T_2$'s frame

In some applications, the receiver is interested in receiving the messages within a period. With PD, the sender delays the transmission until the channel is available. $CCA\_timout$ is another parameter in RIC3-CA that defines the maximum time PD can delay the packet transmission when the transmitter detects preambles on the channel. If the channel is not available after this period, the RIC3 aborts the transmission, reporting a $TX\_failed$ message.

### *D. Interference reduction (IR) using PC and PAC*

While RIC3-CA avoids the transmission of $S$ during $T_{RXbusy}$, RIC3-IR attempts to reduce $T_{RXbusy}$ by preventing $R$ from detecting $I$'s frames. Isolating the communication link is a common approach in wireless technology to prevent nodes from sensing signals from other senders. UWB applications can isolate the communication using a different center frequency or pulse repetition frequency (PRF). In addition to these two parameters, RIC3-IR introduces Interference Reduction (IR), utilizing PC and PAC size to prevent nodes from sensing unwanted preambles.

UWB nodes detect preambles by cross-correlating the incoming symbols with a chunk of preamble symbols. Ideally, if PCs were orthogonal to each other, UWB receivers would not sense preambles that use different PC. Since the codes in UWB standard are not entirely orthogonal, changing the PC cannot isolate the receiver from synchronizing with unwanted frames [16]. In addition to PC, PAC size is another parameter

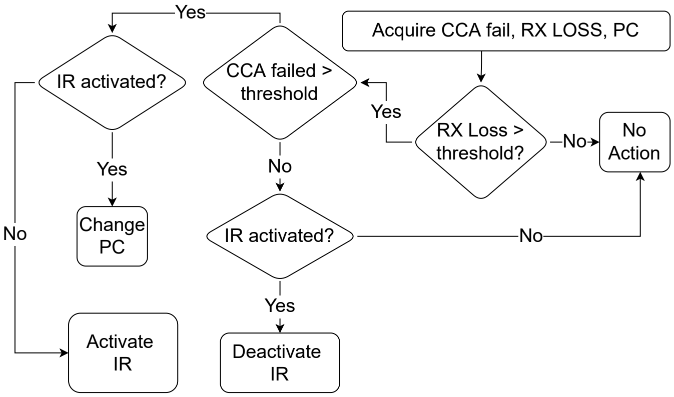



Fig. 6: Decision flow for config change process. Activate IR sets the PAC size to 8 for sender and the receiver and changes the PC. Deactivate IR sets the PAC size to recommended value mentioned in [19].

determining the quality of preamble detection in the UWB receiver. A larger PAC size usually increases the sensitivity of preamble detection in UWB receivers due to collecting more symbols for cross-correlation [20].

Our observations in section IV-C note that lowering the PAC size reduces the chance of detecting preambles that use different PCs. Based on this finding, RIC3-IR develops a configuration change mechanism that reduces the PAC size and changes the PC when CCA fail rate exceeds a certain threshold. Fig. 6 describes the design flow of this mechanism. When the link suffers from frame losses due to CCA fails, RIC3-IR activates IR by reducing the PAC size to 8, which has the lowest sensitivity level [20]. If the number of CCA fails is still high, RIC3-IR will repetitively change the PC to find a complex channel with a lower preamble occupation.

When activating IR, RIC3-IR reduces the PAC size resulting in lower receiver sensitivity. Although this is beneficial for filtering unwanted frames, it also reduces the reception sensitivity toward wanted packets. If wanted packets have poor reception power, lowering PAC size could lead to lower packet reception. Therefore, if reception losses are not due to CCA failures, RIC3-IR needs to deactivate IR to increase reception sensitivity. RIC3-IR operates separately from RIC3-CA. While RIC3-CA constantly avoids destructive collisions, RIC3-IR can activate or deactivate the IR to enhance RIC3's performance. RIC3-IR also requires a control channel to exchange data and radio configuration. Designers can use the UWB radio interface or an auxiliary radio to transfer these control messages. The config change can execute in either the receiver, or the sender.

