SRAC: Simultaneous Ranging and Communication in UWB Networks

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***Abstract*—Ultra-wideband signals have been used for accurate ranging and localization application during the last few years. State of the art UWB ranging applications can estimate the distances with less than a 5 cm error. Existing localization solutions create their own ranging traffic. In this paper, we investigate the possibility of piggybacking the information required by ranging application over existing network traffic. In addition, we study the feasibility of piggybacking of sensing information over ranging traffic and finally, we propose our technique for Simultaneous Ranging and Communication (SRAC) in UWB networks which adaptively changes the ranging mode from active to passive by using either ranging traffic or sensing traffic to accomplish the ranging and sensing goals while reducing the network traffic to minimum possible. We integrated our proposed solution to RIOT operating system and evaluated its performance over a mesh of UWB-enabled nodes. Our results indicate almost 40% reduction in network traffic.**

***Index Terms*—UWB, Piggybacking, Communication, Ranging**

I. Introduction

One of the physical layers covered by IEEE802.15.4 standard is Ultra-wideband (UWB) communication which supports high data rate (up to 27 Mbps) communication alongside with centimeter-level ranging capability. Accurate ranging based on UWB signals provides a unique opportunity for wireless nodes to estimate their distance from their neighbors and locate themselves in the indoor networks. UWB signals are very promising solutions for accurate ranging (less than 5 cm accuracy).

Currently ranging capability of UWB signals has been investigated by both research and industry which has led to very accurate indoor localization solutions but communication capacity of UWB based LR-WPANs have not received much attention.

The primary application of wireless sensor networks (WSN) is for monitoring physical events (temperature, humidity, and movement) in environments through network of sensors. In some of applications, a mobile sink moves around the building and collects data from the deployed sensors. Accurate ranging and localizing nodes can enable lots of location-based services in sensor network applications. In current systems, UWB nodes are added to existing wireless systems to provide an accurate ranging capability to WSN.

The network traffic on today's LR-WPAN networks can be divided into two categories: ranging traffic and non-ranging traffic. In the applications which require both communication and localization, separate hardware and software parts are responsible for each of the tasks. In other words, one chip/software reads the sensor values and reports it through WiFi or Bluetooth to the sink. In addition, a UWB chip, runs simple ranging applications and using time of flight measurement, estimates the distance between two nodes.

Existing solutions suffer from being complicated (different hardware/ software modules need to be assembled) and also high network traffic and duty cycle (handling both ranging traffic and non-ranging traffic). To be more specific, each location estimation in minimum requires at least 5 to 8 packets to be exchanged between nodes which consume more power and causes shorter network lifetime and higher chances of interference.

In our work, we investigate the possibility of using existing non-ranging traffic to estimate the distance between sender and receiver in the scenarios with high non-ranging traffic and also the feasibility of piggybacking non-ranging information (sensing data or routing information) over ranging packets in the scenarios with low non-ranging traffic and high location update rate requirements. In the end, we propose our adaptive scheduler algorithm to optimize the ranging/non-ranging traffic by piggybacking of information which reduces the complicity of the hardware and also significantly reduces the network overhead and duty cycle.

Our contributions at this work can be summarized as the following:

- Investigate the feasibility of using existing network traffic to estimate the range
- Study the feasibility of piggybacking of non-ranging information such as sensing data or routing information on ranging packets.
- Propose an efficient adaptive scheduler algorithm to reduce the network overhead by utilizing existing traffic and piggybacking of information
- Evaluate our proposed algorithm over real deployment and using normal traffic on standard network stacks for low rate personal area wireless networks (LR-PAWN)

II. Related Work

A. Ranging in IEEE802.15.4-11

IEEE802.15.4-11 standard [1] suggests the following procedures for ranging. First the application asks for ranging services from MAC layer. MAC layer increases the preamble length from its default value (to improve the ranging performance) and informs the designated receiver about new preamble length. Both sender and receiver should agree on new preamble length before starting the ranging session. Ranging will be conducted through acknowledgment packets. During ranging session, the MAC layer attaches turn around time (TX-to-RX) for all the received packets before sending them up to the higher layers. Application will inform the MAC layer to exit from ranging session and stop timestamping the packets. MAC layer informs the receiver and reduces the preamble length to its default value. This approach is only useful for single-sided ranging which suffers from clock drift problem which leads to less accurate ranging [2]. It is also based on acknowledgment packets which increases the network traffic. The standard does not provide any further details about ranging process and ranging rates.

