R3: Reflection Resilient Concurrent Ranging with Ultra-Wideband Radios

Milad Heydariaan
Department of Computer Science
University of Houston
milad@cs.uh.edu

Hessam Mohammadmoradi
Department of Computer Science
University of Houston
hmoradi@cs.uh.edu

Omprakash Gnawali
Department of Computer Science
University of Houston
gnawali@cs.uh.edu

***Abstract*—Concurrent ranging exploits features of the channel impulse response (CIR) of received packets to allow an ultra-wideband (UWB) initiator node to concurrently measure the distance from multiple UWB responder nodes. Concurrent ranging enables indoor localization systems to reduce the required number of ranging packet exchanges, leading to less air utilization and energy consumption, and faster location update rate. Despite the research in this area, it is still challenging to build a practical UWB concurrent ranging system for real-world environments. Existing concurrent ranging solutions are not scalable because (1) they require strong assumptions about either the responders or the environment and (2) they fail to maintain the ranging accuracy in longer distances due to errors caused by clock drift. In this work, we present R3, a Reflection Resilient Ranging solution, to address these critical scalability issues in UWB concurrent ranging. R3 makes use of the difference in the time deviation of ranging signals to detect concurrent responders and it is equipped with a clock skew correction method that enables accurate concurrent ranging in long distances. We evaluate R3 using Decawave DW1000 UWB chip by deploying the radio nodes in an office environment. Our results show that R3 effectively detects concurrent ranging peaks in the presence of strong multipath. When we equip R3 with a clock skew correction method, it reduces the concurrent ranging error induced by clock drift by at least $54\ cm$ in long distances ($>50\ m$) and by more than 97% in average when the ranging response delay is arbitrarily large.**

***Index Terms*—distance measurement, concurrent ranging, ultra-wideband, channel impulse response, multipath components, Decawave, DW1000, UWB, CIR, MPC**

I. Introduction

The challenge of finding the precise location of things and people in buildings has made indoor localization a very important field of application for the Internet of Things (IoT). Ultra-wideband (UWB) radios have facilitated accurate and precise indoor localization in the past few years due to the availability of low-cost commercial UWB chips such as Decawave DW1000 [1]. With the daily increase in the number of IoT devices, it is necessary to build localization solutions with more efficient power consumption and air utilization. It is still challenging to maintain a fast location update rate under these constraints. Concurrent ranging with UWB radios [2] aims to tackle this challenge by making use of the Channel Impulse Response (CIR) of concurrent packets and simultaneously measuring the distance from multiple responders based on the difference in their time of arrival (ToA). However, existing solutions for concurrent ranging are not practical in real-world environments due to critical scalability issues.

Concurrent ranging is ideally more efficient than conventional ranging methods. In a typical ranging scenario, an initiator node has to exchange packets with every responder node separately. This method requires either a separate request and response between the initiator node and each responder node or one request from the initiator node and sequential responses from all responder nodes. The latter case requires time scheduling for all responder nodes to determine their time of transmission (TX). In concurrent ranging, the initiator node measures the distance from all responder nodes by sending one request. The responders send their response concurrently. Thus, the response packet received by the initiator node contains signals combined from multiple responders. The initiator then extracts ranging information from the CIR of this concurrent response packet. This way, the number of required packets is drastically reduced, and there is no need for scheduling between the responder nodes. Consequently, concurrent ranging is less power-hungry, has less air utilization, and it is faster.

Concurrent ranging faces a number of critical challenges in real-world applications such as automatic detection of responses in run-time, detection of responses overlapping with multipath components (MPCs), and failure to maintain ranging precision and accuracy due to hardware timestamping uncertainty and clock drift. Existing research work [2], [3] propose solutions for such challenges. To automatically detect concurrent responses in run-time, Corbalán and Picco [2] suggested either using a power boundary to filter MPCs, or to exploit a priori knowledge about the environment. Großwindhager and Boano [3] suggested either using different pulse shapes, by using different Pulse Generator Delay (PG_DELAY) values and correlating a signal shape template with the estimated CIR of the received packet or to mitigate overlapping by delaying each response to separate them in time. However, these solutions fail in presence of strong MPCs or not scalable due to the limitation of CIR in time length and also due to clock drift. To solve the ranging accuracy issue caused by clock drift, Corbalán and Picco [2] suggested minimizing the response delay for each responder node to minimize the clock drift, which prevents long-range communication due to limitation in using proper radio configurations. A potential solution to the ranging precision issue caused by timing limitations is to use multiple rounds of concurrent ranging, but it can limit the location update rate. To use this method safely, we need to identify how many rounds would be sufficient to achieve sub-meter ranging precision, for which the related work did not identify.

We take steps toward a practical UWB-based concurrent ranging solution and tackle the challenges mentioned above. We present R3, a Reflection Resilient Ranging solution, and specifically target the problem of scalability in concurrent ranging with UWB radios using two techniques. First, we propose a methodology that enables us to detect concurrent responses in run-time, even in the presence of strong MPCs. We are the first to identify how many concurrent ranging rounds are required to achieve sub-meter ranging precision. Second, we relax time constraints on the response delay by using a clock skew correction method to achieve higher operating range. R3 reduces the ranging error in long distances ($>50\ m$) by at least $54\ cm$ and by 97% in average for arbitrarily large ranging response delays, compared to when we do not use a clock skew correction method.

