# UWB-ND: Low-power Neighbor Discovery Protocol for Ultra-Wideband Radio Networks

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***Abstract*—Due to the frequent topology changes in most wireless networks, low-power Neighbor Discovery (ND) is essential for many Wireless Sensor Networks (WSNs) and Internet of Things (IoT) applications. In this work, we present UWB-ND, a low-power ND protocol for ultra-wideband (UWB) radio networks that are becoming increasingly popular in IoT applications. To conserve energy, these IoT applications typically rely on other low-power radio technology such as Bluetooth Low Energy (BLE) for ND, requiring the integration of auxiliary radios in all nodes. Utilizing specific characteristics of UWB radios such as efficient Channel Activity Detection (CAD) and varying preamble modulation, UWB-ND introduces a low-power ND approach specific to UWB radios. Our evaluation shows that UWB-ND can reduce ND power consumption by 50%, compared to the state-of-the-art PI-based approach.**

***Index Terms*—Utra-wideband, Neighbor discovery, Low-power listening, Energy efficiency**

## I. INTRODUCTION

Neighbor Discovery (ND) is a vital aspect of most network applications, enabling nodes to locate other nodes and services within the network. In a dynamic network, frequent ND is necessary for IoT applications, which can increase energy consumption and decrease network's lifespan. As a result, researchers have been developing low-power ND protocols to minimize energy usage during the ND process.

IoT applications such as ranging, indoor navigation, location tracking, time synchronization, and data communication are common use cases of UWB radio networks due to their advantages such as high-resolution timestamping and high data-rate communication. Since the 802.15.4 standard does not define a specific ND protocol for UWB radios, UWB-based applications need to use other low-power ND protocols. Although UWB radios are generally considered low-power, they still consume more energy compared to radio technologies like Bluetooth Low Energy (BLE) or Zigbee. For instance, the NRF52810 BLE chip consumes approximately 6 mA during RX and TX, while the DW3000 UWB radio consumes 40 mA during TX and 70 mA during RX. Researchers have proposed techniques such as using low-power auxiliary radio to minimize ND power consumption [1].

In Neighbor Discovery (ND) protocols, discovery occurs when a node receives an advertisement (ADV) message from a neighboring node. As most networks do not have a global schedule for ADV transmissions, nodes must continuously listen to capture all incoming ADV messages, leading to significant energy consumption. Low-power ND protocols mitigate this by reducing the duty cycle (DC) and have nodes periodically perform discovery when they are awake. However, during sleep periods, nodes may miss ADV packets, increasing the maximum Discovery Latency (DL). While some low-power ND protocols, such as birthday protocols [2], do not guarantee a maximum discovery time, others like DISCO [3], U-connect [4], and Nihao [5] ensure that nodes are discovered within a specified maximum discovery time.

UWB-ND utilizes the characteristics of UWB radios to enhance efficiency in heterogeneous networks, where nodes have different battery capacities and power consumption. Examples include location tracking systems with wall-powered anchors and battery-powered tags, or a network consisting of UWB-equipped smartphones with large, rechargeable batteries and smaller battery-powered UWB tags. In both examples, users prefer to keep the tags running on the battery for a long period. UWB-ND focuses on conserving the energy of the tags in these systems to extend the lifetime of the network.

By exploiting the specific characteristics of UWB radios, researchers have proposed efficient preamble detection enabling Channel Activity Detection (CAD). In Flick [6], researchers utilized this feature to reduce the latency of Glossy in making global state decisions. Decawave utilizes CAD in UWB radios for low-power preamble hunting [7] to reduce the energy consumption of receivers in UWB radio network. Our work utilizes this feature in a different way as described below.

UWB-ND leverages CAD and introduces a Low-Power Listen (LPL) based ND specifically designed for UWB radio networks to enhance energy efficiency in UWB tags. In this protocol, tags only transmit advertisement (ADV) messages in response to receiving an ND request, significantly reducing the duration radio is on when no ND requests are present. Traditional LPL-based approaches often struggle with long preamble reception and false wake-ups [8]. UWB-ND introduces two-phase activation (2PA) and wake-up key (WaK) to mitigate these problems in the LPL-based ND protocol.

We evaluated our solution on the CLOVES testbed using DW1000 radio chips. The results show that compared to PI-based approaches, UWB-ND can reduce the energy consumption of the tags up to 50% depending on the ND request rate and the portion of non-ND traffic. Our contributions include:

- Designing a low-power ND protocol for UWB radio networks.
- Enhancing the efficiency of activity detection in UWB-based LPL.

- Mitigating false wake-ups in LPL-based ND protocols in UWB radio networks.
- Evaluating the energy efficiency of UWB-ND and trade-offs compared to PI-based ND approach.

## II. Related Work

We summarize the literature on low-power UWB technologies and what we utilize to build UWB-ND.

### A. Low-power MAC protocols

Low-power listening (LPL) based approaches are a group of MAC protocols that utilize CAD for mitigating idle listening. In B-MAC [9], receivers periodically perform a Clear Channel Assessment (CCA) to check for channel activity. If no activity is detected during CCA, the receiver sleeps until the next interval. If the receiver finds the channel busy, it will continue to receive symbols. To activate receivers, senders transmit a wake-up call (WaC) consisting of a long preamble. However, this approach suffers from false wake-ups, where receivers activate for unrelated packets if they detect activity on the channel [8]. This technique has been adopted to other low-power packet radios, e.g., the work on X-MAC [8]. A robust packet filtering helps minimize false wakeups. X-MAC also introduced an early ACK mechanism that stops the sender from transmitting WaC once the intended receiver detects the WaC. BoX-MAC [10] and Contiki-MAC [11] further lowered the CCA time, these family of techniques have been extensively studied in UWB radios.