## IV. Evaluation

Fig. 7 shows our two experimental settings that we used for our evaluation. Nodes $S_1$, $R$, and $TS$ are common across the two settings. $TS$ transmits a timeSync message every 70 ms. $S_1$ and $R$ are the transmitter and receiver on the link $S_1 \rightarrow R$. We define *wanted frames* as the frames transmitted by $S_1$ to be received by $R$. In our first experimental setting (topology #1) that covers sections IV-A, IV-B, and IV-C, we timed packet transmissions to cause different packet collisions to evaluate RIC3-CA and RIC3-IR in a more controlled environment. The second experiment setting (topology #2), covering sections IV-D1 and IV-D2, evaluates RIC3's performance in a multi-application UWB network with different traffics. We used Packet Reception Ratio (PRR) as a measure of link reliability.

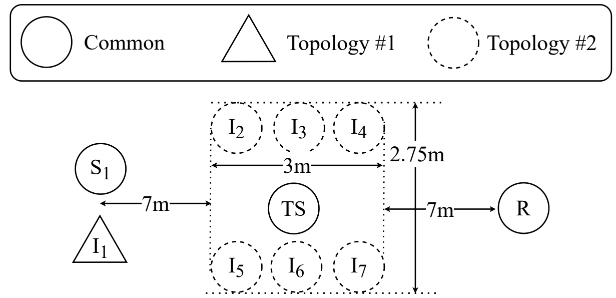



Fig. 7: Node placement for the packet collision experiment (topology #1) and multi-application network experiment (topology #2). Nodes $S_1$, $TS$, and $R$ are common among all the experiments.

### A. Baseline evaluation

We configured $S_1$, $R$, and $I_1$ with the configuration suggested by Decawave [19]. However, we increased the preamble length to 512 to evaluate different synchronization header collisions. With this configuration, we assessed the link quality of $S_1 \rightarrow R$ to measure the impact of environmental factors on link quality. When no other node was sending, $S_1$ transmitted 100 packets to $R$, and $R$ received all 100 packets from $S_1$, ensuring that environmental factors did not affect $S_1 \rightarrow R$ link reliability in our experimental setting.

### B. Impact of packet collisions on UWB frame reception

This section focuses on the impact of interfering signals on the quality of frame reception and their effect on the packet reception rate (PRR) of the $S_1 \rightarrow R$ link. To measure the quality of frame reception while interference, previous studies have suggested using Received Signal Power ($RSP$) to estimate reception quality [19], [21]. As a better approximation of application-level performance, we also use the PRR metric.

In the first experiment, $R$ measured the RSP on the packets transmitted by $S_1$ and $I_1$ for 100 packets each. Then, $S_1$ scheduled its transmission 10 ms after the reception of the timeSync packet. Meanwhile, $I_1$ scheduled its transmission later than $S_1$ creating synchronization phase or payload phase collision. Both nodes transmitted 100 packets, and $R$ calculated the PRR of $S_1 \rightarrow R$. We repeated this experiment with different transmission power for $I_1$.

According to the results in Fig. 8, the $\overline{RSP}$ of $S_1$ frames decreased as we increased the $\overline{RSP}$ of the interfering signals. When $R$ synchronizes with $S_1$'s frame, it tolerates the interfering frames with lower and equal reception power. However, when $I_1$'s frame had more than 6 dB reception power than

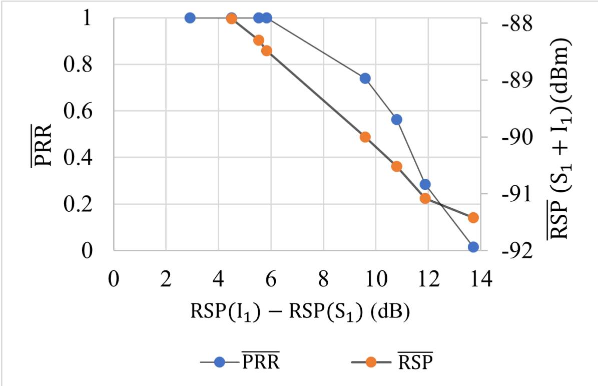



Fig. 8: Impact of interfering signals from $I_1$ on the reception quality of $S_1$'s frames and PPR of $S_1 \rightarrow R$. The horizontal axis represents the RSP difference between $I_1$'s frames and $S_1$'s frames. $RSP(I_1 + S_1)$ represents the $S_1$'s reception power combined with $I_1$'s interference. Interfering signals reduce the reception quality of *wanted frames* and can lead to frame loss if the reception quality falls below -90 dBm.

$S_1$'s frame, reception errors emerged due to the low link quality. These reception errors consist of Physical Header Errors (PHE) or Frame Sync Loss (FSL) that occur after the synchronization phase of the frame. When switching from a data rate of 6.8 Mbps to 850 kbps, the interfering packet could not ruin the synchronization due to the higher robustness of the payload.