In this paper, we make these contributions:

- Design an algorithm to detect concurrent responses in run-time, resilient to strong reflections.
- Relax responder processing time constraints by using a clock skew correction method.
- Implementation and evaluation of R3 on Decawave TREK1000 [4].

II. Related Work

Concurrent ranging refers to a methodology that an initiator radio node measures the distance from multiple responder radio nodes simultaneously. Feasibility of UWB concurrent ranging was first studied by Corbalán and Picco [2]. To build a real-world UWB concurrent ranging, there are a number of critical issues that we need to solve. Some of these issues were identified in [2], [3], accompanied by potential solutions.

A. Detection of Concurrent Responses in Run-time

A practical UWB concurrent ranging system needs to automatically detect concurrent signal peaks in run-time. Researchers have developed several peak detection and first path detection methods which are widely used in the existing research work and patents [2], [5]–[8]. However, it is still hard to detect concurrent responses when response signals overlap with each other or when responders are in approximately the same distance from the initiator (equidistant responders), or their MPCs. Corbalán and Picco [2] used a priori knowledge of the location of the responder nodes to detect concurrent signals. Their method still does not solve the problem of equidistant responders. They further suggested several methods for automatic peak detection, but these methods are not comprehensively evaluated for real-world UWB concurrent ranging systems. Großwindhager and Boano [3] proposed two solutions. The first solution is to use a matched filter and correlate the CIR with a pulse shape template to find responder signals. To create different signal shapes, they suggested using different Pulse Generator Delay (PG_DELAY) values. Their method also aims to solve the problem of equidistant responders. However, the overlapping strong MPCs can completely obscure the concurrent signals, which makes it very hard to detect them. The second solution is to mitigate the impact of strong MPCs by using a response position modulation, which adds a delay to each concurrent response to separate them in time. However, we can only fit a limited number of concurrent responses in CIR samples due to its limited size. Combining these two methods can theoretically increase the maximum number of concurrent responses, but it is not thoroughly evaluated in the presence of strong MPCs.

B. Identification of Concurrent Responders

UWB concurrent ranging relies on receiving all the responses within a short period of time. However, the initiator node only receives one packet (usually from the nearest responder). The initiator then detects concurrent responses by analyzing the estimated CIR for the received packet. Thus, the initiator cannot use any identification information inside the concurrent responses. Großwindhager and Boano [3] suggested that using different pulse shapes (by using different PG_DELAY) for each responder and using a matched filter can potentially solve the problem.

C. Ranging Error Due to Clock Drift

Typically, responders use independent frequency oscillators which can drift against each other due to both environmental effects and mechanical differences. Since we are measuring the difference in the distance only using the difference in the ToA, each responder needs to minimize the jitter in its reply time. Hence, every responder adds a constant delay to the reception (RX) time of a request packet to calculate the TX time of the response packet. Since this time delay is referenced to a local frequency oscillator, the actual TX delay is not consistent with other responders. The jitter in the TX time caused by clock drift causes inaccuracy in ToA of concurrent signals received by the initiator node. Corbalán and Picco [2] suggested minimizing the constant delay so that all responders transmit as fast as possible to reduce the clock drift-induced error. Minimizing the delay requires a certain set of radio configurations and specialized software on the main processor. For DW1000 chip, each preamble symbol duration is $\approx 1\ \mu s$ [9]. The chip supports preamble lengths up to 4096 symbols. Since preamble needs to be sent before the scheduled TX time, the $330\ \mu s$ delay used in [2] requires using a maximum preamble length of 256 symbols. However, achieving longer range requires longer preamble lengths [9]. Also, the specialized software should be fast enough in reading and processing the packet to be able to minimize the delay, which limits its functionalities. To solve this problem, we use a clock skew correction method based on time transfer techniques. Researchers developed several time transfer methods [10]–[12] to synchronize independent clocks and frequency oscillator disciplining methods [13], [14] to synchronize the frequency of local oscillators. Our work uses a clock skew estimation technique similar to [15], [16].

III. Background

In this section, we review the basics of UWB concurrent ranging and clock modeling.

A. Conventional vs. Concurrent Ranging with UWB Radios

There are several ways to estimate the distance between two UWB radio transceivers [17], [18]. Single-sided two-way ranging (SS-TWR) [19], a part of IEEE 802.15.4 UWB standard [20], estimates the distance between two radio transceivers without needing to synchronize both sides. As shown in Fig. 1a, the side which estimates the distance (initiator node) sends a ranging poll message. The receiver side (responder node) then replies back with a response message including the dynamically calculated T_{reply} value embedded in the packet. Finally, the initiator uses Eq. 1 to calculate the ToF and the corresponding distance using Eq. 2 with v being the propagation speed of electromagnetic waves in the medium. In wireless transmission, v is approximately the speed of light ($\approx 3 \times 10^8\ m/s$).

$$ToF = \frac{T_{round} - T_{reply}}{2} \tag{1}$$

$$d = v \times ToF \tag{2}$$

Unlike the conventional ranging, in concurrent ranging an initiator node measures the distance with all responder nodes simultaneously. As shown in Fig. 1b, the initiator node broadcasts a ranging poll message. Every responder node replies with the same T_{reply} delay. The initiator node receives the response from the closest responder node (R_1) first. All other responses (R_2, R_3, ..., and R_n) reach the initiator node with an additional $2 \times \Delta t_i$ delay, with Δt_i being the time difference between reception of the ranging poll message in R_1 and R_{i+1}. More precisely, the initiator node only receives the packet from R_1, but signals from other responders are also visible in the estimated CIR. The initiator first calculates its distance with R_1 using Eq. 1. The initiator node can then calculate the difference in ToF between R_1 and all other responders by analyzing the CIR.

