

Combining Positioning and Communication Using UWB Transceivers

Paul Alcock, Utz Roedig and Mike Hazas
Email: {p.alcock|u.roedig|m.hazas}@lancaster.ac.uk

Lancaster University, UK

Abstract. A new generation of ultra wideband (UWB) communication transceivers are becoming available which support both positioning and communication tasks. Transceiver manufacturers envision that communication and positioning features are used separately. We believe that this is an unnecessary restriction of the available hardware and that positioning and communication tasks can be active concurrently. This paper presents and investigates a medium access control (MAC) protocol which combines communication and positioning functions. Our experiments show that the existing data communication of a network can be exploited to gather position information efficiently.

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 of how 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 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 nanoLOC TRX [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. We argue that 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. If however there is currently not enough data communication taking place between nodes to accurately satisfy the positioning needs of the application, ranging packets may still need to be generated. Evidently the interplay of the transmission of data packets and ranging packets has to be organized to achieve communication *and* positioning goals. Transceiver usage for communication purposes is defined by the MAC layer. The MAC layer determines when packets are transmitted and how their transmission shall be organized. Thus we propose to combine positioning and communication tasks within the MAC layer.

This paper describes in general how positioning and communication tasks can be combined within the MAC layer on nodes which utilize an UWB transceiver. In particular, the paper shows how the existing FrameComm MAC protocol [13] can be extended to support positioning tasks. The resulting MAC protocol can be used with any transceivers adhering to the 802.15.4a IEEE standard. This paper has the following contributions:

- Protocol Specification: A detailed description of the necessary FrameComm modifications to integrate communication and positioning functions is given.
- Protocol Evaluation: A comprehensive evaluation using simulations of the modified FrameComm MAC protocol is presented.

The simulations show that the necessary modifications to FrameComm lead to an acceptable level of reduced network performance and a marginal increased energy consumption. The results indicate that positioning information can be collected almost for free if positioning and communication functions are combined as proposed.

The next Section gives an overview on related work. Section 3 describes the basic framelet communication mechanism. Section 4 details the proposed enhancements for existing framelet based MAC protocols, combining ranging estimations and communication as a single function. Section 5 outlines the simulation testbed and results of these experiments. 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.

Gezici et al. [5] provide an in-depth introduction into the use of UWB as a means of positioning. They discuss the fundamental positioning techniques that make our work possible, and how to reduce sources of error in UWB location estimation. Alsindi and Pahlavan [7] analyze the use of UWB positioning in WSNs using a cooperative location algorithm. They determine bounds for UWB location accuracy in a number of challenging indoor environments, and discuss issues relating to range estimation accuracy. Correal et al. [6] 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 method of positioning and communication functions affect one another.

Cheong and Oppermann [8] 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 [13] 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[9], but employs message retransmission instead of a long preamble in order to accommodate packet-based radios. X-MAC [10] 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. Other related duty-cycled schemes include Koala [11] and CSMA-MPS [12]. 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

FrameComm, like many wireless contention based MAC protocols, performs duty cycling of node transceivers. To ensure that rendezvous between transceivers occur, FrameComm 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 Fig. 1). A full description of FrameComm is given in [13]. The following paragraphs explain the basic functionality of the protocol and of the elements used to integrate positioning features as explained in Section 4.



Fig. 1. FrameComm communication

3.1 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 $P = \Delta + \Delta_0$, where Δ is the time the radio remains active and Δ_0 is the time the radio is in sleep mode. The duty cycle ratio is defined as:

$$DutyCycle = \frac{\Delta}{P} = \frac{D}{\Delta + \Delta_0} \quad (1)$$

3.2 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 Δ , Δ_0 , n , δ , and δ_0 . First, the listening phase of the duty cycle Δ

must be such that: $\Delta \geq 2 \cdot \delta + \delta_0$. 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 $\Delta_0 > 0$: $n \geq \lceil \Delta_0 + 2 \cdot \delta + \delta_0 / (\delta + \delta_0) \rceil$. 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 Δ determines message delay, throughput and energy savings.