LPL-based approaches reduce application performance as packet transmission rate increases. To eliminate WaCs, RI-MAC [12] proposes the idea of Receiver Initiated (RI) based MAC. In RI-based MAC protocols, receivers initiate the communication by sending beacon messages when they are accepting messages and waiting for any incoming message from senders. The receiver goes back to sleep if no activity is detected. This led to idle listening in RI-MAC senders, later addressed by EE-RI-MAC [13]. Fundamentally, both transmitter or receiver-initiated designs use similar underlying techniques and also suffer from common problems such as idle listening and false detection. UWB-ND saves power on the tags by having the more capable anchor nodes transmit packet train to emulate long preambles.

### B. Low-power neighbor discovery

*Time-slotted ND protocols* divide time into equal slots where the radio is active or sleeping in each slot. Birthday protocol [2] randomly assigns the radio to transmit, receive, or sleep in each slot but do not guarantee a maximum DT. To solve this shortcoming, DISCO [3] and U-connect [4] developed deterministic approaches that create a trade-off between energy conservancy and lower DL for applications. To enhance the DC/DL trade-off, Nihao [5] suggested nodes spend more time transmitting advertisement messages in their active time slots.

In *Periodic Interval (PI) based ND protocols* (Figure 1), nodes take a role (advertiser, scanner, or both). Every time the scanner wants to discover advertisers, it listens on the channel for $T_{Scan}^{Duration}$ to capture ADV messages. For continuous discovery, scanners perform this scan once every $T_{Scan}^{Interval}$. In PI-based approaches, both the scanners and advertisers can independently set $T_{ADV}$, $T_{Scan}^{Interval}$, and $T_{Scan}^{Duration}$. This degree of freedom is beneficial for some applications [14]. For instance, Griassdi [15] proposed assisted-two-way (A2W) discovery where nodes send out-of-order advertisement messages to expedite the two-way discovery process.

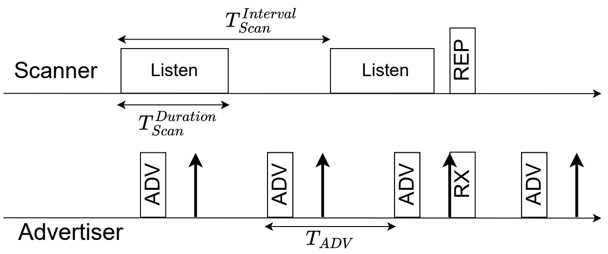


Fig. 1: Scanner and advertiser in PI-based ND protocols. The advertiser transmits ADV messages every $T_{ADV}$ and checks for a reply message for two-way discovery. Scanner listens for $T_{Scan}^{Duration}$ every $T_{Scan}^{Interval}$ to capture ADV messages.

Simulation results show that some combinations of advertisement interval, scan interval, and scan duration may cause a huge increase in DL [16]. One way to ensure a guaranteed maximum delay is to set $T_{Scan}^{Duration} \geq T_{ADV}^{MaX}$, where $T_{ADV}^{MaX}$ is the maximum advertisement interval. Usually, this value is enforced by the ND protocol (e.g. in BLE $20ms \leq T_{ADV} \leq 10.24s$). This condition ensures that during the scan window, scanners capture at least one ADV message if none of them gets lost or corrupted. Co-circle [17] also introduces a collaborative approach where a group of sensors connected to a gateway can collaborate to discover another node. Researchers have also proposed adaptive scheduling to optimize energy consumption while considering DL [18], [19]. Android BLE API allows the BLE to operate with high DC in *SCAN_MODE_LOW_LATENCY* to minimize DL or with low DC in *SCAN_MODE_LOW_POWER* to conserve energy.

UWB-ND proposes an LPL-based approach for ND in UWB networks. The energy use asymmetry and the adaptiveness of the PI-based approaches allow UWB-ND to save the energy of battery-powered tags at the expense of the wall-powered anchor nodes or smartphones.

## III. Baseline LPL-based ND protocols for UWB radio networks: design and challenges

Figure 2 illustrates a baseline ND protocol for UWB radio networks based on the principles explored in the LPL literature. The advertiser starts as a B-MAC receiver in this network and sniffs the channel every $T_{Sniff}$. In each sniff, the sender performs a CAD to check for preamble symbols. The scanner starts the scan by sending a Wake-up Call (WaC) which is a series of preamble symbols. Once the advertiser detects the WaC, it continues to collect preamble symbols and transmits the advertisement (ADV) message after $0 \leq T_{ADV} \leq T_{ADV}^{Max}$

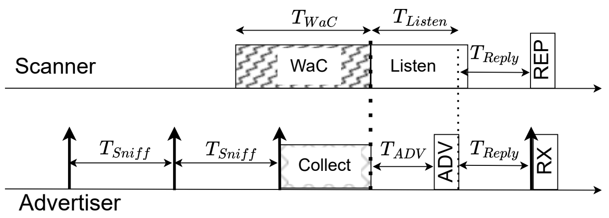


Fig. 2: LPL-based ND protocols for UWB radio networks. This approach suffers from overhearing and false wake-ups since the advertiser must collect the whole packet before making any decision

to avoid collision with other advertisers. The scanner listens to the channel for $T_{Listen}$ after transmitting the WaC. In the advertisement message, advertisers include $T_{Reply}$ determining the time they sniff the channel for the reply message after transmitting ADV. If the scanner wants to connect to that advertiser, it schedules a reply (REP) message based on the reception time of the ADV message and $T_{Reply}$. If the advertiser detects a preamble in the sniff that is meant for reply messages, it continues to capture the packet.

