Implementation and Evaluation of Combined Positioning and Communication

Paul Alcock, James Brown, and Utz Roedig

Lancaster University, UK
{p.alcock,j.brown,u.roedig}@lancaster.ac.uk

Abstract. A new generation of communication transceivers are able to support Time of Flight (TOF) distance measurements. Transceiver manufacturers envision that communication and positioning features are used separately and one at a time. However, we have demonstrated that such separation is unnecessary and that TOF measurements can be obtained during data communication. Thus, distance measurements required by positioning services can be collected both energy and bandwidth efficiently. In this paper we describe the modification of an existing low power wireless sensor network (WSN) medium access control (MAC) protocol called FrameComm to include collection of distance measurements. We describe the implementation of the modified FrameComm protocol (called FrameCommDM) on a Nanotron DK development kit comprising of an Atmel ATmega128 MCU and a Nanotron NA5TR1 transceiver. The performance of the FrameComm and FrameCommDM implementation on the Nanotron platform is evaluated and compared. It is shown that the collection of distance measurements has no significant impact on communication performance. Furthermore, the difference in energy consumption used to perform the additional ranging tasks of FrameCommDM is examined and quantified.

1 Introduction

Many positioning systems have been developed which use the existing communication transceiver of a sensor node. Positioning systems relying on conventional low-power communication transceivers typically make use of either the received signal strength (RSS) or the measured time-of-flight (TOF) of a signal as input for a positioning algorithm. Both methods can be used to determine the distance between transceivers and ultimately the position of all transceivers in relation to each other. These methods of distance measurements have been investigated at length and reports show that using current transceivers yield unreliable and inaccurate results. Patwari et al. [1] present an in-depth report of their findings, which show that multipath signals and shadowing obscure distance measurements.

The recent development of low-power, ultra wideband (UWB) transceivers for use in sensor nodes, overcomes the aforementioned ranging inaccuracies. The physical signal properties of UWB communication make it possible to accurately determine the time-of-arrival (TOA) of signals. By utilizing either clock synchronization or two-way-ranging it is therefore possible to accurately determine the time of flight (TOF) of the signal. Thus, the distance between communicating transceivers and node positions can

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be determined. The IEEE 802.15.4a physical layer specification [2], standardized in 2007, defines the use of UWB transceivers for use in wireless personal area networks and the functionality of positioning. The Nanotron NA5TR1 [3] transceiver is an example of one such transceiver which adheres to this standard.

UWB transceiver manufacturers envision that communication and positioning features are used separately and one at a time. Either the transceiver is used to transfer data packets between sender and receiver *or* the transceiver is used to send ranging packets to determine the TOF between nodes. This leads to inefficient transceiver usage as excess packets might be generated unnecessarily. If an exchange of data packets is currently taking place between two nodes using a send and acknowledge scheme, the same packets can also be used to measure TOF between the nodes. Therefore the distance can be estimated using the existing data packets, alleviating the need to transmit specialized ranging packets.

We have shown in our previous, simulated work [10] how standard low power MAC protocols for WSNs can be modified to perform ranging while transmitting data. In particular, our previous work shows how the existing FrameComm MAC protocol [4] can be extended to support positioning tasks. In this paper we take our work one step further and describe a real world implementation of the modified FrameComm MAC protocol (called FrameCommDM) for the Nanotron NA5TR1 transceiver. This paper has the following specific contributions:

- Implementation Details: A detailed description of the FrameCommDM implementation for the Nanotron platform is given. We identify potential hardware changes to the Nanotron platform which would allow us to implement combined positioning and communication more efficiently.
- Prototype Evaluation: A comprehensive evaluation of the prototype system is given. In particular the impact of positioning on communication performance and system power consumption is quantified.

The prototype evaluation supports our previous results obtained via simulation (see [10]). Positioning features can be integrated into a low power WSN MAC protocol without significant impact on communication performance.

The next Section gives an overview on related work. Section 3 describes FrameComm and FrameCommDM. Section 4 details the implementation of FrameCommDM on the Nanotron platform. Section 5 outlines the evaluation setup and explains the obtained measurement results. The paper then concludes in Section 6 and describes proposed future work.