B. Impact of Clock Drift on Concurrent Ranging Performance

Oscillators have different behavior over time due to mechanical characteristics and environmental effects such as the change in temperature, vibration, pressure, and voltage. A clock consists of an oscillator to measure time. Embedded devices are usually equipped with a clock to facilitate timing. Any two independent clocks cause inaccuracies that directly affect the performance of UWB concurrent ranging systems. Each concurrent responder should reply with a fixed delay after reception of the ranging poll message, but they cannot count time at the same rate due to clock drift. These inaccuracies can potentially be corrected by modeling the clock behaviors. With a continuous clock model, $C(t)$ is the time reported by a clock at ideal time t. Clock offset, $\theta(t)$, is the difference between the ideal time and a clock time as shown in Eq. 3.

$$\theta(t) = C(t) - t \tag{3}$$

We can also define relative clock offset for clocks A and B with Eq. 4.

$$\theta_B^A(t) = C_A(t) - C_B(t) = \theta_A(t) - \theta_B(t) \tag{4}$$

Clock skew, $\alpha(t)$, is defined as the first derivative of clock offset. As shown in Eq. 5, we can estimate the clock skew using the normalized difference of two different offset values in a time period of τ.

$$\alpha(t) = \frac{d\theta(t)}{dt} \approx \frac{\theta(t+\tau) - \theta(t)}{\tau} \tag{5}$$

With a discrete clock model, we can estimate the clock skew by re-writing the Eq. 5 as the normalized difference of offsets in two sequential time steps, $\theta[n-1]$ and $\theta[n]$, as Eq. 6. Each time step might have a different length. $\tau[n]$ refers to the length of the time period in step n.

$$\hat{\alpha}[n] = \frac{\theta[n] - \theta[n-1]}{\tau[n]} \tag{6}$$

Finally, we can define the estimated relative clock skew for clocks A and B as Eq. 7.

$$\hat{\alpha}_B^A[n] = \hat{\alpha}_A[n] - \hat{\alpha}_B[n] = \frac{\theta_B^A[n] - \theta_B^A[n-1]}{\tau[n]} \tag{7}$$

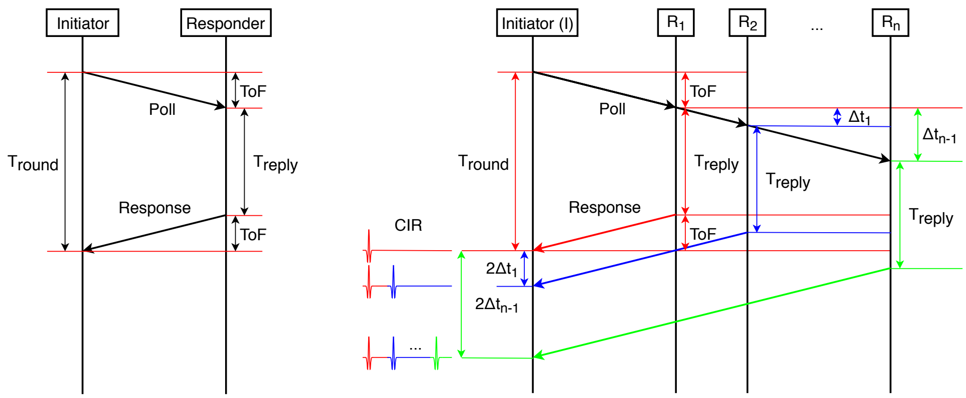
IV. Empirical Observations

We discuss the empirical observations we made while experimenting with concurrent signals and MPCs on our UWB testbed. These observations inform the design of R3.

A. Multipath Deviation

The DW1000 chip has a limitation in the resolution of TX timestamp. The chip reports the RX timestamp for each packet with a resolution of $\approx 15.6\ ps$. However, the chip can only schedule the TX time of a packet with a resolution of $\approx 8\ ns$. Since we schedule the response packets for concurrent ranging by adding a delay to the RX timestamp of the ranging poll message, the TX timestamp has $\pm 8\ ns$ of jitter. Consequently, the concurrent signals received by the initiator have the same level of jitter which causes uncertainty in ToA estimation.

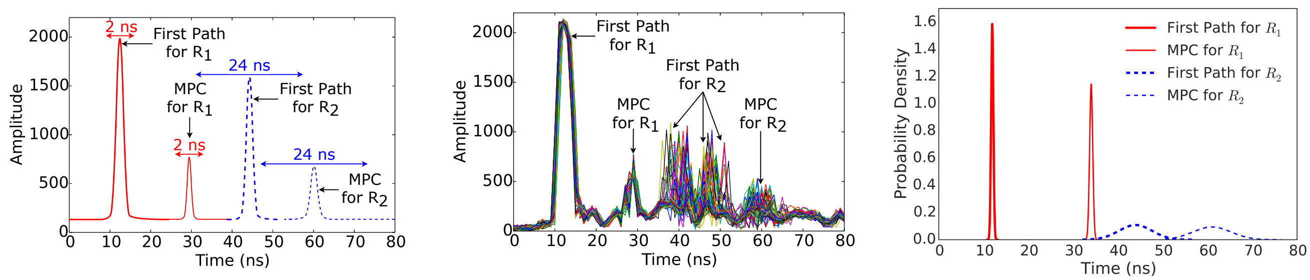
If we repeat concurrent ranging, we can align signals from R_1 so that the jitter only accumulates on the other responders' signals ($R_{i>1}$). As illustrated in Fig. 2, MPCs for each responder signals have similar time distribution compared to their first path signal. However, signals from R_2 have larger time deviation compared to signals from R_1 due to the hardware timestamping uncertainty.