Equation 1 describes the duration of the scan process in LPL-based ND. To ensure that all advertisers detect channel activity, WaC must be long enough to cover one sniffing interval. Also, listen intervals have to be large enough to capture all ADV messages. Equations 2 and 3 ensure these constraints in this approach.

$$T_{Scan}^{Duration} = T_{WaC} + T_{Listen} \tag{1}$$

$$T_{WaC} \geq T_{Sniff}. \tag{2}$$

$$T_{Listen} \geq T_{ADV}^{Max}. \tag{3}$$

If the network is mostly idle, advertisers in the LPL-based approach only perform a sniff in each activation. In UWB radios, sniffs can be as low as 4 $\mu s$ which is shorter and more energy efficient than sending an ADV message that is approximately 90 $\mu s$. In a network where the scanner wants to find all the advertisers, equation 4 calculates the maximum DL for the LPL-based approach.

$$T_{Discovery}^{Max} = T_{WaC} + T_{ADV}^{Max} \tag{4}$$

If ND requests are rare in the network and advertisers are mostly idle, equation 5 calculates the energy consumption of the LPL-based approach. Equation 6 estimates the power consumption of the PI-based approach in the same setting. $E_{Sniff}$ is the energy consumption of a sniff that is used for CAD.

$$P_{LPL} = \frac{E_{Sniff}}{T_{Sniff}} \tag{5}$$

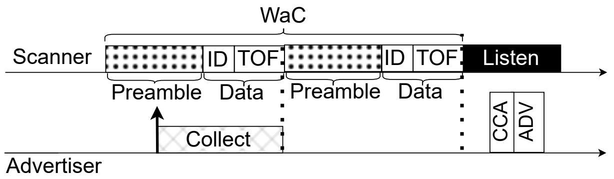


Fig. 3: LPL-based ND protocol based on WaC packetization. In this approach, WaC is the series of WaC packet containing and WaC identifier (ID), and time-to-finish (TOF). By capturing this information, advertisers can disregard the rest of WaC and only activate the radio for transmitting the ADV message when the scanner is in the listen phase.

$$P_{PI} = \frac{E_{Sniff} + E_{ADV}}{T_{ADV}} \tag{6}$$

If we set $T_{ADV} = T_{Sniff} = T$, equation 7 describes the comparison of power consumption in these two approaches. Even though the amount of improvement is device-dependent and may vary for each UWB radio, LPL-based method has lower power consumption since the numerator of the fraction is always smaller than the denominator in equation 7.

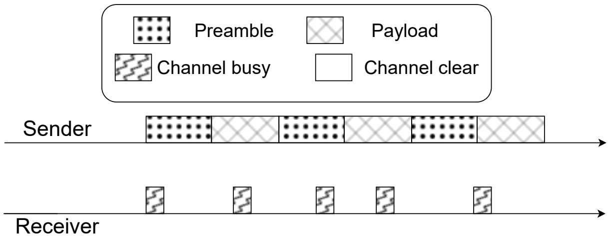
$$\frac{P_{LPL}}{P_{PI}} = \frac{E_{Sniff}}{E_{Sniff} + E_{ADV}} \tag{7}$$

### A. *WaC packetization*

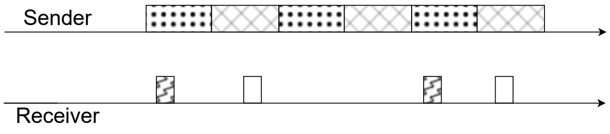
Despite the energy efficiency of the preliminary LPL-based ND approach, it suffers from long preamble collection and false wake-ups. Additionally, most UWB radios offer a limited number of preamble lengths for the application to choose from, making it impossible for the scanner to have customized $T_{WaC}$ that is a few hundred milliseconds long.

Packetizing the WaC is a solution to solve the challenges in the preliminary LPL-based ND approach. Figure 3 illustrates the proposed NP protocol based on this approach. Scanners add a WaC identifier (ID), allowing advertisers to classify WaCs. They can also add a time-to-finish (TOF) to announce the start of listening phase. Advertiser only collect one of the WaC packets. Then, it computes the transmission time of the ADV message based on ToF and disables the radio until then, disregarding the rest of the WaC. Compared to the preliminary LPL-based approach, WaC packetization mitigates the advertisers' long WaC processing as it only needs to collect the preamble symbols of one WaC packet. WaCs are usually a few hundred milliseconds to cover a sniffing interval while a WaC packet with the minimum number of preamble symbols could be as small as $90 \mu s$.

Although WaC packetization reduces WaC processing time and avoids false wake-ups, it also causes WaC misses which is undesirable for our approach. Figure 4 illustrates the challenge of this approach in UWB-ND. LPL-based approach use these two methods for CAD: (1) signal power level, and (2) preamble detection (PD) channel occupancy. B-MAC, X-MAC, and Box-MAC use the signal power level for CAD. In radio technologies where reception signal power is greater than noise level, radios can detect channel occupancy by assessing signal power. As we see in figure 4(a), the receiver can detect the occupancy using the signal power channel occupancy detection during both payload and preamble transmission. However, since signal power in UWB radios is close to noise level, receivers can only detect preamble symbols [20]. According to figure 4(b), PD methods cannot detect payload symbols without first detecting the preamble symbols. If the sniffing occurs while the scanner is sending payload symbols of the WaC packet, advertisers cannot detect the WaC.



(a) Signal power level



(b) Preamble detection

Fig. 4: Channel occupancy detection using (a) signal power and (b) preamble detection. UWB radios only allows preamble detection method due to its signal modulation. Preamble detection CCA cannot detect payload symbols as they are modulated differently than preamble symbols.

To reduce the chances of WaC misses, scanners can increase the portion of the preamble in WaC by using larger PLENs for WaC packets or reducing payload transmission time. However, longer PLENs for WaC packets makes advertisers collect more preamble symbols before collecting ID and ToF. Advertisers can also use the same method proposed in Contiki-MAC to avoid WaC misses when there are gaps. However, these approaches lead to longer sniff times or more sniffs in each sniff interval.