2 Related Work

There is a large body of work which has focused on exploiting UWB for either communication or positioning in wireless sensor networks. However, there is little research on how to tightly integrate both positioning and communication functions.

Correal et al. [5] present a method of positioning using UWB transceivers in which a packet sent by a node is followed by acknowledgements which can be used to derive round-trip times. This method provides a compelling proof-of-concept for our proposed system. However, the method discussed by Correal et al. differs from our method in that ranging is not formally integrated into the protocol, and there is no analysis of how their methods of positioning and communication functions affect one another.

Cheong and Oppermann [6] describe a positioning-enabled MAC protocol for UWB sensor networks. First, their solution differs from our work as data packets themselves are not used to support positioning; positioning and communication are handled completely separately by the MAC layer. Second, Cheong's work proposes a TDMA protocol, while the modified FrameComm protocol presented in this paper is a contention-based protocol.

The IEEE 802.15.4a physical layer specification [2], standardized in 2007, defines the use of UWB transceivers in wireless personal area networks. The standard defines positioning and communication as separate functions but does not discuss their integration. However, modern packet-based transceivers conforming to the 802.15.4a standard could potentially be used to support the MAC protocol defined in this paper.

The use of packetized radios requires a fresh approach of implementing asynchronous duty cycles in WSNs. Some schemes use the same concept of framelet trails as used by the FrameComm [4] MAC protocol used for the work presented in this paper. The current default energy saving protocol in TinyOS is based on the Low Power Listening component of BMAC [7], but employs message retransmission instead of a long preamble in order to accommodate packet-based radios. X-MAC [8] also uses framelets to establish rendezvous between sender and receiver but only retransmits the message header. The payload is sent only after one of the headers has been acknowledged by the destination. These and other existing framelet based MAC protocols can potentially be used in conjunction with UWB transceivers to integrate positioning and communication. Hence, the basic mechanisms described in this paper are not limited to the particular MAC protocol we have chosen (FrameComm).

3 FrameComm and FrameCommDM

This section describes the most important aspects of FrameComm and the ranging enabled variation FrameCommDM. A detailed description of FrameComm and FrameCommDM can be found in [4] and [10] respectively.

a) b)

Fig. 1. FrameComm and FrameCommDM comunication mechanism

3.1 FrameComm

FrameComm, like many wireless contention based MAC protocols, performs duty cycling of node transceivers. To ensure that rendezvous between transceivers occur, Frame-Comm deploys a method in which a trail of identical packets of data, called framelets, is transmitted by the sender with gaps between each. The receiver sends an acknowledgement to the source after successfully receiving a framelet. Upon the reception of this acknowledgement, the sender may then cease sending and yield control of the channel (See Figure 1).

Assumptions and Definitions : It is assumed that the clocks of the transmitter and receiver operate at approximately the same rate. Note that this does not imply time or sleep cycle synchronization; rather the clock drift between any two nodes is insignificant over a short period. It is also assumed that a fixed rate radio duty cycle is used, i.e., each node periodically activates its radio for a fixed time interval to monitor activity in the channel. The duty cycle period is represented as $P = \triangle + \triangle_0$, where $\triangle$ is the time the radio remains active and $\triangle_0$ is the time the radio is in sleep mode. The duty cycle ratio is defined as:

$$DutyCycle = \frac{\triangle}{P} = \frac{D}{\triangle + \triangle_0} \tag{1}$$

Rendezvous using Framelets : Framelets are small, fixed-sized frames that can be transmitted at relatively high speeds. Successful duty cycle rendezvous require a sequence of identical frames to be repeatedly transmitted from the source node; each frame contains the entire payload of the intended message as depicted in Fig. 1. If the receiver captures one of these, the payload is delivered. The trail of framelets is defined by three parameters: Number of transmissions: n ; time between framelets: δ_0 ; framelet transmission time: δ .