(a) Single-sided two-way ranging. Initiator node sends a ranging poll message. Responder node replies with a message including dynamically calculated T_{reply}, so the initiator can calculate time-of-flight.

(b) Concurrent ranging. Initiator node sends a ranging poll message. All responders (R_1, R_2, ..., and R_n) reply with the same T_{reply} delay. Since R_{i+1} receives the poll message with Δt_i delay, the response from R_{i+1} would be received by the initiator node by $2 \times \Delta t_i$ delay. Although the initiator only receives the packet from R_1, signals from all other responders are visible in the estimated CIR.

Fig. 1: Ranging vs Concurrent Ranging with UWB



(a) Theoretical illustration of peak time distribution.

(b) Estimated CIR for 100 packets with packets received from both R_1 and R_2.

(c) Empirical illustration of peak time distribution.

Fig. 2: Illustration of peak time distribution for signals from R_1 vs. R_2. Signals from R_2 have more time deviation than the MPCs for signals from R_1.

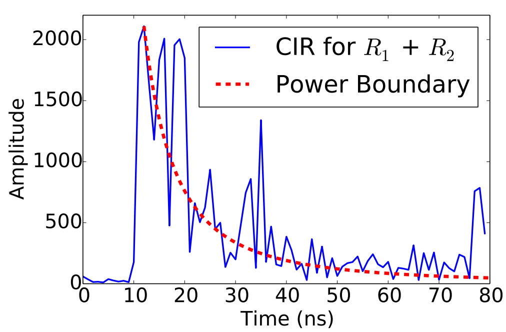


Fig. 3: CIR for R_1 + R_2 and a power boundary. MPCs can easily exceed the power boundary and make it difficult to detect concurrent response peaks.

B. Multipath Amplitudes and Power Boundary

To reliably detect concurrent responses, Corbalán and Picco [2] suggested using a power boundary. The rationale behind this is if MPCs have the same power level as the first path, they remain below the power boundary since they traveled a longer path. But in reality, signals can constructively interfere with each other resulting in strong MPCs with very large amplitudes. Fig. 3 shows CIR for concurrent responses from R_1 and R_2. Strong MPCs easily exceed the power boundary and make it difficult to detect concurrent responses. Thus, despite the suggestion in the literature, our solution cannot fully rely on MPCs not exceeding the power boundary.

C. Wired vs. Wireless Experiments

To study UWB concurrent ranging in a controlled environment, we may need to remove MPCs. Conducting experiments in an anechoic chamber, in which the walls are covered with radio frequency (RF) absorbent materials, is helpful to minimize MPCs. However, in some experiments, we need larger distances which require very large anechoic chambers that might not be easily accessible. Another option is to directly connect radio transceivers using RF coaxial cables. Fig. 4 shows CIR for a typical concurrent ranging scenario with an initiator and two responder nodes. We can easily see that wired experiment setup removes MPCs and make it easier to see concurrent ranging signals. Fig. 2b shows CIR for 100 packets collected from R_1 and R_2, where MPC is created by attaching a RF coaxial cable with one end left open. We also

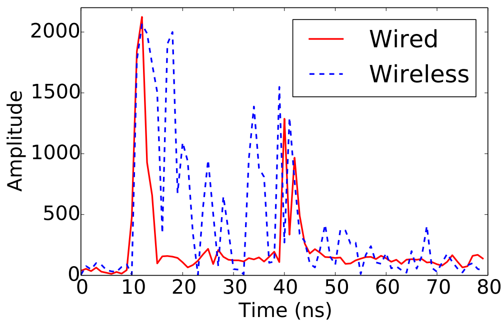


Fig. 4: Comparison of CIR in wired and wireless setups for concurrent ranging experiments with two responders, R_1 and R_2. We can easily detect R_2 signal in the CIR for wired setup (around 40 ns). Multipath propagation of wireless signals creates a lot of strong MPCs, making it very hard to detect R_2 signal.

need to be aware of the difference in propagation speed of RF signals in air ($\approx 3\times10^8\ m/s$) and in RF coaxial copper cables ($\approx 2\times10^8\ m/s$), which is very important in calculating the distance between responder nodes based on the difference in ToA of signal peaks.