3.3 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. Using 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.

4 FrameComm with Positioning

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.

We propose extending this positioning enhancement further, in such a manner that the 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 and overhear a framelet. Before discarding the framelet and returning to sleep, the node exploits this overhearing and sends what we call a ranging acknowledgement. Upon receiving the ranging acknowledgement the sender knows the distance to this third node (See Fig. 1.b.).

4.1 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: $TOF = (t_a - t_t - t_p)/2$.

The distance between the two nodes is proportional to the measured TOF. The measured TOF is in the order of nanoseconds for most wireless sensor networks where communication ranges are below one hundred metres. Time measurements on such scale must be performed by hardware on the used UWB transceiver chip. Available hardware such as the NanoLoc transceiver provide measurement facilities and automatic acknowledgements which allow us to determine t_t , t_a and t_p . 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.

4.2 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 Fig. 1.b.).

This ranging acknowledgement is not sent immediately after the framelet is received. The transmission of the ranging acknowledgement is delayed by the time needed to transmit a message acknowledgement. Thus, collisions between ranging acknowledgements and with the message acknowledgement are avoided (See Fig. 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 is increased by the introduction of ranging acknowledgements

as additional messages need to be transmitted. However, our experiments show that this increase is acceptably small.

4.3 Selective Ranging

Ranging acknowledgements only need to be transmitted if either the current sender of a framelet transmission or the nodes overhearing the transmission have changed position since the last distance measurement. To facilitate selective ranging, additional information has to be included within each framelet. The additional information is used to signal to the overhearing node that it is necessary to respond with a ranging acknowledgement.

To keep communication overhead minimal, one additional bit (the ranging flag) is used to signify selective ranging in each framelet. If this ranging flag is set, an overhearing node will respond with a ranging acknowledgement. In addition, if the overhearing node has determined itself to have moved it will always respond with a ranging acknowledgement, regardless if the ranging flag is set or not.

To implement the outlined functionality a node must be able to determine if its position has changed. This can either be achieved by using additional hardware such as an accelerometer or by analyzing the collected distance measurements of a node. In addition, a threshold might be defined to ensure that only significant changes in position result in sending new ranging acknowledgements.

4.4 Usage of Distance Information

While communicating, a node collects distance information to its immediate neighbors. This distance information can be used for different purposes.

Obviously, the distance information can be used by positioning algorithms either locally on the node or centrally somewhere in the network. However, the distance information can also be used to deal with node mobility in an effective way. If a node forwards a message and does not receive a data acknowledgement after sending all framelets it might indicate that the destination is no longer within communication range. In this case the existing table of distances to neighboring nodes can be used to select a new destination node to forward the message. The destination table contains set of nodes which are in communication range. The exact implementation of this would be specific to the routing strategy employed.

5 Evaluation

The modified FrameComm protocol as outlined in the previous section is evaluated using a simulation environment. We used our own purpose-built simulator written in C++ as other available simulation environments such as tossim or ns2 did not provide the necessary fine-grained UWB transceiver model necessary to determine transceiver activity and thus energy consumption of nodes.

The correct function of the simulation environment was calibrated using real-world experiments with the standard FrameComm protocol on Tmote Sky nodes to ensure accuracy.

5.1 Application Scenario

A small warehouse is used to store crates which contain medicine. The medicine needs to be kept cool below a specific temperature at all times to ensure effectiveness, therefore constant monitoring is required to audit temperatures. It is necessary to track the location of each crate in order to find them easily, and in addition it is necessary to know where temperature readings were taken.