B. Traffic Reduction Techniques in Wireless Networks

One of the key techniques to improve the network throughput is reducing the number of broadcast packets. RPL [3] is a standard routing protocol for Internet of Things and WSN applications. One of the main components of RPL is trickle timer [4]. The Trickle algorithm benefits from simple suppression mechanism and also transmission point selection technique which allows Trickle's communication rate to scale logarithmically with density [4]. Trickle algorithm is not efficient in highly mobile networks and in [5] some improvements on trickle timer has been suggested to make it more practical in mobile sensor networks.

The idea of piggybacking of packets on networks to reduce traffic overhead has been tried before. For instance, acknowledgment packets are one the most obvious candidates for piggybacking and studies [6] showed the effectiveness of this technique in network performance improvements. In [7] results show up to 40% improvement by piggybacking acknowledgment messages to data messages but it is essential to mention that the achieved improvements in throughput are highly dependent on available network traffic and maximum possible delay for applications.

Utilizing acknowledgment packets for ranging in UWB networks has been investigated before [8]. The study [8] shows that piggybacking ranging information with sensing data does not significantly change the duty cycle of network while provides reasonable location update rate. The evaluation of the idea is not extensive and the rigid timing constraints (constant processing time) makes the proposed method not applicable in current UWB networks.

III. DESIGN

In this section, we explain building blocks of SRAC. First we talk about our observation in two-way ranging algorithm which leads us to design two modes for ranging: active ranging and passive ranging. Finally we elaborate scheduler algorithm in SRAC.

A. UWB Ranging

1) UWB in IEEE802.15.4: As defined in IEEE802.15.4, UWB has 16 different channels which are spread across 0 to 10 GHz frequency with the minimum bandwidth of 500 Mhz. The UWB signals are sent as a sequence of short pulses (2 ns) which makes them resilient to multipath fading. Due to the short width of pulses, the probability of collision between multiple paths which are reflected from different surfaces is smaller and the receiver can accurately identify the first arriving path from the rest of reflected paths. This ability leads to very accurate time of flight measurements which is used for distance estimation with centimeter-level accuracy.

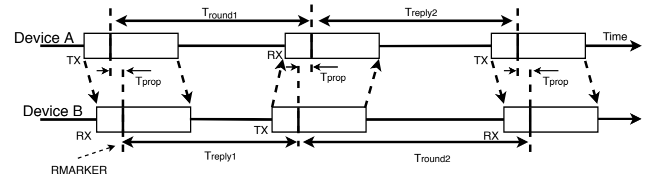


Fig. 1: Double Sided Two Way Ranging

2) Two Way Ranging: Double-sided two-way ranging (DS-TWR) is one of the most common range estimation techniques used in UWB localization. The overall procedure for double-sided two way ranging is shown in Figure 1 in which device A starts the transmission and device B replies to that message. Upon reception of B's response, device A again sends another message to B. All the communications are precisely timestamped by devices. The estimated $\hat{T}_{prop}$ can be calculated as shown in formula 1 [9]:

$$\hat{T}_{prop} = \frac{(T_{round_1} \times T_{round_2} - T_{reply_1} \times T_{reply_2})}{(T_{round_1} + T_{round_2} + T_{reply_1} + T_{reply_2})} \quad (1)$$

let's assume device A runs k_A times faster than its default frequency and device B runs k_B times faster than its frequency.

$$\hat{T}_{prop} = \frac{(k_A T_{round_1} \times k_B T_{round_2}) - (k_A T_{reply_1} \times k_B T_{reply_2})}{(k_A T_{round_1} + k_B T_{round_2} + k_A T_{reply_1} + k_B T_{reply_2}} \quad (2)$$

After small back of the envelope calculation using formula 2, estimated propagation time would be:

$$\hat{T}_{prop} = \frac{2 T_{prop} k_A k_B}{k_A + k_B} \quad (3)$$

finally the error in time of flight estimation can be written as formula 4

$$error = \hat{T}_{prop} - T_{prop} = \hat{T}_{prop} \times (1 - \frac{k_A + k_B}{2 k_A k_B}) \quad (4)$$

3) Resilience to Clock Drift: One of the key ideas in our paper can be inferred from formula 4 in which the time of flight estimation error is not dependent to the T_{reply1} or T_{reply2} which means the response messages (from device B and A) are not necessarily sent immediately. Our hypothesize is existing network traffic (sensor reports or routing information) can be utilized for ranging without sending any specific ranging packet.