In the second experiment, $I_1$ started transmission 10 ms after receiving the timeSync message. $S_1$ starts PD while $I_1$ was transmitting the preamble. We also set $CCA\_wait = 800\mu s$ to consider $R$ processing time ($T_{FF}+T_{RXEN}$). Similar to the results of our first scenario, we observed that when FF stops $R$ from receiving $I_1$'s payload symbols, $R$ synchronized with $S_1$'s preamble regardless of $I_1$'s reception power. However, when $I_1$'s payload symbols collided with $S_1$'s payload symbols, we encountered RSL and PHE errors in receiving $S_1$'s packets.

These findings indicate that in UWB networks, if the difference in the received signal power of the interfering signals is lower than 6 dB, RIC3-CA enhances the reliability of the links by utilizing frame synchronization to capture *wanted frames*. Otherwise, the receiver still captures the preamble and SFD. Still, due to the noise of these interfering signals in the reception process, they can corrupt payload symbols of the desired frame, leading to PHE or FSL errors.

### C. Impact of PAC and PC on frame reception and link reliability

The experiments in this section evaluate the impact of modifying PC and PAC on frame synchronization and reception, and hence their impact on RIC3-IR's performance. TABLE I shows the PCs we used to configure the nodes in our testbed.

The third experiment compared the receiver's sensitivity with different PAC sizes. In each round, $I_1$ transmitted 100

TABLE I: PC configuration for the timesync node $TS$, receiver $R$, sender $S_1$, and interferer $I_1$

| Node | $TS$ | $R$ | $S_1$ | $I_1$ |
|---|---|---|---|---|
| RX PC | 9 | 10 | 9 | 9 |
| TX PC | 9 | 10 | 10 | 9 |

packets and $R$ listened to the incoming frames using either $PACsize = 32$ or $PACsize = 8$. Since $I_1$ and $R$ used different PC for transmission and reception, we expected $R$ only to report reception errors. TABLE II illustrates the fraction of the $I$'s preambles detected by $R$. According to this figure, changing the PC alone did not isolate $R$ against $I_1$'s preambles since $R$. However, decreasing the PAC size entirely isolated $R$ from detecting interfering frames. When $S_1$ started transmitting 10 ms after the timeSync message and $I_1$ created frame collisions similar to ones in section IV-B, The PRR of $S_1 \rightarrow R$ and the reception errors were similar to the results in section IV-B, regardless of $R$'s PAC size. These results suggest that although RIC3-IR prevents the receiver from synchronizing with frames with different PCs, it cannot reduce the destructive noise of the interfering signals on payload reception.

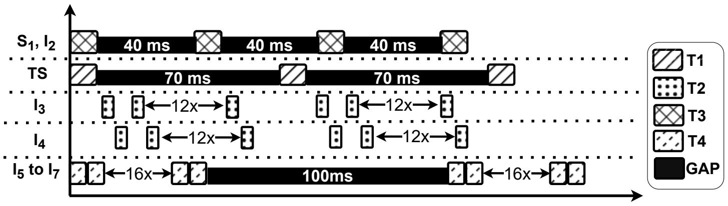
TABLE II: Fraction of interfering frames received (FIFR) by $R$, transmitted by interferer $I_1$. Changing the PC did not isolate $R$ from synchronizing with $I_1$'s frame. However, a smaller PAC size significantly reduced $R$'s sensitivity toward packets with different PCs.

| rxPAC: 32 | | | | | |
|---|---|---|---|---|---|
| $\overline{RSP(I_1)} - \overline{RSP(S_1)}$ (dB) | 0 | 6 | 8 | 9 | 15 |
| FIFR | 0.1 | 1.0 | 1.0 | 1.0 | 1.0 |
| rxPAC: 8 | | | | | |
| $\overline{RSP(I_1)} - \overline{RSP(S_1)}$ (dB) | 0 | 6 | 8 | 9 | 15 |
| FIFR | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

### D. Evaluation of RIC3 in multi-application network

To evaluate RIC3 in a multi-application UWB network, we used different traffic types in our evaluation. Fig. 9a shows the pattern of packet transmission for each traffic, and Fig. 9b illustrates the frame characteristics related to each traffic pattern. $T1$ describes the traffic pattern of the time synchronization node ($TS$) transmitting packets every 70 ms. $T2$ describes a TDMA traffic pattern common among localization applications with multiple tags [22]. In this traffic pattern, tags periodically listen to the timeSync message. Upon reception, they schedule their transmission to avoid collisions with other tags. $T3$ represents a node's traffic pattern that periodically transmits data messages every 40 ms. $T4$ is a traffic type that bursts the channel with preambles for a period and waits for 100 ms. For our evaluation, we set $CCA\_timeout = 2ms$.