Topology In the network topology, shown in Fig. 2, a sink node located in a corner of the warehouse is used to collect data. Fourteen static nodes are used in the warehouse to create an infrastructure. The static nodes ensure that any node placed in the storage area has connectivity to the network. For the experiments, twelve mobile nodes are used to monitor crates. Initially these twelve free-to-roam mobile nodes are placed in a grid as shown in Fig. 2. The communication range of each node is seven metres. Routing paths according to the arrows depicted in Fig. 2 are used initially; if nodes move, the routing topology will change as described later in the experiments.

Traffic Within each experiment all nodes generate messages periodically which are routed hop-by-hop towards the sink node. The message generation frequency λ is used as parameter in the experiments. A node divides time into slots of the length $1/\lambda$; the point in time within a slot when the message is generated is determined randomly (using a uniform distribution). Thus, nodes in the network do not generate messages synchronously.

In all of the following experiments nodes are configured with a limited MAC buffer size of $b = 3$. A node can hold three messages in addition to the one that might currently be in processing. Messages are placed in this buffer when a node generates a message or receives a message for forwarding. Messages are dropped when the buffer is full. If a message is not acknowledged by a receiver (for example, a framelet or an acknowledgement was destroyed by a collision) it remains in the buffer and the node will re-transmit the message indefinitely. Thus, message losses in the network occur solely due to full MAC buffers.

5.2 Experiment 1: The Cost of Positioning

The first experiment is used to determine the cost of introducing positioning functions to the FrameComm protocol. To determine the cost the previously described application scenario is first utilized with the standard FrameComm protocol and thereafter with the extended FrameComm protocol as previously described in Section 4. For this experiment all nodes have static locations and use fixed routing paths as shown in Fig. 2.

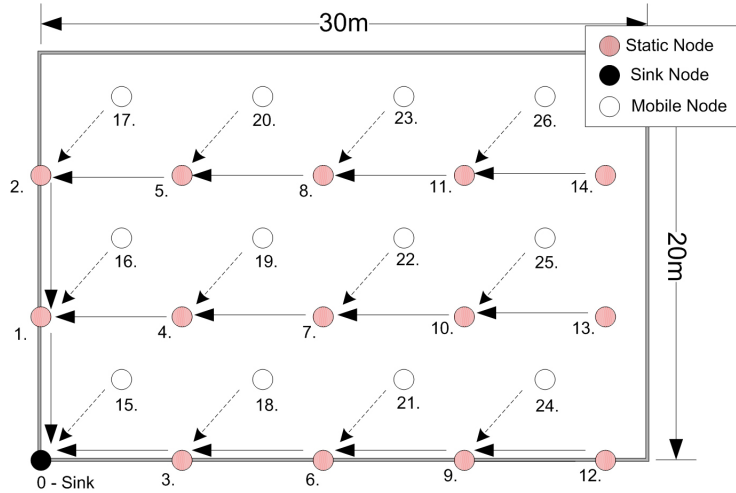


Fig. 2. Network Topology used for the evaluation

Each experimental run has the duration of 600 s. Different traffic loads are used which are denoted by the message generation frequency λ . The message throughput ϕ_n achieved by each node n_n during the experiment is measured. ϕ_n is defined as the number of messages generated by node n_n which are received at the sink during the experiment run. The relationship between message generation rate and throughput is $\phi_n \leq 1/\lambda$; in a congested network messages will be lost along the transport path. The time τ_n that the transceiver of each node spends in an active states (sending or listening) during the experiment is measured in as a percentage of the experiment duration. This figure is used to determine the energy consumption of each node. It has to be noted that τ_n is larger than the duty cycle as defined in Equation (1) as it includes not only idle listening but also the sending operations.

Fig. 3 shows the measured values for experimental runs for throughput ϕ_n and energy consumption τ_n for $\lambda = 1$ and $\lambda = 10$. When $\lambda = 1$ the network is overloaded and a relatively large number of messages are lost. For $\lambda = 10$ the network is loaded moderately and a low number of losses is observed (less than 5% for all nodes). Fig. 3 b) and d) show that different nodes have a very different energy consumption pattern. These pattern emerge due to different node positions in the topology. The nodes n_1, n_3, n_{15} , for example, have a low energy consumption as they forward messages to the sink, whose transceiver is continually listening/active. Thus, these three nodes can forward messages quickly, as the first framelet in a trail is always received. Nodes n_{12}, n_{13}, n_{14} have a low energy consumption as they do not have to forward traffic in this particular experiment. Node n_2 generally has the highest energy consumption as it has to forward messages from four nodes and is not directly connected to the sink.