To verify our hypothesis, we conducted a simple experiment. We placed two UWB-enabled chips (EVB1000 nodes [10]) in three different distances (3 m, 6 m ,and 10 m) and used double sided two way ranging to estimate the distance

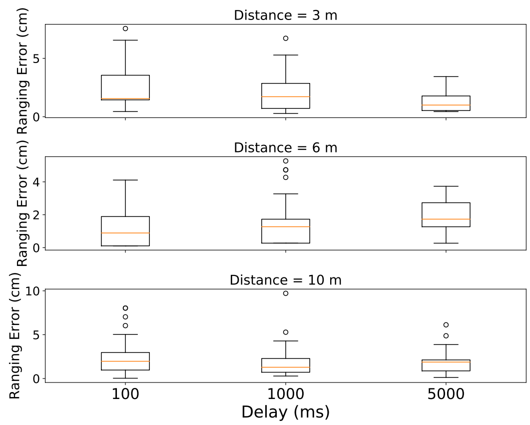


Fig. 2: Ranging Error with Different T_{reply} Times. Increasing T_{reply} does not increase the ranging error

between the two nodes. In each experiment, we increased the T_{reply} time and measured the ranging error. The results are reported in Figure 2. As shown in Figure 2, as we increase the T_{reply} time in two way ranging (which also leads to an increase in T_{round} time), the observed ranging error does not change. This observation follows our expectation and proves the validity of our hypothesis.

Another interesting result from Figure 2 is the fact that increasing distance will not significantly change the error even during long delays. As it is mentioned in formula 4 T_{prop} has direct relationship with the error but the speed of light in air is approximately 3×10^8 which means the UWB pulse travels almost 30 cm in each nanosecond. Even if the distance of two nodes is around 100 m the total T_{prop} is around 300 ns which causes errors less then few millimeters in ranging.

This observation relaxes the requirement for immediate reply in two-way ranging algorithm. In our paper, we leverage this observation to add ranging capability to sensor network applications using their existing traffic.

B. Passive Ranging

In passive ranging, we utilize existing network traffic to estimate the distance between nodes. Each packet contains precise timing information which helps the receiver to estimate the distance between sender and receiver of the packets.

In passive ranging, upon reception of each packet from the neighbor, the packet's sequence number and the reception timestamp is stored in the local memory. Each outgoing packet with the destination address of one of the already seen neighbors contains reply times ($T_{LastTX} - T_{LastRx}$) and delay times ($T_{CurrentTX} - T_{LastRX}$) which are calculated from packets received or overheard from neighbors. It also includes the $LastTX$ sequence number which is the last sequence number sender node has sent to target neighbor and $LastRx$ which is the last sequence number sender node has received from target neighbor. Having sequence numbers and reply and delay times, each node can calculate its distance to its neighbors.

For broadcast messages the procedure is almost the same with a slight difference. The broadcast packet contains information from all the neighbors the node has received a packet from them in the past .

Since the size of reply time and delay time does not impact the ranging error (formula 4) the age of timestamps in each node's local memory does not impact ranging performance. The node could have received a packet from its neighbor 20 seconds ago and now it is sending a message to that node or broadcasting a message to all the neighbors. Upon reception of this message, the receiving neighbor can calculate its distance to the sending node.

C. Active Ranging

In the high mobility networks, the non-ranging traffic may not be enough for frequent ranging which means in passive ranging the location update rate will be so low and not efficient. In this situation, SRAC switches from passive ranging to active ranging. During active ranging double sided ranging is conducted through sequence of 3 messages. The first packet is called poll message and it is a broadcast message (sent by initiator). All the recipients of poll packet immediately reply to poll message with response message which includes their calculated delay time for responding to poll message ($Response_{TX} - Poll_{RX}$). Upon reception of response messages from at least 3 responders at initiator, it sends out another broadcast message (final message) which includes initiator's reply time ($Response_{RX} - Poll_{TX}$) and delay time ($Final_{TX} - Response_{RX}$). After receiving the final message, the responder nodes calculate second reply time ($Final_{RX} - Response_{TX}$) and finally are able to calculate time of flight and their distance to initiator node. The fourth message which is an optional message is sent from responders to the initiator with calculated distance of each responder to the initiator.

During active ranging phase, SRAC piggybacks the non-ranging traffic over ranging packets. We call this case active ranging since in active ranging mode the primary traffic of the network is ranging and the non-ranging traffic has lower priority. All the non-ranging traffic will be stored in the queue and upon availability of next ranging packet, the non-ranging data is piggybacked over ranging packets.

D. SRAC:Simultaneous Ranging and Communication

We propose an adaptive scheduler to decide about active or passive ranging modes based on network conditions. In this section, we explain in details all the components of SRAC.

1) SRAC's Packet Format: To run double sided two way ranging, time information need to be exchanged between each pair of nodes. Figure 3 shows our proposed packet format to be used in SRAC.