## IV. UWB-ND: MITIGATING LONG WAC PROCESSING AND FALSE WAKE-UPS IN LPL-BASED ND PROTOCOLS

Figure 5 illustrates an overview of the techniques used in our approach to tackle the challenges in preliminary LPL-based ND. Instead of embedding the data into WaC with WaC packets, UWB-ND uses two-phase activation (2PA) to determine WaC termination. It also uses the wake-up key (WaK) to distinguish between WaCs and other non-ND preambles.

### *A. two-phase activation and rapid sniffing*

Advertiser can terminate the reception upon activity detection. Assuming that the advertiser knows WaC transmission time ($T_{WaC}$), setting the transmission time to $T_{ADV} \geq T_{WaC}$ avoids collision between WaC and ADV message. Even though this approach is energy efficient for the advertiser, constraint 3 forces scanners to set $T_{Listen} \geq T_{WaC}$ to capture all ADV messages.

Figure 6 illustrates 2PA that is used to reduce $T_{Listen}$. When the advertiser first detects channel activity, it changes the sniffing interval to $\delta$ where $\delta < T_{Sniff}$. The advertiser will sniff until one of them does not detect channel activity. Once the channel is clear, the advertiser sends the ADV message. With 2PA, advertisers determine WaC termination time more precisely. Scanners can also set $T_{Listen} = \delta$ to reduce listening time.

With 2PA, advertisers collect much fewer preamble symbols in comparison to WaC packetization and the preliminary LPL-based ND. They also have the same power consumption as the LPL-based approaches when there are no scanners. However, as ND requests become more frequent, applications need to make a trade-off between the energy efficiency of the advertisers and the scanners. Lower $\delta$ allows the scanner to reduce $T_{Listen}$ and reduce energy but forces advertisers to perform more sniffs to determine WaC termination time. With larger $\delta$, advertisers estimate WaC termination with lower energy but the scanner needs to increase $T_{Listen}$ accordingly.

### *B. False wake-up mitigation using wake-up keys*

With 2PA, UWB-ND still suffers from false activation when other transmitters in the network are sending packets with the same configuration as advertisers. There are two occurrences of false wake-up in UWB-ND. When the advertiser accidentally senses a non-ND preamble, it transmits an ADV message as soon as the channel becomes available. Then it sniffs the channel for the reply message. If the advertiser senses another non-ND packet in this sniff, it confuses the non-ND frame with a reply message and continues to collect the packet. Since the former false wake-up happens only when the first false wake-up occurs, it has a lower probability of occurrence. However, it is significantly more energy-consuming.

To determine the likelihood of false wake-ups in this LPL-based ND, we define preamble occupation ($\alpha$) which is the portion of the time the channel is occupied by the preamble of non-ND packets in the network. If $\alpha = \hat{\alpha}$ in a network without scanners, the probability of advertisers detecting a non-ND preamble when sniffing is $P^{False}_{Detect} = \hat{\alpha}$. Since preamble transmission times are shorter than $\delta$, advertisers enter the rapid sniffing phase and transmit their ADV frame after performing one sniff. Equation 8 calculates the energy consumption of the advertiser during a period $T$. The advertiser performs $\frac{T}{T_{Sniff}}$ amount of sniffs in this period. each sniff has $\alpha$ probability of false wake-up, leading to spending $E_{Loss}$ more than the initial sniff.

$$E = (E_{Sniff} + \alpha * E_{Loss}) * \frac{T}{T_{Sniff}} \tag{8}$$

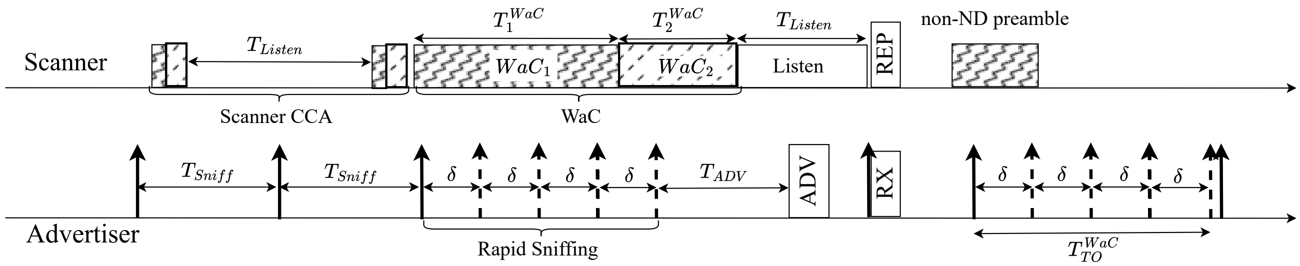


Fig. 5: Overview of UWB-ND. With two-phase activation (2PA), the advertiser performs rapid sniffing to detect WaC termination time. The wake-up key allows advertisers to distinguish WaC from non-ND preambles. Scanner CCA also avoids WaC collision and WaC overlapping.

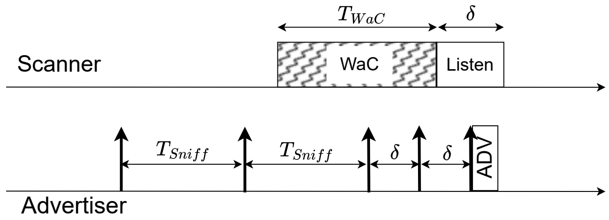


Fig. 6: 2PA allows advertisers to detect WaC termination more precisely. This allows scanners to set $T_{Listen} \geq \delta$ where $\delta < T_{WaC}$.