To achieve successful rendezvous a relationship must be established between the parameters $\triangle$, $\triangle_0$, n, δ, and δ_0. First, the listening phase of the duty cycle $\triangle$ must be such that: $\triangle \geq 2 \cdot \delta + \delta_0$. This ensures that at least one full framelet will be intercepted during a listen phase. Furthermore, to ensure overlap between transmission and listening activities, the number of retransmissions n needs to comply with the following inequality when $\triangle_0 > 0 : n \geq [\triangle_0 + 2 \cdot \delta + \delta_0/(\delta + \delta_0)]$. This ensures that a framelet trail is sufficiently long enough to guarantee rendezvous with the listening phase of the receiver, and ensures that at least one framelet can be correctly received. The duration of $\triangle$ determines message delay, throughput and energy savings.

Message Acknowledgments : Between framelet transmissions, the source node switches its radio to a listening state. Upon successful reception of a frame at the destination node, this receiving node should respond with an acknowledgement transmitted during the framelet transmission gaps δ_0. After reception of this acknowledgment the sender should terminate transmission of its framelet trail as communication has been successful. The use of acknowledgments reduces the amount of framelets needed for each transmission, and as a result, transmissions will occupy the channel for a shorter period of time, reducing contention whilst increasing throughput and energy efficiency.

3.2 FrameCommDM

The basic principle of FrameComm is ideally suited for the integration of positioning functions. The method of exchanging packets and acknowledgements mirrors that of two-way-ranging methods used to determine the round-trip-time, and ultimately the TOF of signals. If the sender records the time of transmission of its last framelet, and the time upon receiving its acknowledgement, the distance between nodes can be determined. Furthermore, a sender may derive not only the distance to its intended recipient, but potentially the distance to any node within transmission range. During the exchange of framelets between the sender and receiver, a third node may enter its listening period, overhear a framelet and respond with a so called ranging acknowledgement (See Figure 1.b.).

Basic Ranging : To determine the distance between two communicating nodes the time-of-flight (TOF) of exchanged signals needs to be measured. To avoid the need of tight clock synchronization between both nodes two-way-ranging can be performed using the existing FrameComm data exchange. The sender of a message keeps track of the time t_t when a framelet is transmitted. If an acknowledgement is received, its arrival time t_a is recorded. The TOF can be determined using t_t and t_a if the processing time t_p at the message receiver is known. The processing time t_p is the time required by the message receiver to respond with an acknowledgement to the received framelet. It is assumed that the processing time t_p is constant and thus known by the message transmitter. The TOF can be calculated as: $TOF = (t_t - t_a - t_p)/2$. The distance between the two nodes is proportional to the measured TOF.

It has to be noted that a transmitter of a message can determine the distance to the message receiver without consuming additional energy for ranging as existing messages are used. Likewise, network performance in terms of achievable throughput and message transfer delay is not degraded by introducing ranging.

Ranging Acknowledgements : The previously outlined basic ranging mechanism can be improved by introducing ranging acknowledgements. The improvement exploits the fact that nodes not directly involved in the message transport might overhear framelets.

During regular communication a source node will generate data and begin transmitting its framelet trail, and await an acknowledgement. It is possible for nodes whom the packet is not the intended recipient to overhear framelets of the transmission. Normally, a node overhearing a packet not addressed to it would simply ignore the received packet and enter its sleep cycle. However, to improve ranging we propose that a node sends a ranging acknowledgement packet before entering the sleep state. Thus, a sender of a message does not only obtain the distance to the communication partner, but will potentially also collect distance information to nodes overhearing the communication (See Figure 1.b.).

This ranging acknowledgement is not sent immediately after the framelet is received. The transmission of the ranging acknowledgement is delayed by a time δ_R which is greater than the time needed to transmit a message acknowledgement. Thus, collisions between ranging acknowledgements with the message acknowledgement are avoided (See Figure 1.b.). In some cases, ranging acknowledgements transmitted by several overhearing nodes in response to the same framelet might collide. However, this will only reduce the effectiveness of the positioning function of FrameComm but will not have an impact on message transmission or network performance.

Ranging acknowledgements are transmitted within the gaps of an existing framelet trail. Thus, the introduction of ranging acknowledgements has no immediate impact on the network performance in terms of message transfer delay or network throughput (See experimental evaluation in Section 5). Energy consumption of nodes may vary by the introduction of ranging acknowledgements as additional messages need to be transmitted. However, our experiments show that this variance is acceptably small.