As illustrated in Figure 3, each packet starts with one octet *sequence number* and 1 bit indicator of *auto reply*. In active ranging mode, poll and response messages require immediate reply which means auto reply bit has be set in those packets. Receiver of a packet with auto reply flag on, should immediately reply to that message and include ranging timestamps. The next octet is *Ranging info Len* which determines the size

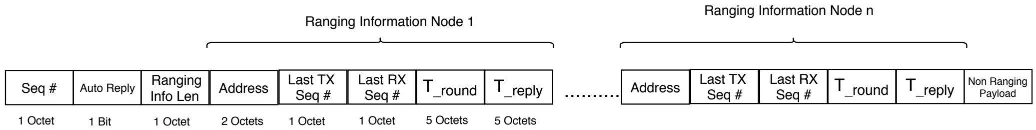


Fig. 3: SRAC's Proposed Packet Format

of ranging information. In broadcast messages, the sender includes timestamps for all the previously seen neighbors. In unicast messages *Ranging info Len* field equals by one. Next, ranging information for each neighbor starts. The first 2 octets are short *Address* of the neighbor. *Last TX Sequence Number* is the last sequence number sent by the sender to the target node and *Last RX Sequence Number* is the last sequence number received from target address by sender node. T_{round} is $T_{lastRX} - T_{lastTX}$ and T_{reply} is $T_{TX} - T_{lastRX}$. After ranging information the packet can have non-ranging traffic which can vary in length.

2) Scheduler Algorithm: SRAC utilizes both active and passive ranging. In this section, we explain our designed adaptive scheduler which switches between active and passive ranging based on network condition. Our algorithm considers following parameters to decide about suitable ranging mode:

- Window Size: Scheduler constantly monitoring both ranging and non-ranging traffic. It uses windowing average to calculate recent traffic rates. Windows size determines the length of window to be used for averaging.
- Maximum Delay - NonRanging: Maximum delay the non-ranging traffic can tolerate. For instance, simple temperature sensor which reports every 10 seconds has the maximum delay of 10 seconds or router solicitation message which has expiration time of 30 seconds should be sent before its expiration.
- Ranging Rate: The interval for estimating the distance between neighbors. It totally depends to the mobility of the network. In slightly mobile networks low ranges like 2 range estimations per second should be enough while in more mobile networks ranging rate could go up to 10 or 20 Hz.
- Movement Threshold: In some applications, the ranging rate can change depending on the mobility of the network. This threshold can be defined to increase the ranging rate in movements higher than this threshold.
- Buffer Size: In active ranging mode, the non-ranging traffic can be stored in the internal buffer while it's waiting for next ranging packet. Long buffer size is indicator of high non-ranging traffic and triggers the SRAC to switch to passive ranging.

Our scheduler algorithm minimizes the network traffic while satisfying all the application and network constraints:

$$\begin{aligned} \text{minimize} \quad & Ranging_{Traffic} + NonRanging_{Traffic} \\ \text{subject to} \quad & Ranging_{Rate} \geq Min_{Ranging_{Rate}} \\ & NonRanging_{Delay} \leq Max_{NonRanging_{Delay}} \\ & Buffer_{Size} \leq Max_{Buffer_{Size}} \end{aligned} \tag{5}$$

Algorithm 1 summarizes the SRAC algorithm.

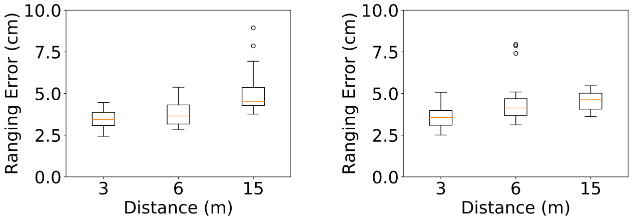
Algorithm 1 SRAC

$Delay_{Max} \leftarrow$ Maximum Non-Ranging Delay
$RR_{Min} \leftarrow$ Default Minimum Ranging Rate
$Th_{mov} \leftarrow$ Movement Threshold
$Window_{size} \leftarrow$ Widowing Average Size
$Buffer \leftarrow$ Buffer to Store Non-Ranging Traffic
while TRUE **do**
  if $Movement \geq Th_{Mov}$ **then**
    Increase RR_{Min}
  end if
  $R_{Ranging} \leftarrow$ Calculate Ranging Rate
  $R_{NonRanging} \leftarrow$ Calculate NonRanging Rate
  if $R_{Ranging} \leq R_{NonRanging}$ **then**
    if $Delay_{Max} \leq \frac{1}{R_{Ranging}}$ and $len(Buffer) \leq MaxBuffer$ **then**
      Switch to Active Ranging
    else
      Switch to Passive Ranging
    end if
  else
    if $R_{NonRanging} \geq RR_{Min}$ **then**
      Switch to Passive Ranging
    else
      Switch to Active Ranging
    end if
  end if
  Sleep for $Window_{size}$
end while

As summarized in algorithm 1, SRAC runs in a while loop. Every $Window_{size}$, scheduler calculates the ranging rate and non-ranging traffic rate. It also updates minimum ranging rate based on average movement. The algorithm switches to minimum rate (ranging or non-ranging) based on measured values if this switch does not violate other constraints like maximum tolerable delay by non-ranging applications and minimum ranging rate.