In this experiment, nodes $TS$ and $I_2$ used the traditional CCA method that checks for preamble occupation before transmission. We also added STS to some of the transmitters in the network. Nodes $TS, I_3, I_4$ had 256 symbols STS, and $I_2$ put 1024 symbols STS at the end of their frames. In each




(a) Transmission pattern and node mapping

| Traffic Type | Preamble length | Payload size (bytes) | Data Rate (kbps) |
|---|---|---|---|
| T1 | 2048 | 100 | 850 |
| T2 | 256 | 100 | 850 |
| T3 | 2048 | 150 | 850 |
| T4 | 1024 | 20 | 6800 |

(b) Frame characteristics

Fig. 9: Traffic types used for multi-application network experiment. The (a) frame transmission pattern and (b) frame characteristics of these traffic patterns resemble different traffic patterns that are common among UWB applications.

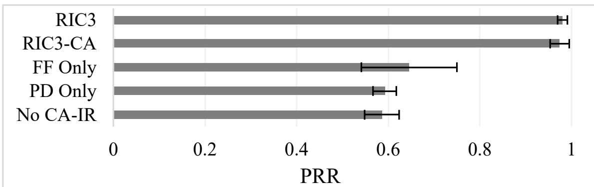



Fig. 10: Impact of various mechanism used by RIC3 individually and together on link reliability of $S_1 \rightarrow R$ with three interfering nodes ($I_2$ to $I_4$). Using PD+FF improves the reliability of the link compared to using only-PD and only-FF.

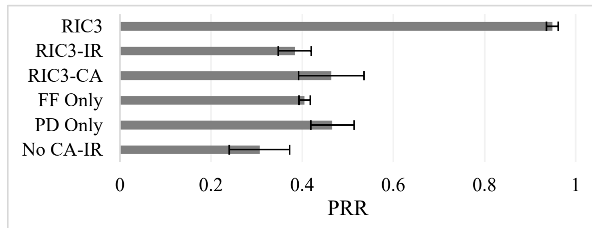



Fig. 11: PRR distribution of $S_1 \rightarrow R$ with six interfering nodes ($I_2$ to $I_7$). Activating IR for $S_1$ and $R$ isolated the link, reducing CCA fails and improving reliability.

scenario, $S_1$ transmits 200 packets to $R$ while other senders had different destination addresses.

*1) Collision avoidance (CA) with RIC3-CA:* In the first experiment of the second topology, nodes $TS, I_1, I_2, I_3$ and $I_4$ started transmitting packets. $S_1$ also transmitted batches of 200 packets. In each batch, $S_1$ and $R$ chose one of the CA methods (No-CA, only PD (traditional CCA in UWB), only FF, RIC3-CA). We recorded the PRR for each CA method five times and report the PRR distribution in Fig. 10. When $S_1$ and $R$ used no CA methods, $S_1 \rightarrow R$'s PRR dropped to 60% due to the interference of the interrupter nodes. However, using RIC3-CA to synchronize $R$ with $S_1$'s frames resulted in a PRR of over 90%.

The utilization of only PD and FF did not significantly improve the reliability of $S_1 \rightarrow R$ due to issues mentioned in section III. Despite its poor performance, PD-only is still implemented in various UWB applications. To investigate the performance of PD-only method further, we conducted an additional experiment where we increased the CCA wait from $800\mu s$ to $3200\mu s$, which is longer than the payload time of all frames in the network and set the CCA timeout to 100ms. We observed that the reliability of $S_1 \rightarrow R$ improved significantly and was similar to that of RIC3-CA. When the CCA wait value exceeds the payload processing time, the receiver finishes processing the frame and is ready to capture new frames. PD-Only can provide high-reliability communication in networks with small frame payloads. However, for applications with large payloads or constrained CCA-wait, RIC3-CA achieves the same link reliability with a much smaller CCA wait.