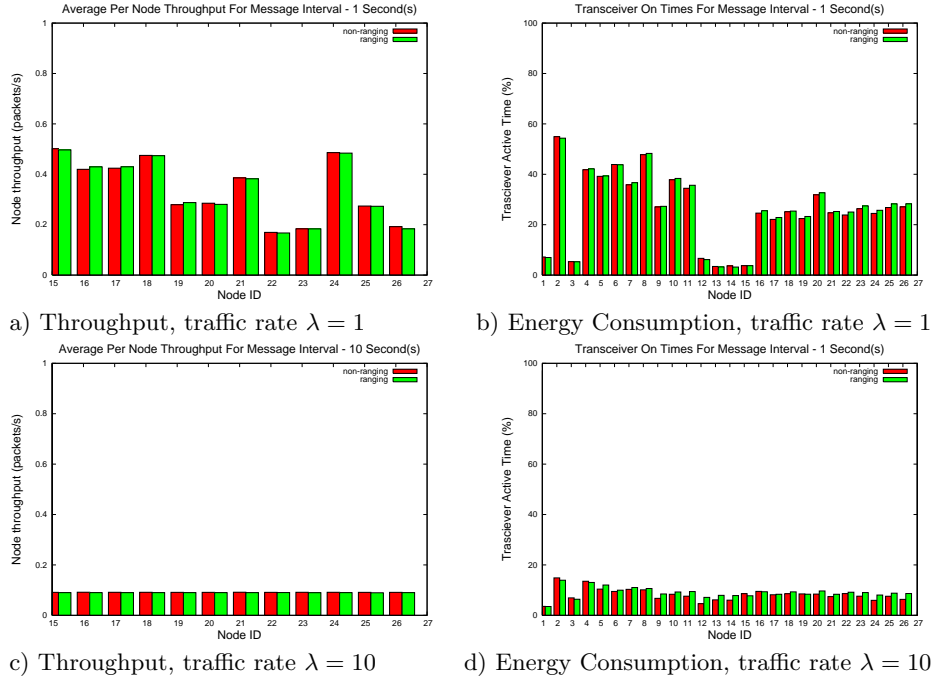


Fig. 3. Throughput ϕ_n and energy consumption τ_n for $\lambda = 1$ and $\lambda = 10$.

For most nodes, the additional positioning functionality leads to an increase in energy consumption ($\tau_{max} = \tau_{25} = 5.38\%$ for $\lambda = 1$; $\tau_{max} = \tau_{12} = 35.3\%$ for $\lambda = 10$). This increase is expected as additional ranging acknowledgements have to be transmitted. However, some nodes consume less energy when ranging functionality is included. This appears contradictory. However, the throughput slightly decreases when positioning is used; as ranging acknowledgements might collide with framelets of an ongoing message transmission. Although ranging acknowledgements are offset to avoid collision with the current, overheard conversation, it is sometimes possible for a ranging acknowledgement to interfere with the data exchange between neighboring nodes. Node n_2 has to forward traffic from four nodes which all achieve a slightly lower throughput when positioning is enabled. Node n_2 therefore consumes less energy when positioning is enabled as it has to forward less packets.