E. Ranging as a Service

One of the key contributions of our paper is analyzing the feasibility of using existing network traffic for ranging. Network traffic in our paper has general definition, it could be a simple sensor which is reporting sensed temperature (few bytes) to the central sink (cluster head) every 10 seconds or it can be a IPV6 enabled IoT device which supports a COAP [11] server and answers the HTTP requests from other devices. Another example could be mesh of UWB-enabled



(a) Without SRAC (b) With SRAC

Fig. 4: Ranging Error with & without SRAC. Piggybacking of ranging information does not change the accuracy of ranging.

nodes which are using RPL [3] and Trickle [4] algorithms for routing dissemination process over IEEE802.15.4 MAC layer.

In other words, we are enabling ranging as a service for UWB-enabled LR-WPAN networks with reasonably small overhead. In our design, ranging capability of UWB physical layer is combined with UWB communication to provide ranging enabled UWB based networks.

1) OS Jitter & DW1000 Delayed Send: One concern may raise about developing ranging service in embedded operating systems is the impact of delay and jitter added by operating system to ranging. To recap, one of the critical points of centimeter level ranging in UWB systems is picoseconds level timestamping of sent and received events. For accurate ranging, we need to know the exact moment the signal left the antenna and the exact moment the first path received by the antenna. In reception, DW1000 timestamps the exact reception moment but for send, it provides concept of delayed send. During delayed send phase , a near future sending time (designated send time) is calculated and written on DW1000 registers. Once the internal timer of DW1000 chip arrives close enough ($designated\,timestamp - antenna\,delay$) to designated send time (40 bit value,15.6 picoseconds granularity) , the chip starts sending the signal.

In our work we utilize delayed send feature to avoid the delay and jitter added by operating system and network stack. Our experiments show if we set send timestamp around 5 ms after the time that application layer provides the outgoing data, it will leave enough gap for operating system to copy the message to DW1000's buffer and arm the chip to send the packet.

IV. Performance Evaluation

We evaluate SRAC in two phases. In the first phase, over the set of controlled experiments, we evaluate the performance of SRAC for reducing network traffic by switching between active and passive ranging modes while meeting application constraints. In the second phase, we show the applicability of SRAC on different sensor network applications.

A. Implementing SRAC as a Network Service

To evaluate performance of SRAC, we decided to implement SRAC as part of existing network stacks which are developed for embedded systems and Internet of Thing applications.

Our hypothesis is that ranging can be implemented as a service provided by network stack along side with other network services. Usually embedded network stacks are part of embedded operating systems. We chose RIOT [12] operating system to implement SRAC. RIOT has smaller memory footprint compared to other embedded operating systems and also supports multi-threading and benefits from modular design [13]. We implemented UWB radio driver for RIOT and integrated it into the RIOT's core.

B. Controlled Experiments: How Effective is the SRAC?

1) Experiment Setup: DW1000 [14] is one of the most popular UWB-enabled radio ICs which already used in many commercial UWB-based indoor localization solutions [15], [16]. In our experiments, we use Radino32 [17] boards which combine an STM32L151 [18] micro-controller with the DW1000 chip.

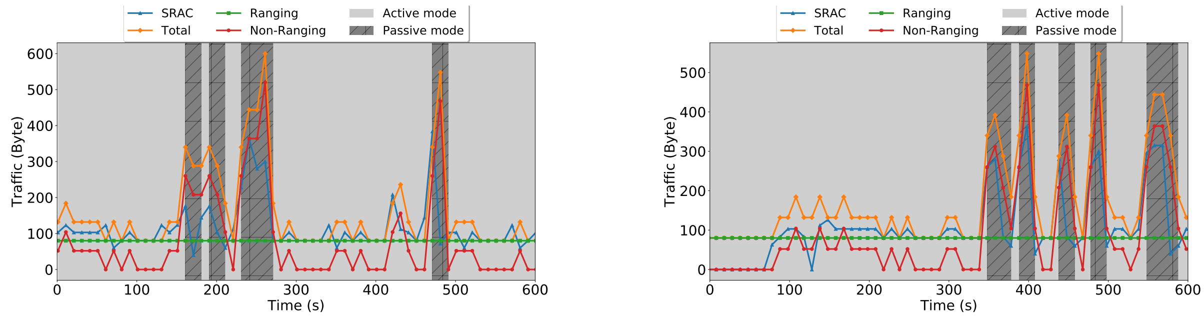
In this phase of evaluation, we placed two Radino32 nodes in three different distances (3 m, 6 m , and 15 m) and ran SRAC on both of them which by default is in active ranging mode (1 ranging every 5 seconds). Also during the experiment, there is a random UDP traffic generated by application layer (Using RIOT's UDP server/client package). The maximum delay that non-ranging applications can tolerate is 2 seconds in this experiment. Both nodes report ranging results and packet dump of sent and received packets over serial port. In each distance, we collected data for 10 minutes.