4 Prototype Implementation

Our choice of an UWB transceiver type was determined by our needs for implementing FrameCommDM. More specific, the transceiver hardware must provide a programming interface which allows us to implement FrameCommDM. Furthermore, we took power consumption of available transceivers into account. A low power consumption is important to make the system viable for most WSN deployment scenarios. Of the possible candidate systems the Nanotron NA5TR1 [3] best fitted these requirements.

4.1 Prototype Platform

For the FrameCommDM implementation we used the nanoLOC development board which comprises an of ATMega 128L microcontroller with $128kb$ flash memory and $4kb$ of SRAM, driving a nanoLOC EVR module; the main components of which being the NA5TR1 transceiver. Although it would be possible to port a common sensor network operating systems such as TinyOS or Contiki to the nanoLOC platform, we decided to implemented our own simple OS solely for testing MAC protocol performance.

The Nanotron NA5TR1 transceiver uses chirp spread spectrum (CSS), which is included as an alternate physical layer specification in the IEEE 802.15.4a. CSS is similar to other spread spectrum techniques in that it uses the entire allocated bandwidth to transmit a signal, however, CSS uses Linear Frequency Modulation (LFM), called chirp pulses, which fill the allocated bandwidth over a predefined duration. This makes CSS modulation resilient against channel noise, and also robust against multipath signals, allowing for increased accurate estimation of the Time-Of-Arrival (TOA) of the Line-Of-Sight (LOS) signal, which therefore results in greater accuracy of range estimations. The transceiver operates in the $2.45GHz$ ISM band at programmable data rates of between $125Kbps$ and $2Mbps$, with typical current consumptions of $35mA$ while transmitting, $33mA$ in a receiving state, and $2\mu A$ in a shutdown state. These figures compare to those of the Texas Instruments CC2420 transceiver [9] commonly used in WSN platforms as $17.4mA$ transmitting, $19.7mA$ receiving, and $20\mu A$ when shutdown.

4.2 Nanotron Ranging API

To facilitate distance estimations the transceiver hardware provides two types of ranging, defined as *normal* and as *fast* ranging. Nanotron's normal ranging technique allows both participating nodes to perform range estimations and the initiating node to average the estimations for increased accuracy (see [3]). Nanotron's fast ranging mode is similar to that of the two-way ranging method of range estimation, only one round trip measurement is used for range estimation. It has to be noted however that 2 acknowledgments are used. The first is a hardware generated acknowledgement (also called ranging pulse), having a fixed payload which cannot carry user data. If the receiver intends to report data in the acknowledgement a second data transmission must follow the ranging pulse (see Figure 2). Essentially the acknowledgement is split into two packet transmissions. Despite the additional ranging pulse, the fast ranging implementation closely resembles that of the packet exchange of the FrameCommDM protocol. Therefore, the fast ranging capability of the Nanotron hardware was used to implement FrameCommDM.

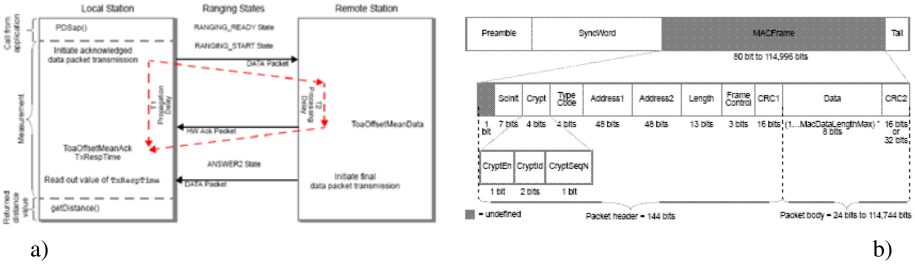

Fig. 2. *a)* Fast Ranging. Node 1 Generates a packet, sends to Node 2. Node 2 returns a hardware generated ack, followed by a data packet to transmit user data. Node 1 estimates distance to Node 2; b) Packet format the Nanotron NA5TR1.