V. SYSTEM DESIGN

In concurrent ranging systems, an initiator node concurrently measures the distance from multiple responder nodes by measuring the difference in the ToA of their response to a poll message. Typically a radio transceiver can only receive one packet at a time. Therefore, concurrent ranging cannot rely on receiving the actual packets. Decawave DW1000 reports the estimated CIR for every received packet. If multiple packets arrive within a very short time period (≈ 1 µs), their signals are visible in the CIR estimated for the first arrived packet. For simplicity, we use the same notation for responder nodes as shown in Fig. 1b, with all responder nodes (R_1, R_2, ..., and R_n) ordered by their distance to the initiator node (I). R_1 is the closest node to I; hence, I only receives the response packet from R_1. DW1000 precisely estimates and reports the ToA for the response from R_1 by combining information from multiple estimations and interpolation components. One of these components is a leading detection algorithm (LDE), a threshold-based algorithm, which finds the CIR index corresponding to the first path of a signal. By applying a similar method to the same CIR estimate, we can find the first path corresponding to the other concurrently received signals (R_2, R_3, ..., and R_n). We can then translate the time difference between the first signal and other concurrent signals to the difference in their distance to I. We break down the design of R3 into two components. The first component enables R3 to detect concurrent responses in run-time, resilient to the impact of strong reflections and MPCs. The second component enables R3 to operate in longer distances while maintaining the accuracy of concurrent ranging.

A. Detecting Concurrent Responses

Detecting concurrent responses in run-time can be challenging, especially when they overlap with strong MPCs. When two or more signals arrive at the same time, there might be constructive or destructive interference depending on their phase difference. Concurrent ranging responses might overlap with MPCs from other responses. In our design, we take advantage of the limitation of the DW1000 chip in the resolution of TX timestamps to approach the overlapping problem. As mentioned earlier in this paper, $R_{i>1}$ responder signals have larger time deviation compared to MPCs for R_1. When we look at the CIR for a sequence of packets, concurrent signals peaks are more spread over different time indices than MPC peaks for R_1. This difference in the distribution of peaks makes it possible to distinguish R_i responses from MPCs belonging to R_1. With this observation in mind, we design Algorithm 1, a concurrent response detection algorithm that makes use of a power boundary filter and a matched filter. Before using this algorithm, R3 collects CIR for N packets, then it aligns CIR for each packet according to their first path index, reported by DW1000 chip. $DetectCR$ function takes these aligned CIRs and calculates their amplitudes. Since each CIR sample consists of I_j and Q_j components, we can calculate the amplitude of each sample using a Euclidean norm as $Amp_j = \sqrt{(I_j{}^2 + Q_j{}^2)}$. Then the function passes the calculated amplitudes to a $PowerBoundaryFilter$ function, which subtracts a power boundary from amplitudes, calculated by Eq. 8, based on the Friis transmission equation.

$$P[m] = Amplitude_{FirstPathPeak} \times \frac{Index^2_{FirstPathPeak}}{m^2} \tag{8}$$

After applying the power boundary filter, R3 applies a matched filter on maximum amplitude observed in each time index, by calling $MatchedFilter$ function. The matched filter calculates cross-correlation between the upsampled and normalized version of the input signal and a signal template by calculating the convolution of the two signals. R3 uses a Gaussian function as a signal template, with a constant standard deviation calculated based on empirical observations. $MatchedFilter$ reports index ($Index_{Max}$) and value ($Value_{Max}$) of the maximum calculated correlation. If the maximum correlation value is too small, it indicates the presence of a strong MPC, with a larger amplitude than concurrent response. If $Value_{Max}$ is below a constant predefined threshold, calculated based on empirical observations, R3 removes the sample at $Index_{Max}$. R3 repeats applying the matched filter until the maximum calculated correlation exceeds the pre-defined threshold.

B. Increasing the Ranging Accuracy with Clock Skew Correction in Long Distances

Usually, a lower data rate and a longer preamble sequence increase the range at which two transceivers can communicate. Lower data rate naturally increases the communication range, but without a longer preamble sequence, it is harder for the

Algorithm 1 Concurrent Response Detection

Input: $Threshold_{Correlation}, Template_{ConcurrentResponse}, CIR_{Packet_1}[], \ldots, CIR_{Packet_N}[]$
Output: $Index_{ConcurrentResponse}$
  function MATCHEDFILTER($Signal[], Template[]$)
    $Signal[] \leftarrow Upsample(Signal)$
    $Signal[] \leftarrow Normalize(Signal)$
    $CrossCorrelation[] \leftarrow Signal * Template$
    $L \leftarrow length(Signal)$
    $Index_{Max} \leftarrow NULL$
    $Value_{Max} \leftarrow 0$
    for $l \leftarrow 1$ to L **do**
      if $Value_{Max} < CrossCorrelation[l]$ **then**
        $Index_{Max} \leftarrow l$
        $Value_{Max} \leftarrow CrossCorrelation[l]$
      end if
    end for
    return $Index_{Max}, Value_{Max}$
  end function
  function DETECTCR($Thresh, Template[], CIR[][]$)
    $N, M \leftarrow dim(CIR)$
    $Amp[][] \leftarrow CalculateAmplitudes(CIR)$
    $Amp[][] \leftarrow PowerBoundaryFilter(Amp)$
    $Amp_{Max}[] \leftarrow$ Zeros Array of Size M
    for $j \leftarrow 1$ to M **do**
      $Amp_{Max}[j] \leftarrow max(Amp[1 \ldots N][j])$
    end for
    while TRUE **do**
      $I, V \leftarrow MatchedFilter(Amp_{Max}, Template)$
      if $V > Thresh$ **then**
        return I
      else if $V = 0$ **then**
        return $NULL$
      else
        $Amp_{Max}[I] \leftarrow 0$
      end if
    end while
  end function

receiver to synchronize with the transmitter due to lower signal-to-noise- ratio (SNR). A longer preamble makes it easier for the receiver to synchronize with the transmitter. The problem appears when each responder node in a concurrent ranging system wants to reply with the same delay. Each responder calculates the TX timestamp by adding a constant delay, δ_{TX}, to the RX timestamp of the ranging poll message as shown in Eq. 9.