2) Ranging Accuracy: First metric to evaluate is accuracy of ranging conducted by SRAC. Figure 4b shows the average errors in range estimation in each experiment. It can be seen in Figure 4b that regardless of active or passive mode running on the devices, the ranging error never exceeds few centimeters (10 cm). As we expected even long ranging interval (5 seconds) does not have any impact on the ranging performance.

We also conduct the same set of experiments but this time just running simple ranging application between pair of UWB nodes. The ranging errors are shown in Figure 4a. Comparing Figure 4a and 4b the difference between errors is less than 1 cm which proves that SRAC does not increase the ranging errors.

3) Traffic Reduction: In this section, we show the ranging and non-ranging traffic during previous experiments at 3 m and 6 m distances. Figure 5 shows the ranging, non-ranging, total (ranging + non-ranging) and SRAC (real traffic sent by physical layer) traffic observed during the experiment. The windows size in scheduler algorithm in this experiment has been set to 10 seconds which means scheduler algorithm always calculates the average traffic over last 10 seconds to decide about the ranging modes. The reported values in Figure 5 are also traffic measured in each windows (10 seconds). Since in this experiment both nodes are static, the ranging traffic is always on default values (once every 5 seconds).

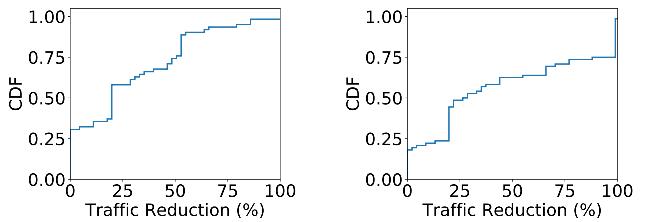
As shown in Figure 5, the proposed solution adapts to the network changes and reduces the network traffic. In Figure 5 the total line shows the amount of traffic would have been sent by physical layer if SRAC was not there and the SRAC line, shows the traffic sent by physical layer after SRAC



(a) 6 m Distance between Ranging Pairs

(b) 3 m Distance between Ranging Pairs

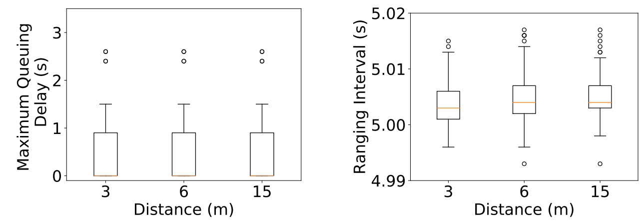
Fig. 5: Traffic Reduction by SRAC. Traffic is measured in 10s intervals. SRAC adaptively switches between active and passive modes and piggybacks traffic. (Total = Ranging Traffic + Non-Ranging Traffic).



(a) 6 m Distance

(b) 3 m Distance

Fig. 6: SRAC achieves more than 40% traffic reduction in 50% of times. Traffic reduction is computed relative to the baseline that does not combine ranging and non-ranging traffic.



(a) Maximum Queue Time

(b) Ranging Update Intervals

Fig. 7: Time Delay in SRAC. SRAC does not violate time constraints in ranging and non-ranging applications.(Minimum acceptable ranging interval in our experiment is 5 seconds and maximum tolerable delay by non-ranging application is 2 seconds)

piggybacked either ranging traffic over non-ranging traffic or visa-versa.

Figure 5 also shows the proposed scheduler algorithm is effectively changing the mode based on the network condition shortly after sudden changes to the non-ranging traffic.

To quantify the amount of traffic reduction achieved by SRAC, we calculated traffic reduction ($TrafficReduction = \frac{Total_{traffic} - SRAC_{traffic}}{Total_{traffic}}$) for intervals of 10 seconds and plotted the CDF of the savings in Figure 6.

As shown in Figure 6, for almost 50% of the times the amount of traffic reduction achieved by SRAC is bigger than 40%. In 75% of the times, the amount of reduction is higher than 25%.