*2) Interference reduction with RIC3-IR:* Although the traffic of nodes $I_2$ to $I_5$ occupied 68% of the channel, $S_1$ reported that approximately 5% of the transmissions resulted in CCA fail. The reason for this lies within the preamble portion of the frames, which occupy around 9% of the channel. Since the PD only detects the preamble of the frames, the occupancy of the UWB channel is related to the preamble occupancy.

Due to the low CCA fails in the first scenario, RIC3-IR did not activate IR, and $R$ was using $PACsize = 32$ to capture packets. In the second experiment, we increased the interference in the network by adding interfering nodes $I_5, I_6, I_7$ with PCs 9, 10, and 11. $TS$, $I_2, I_3, I_4$ switched PC 12 and $S_1$ and $R$ still operated on PC 9. After transmitting the first batch of packets, $R$ reported approximately 54% frame loss, and $S_1$ reported 50% CCA failure. According to the procedure in Fig. 6, RIC3-IR first activated IR and triggered config update to change PC of $S_1$ and $R$. The config update tried PC 10 and 11, reporting similar packet losses and CCA fails. When the $S_1$ and $R$ synced on PC 12, the CCA failure rate dropped to nearly 3%. Fig. 11 shows how activating IR along with RIC3-CA provided more than 90% reliability for $S_1 \rightarrow R$. We can also see that when we relied on just IR, we did not achieve high link reliability due to the traffic of the senders on PC 12. Since all of our nodes in the second experiment were configured to use the same transmission power, the power of the interfering signals was not strong enough to compromise the packet reception of $S_1 \rightarrow R$.

In the final experiment, we removed $I_5, I_6, I_7$ while $S_1$ and $R$ enabled IR to isolate their traffic. We reduced $S_1$'s transmission power to decrease the reception quality of its frame. Since activating IR reduced the receiver's sensitivity, we observed a noticeable amount of packet losses. The sender also reported no CCA fails for this scenario. According to the

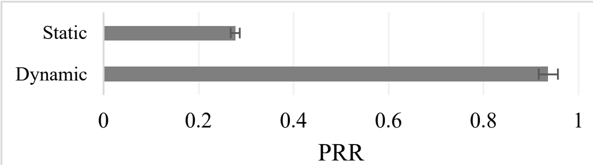



Fig. 12: Average PRR for $S_1 \rightarrow R$ link when $S_1$ uses low-power transmission. When the reception quality of $S_1$ packets is low, disabling IR increases the receiver's sensitivity, leading to more packet reception and higher link reliability.

config change algorithm, RIC3-IR disabled IR and increased PAC size to 16 for $S_1$ and $R$. Fig. 12 shows the PRR improvement when RIC3-IR deactivated IR to enhance the receiver's sensitivity.

## V. Discussion

The latest UWB standard (IEEE802.15.4z) introduced Scrambled Timestamp Sequence (STS) to enable secure ranging and localization for UWB applications. With STS, IEEE802.15.4z added three new frame structures to the previous standard. In sections IV-D1 and IV-D2, we evaluated one of these structures (SP2) with RIC3. SP2 configuration appends the STS at the end of the frame payload to provide security while maintaining backward compatibility with the previous standard. Our observations indicate that RIC3 can accommodate this frame structure since the PHR and payload placement is the same as the previous standard. Future work could explore these and other implications of PHY/link layer security mechanisms in the performance of concurrent transmission systems.

In applications which multiple senders want to communicate with a specific receiver, the receiver calculates the CCA_wait and PC and shares it among senders. Since multiple senders that simultaneously send messages with receiver's destination address, FF does not terminate the reception of wanted packets and the preamble of one wanted packet might overlap with the payload of another wanted packet. To avoid these type of overlaps that causes frame drop, receiver needs to consider a collision avoidance method (such as RTS-CTS or TDMA) to avoid payload phase collision among its senders.

## VI. Conclusion

In this paper, we introduced a method to improve link reliability in multi-application UWB networks. Our proposed method uses preamble detection and frame filtering to avoid collisions and perform early drop of unwanted packets. We also used complex channels along with PAC size to reduce the interference of other complex channels. We analyzed the scenarios where each method provided high and poor link reliability, emphasizing the importance of both methods for higher link reliability. Finally, our evaluation using real hardware testbed indicated that using our proposed method improved the PRR by 30% in UWB networks with moderate traffic and 60% in busy networks.

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