Fig. 4 shows the average throughput $\phi = \frac{1}{12} \sum_{n=15}^{n=26} \phi_n$ and average energy consumption $\tau = \frac{1}{26} \sum_{n=1}^{n=26} \tau_n$ of nodes for all traffic rates $1 \leq \lambda \leq 20$. Fig. 4 shows that for high traffic loads, $\lambda < 5$, the throughput for the positioning enabled FrameComm is smaller than for the standard FrameComm. Framelets are lost due to collisions with ranging acknowledgements. As a consequence, the energy consumption for the positioning enabled FrameComm is reduced as less traffic is transported. For low traffic loads, $\lambda \geq 5$, the throughput for both

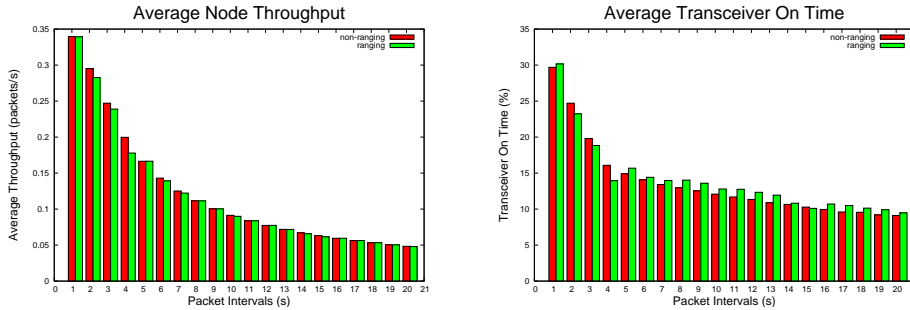


Fig. 4. Average throughput ϕ and average energy consumption τ for $1 \leq \lambda \leq 20$.

FrameComm variants is similar. Thus, a similar amount of traffic is transported in both settings and the additional effort for ranging acknowledgements is visible in the increased energy consumption for FrameComm with positioning. This additional cost in terms of energy is at most 15% (for n_2 at $\lambda = 5$) and in average 4.57% for all nodes at all traffic loads $5 < \lambda \leq 20$.

5.3 Experiment 2: Selective Ranging

The second experiment is designed to evaluate the proposed optimization as described in Section 4.3. Nodes only respond with ranging acknowledgements to overheard messages if either the overhearing node has moved, or the ranging bit is set in the overheard message header.

To evaluate the selective ranging feature some node mobility is required. Node n_{26} is set in constant motion for the duration of the experiment on a fixed path between its starting position of $(x = 25, y = 17)$ (See Fig. 2) and coordinate $(x = 5, y = 3)$, at a constant velocity $v = 1m/s$. This movement pattern is utilized throughout the experiment for the traffic rates $1 \leq \lambda \leq 20$. To ensure fair comparison between different evaluation runs, deterministic, hardcoded handover sequences are enforced to reallocate forwarding nodes once the node moves outside of communication range of their current forwarding node. The experiments are each run for a duration of 600 s. The message throughput ϕ_n and the energy consumption τ_n as defined in Section 5.2 are recorded.

The results are shown in Fig. 5. For low traffic loads, $\lambda \geq 5$, the throughput for all evaluated FrameComm variants is similar. As expected, the selective ranging FrameComm variant requires nearly as much energy as the standard FrameComm variant without ranging. Thus, the selective ranging optimisation allows us to obtain ranging measurements at a very low energy cost. This additional cost in terms of energy is at most 7.02% (for n_5 at $\lambda = 4$) and in average 0.1% for all nodes at all traffic loads $5 < \lambda \leq 20$.