The data packet format of the transceiver consists of a $30bit$ preamble, a $64bit$ sync word, a $4bit$ tail, and a MAC frame with a header size of $176bits$ and a maximum data payload field size of $8192bytes$ (see Figure 2). This is an increase of 50% in header size when compared to the frame format of the CC2440; assuming the same $48bit$ addressing scheme.

Obviously the efficiency of our FrameCommDM implementation is limited due to hardware constraints. Packets are relatively large and an additional short ranging pulse has to be transmitted for each message exchange. However, these issues could be addressed with hardware re-design. The header size could be reduced and the ranging pulse could carry user data.

4.3 FrameCommDM Implementation

Parameter Settings: The implementation values for various FrameComm parameters, as outlined in Section 3, have to be selected. The maximum framelet size is $578bit$ in length, consisting of a $274bit$ of frame header, $136bit$ of FrameComm header, and a maximum payload size of a simple $8bit$ sensor reading, and four times a structure of $8bit$ node ID and $32bit$ range estimation. This allows each node to forward a sensor reading with attached range estimation of a maximum of four neighbours to the sink for each message. We assume the sink is collecting ranging information and executes a positioning algorithm. This equates to a Framelet transmission time $\delta = 2.3ms$. We implement a 2% duty cycle using a framelet transmission period of $P = 600ms$ with a listen period $\triangle = 12ms$ and a sleep period $\triangle_0 = 588ms$. To satisfy the FrameComm specifications that $\triangle \geq 2 \cdot \delta + \delta_0$, where δ_0 is the time between framelets, and δ the framelet transmission time, we determine the Framlett interval to be $\delta_0 \leq 7.37ms$. Given that it takes under $2ms$ to generate a data ack of the required size of $410bit$, we can safely assume that after $\delta_R = 4ms$, overhearing nodes may choose to send ranging acknowledgements which will not collide with the data acknowledgements, and still arrive in adequate time to be received and processed before the next framelet transmission.

Fast Ranging: The implementation uses nanotron's fast ranging mechanism. Thus, an acknowledgement is split in two parts: ranging pulse and acknowledgement (see Figure 3). As previously explained, δ_R prevents collision of ranging acknowledgement and data acknowledgement, however, the collision of ranging pulses cannot be avoided with the existing hardware. Therefore a ranging measurement must be discarded if ranging acknowledgement and data acknowledgement are received after framelet transmission as it indicates a ranging pulse collision.

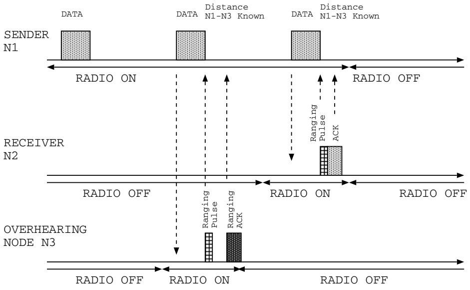

Fig. 3. FrameCommDM implementation on the Nanotron NA5TR1 using fast ranging

MAC Address Handling: For the NA5TR1 transceivers to facilitate the fast ranging mode, a sender must initiate a transmission with the $3bit$ Frame Control Field of the MAC frame set to $0x04$ and the frame must be addressed to a unicast address. A transceiver which is listening within communication range will check the frame control flag and reply with a ranging pulse to complete the TOF measurement, should this node have the destination address. The MAC layer may then retrieve the received data from the transceiver and return a ranging acknowledgement following the ranging pulse.

To implement our concept of ranging acknowledgements on the Nanotron hardware, all receiving nodes must have the same physical layer address, otherwise the transceiver would determine a packet not to be destined for this node, and therefore not send a ranging pulse. Ranging cannot be successful on this hardware if a node sends to its own physical address. Therefore, after a node has sampled the channel, before sending its framelet trail, it first sets its physical layer address to a different address to that of the global receive address. Once communication is successful, the node switches its physical layer address back to the predetermined global receive address. To uniquely identify a node sending an acknowledgement the payload uses the previously mentioned FrameComm header. Overhearing nodes can respond with a hardware pulse, followed by a ranging acknowledgement containing the node's FrameComm address.