$$t_{RESP_{TX}}[n] = t_{POLL_{RX}}[n] + \delta_{TX} \tag{9}$$

IEEE 802.15.4 UWB standard [20] defines a ranging marker (RMARKER) as the reference for the TX and RX timestamps for two-way ranging. The standard specifies the first pulse of physical layer (PHY) header (PHR) as the RMARKER. Since the transmitter has to send the preamble sequence

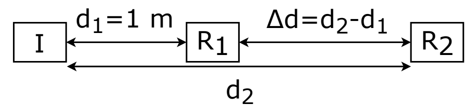


Fig. 5: Experimental setup for concurrent ranging evaluation. d_1 was fixed to 1 m, while we changed d_2 for different experiments.

before the PHR, a longer preamble sequence needs a longer time period before sending the RMARKER. Consequently, responders need to increase their reply delay, giving the radio transceiver enough time to first send the preamble sequence. A larger reply delay increases the clock drift-induced error for transceivers using independent oscillators. We tackle this issue by using clock skew estimation and correction.

If each responder has an estimate for the clock skew ($\hat{\alpha}[n]$) relative to the initiator node, it can correct the clock skew by using Eq. 10.

$$t_{RESP_{TX}}[n] = t_{POLL_{RX}}[n] + \delta_{TX} \times (1 + \hat{\alpha}[n]) \tag{10}$$

According to Eq. 7, we need to calculate the difference of two consecutive clock offset values between each responder and the initiator node. By embedding the TX timestamp in the ranging poll message and using the RX timestamp, each responder can calculate $\theta_{ToF}[n]$, the relative clock offset including the ToF as shown in Eq. 11.

$$\theta_{ToF}[n] = \theta[n] + ToF = t_{POLL_{RX}}[n] - t_{POLL_{TX}}[n] \tag{11}$$

Since $\theta_{ToF}[n] - \theta_{ToF}[n-1] = \theta[n] - \theta[n-1]$, we do not need to calculate the ToF. If we assume the initiator node as the time reference, we can estimate $\tau[n]$ by using Eq. 12. Finally, we can re-write Eq. 7 as Eq. 13.

$$\tau[n] \approx t_{POLL_{TX}}[n] - t_{POLL_{TX}}[n-1] \tag{12}$$

$$\hat{\alpha}_B^A[n] = \frac{\theta_{ToF}{}_B^A[n] - \theta_{ToF}{}_B^A[n-1]}{t_{POLL_{TX}}[n] - t_{POLL_{TX}}[n-1]} \tag{13}$$

VI. Evaluation

We evaluate our system by analyzing the ranging performance in terms of accuracy and precision and explore the strengths and limitations of R3.

A. Experimental Setup

In our experiments, we used Decawave TREK1000, a development kit based on DW1000 chip, as our UWB radio transceivers. We deployed all the radio nodes inside a university building in a 23 m × 3 m corridor. As illustrated in Fig. 5, we used one initiator node, I, and two responder nodes, R_1 and R_2. We placed R_1 in 1 m distance from I (d_1) and placed R_2 on the same line in different distances. Although all responders were in Line-of-Sight (LoS) with I, in most of our experiments we observed strong reflected MPCs in CIR.

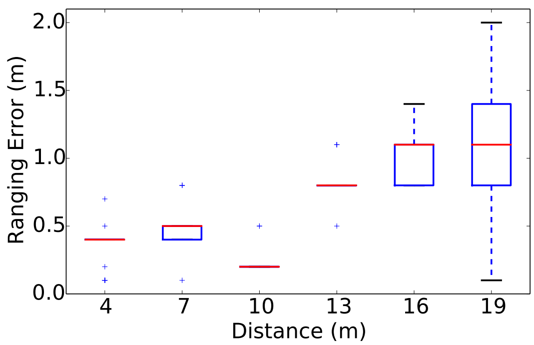


Fig. 6: Ranging error for 200 packets as a function of d_2, the distance between I and R_2. Ranging accuracy and precision decrease in longer distances due to lower SNR. Better performance at 10 m is due to absence of strong MPCs at that distance.

B. Impact of Distance on Ranging Error

We placed responder nodes in different distances to I, using the experimental setup illustrated in Fig. 5. We verified that the distance between I and R_1 does not significantly affect the performance of concurrent ranging since its ToA is estimated by the DW1000 chip itself. Thus, we only used a fixed distance for R_1 ($d_1 = 1\ m$). We increased d_2 from 4 m to 19 m and run Algorithm 1 for 200 packets, with correlation threshold set to 40 and standard deviation of the Gaussian signal template set to 10. We observed the presence of strong MPCs between 5 ns and 45 ns after the first peak (R_1), overlapping with R_2 peaks at $d_2 = 4\ m$ ($\Delta d = 3\ m$) and $d_2 = 7\ m$ ($\Delta d = 6\ m$), which should arrive at approximately $20\ ns \pm 8\ ns$ and $40\ ns \pm 8\ ns$ after R_1. Fig. 6 shows the resulting ranging error for different d_2 distances. Ranging accuracy and precision decrease with the increase of distance, but we observe improvement for some distances due to absence of strong MPCs after $d_2 = 7\ m$. However, in longer distances with the decrease in SNR, R3 cannot easily distinguish the concurrent ranging signals from noise. These observations suggest that R3 effectively removes the impact of strong MPCs even when overlapping with concurrent ranging signals.