Equation 9 calculates $E_{Loss}$ for UWB-ND. Similar to equation 8, advertisers capture a non-ND packet in $\alpha$ ratio of false wake-ups as a reply message.

$$E_{Loss} = E_{ADV} + E_{Sniff} + \alpha * E_{RX} \tag{9}$$

According to equations 9 and 8, there is $\alpha^2$ chance that the advertiser captures an unintended UWB frame. Depending on $\alpha$, the energy loss of the advertisers can be noticeable. To mitigate false reply reception, WaK proposes a mechanism for advertisers to distinguish WaCs from non-ND preambles. Even though the UWB standard does not allow users to define customized preamble symbols, it provides multiple options for users to modulate preamble symbols. By changing the Pulse Repetition Frequency (PRF) in radio configuration, UWB radios can create different preamble symbols that are undetectable by receivers configured on another PRF. UWB-ND utilizes PRF to define WaK and divide WaC into multiple segments with different radio configurations. Equation 10 defines a WaK as a pair of PRFs that is shared between scanners and advertisers.

$$WaK =< PRF_1, PRF_2 > \tag{10}$$

Scanners modulate each segment of WaC based on the order defined in WaK with $T_i^{WaC}$ as the transmission time of $i$-th segment. The advertiser starts sniffing using the first PRF in WaK. The advertiser only activates if it detects all the segments in WaK. Otherwise, it will restart the detection process after $T_{TO}^{WaC}$. In detection reset, the advertiser immediately sniffs the channel using the first configuration in the WaK to ensure that there is no WaC in the channel with $PRF_1$ while it is looking for the second segment of WaC. This approach avoids false wake-ups when the non-ND traffic is on one of the PRFs.

To ensure that advertisers detect all segments of WaC, $T_1^{WaC} \geq T_{Sniff}$ and $T_2^{WaC} \geq \delta$. To ensure ADV message does not collide with WaC, $T_{ADV} \geq T_2^{WaC}$. Finally for the scanner to capture the ADV packet $T_{Listen} \geq T_{ADV}$. Unlike the LPL-based approach, $T_{ADV}$ can be fixed as different sniff patterns of advertisers create different transmission time. $T_{TO}^{WaC}$ can be set independently by the advertiser. If $T_1^{WaC} \geq T_{TO}^{WaC}$, the advertiser may reset detection while the scanner is sending the first part of WaC. It detects it again in the immediate sniff. This loop continues until the advertiser detects the second part. Selecting short $T_{TO}^{WaC}$ causes advertisers to perform more immediate sniffs. A large $T_{TO}^{WaC}$ causes advertisers to stay in rapid sniff longer when they mistakenly detect a non-ND packet sent with $PRF_1$.

Equation 11 calculates the energy consumption of the advertiser with a transmitter sending a non-ND frame using the same radio configuration as the first part of WaC.

$$E = (E_{Sniff} + \alpha * [\frac{T_{TO}^{WaC}}{\delta} * E_{Sniff}]) * \frac{T}{T_{Sniff}} \tag{11}$$

### *C. WaC collision avoidance with scanner CCA*

Managing scan overlaps is essential for ensuring the completeness of UWB-ND when multiple scanners initiate scanning at the same time. In this situation, the combined WaC functions as a single wake-up call that activates all advertisers. If all scanners enter the listening phase simultaneously, they captures all ADV messages. However, when scanners start listening at different time, some may miss a number ADV messages. Depending on the modulation of the ADV messages, overlap between WaC and the listening phase can cause packet collision, leading to detection failure for scanners that are listening to ADV messages.

In UWB-ND, scanner CCA helps prevent unwanted situations by passive scanning. In the start of a scan, the scanner performs a CCA in both PRFs to check for any existing WaC packets. If no WaC packet is detected, scanner waits for $T_{Listen}$ to avoid WaC transmission during listening phase. A final CCA ensures that no other scanner has start WaC transmission during the wait period. If both CCAs do not detect WaC packets, the scanner begins transmitting the WaC. Otherwise, the scanner enters passive scanning. In this approach, the scanner keeps listening to the incoming WaC. Once the WAC is complete, the scanner starts the listening phase simultaneously with the other scanner. Scanner CCA categorizes scanners into active and passive scanners. Active scanners initiate scan by sending a WaC while passive scanners listen to the WAC and enter listening phase with active scanners.

### *D. Discovery latency in UWB-ND*

Similar to PI-based approach, UWB-ND scanner can sleep between scans to save energy. If $T_{Scan}^{Sleep}$ represents the time where the scanner spends in sleep mode between two ND sessions, equation 12 determines the discovery latency (DL) in UWB-ND. An active scanner requires to send one WaC to detect advertisers in the network. Advertisers that join after the initial WaC transmission must wait until the next ND session, plus the duration of one scan, to be detected.

$$\begin{aligned} DL^{Min} &\leq DL \leq DL^{Max} \\ DL^{Min} &= T_{scan}^{CCA} + T_1^{WaC} + T_2^{WaC} + T_{ADV} \\ DL^{Max} &= T_{Scan}^{Sleep} + T_{Listen} + T_2^{WaC} + DL^{Min} \end{aligned} \tag{12}$$

## V. EVALUATION

We conducted all evaluations for this work using the CLOVES testbed, setting up three distinct environments: the first two are hallways in two different floors and the third one is a room with higher node density. Table I provides details on the node IDs for each environment, along with the specific radio devices used. Both EVB1000 and DWM1001 use the Qorvo DW1000 radio chip as the UWB radio interface. However, they have different antennas and microcontrollers.

TABLE I: Environments dedicated for UWB-ND evaluations in the CLOVES testbed.

| Environment | Area | Nodes IDs | Radio device |
|---|---|---|---|
| 1 | DEPT | 7-17 | Qorvo EVB1000 |
| 2 | HALL-A | 50-58, 61-65 | Qorvo EVB1000 |
| 3 | DEPT | 160-173 | Qorvo DWM1001 |

Table II presents the parameter values selected for our evaluation. Following the recommendation from the previous studies [21], we set $T_{ADV} = 500ms$ for the PI-based approach. By choosing $T_{ADV} = T_{Sniff}$ and setting $\delta$ to be approximately 10% of $T_{Sniff}$, UWB-ND tries to keep the maximum discovery time close to PI-based technique while being energy efficient during ND requests or non-ND traffic. We also determined the values for $T_1^{WaC}$, $T_2^{WaC}$, according to $T_{Sniff}$ and $\delta$.