4) Time Delay in SRAC: To achieve network traffic reduction, our scheduler may have to queue the packets. Queuing may lead to an increase in the transmission delay in non-ranging traffic. Figure 7a shows the delay faced by packets during the experiments. The added delay is reasonably low considering amount of saving on network traffic.

We also measured the time difference between every two consecutive range estimations to make sure the ranging update interval is never below the minimum acceptable ranging rate. The calculated intervals are reported in Figure 7b.

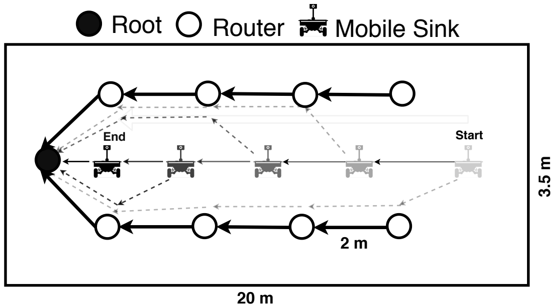
As shown in Figure 7b, the time interval between two consecutive ranging updates never exceeds 5.2 seconds which shows the fact that SRAC keeps its promise to meet application constraints (20 ms of delay can be tolerated by ranging applications).

Overall, SRAC achieves to significant ($\approx$ 40%)traffic reductions and reduces the air time. Reduced air time reduces the chance of interference in UWB networks and this is very important in UWB networks. Since UWB signals have a limit on the maximum transmission power (-41.3 dbm/MHz), carrier sensing techniques are not applicable in UWB communications [19]. IEEE 802.15.4 suggests ALOHA for UWB networks which its performance is pretty poor in crowded environments. Reducing air time, reduces the chance of collision in UWB communication and increase the network throughput.

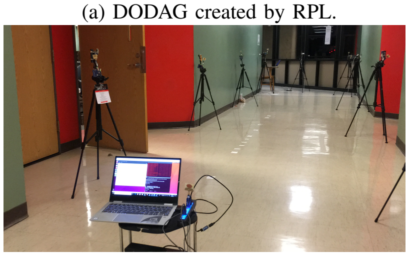
C. Uncontrolled Experiments: Is SRAC applicable in existing WSN applications?

Mesh networks in combination with IPv6 can connect local area networks to the Internet and turn the local network to real Internet of Things. In the second phase of our evaluations, over a set of uncontrolled experiments,we show applicability of our solution to add ranging to UWB networks using existing traffic. The idea here is to have ranging enabled UWB mesh networks which are able to simultaneously transfer data (sensing,routing or etc) and estimate their distance to neighbor nodes. In other words, we wanted to know the scenarios in which SRAC is applicable and can it save significant traffic in real world applications?

Many applications can benefit from accurate distance measurement between nodes and being able to track/localize mesh



(a) DODAG created by RPL.



(b) Deployed UWB Mesh Network

Fig. 8: UWB Mesh Network Experiment Setup. Mobile robot moves from start point toward the end point while transmitting UDP traffic to root using multihop communication. Robot updates its parent while it moves and discovers hops which are closer to root. Updating next hop by mobile node changes number of hops for UDP traffic during the experiment.

network members. Mobile sensor and ad-hoc networks can directly benefit from accurate ranging. Location aware routing [20] and mobile sink sensor networks [21] can be named as a few examples. 1

1) Experiment Setup: To evaluate the performance of proposed solution in IPv6 enabled mesh networks, we set up network of 12 UWB-enabled nodes (Radino32) in a corridor (3.5 m × 20 m). They are all running RPL protocol (implemented by RIOT operating system) over 6LOWPAN [22] and IEEE802.15.4 MAC Layers. In the physical layer our implemented UWB driver (SRAC) is running. Figure 8b shows our setup in the corridor.

The deployed network has one root and 11 RPL routers. As shown in Figure 8a, root and 10 of the nodes are in static locations but the 12th node is mounted on top of a robot. We configure transmission power of UWB nodes in a way that RPL forms the DODAG (Destination Oriented Directed Acyclic Graph) shown in Figure 8a. The robot travels from starting point which is 4 hops away from the root to the end point in which the root is directly visible by the mobile node. During the travel, every 3 m, mobile node stops for 1 minute and again resumes the move. During the move from start to end point, mobile node generates a UDP traffic with constant rate and sends it to the root of DODAG over multihop network. During stop times, the mobile node looks for new parent (node which is closer to the root) and updates its next hop accordingly. Localization is also running on the Robot.