C. Number of Concurrent Ranging Rounds

Since DW1000 is limited to 8 ns in TX timestamp resolution, we need to repeat concurrent ranging in multiple rounds and analyze the distribution of the estimated ToA for $R_{i>1}$. We need to identify how many rounds of concurrent ranging are required for this purpose. We used the same experimental data and algorithm configurations as Section VI-B to analyze the effect of the number of ranging rounds on ranging error. Fig. 7 shows that even with 20 rounds of ranging, we can achieve sub-meter concurrent ranging precision and accuracies better than 2 m. For longer distances the number of ranging rounds does not improve the performance since the SNR is very low and it is very hard to distinguish signal from noise.

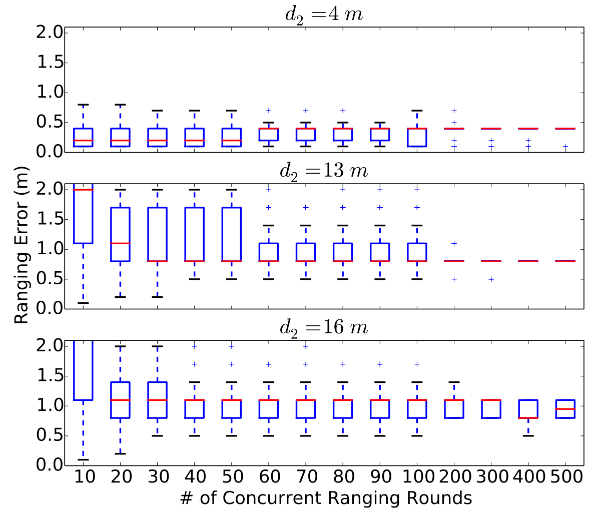


Fig. 7: Ranging error as a function of the number of concurrent ranging rounds, for 3 different d_2 distances. Overall, the ranging error decreases with the increase in the number of rounds. At 16 m the performance does not increase after 40 rounds due to low SNR.

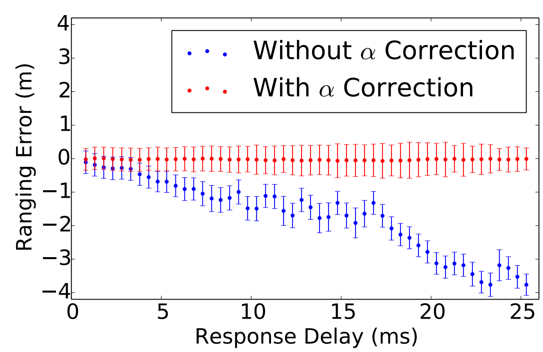


Fig. 8: Ranging error as a function of response delay (δ_{TX}). Increase in the response delay significantly increases the error due to clock drift. When we use the clock skew (α) correction method, the error is significantly decreased, with very small jitter. Each dot represents the mean ranging error calculated for 10000 packets and error bars represent one standard deviation.

D. Impact of Clock Skew Correction on Ranging Error

To evaluate our α correction method, we increased the response delay δ_{TX} from 800 µs to 25 ms and measured the ToA in two cases switching the α correction on and off. In Fig. 8 we can easily see that increasing δ_{TX} to 25.3 ms increases the ranging error up to 3.76 m. When we use the α correction method, regardless of the value of δ_{TX}, the ranging error does not significantly change. For longer distance communication and ranging, we need to use the data rate of 110 kbps which requires using a longer preamble sequence. A preamble sequence of length 4096 results in an increase of δ_{TX} to at least 4096 µs or approximately 4.1 ms. From Fig. 8 we can see that for 4.3 ms the ranging error is around

55 cm without α correction compared to 1 cm error with α correction. Thus, R3 improves the ranging accuracy by at least 54 cm for distances larger than 50 m. Further, the average accuracy improvement is 97.4% for all different tested response delays.

VII. Discussion

We calculated the peak detection algorithm parameters based on empirical observations. The standard deviation of Gaussian template represents the hardware timing uncertainty and should not change in other environments. The required number of ranging rounds and the correlation threshold depend on the number and the strength of MPCs present in the received signal. We believe our evaluation environment is representative of scenarios where strong MPCs are present. The results are likely to generalize to other real-world environments.

The design of R3 relies on the difference between ToA of the first concurrent response (from R_1) and other responses (from $R_i > 1$). However, all other responders have the same deviation in ToA, making it hard to distinguish them from each other. We can extend the design of R3 to potentially solve this problem. After the detection of R_2 signals, we can narrow the search window down to ± 8 ns around the output index from the detection algorithm and find all peaks belonging to R_2 signals. Then we turn the problem into a similar problem by aligning the remainder of CIR with respect to the newly discovered peaks. When we align CIR with respect to the responder peaks, we accumulate the time deviation on farther responder peaks and make it possible to differentiate R_j peaks from R_{j+1} peaks. We can run the same peak detection algorithm on the newly aligned signals to discover the next closest responder.