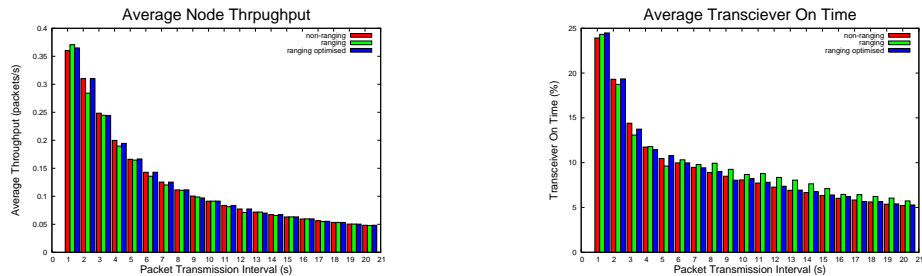


Fig. 5. Results Of Selective Ranging Optimization

5.4 Experiment 3: Location Update Frequency

The last experiment is used to evaluate how well the position enabled FrameComm protocol can be used together with a centralised position algorithm. Centralised location algorithms are less energy-efficient than distributed algorithms as each node must forward ranging measurements to the node responsible for computing location [1]. However, for sensor network deployments in which nodes forward sensor readings to the same node that also executes the centralised positioning algorithm, ranging measurements can be transferred at very little extra cost. The ranging measurements can be piggy-backed on data packets. Often, fixed packet sizes are used which are underutilised and thus ranging measurements can be transported at no additional cost. We use this method to evaluate the positioning capabilities of a sensor network using the positioning enabled FrameComm MAC protocol.

For the purposes of this evaluation, we have chosen to implement a basic centralised trilateration algorithm. Each node creates a table containing distance information to its neighbors using the positioning-enabled FrameComm protocol (See Section 4.4). The content of this table is transmitted with each message reporting a sensor reading to the sink. The central or sink node gathers and stores the most current ranging information of each node. If for a given node, there exist range measurements from three reference nodes which form intersecting circles, the location of the node can be determined. All infrastructure nodes as outlined in Section 5.1 are used as reference nodes within the evaluation setup. For evaluation, node n_{26} is selected to be a mobile node constantly in motion using a random waypoint model; all other nodes remain at fixed position as shown in Fig. 2. Node n_{26} randomly determines a destination location and the node moves with speed $v = 1m/s$ towards this destination. When reaching this position, the node selects a new random destination.

The location update frequency ω_n is analysed in this experiment. The achievable location update frequency indicates how well a system is able to keep track of node positions. ω_n is defined as the time between two position updates for node n_n . The shorter the time between calculated position updates at the sink the better the system is aware of the correct position of nodes.

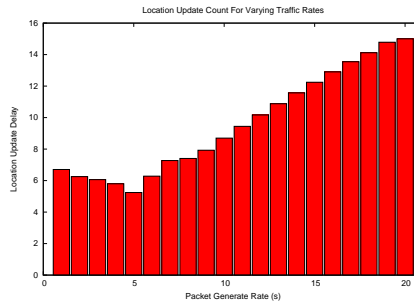


Fig. 6. Average location update frequency of node w_{26}

Fig. 6 shows the average location update frequency w_{26} of node n_{26} . As expected, the location update frequency increases linearly with the linear increasing traffic load ($5 \leq \lambda \leq 20$). With a reduced traffic load a decreasing number of ranging measurements reaches the sink and the location update frequency is increasing accordingly. However, for high traffic loads ($\lambda < 5$) an inverse pattern is observed. For the high traffic loads the network capacity is reached and packets are dropped. The more traffic is offered to the network the more packets have to be dropped and this can lead to a high number of packets being dropped which are required to calculate the position of node n_{26} . We believe it is possible to keep the average location update frequency constant low for $\lambda < 5$ if the network implements an appropriate packet dropping strategy. An available FrameComm extension called priority interrupts [13] is available which could help to implement such mechanism.

The experiments show that communication and position estimation are linked in two ways. First, there is a complex interdependency between data transport and the gathering of ranging measurements as shown in the previous two experiments. Second, there is a non-trivial interdependency between data transport and location estimation as shown in this experiment.