TABLE II: Parameters for UWB-ND and PI-based protocols

| Method | Parameter | Value |
|---|---|---|
| PI-based | $T_{ADV}$ | 500 ms |
| UWB-ND | $T_{Sniff}$ | 500 ms |
| UWB-ND | $\delta$ | 50 ms |
| UWB-ND | $T_2^{WaC}$ | 52 ms |
| UWB-ND | $T_1^{WaC}$ | 505 ms |

TABLE III: Energy consumption of actions for DW1000 and DW3000

| Action | Symbol | Value ($\mu J$) | |
|---|---|---|---|
| | | DW1000 | DW3000 |
| Sniff | $E_{Sniff}$ | 25.03 | 8.58 |
| ADV transmission | $E_{ADV}$ | 38.59 | 18.53 |
| Receive for 1 $\mu s$ | $E_{RX}$ | 0.34 | 0.21 |
| Transmit for 1 $\mu s$ | $E_{TX}$ | 0.20 | 0.12 |

### *A. Power consumption model*

We used equation 13 to calculate the average power consumption of the node based on previous studies [22]. For each action, $E_i$ describes the energy consumption and $N_i$ describes the frequency of that action.

$$\overline{P} = \frac{\Sigma(E_i * N_i)}{T} \tag{13}$$

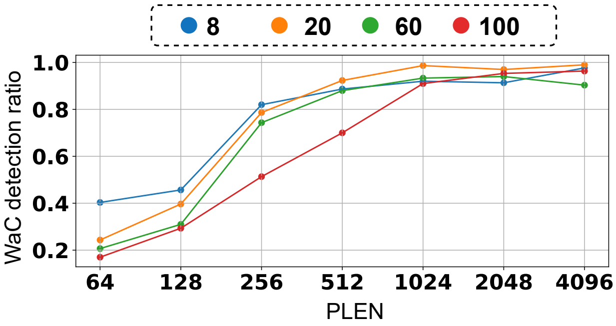
Table III lists the actions of UWB radio node and shows the $E_i$ for DW1000 and DW3000 UWB radio chips commonly used for developing UWB radio networks.

### *B. WaC packetization*

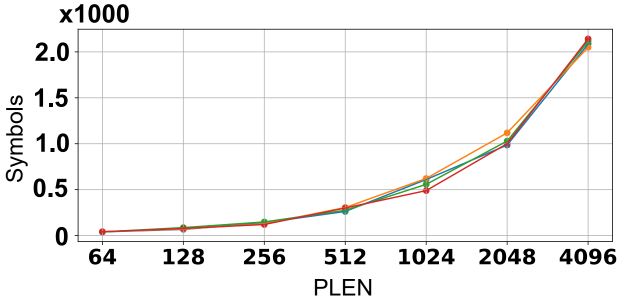
In this experiment, nodes 12, 62, and 160 are scanners in each environment. We set other nodes to be advertisers. Using different payload sizes and preamble lengths (PLEN) for WaC packets, we measured WaC detection ratio. We also measured the number of collected preamble symbols for each WaC packet to estimate the energy consumption. We used the highest data rate available (6.8 Mbps) to modulate the payload of the WaC packet that is at least 8 bytes (1 byte ID, 1 byte SEQ number, 4 bytes ToF, and 2 bytes CRC). We also increased the payload size to 20, 60, and 100 by padding.

Figures 7 shows that when the scanner chose $PLEN = 64$ with the minimum payload size, advertisers missed 60% of the WaCs. Larger packets reduce the probability of WaC detection as it decreases the preamble portion of the WaC. When scanner chose the highest PLEN $PLEN = 4096$, WaC detection increased to more than 90%. However, Figure 7(b) shows that using higher PLEN also increased the average number of symbols that advertisers collected to capture the payload of the WaC packet. If the scanner uses $PLEN = 1024$ for high WaC detection, advertisers approximately collect 512 symbols. Using the value of $E_{RX}$ from TABLE III, advertisers spent 6x more in DW1000 than $E_{Sniff}$.

Compared to Contiki-MAC which uses two sniffs per activation instead of increasing the CAD time, UWB-ND only sniffs once when there is no traffic in the network. Also in DW radio chips, it takes approximately 2 ms for the node to



(a) Average WaC detection ratio



(b) Average preamble symbols collected

Fig. 7: Increasing the portion of preamble symbols in WaC packets increases the chances of WaC detections by advertisers. However, longer PLENs causes advertisers to collect more preamble symbols to capture the WaC packet

perform a sniff due to OSC start. This forces WaC packets to have more than 2 ms of preamble to ensure WaC detection.

### C. False wake-ups mitigation with WaK

First, we measure the likelihood of false wake-ups in a network with different non-ND traffic. Then, we evaluate the impact of $T_{TO}^{WAC}$ on false wake-up on the energy waste of the WaK approach. The experiments in this section had one or two transmitters (depending on the experiment) nodes generating non-ND traffic. For generating different preamble occupation ($\alpha$), the transmitter divided the time into slots of $T_{Interval}^{TX}$ and randomly chose a time in each slot to transmit a non-ND frame. For each experiment, we selected $\alpha$ based on equation 14. In this experiment, we set $PLEN = 4096$ with the minimum 3-byte payload for the transmitter.

$$\alpha = \frac{PLEN}{T_{Interval}^{TX}} \tag{14}$$

In our initial experiment in the three environments (Table I), we set one nodes 11, 61, 160 to be the transmitter for the non-ND traffic in each environment respectively and set other nodes to be advertisers. Since there are no scanners in the network, any WaC detection in advertisers is a false wake-up. Table IV shows when advertisers only use 2PA without a false wake-up mitigation approach. The average false detection ratio is close to $\alpha$, and the average false reception of reply messages is $\alpha^2$ as we mentioned in section IV-B.