In longer distances, with the decrease in SNR, it is harder for R3 to distinguish responder signals from noise. One potential solution is to increase the TX power for farther responders to increase the SNR. Each responder can estimate the received signal level for ranging poll messages from the initiator and adaptively increase its TX power. DW1000 supports up to 33.5 dB TX power boost, with a resolution of 0.5 dB, making adaptive precise tuning of the TX power possible for each responder.

VIII. Conclusions

We designed and implemented R3, a Reflection Resilient Ranging solution, that exploits the difference in the distribution of time of arrival between first responder MPCs and other responders' signals to reliably detect concurrent responses, even in the presence of strong MPCs. R3 also makes use of the precise timing features of DW1000 and accurately estimates the clock skew between the initiator and responders to make accurate concurrent ranging feasible in distances longer than 50 m. We consider the design of R3 as steps toward a practical UWB concurrent ranging solution that can be used in real-world environments where RF multipath propagation severely impacts the quality of concurrent ranging. The results indicate that R3 is able to achieve sub-meter precision concurrent ranging in long distances using only a small number of ranging rounds.

Acknowledgment

We thank Prof. Gian Pietro Picco for identifying an error in the early draft of this work and his suggestions on how to fix it. We also thank Prof. Kyungki Kim and Prof. Miao Pan for providing some of the materials used for the experiments.

References

[1] *DW1000*, Decawave, 2019.

[2] P. Corbalán and G. P. Picco, "Concurrent ranging in ultra-wideband radios: Experimental evidence, challenges, and opportunities." in *EWSN*, 2018.

[3] B. Großwindhager, C. A. Boano, M. Rath, and K. Römer, "Concurrent ranging with ultra-wideband radios: From experimental evidence to a practical solution," in *ICDCS*. IEEE, 2018.

[4] *TREK1000 User Manual*, Decawave, 2019.

[5] D. Humphrey and M. Hedley, "Super-resolution time of arrival for indoor localization," in *Communications, 2008. ICC'08. IEEE International Conference on*. IEEE, 2008.

[6] B. Kempke, P. Pannuto, and P. Dutta, "Harmonium: Asymmetric, bandstitched uwb for fast, accurate, and robust indoor localization," in *IPSN*. IEEE.

[7] C. Falsi, D. Dardari, L. Mucchi, and M. Z. Win, "Time of arrival estimation for uwb localizers in realistic environments," *EURASIP Journal on Advances in Signal Processing*, vol. 2006, no. 1, p. 032082, 2006.

[8] M. McLaughlin, C. McElroy, S. Wilmot, and T. Proudfoot, "Receiver for use in an ultra-wideband communication system," Jun. 24 2014, uS Patent 8,760,334.

[9] *DW1000 User Manual*, Decawave, 2019.

[10] M. Maróti, B. Kusy, G. Simon, and Á. Lédeczi, "The flooding time synchronization protocol," in *Proceedings of the 2nd international conference on Embedded networked sensor systems*. ACM, 2004.

[11] F. Ferrari, M. Zimmerling, L. Thiele, and O. Saukh, "Efficient network flooding and time synchronization with glossy," in *IPSN*. IEEE, 2011.

[12] K. S. Yildirim and A. Kantarci, "Time synchronization based on slow-flooding in wireless sensor networks," *IEEE Transactions on Parallel and Distributed Systems*, vol. 25, no. 1, pp. 244–253, 2014.

[13] A. Dongare, P. Lazik, N. Rajagopal, and A. Rowe, "Pulsar: A wireless propagation-aware clock synchronization platform," in *Real-Time and Embedded Technology and Applications Symposium (RTAS), 2017 IEEE*. IEEE, 2017.

[14] A. Luong, P. Hillyard, A. S. Abrar, C. Che, A. Rowe, T. Schmid, and N. Patwari, "A stitch in time and frequency synchronization saves bandwidth," in *Proceedings of the 17th ACM/IEEE International Conference on Information Processing in Sensor Networks*. IEEE Press, 2018, pp. 96–107.

[15] H. Kim, X. Ma, and B. R. Hamilton, "Tracking low-precision clocks with time-varying drifts using kalman filtering," *IEEE/ACM Transactions on Networking (TON)*, vol. 20, no. 1, pp. 257–270, 2012.

[16] K.-L. Noh, Q. M. Chaudhari, E. Serpedin, and B. W. Suter, "Novel clock phase offset and skew estimation using two-way timing message exchanges for wireless sensor networks," *IEEE transactions on communications*, vol. 55, no. 4, pp. 766–777, 2007.

[17] F. Mazhar, M. G. Khan, and B. Sällberg, "Precise indoor positioning using uwb: A review of methods, algorithms and implementations," *Wireless Personal Communications*, vol. 97, no. 3, pp. 4467–4491, 2017.

[18] M. McLaughlin and B. Verso, "Asymmetric double-sided two-way ranging in an ultrawideband communication system," Mar. 1 2018, uS Patent App. 15/500,633.

[19] Z. Sahinoglu and S. Gezici, "Ranging in the ieee 802.15. 4a standard," in *Wireless and Microwave Technology Conference, 2006. WAMICON'06. IEEE Annual*. IEEE, 2006, pp. 1–5.

[20] I. S. Association *et al.*, "Ieee std 802.15. 4-2011, ieee standard for local and metropolitan area networks—part 15.4: Low-rate wireless personal area networks (lr-wpans)," https://standards.ieee.org/standard/802_15_4-2011.html, 2011.