6 Conclusion

We have shown in this paper how positioning and communication tasks can be combined within the MAC layer on nodes which utilize an UWB transceiver. We investigated how the existing FrameComm MAC protocol can be extended to support positioning tasks. The experiments show that the positioning-enabled FrameComm MAC protocol consumes in average 4.57% more energy in the investigated scenarios than the standard FrameComm protocol. Using selective ranging this value can be reduced further to 0.1% in the scenarios investigated. We believe that this is an acceptable trade-off, especially as other network parameters such as throughput are not significantly altered by implementing ranging functionality. The experiments also show that if ranging information is transported together with sensing information, a strategy is required for dropping

packets in overload situations. In a next step we plan to investigate the proposed positioning-enabled FrameComm protocol in more detail and we plan to run real-world experiments using sensor nodes with IEEE 802.15.4a transceivers.

References

1. N. Patwari, J.N. Ash, S. Kyperountas, A.O. Hero, R.L. Moses, N.S. Correal. "Locating the nodes." *Signal Processing Magazine, IEEE*, Vol. 22, No. 4. (2005), pp. 54-69.
2. IEEE 802.15 WPAN Low Rate Alternative PHY Task Group 4a (TG4a). <http://ieee802.org/15/pub/TG4a.html>.
3. Nanotron nanoLOC TRX Data Sheet. <http://www.nanotron.com>. 2007.
4. Federal Communications Commission, "Revision of Part 15 of the Commission's Rules Regarding Ultra-Wideband Transmission Systems." http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-02-48A1.pdf
5. S. Gezici, Z. Tian, G. B. Giannakis, H. Kobayashi, A. F. Molisch, H. V. Poor, and Z. Sahinoglu, "Localization via ultra-wideband radios: a look at positioning aspects for future sensor networks," *Signal Processing Magazine, IEEE*, vol. 22, no. 4, pp. 70-84, 2005.
6. N. S. Correal, S. Kyperountas, Q. Shi, and M. Welborn, "An uwb relative location system," in *Ultra Wideband Systems and Technologies, 2003 IEEE Conference on*, 2003, pp. 394-397.
7. N. Alsindi and K. Pahlavan, "Cooperative Localization Bounds for Indoor Ultra-Wideband Wireless Sensor Networks," *EURASIP Journal on Advances in Signal Processing*, vol. 2008, Article ID 852509, 13 pages, 2008.
8. P. Cheong and I. Oppermann, "An Energy-Efficient Positioning-Enabled MAC Protocol (PMAC) for UWB Sensor Networks," in *Proceedings of IST Mobile and Wireless Communications Summit, Dresden, Germany, June 2005*, pp. 95-107.
9. J. Polastre, J. Hill, and D. Culler, "Versatile low power media access for wireless sensor networks," in *SenSys '04: Proceedings of the 2nd international conference on Embedded networked sensor systems*. New York, NY, USA: ACM Press, 2004, pp. 95-107.
10. M. Buettner, G. V. Yee, E. Anderson, and R. Han, "X-mac: a short preamble mac protocol for duty-cycled wireless sensor networks," in *SenSys '06: Proceedings of the 4th international conference on Embedded networked sensor systems*. New York, NY, USA: ACM Press, 2006, pp. 307-320.
11. R. Musaloiu-E, C. Liang, A. Terzis, "Koala: Ultra-Low Power Data Retrieval in Wireless Sensor Networks." *Proceedings of the 7th international conference on Information processing in sensor networks*, p.421-432, April 22-24, 2008.
12. S. Mahlknecht and M. Bock, "CSMA-MPS: a minimum preamble sampling MAC protocol for low power wireless sensor networks," in *Proceedings of the 2004 IEEE International Workshop on Factory Communication Systems*, 2004, pp. 73-80.
13. T. O'Donovan, J. Benson, U. Roedig, and C. Sreenan, "Priority Interrupts of Duty Cycled Communications in Wireless Sensor Networks." In *Proceedings of the Third IEEE International Workshop on Practical Issues in Building Sensor Network Applications (SENSEAPP2008)*, Montreal, Canada, IEEE Computer Society Press, October 2008.
14. Chipcon Products From Texas Instruments, "CC2420 - Data sheet." <http://focus.ti.com/lit/ds/symlink/cc2420.pdf>.