TABLE IV: Average false WaC detection and reply reception ratio in a network with one transmitter. The probability of false WaC detection is $\alpha$ and false reply reception is $\alpha^2$

| $\alpha$ | 0.33 | 0.20 | 0.10 | 0.04 |
|---|---|---|---|---|
| False WaC detection ratio | 0.30 | 0.17 | 0.10 | 0.05 |
| False reply reception ratio | 0.11 | 0.03 | 0.01 | 0.00 |

We used the same node placement for our second experiment. However, we enabled WaK on our advertisers and set $WaK =< PRF\_64, PRF\_16 >$. We also configured the transmitter to use PRF_64. As expected, advertisers did not wake up. However, as figure 5 depicts, every time advertisers mistakenly sensed a non-ND packet with PRF_64, they entered rapid sniffing phase, performing additional sniffs. Figure 8 displays the average sniff rate ($\overline{\omega_{Sniff}}$) of advertisers with different $\alpha$ and $T_{TO}^{WaC}$. When $\alpha$ was low in the network, changing $T_{TO}^{WaC}$ did not dramatically change $\overline{\omega_{Sniff}}$. However, when $\alpha = 0.33$ and $T_{TO}^{WaC} = 500ms$, $\overline{\omega_{Sniff}}$ increased approximately 58% compared to $T_{TO}^{WaC} = 150ms$ with the same $\alpha$.

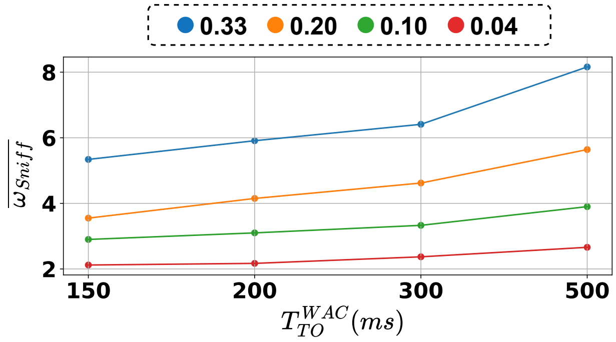


Fig. 8: Average sniff rate of UWB-ND with with different $\alpha$ and $T_{TO}^{WaC}$. Increasing $T_{TO}^{WaC}$ causes advertisers to stay longer in the rapid sniffing state, leading to higher sniff rate.

To compare energy consumption, we assumed each non-ND packet is 500 $\mu s$ (PLEN=256, payload=128 bytes). When $\alpha = 0.33$ and $T_{TO}^{WaC} = 150$, UWB-ND had approximately 2x sniffs on average compared to 2PA. The extra sniffs increased power consumption by 2% in DW1000. However, for DW3000 where sniffing is much more energy efficient than ADV transmission, UWB-ND reduced power by nearly 21%.

The third experiment evaluated the performance of false wake-up detection in UWB-ND with two transmitters. The first transmitter used PRF_64 and the second transmitter used PRF_16. Since there was traffic in both configurations of WaK, false wake-ups are probable in this experiment. Comparing the results in Table IV and V, the ratio of false wake-ups and reply reception is lower in UWB-ND even when there is traffic in both PRF_16 and PRF_64.

TABLE V: Average false WaC detection and reply reception ratio in a network with two transmitters

| $\alpha$ | 0.33 | 0.20 | 0.10 | 0.04 |
|---|---|---|---|---|
| False WaC detection ratio | 0.21 | 0.10 | 0.04 | 0.01 |
| False reply reception ratio | 0.05 | 0.02 | 0.01 | 0.00 |

### *D. Completeness*

Due to packet drops, UWB-ND scanners cannot detect all advertisers in the network with a single scan. To enhance completeness, UWB-ND repeats the scan process.

Our first experiment measured detectability among 402 pairs (Env #1: 110, Env #2: 182, Env #3: 110) of scanner-advertiser. In this experiment, we configured scanners with 10 repetitions in each ND session. The scanner detected the advertiser in nearly 95% of the pairs. The radio configuration of the tags were optimized for minimum energy consumption causing reduction in the reliability of the links between some scanners and advertisers, thereby detection failure in some pairs. Even though there is no upper limit to the number of retires to guarantee completeness, 97% of 399 discoverable pairs were discovered with up to three retries.

To evaluate the impact of random wait (jitter before ADV transmission) on the completeness of UWB-ND, we initially conducted experiments in 30 different settings varying the number of advertisers and the advertiser nodes without random wait in Env #1. In these experiments, one scanner started the ND session with multiple advertisers (3, 7, and 13) that were all discoverable. With three random advertisers in each, no collision occurred between ADV messages. Since each advertiser scheduled its sniff time individually, ADV transmission times were different, avoiding collisions with each other. With seven advertisers, the randomness of sniff times was not sufficient as we observed 12 packet collisions between advertisers in 22 ND sessions. By adding a random wait between 0-20 ms, the number of collisions was reduced to 3 for seven advertisers. With 13 advertisers, we also observed 14 collisions in 22 ND sessions. For this number of advertisers, setting the random number between 0-200 ms reduced the number of collisions to 6 in 36 ND sessions. These results suggest that even though random wait increases completeness, it does not guarantee it.

Similar to experiments with multiple advertisers, we performed experiments in 30 different settings with scanners (2, 5, 10) and multiple advertisers. For two scanners and 12 advertisers, we first disabled scanner CCA to measure the impact of WaC collision and WaC overlap. In 20 WaC collisions where two WaCs had less then 4 ms delay, both scanners detected all the ADV messages in the network. When the delay between the WaCs is 4 - 800 ms, one of the advertisers failed to detect 9 ADV messages in average compared to the other one. The proposed method for collision avoidance avoided 93% of the collisions with two scanners in the network. For five and 10 scanners, scanner CCA avoided 88% of the collisions.