We conducted this experiment several times by changing different parameters to measure SRAC's performance on different scenarios. The experiment parameters are listed in table I. First parameter is speed of robot which impacts the minimum acceptable ranging rate for SRAC. We are interested to know the location of the robot every 5 cm movement which means if the robot moves with 10 cm per second speed, the minimum acceptable ranging rate would be 2 updates per second. The second parameter is the UDP traffic generated by mobile node. First traffic replicates traffic generated by a camera with 5 frames per second video. The second traffic simulates a sound sensor with 1 KBps traffic and the last one is traffic generated by a sensor kit with 20 Bps. The last parameter is responsiveness of RPL. In our experiments, we test two different settings for RPL which we call them fast and slow RPL. The main difference between fast and slow RPL is how fast the RPL reacts to network changes which basically defines total traffic generated by RPL protocol. During all the experiments, all the nodes are using the same physical layer settings (Frequency = Channel 2 (3494 MHz), Preamble Length = 1024, PRF = 16 MHz, Data rate = 6.8 Mbps). All the nodes are deployed at a height of 120 cm from the ground and have clear line of sight to each other. The surrounding walls are wooden and there is no blocking by obstacles during the experiments.

TABLE I: Settings of Uncontrolled Experiments

Parameter	Value
Robot Speed (cm per second)	10, 30, 70
Traffic	Video (100 KBps), Sound (1 KBps), Sensor Kit (20 Bps)
Fast RPL	$I_{min} = 64ms, I_{max} = 17m, K = 3$
Slow RPL	$I_{min} = 1024ms, I_{max} = 4h, K = 7$

2) Traffic Reductions by SRAC in Uncontrolled Experiments: In table II, the overall traffic reductions achieved by SRAC are summarized. It can be seen from table II that savings as high as 41% can be achieved by SRAC which is quite interesting and proves the effectiveness of proposed technique. As can be seen in table II in applications with extremely low or high traffic (sensor kit/video) the percentage of traffic reductions are not that significant which is reasonable considering the ratio of ranging traffic over non-ranging traffic. We have to mention, in all numbers reported in table II, the number of required by SRAC to include time information have been included which means during all the scenarios SRAC leads to traffic reduction and the overhead proposed by SRAC to the network is absolute zero.

3) Ranging Accuracy: Figure 9 reports ranging errors during uncontrolled experiments which shows the maximum observed ranging error during our uncontrolled experiments is less than 7 cm and the average error is around 5 cm which is comparable with average ranging accuracy reported by state of the art UWB based indoor localization solutions [23].

V. Discussion

Our approach is mostly practical in mesh networks with moderate mobility. In highly mobile networks, the non-ranging traffic will not be enough and our solution goes to active

TABLE II: Traffic Reductions achieved by SRAC in Uncontrolled Experiments

(a) Fast RPL

Speed \ Traffic	Video	Sound	Sensor Kit
10	0.49%	32.21%	12.52%
30	1.47%	41.57%	5.49 %
70	3.37%	23.40%	2.49%

(b) Slow RPL

Speed \ Traffic	Video	Sound	Sensor Kit
10	0.30%	27.32%	8.07%
30	1.31%	35.05%	3.54%
70	2.07%	20.1%	1.34%

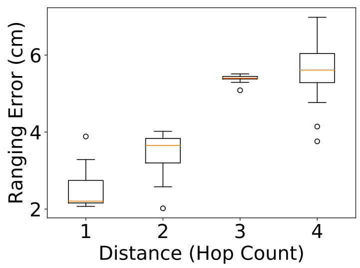


Fig. 9: Ranging Error Observed by Mobile Robot in Uncontrolled Experiments

ranging mode which is still better than having both ranging and non-ranging traffics. Since, in active mode, non-ranging traffic will be piggybacked over ranging traffic.

One of the interesting implications of providing ranging service over mesh networks is ability of estimating distance over several hops. In other words, the target does not need to be in direct contact with all the anchors. Only contacting one anchor can provide location information about other anchors which can be used for localization. The only modification to existing RPL protocol would be including location information from neighbors inside DAO messages. The major benefit would be saving extra ranging traffic.

VI. Conclusion

In this paper, we showed that two way ranging does not require the reply packets to be sent immediately. We utilize this feature and study the feasibility of using existing network traffic for ranging instead of having separate traffic for ranging. We showed the feasibility of piggybacking ranging information over normal network traffic to reduce the ranging overhead in UWB networks. We also investigated the possibility of utilizing ranging traffic for communication purposes and reducing overall network traffic.

Based on observed results, we proposed a simple yet effective scheduling algorithm which simultaneously sends non-ranging and ranging information based on existing network traffic. We developed our proposed solution on RIOT which is a open source embedded system and evaluated the effectiveness of our proposed solution. Our evaluations shows 40% reduction in overall network traffic after using our proposed adaptive scheduler.

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