4.4 Findings

The given hardware features of the NA5TR1 limit efficient implementation of FrameCommDM. However, these inefficiencies can be addressed by redesigning the NA5TR1 hardware. In particular, we recommend the following changes to allow efficient combined communication and positioning: (i) Ranging pulses should be able to carry user data. This would remove the necessity to send ranging pulses followed by a separate acknowledgement. (ii) It should be possible to define a ranging pulse transmission delay in order to avoid acknowledgement collisions. (iii) The transceiver should be able to respond to ranging requests not addressed to the transceiver. This would allow overhearing nodes to respond to ranging requests without MAC address modification.

5 Evaluation

The evaluation of this work considers the performance of FrameComm against that of FrameCommDM, in terms of network throughput, transmission delay and energy consumption. Furthermore, we analyze the ability of FrameCommDM to collect ranging measurements.

5.1 Experimental Setup

The system is evaluated using 5 nodes where 3 nodes are sending data via a forwarding node to a sink node. The sink nodes transceiver is always on while all other nodes use a 2% duty-cycle. The three leaf nodes and the forwarding node generate traffic destined for the sink. The setup is tested using different message generation frequencies λ as a parameter to vary traffic load. Each node generates messages every $1/\lambda$ ($1s \leq \lambda \leq 20s$) with an induced random jitter of $\pm 100ms$; thus nodes do not generate messages synchronously. Each experiment run is 5 minutes in length, and is repeated three times.

For each experiment nodes are configured with a buffer size of $b = 15$. A node can hold 15 messages in its forwarding buffer in addition to one that might currently be in the sending buffer. Messages are placed in this buffer when generated or received for forwarding. This value has been used to ensure messages are not dropped due to lack of buffer space in our experimental setup. Messages remain in the send buffer and will retransmit indefinitely until successfully acknowledged. If a node has multiple messages in its buffer, it sets a flag in packets of a framelet trail to indicate that it has multiple messages to send to the same receiver. When the destination node acknowledges the reception of the first packet, it examines this flag and stays awake to receive the remaining packets.

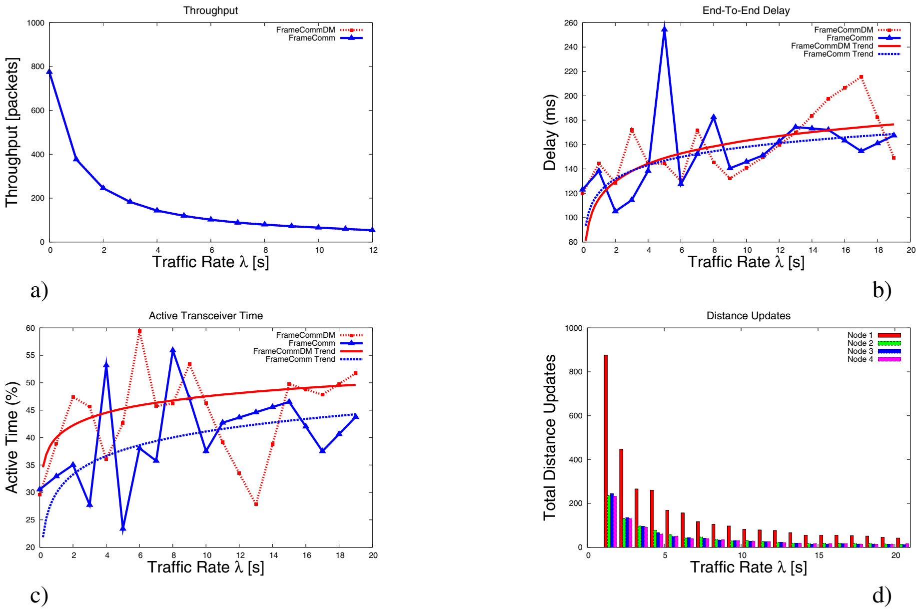

Fig. 4. a) Average throughput; b) Average message end-to-end delay; c) Average transceiver duty cycle of all nodes; d) Average number of distance measurements obtained by forwarding node and leaf nodes during experiment.