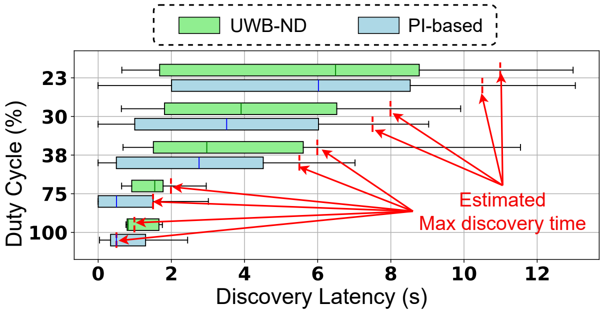


Fig. 9: Discovery Latency for UWB-ND and PI-based with different duty cycle. UWB-ND scanner discovered approximately 88% of the tags before the estimated maximum DL.

### *E. Discovery latency*

We selected one node as the scanner, continuously initiating ND sessions with a certain duty cycle throughout the experiment. Advertisers began operating at random times during the experiment. We measured DL as the interval between an advertiser's activation and its initial detection by the scanner. Figure 9 presents the results for multiple scanner, with the maximum estimated DL indicated based on equation 12.

Like the PI-based approach, increasing duty cycle decreased the discovery time for most advertisers. However, in UWB-ND, $DL^{Max}$ was 500 ms higher than in PI-based when scanners had the same duty cycle causing $DL^{Max}$ to be 50% higher for $DC = 100\%$ and 4% higher when $DC = 23\%$ in UWB-ND compared to PI-based. The results also illustrate that DL for 12% of advertisers exceeded $DL^{Max}$ in UWB-ND. In practice, $DL^{Max}$ does not provide an upper bound for discovery time.

### *F. Energy consumption*

In this section, we compare the energy consumption of tags in UWB-ND versus PI-based. In each round of the experiment, one node started as the scanner, sending ND requests at a certain interval. We use average sniff rate ($\omega_{Sniff}$) and ADV transmission rate ($\omega_{ADV}$) as proxies for power consumption of advertisers. Table VI reports these rates for different ND request intervals. Regardless of the ND request interval, the advertiser in the PI-based approach transmits an ADV message every $T_{ADV} = 0.5s$ followed by a sniff. In UWB-ND, ND requests caused 2PA to change the sniffing interval and send a ADV message. This results in different $\omega_{Sniff}$ and $\omega_{ADV}$ rates for this approach.

Based on $\omega_{Sniff}$ and $\omega_{ADV}$, figure 10 measures the average power consumption of DW1000 advertiser for both PI-based and UWB-ND. When the scanner had $DC = 100\%$ for the lowest DL, UWB-ND advertisers consumed 64% more energy as sniffing became an overhead when advertisers were frequently sending ADV messages. However, when ND requests were more than 70 seconds apart, UWB-ND advertisers consumed 50% less energy compared to PI-based.

TABLE VI: Average number of sniffs and ADV transmission per second for UWB-ND with varying ND request intervals. In contrast to PI-based approach that has fixed rate of sniffs and ADV transmission, these values vary in UWB-ND depending on ND request interval.

| ND request interval (s) | $\overline{\omega}_{Sniff}$ | $\overline{\omega}_{ADV}$ |
|---|---|---|
| UWB-ND | | |
| 2.64 | 6.16 | 0.94 |
| 4.72 | 4.71 | 0.52 |
| 5.62 | 4.30 | 0.45 |
| 7.38 | 3.60 | 0.34 |
| 11.80 | 2.89 | 0.19 |
| 82.67 | 2.16 | 0.03 |
| $\infty$ | 2.00 | 0 |
| PI-based | | |
| $\forall$ | 2.00 | 2.00 |

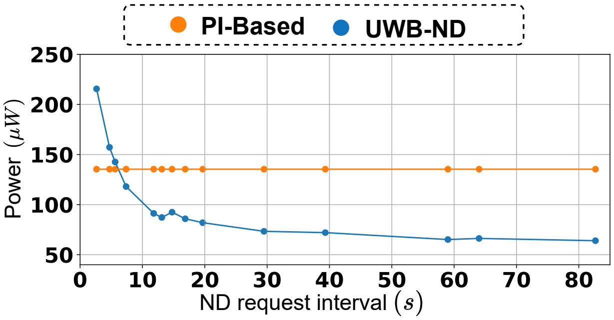


Fig. 10: Power consumption of UWB-ND vs PI-based with different ND request rates. High ND requests cause UWB-ND advertisers to perform more sniffs and ADV transmission, consuming more power than the PI-based approach.

## VI. DISCUSSION

**Energy efficiency and discovery latency tradeoff**: To make UWB-ND as efficient as adaptive PI-based ND protocols [17], [18], applications can map the same approach by setting $T_{WaC} = T^{Duration}_{Scan}$, $T_{ADV} = T_{Sniff}$, and share a globally known $\delta$ among nodes. In this mapping, the probability of detecting WaCs is the same as the probability of and ADV frame to occur during the scan window. Once the advertiser detects $WaC_1$, it will also sense $WaC_2$ and send the ADV message if $\delta$ is same in all nodes.

## VII. CONCLUSION

We proposed UWB-ND, a low-power ND protocol for UWB radio networks. The design consists of two back-to-back preambles with different PRFs and periodic sniffing and advertisements. UWB-ND also proposed two mechanisms to optimize the protocol. 2PA mitigates long preamble reception and WaK reduces false wake-ups. We implemented the protocol on DW1000-based devices. We exploited channel activity detection to reduce the energy consumption of advertisers by approximately 70% when there is no traffic in the network. Our evaluation indicated that the energy efficiency of UWB-ND depends on both ND and non-ND traffic.

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