5.2 Communication Performance

To quantify the cost of implementing ranging into the FrameComm protocol, we use the experiment setup to determine throughput, delay and energy costs for FrameComm and FrameCommDM. Throughput is measured by determining the number of messages received at the sink over the duration of an experiment run. Delay is the end-to-end message delay for each message successfully delivered to the sink. Energy cost is determined by recording the time the transceiver of a node is active (listening, receiving, sending) during the experiment run.

Figure 4 a) shows the achieved throughput for FrameComm and FrameCommDM. From this figure it can be determined that the ranging enhancements introduced in FrameCommDM have no significant impact upon throughput. From the data collected it is found that throughput of FrameCommDM is reduced by a maximum of 0.9% and an average of 0.2%.

The results for the average delay for all nodes are shown in Figure 4 b). These show that, despite anomalous fluctuations in the real world results, the average increase in delay of adding ranging to the standard FrameComm protocol is a maximum of 4*ms*, however FrameCommDM can frequently be seen to yield lower delays than that of the standard protocol. This trend shows that the implementation of FrameCommDM has little impact upon message delay. We believe that prolonged testing in controlled environments will reduce the impact anomalies seen here to produce results closely resembling those of the trend lines shown.

Figure 4 c) depicts the average energy consumption of all nodes for both FrameComm versions. These results show that for high traffic rates where nodes frequently determine the channel to be busy $5 \geq \lambda$, there is an energy increase of around 5% for FrameCommDM. During periods of lower traffic $6 \leq \lambda$ rates there is a lower increase of around 1.5%. These increases, relative to the standard protocol, are due to the small durations in which FrameCommDM must keep the transceiver active while sending the ranging acknowledgements and are therefore relative to the amount of times a node samples the channel, either during its duty cycle period or during CCA, and determines it to be busy. For both variations of the FrameComm protocol we observe that during times of high traffic rates when the wireless channel is saturated, energy consumption is less than the average. This is caused by the more frequent backing off and sleeping of the transceiver when the channel is determined to be busy.

The results shown in all three measurements complement those of our previous, simulated work. This provides proof that the implementation of combined communication and ranging has no significant impact upon throughput or delay, and yields an acceptable increase in energy consumption, which would be more efficient than utilizing communication and ranging as separate functions.

5.3 Ranging Update Frequency

The evaluation of this work does not examine the ranging accuracy of FrameCommDM, as this is determined by the accuracy of range estimations of the NA5TR1 hardware. In accordance with the NA5TR1 data sheet [3], the accuracy of this particular transceiver is claimed to be within $\pm 2m$ indoor, and $\pm 1m$ in open space.

The evaluation of ranging of this work is to determine how frequently nodes estimate the distance to neighbouring nodes. For each new message generated, the node appends the data of its ranging table to the message payload. This data can then be examined by each intermediate node to update its local ranging table, and examined by the sink when the message reaches this destination. It has to be noted that during the experiments the sink does not respond with ranging acknowledgements. As the sink does not duty cycle the transceiver it would respond to every single message in the network with a ranging ack which is unnecessary.

Figure 4 d) portrays the total number of range measurements determined by each node. As expected, when traffic rates are high, nodes receive more frequent range estimations in the form of acknowledgements from their destination node for each message. Nodes also receive more overhearing acknowledgements during times of high traffic, as neighboring nodes more frequently sample the channel, and upon determining it to be busy, send ranging acknowledgements. Intermediary nodes, such as the forwarding node for this topology, receive more ranging estimations. These nodes not only gather range estimations from their generated messages and subsequent ranging acknowledgements, but also from the acknowledgements of the packets which they forward and from the ranging acknowledgments for these.

6 Conclusion

We have demonstrated that combined positioning and communication is implementable within low power MAC protocols, if the sensor platform provides a state of the art communication transceiver. We have found that implementing ranging into the FrameComm protocol has insignificant impact upon network performance, and that we can transport ranging data within the network at no extra cost. We have also shown how currently provided hardware interfaces of transceivers such as the NA5TR1 should be altered to support combined ranging and positioning more efficiently.

We believe that MAC protocol modifications as described in the paper can be applied to most power efficient sensor network MAC protocols. Thus, most existing MAC protocols can be augmented to include efficient positioning services if adapted to new transceiver hardware.

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