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Positioning in Synchronized Ultra Low-Power Wireless Sensor Networks

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Abstract

Wireless Sensor Networks (WSNs) consist of densely deployed, independent, and collaborating low cost sensor nodes. The nodes are highly resource-constrained in terms of energy, processing, and data storage capacity. Thus, the protocols used in WSNs must be highly energy-efficient. WSN communication protocols achieving the lowest power consumption minimize radio usage by accurately synchronizing transmissions and receptions with their neighbors. In this paper, we show how network signaling frames of state-of-the-art synchronized communication protocols for low-power WSNs supporting mobile nodes can be used for positioning. We derive mathematical models for node power consumption analysis. Both centralized and distributed positioning architectures are modeled. The models provide a tool for estimating what kind of network lifetimes can be expected when average positioned node speed, the amount of anchor nodes required by the location estimation algorithm, and the location refresh rate required by the application are known. The presented analysis results are based on two kinds of node hardware: with and without Received Signal Strength Indicator (RSSI). The results show that the positioning parameters and used hardware have significant impact on node power consumption and network lifetime. In the presented results, the network lifetime ranges from over 10 years to 2 months with different positioning requirements and hardware.

keywords: Wireless, Low-Power, Sensor Networks

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1 Introduction

Wireless Sensor Networks (WSNs) consist of densely deployed, independent, and collaborating sensor nodes which are highly resource-constrained in terms of energy, processing, and data storage capacity (Akyildiz, Su, Sankarasubramaniam & Cayirci 2002, Culler, Estrin & Srivastava 2004). The nodes can sense their environment, process data, and communicate over multiple short distance wireless hops. The network self-organizes and implements its functionality by co-operative effort.

Due to the very large number of nodes, frequent battery replacements and manual network configuration are inconvenient or even impossible. Thus, the networks must be self-configuring and self-healing, and the nodes must operate with small batteries for a lifetime of months to years. This results in very scarce energy budget. Thus, the protocols used in WSNs must be highly energy-efficient. Also, low cost of hardware is essential for the feasible usage of these network including large number of devices.

WSNs form a potential technology for ubiquitous positioning due to their autonomous nature, low power consumption, and small size factor (Kaseva, Kohvakka, Kuorilehto, Hannikainen & Hamalainen 2008). The problem of positioning includes determining the physical coordinates or the area of a given node. Typically, it is achieved by doing measurements from nodes with unknown locations (positioned nodes) to anchor nodes, which know their locations a priori. Then, the unknown locations are resolved using these measurements and a location estimation algorithm.

Commonly, WSN nodes communicate using a low-cost radio transceiver. A radio transceiver is the most power-consuming component in a WSN node (Kohvakka, Suhonen, Kuorilehto, Kaseva, Hännikäinen & Hämäläinen 2009). Thus, minimizing communication is essential in achieving high energy-efficiency and long network lifetime. WSN communication protocols achieving the lowest power

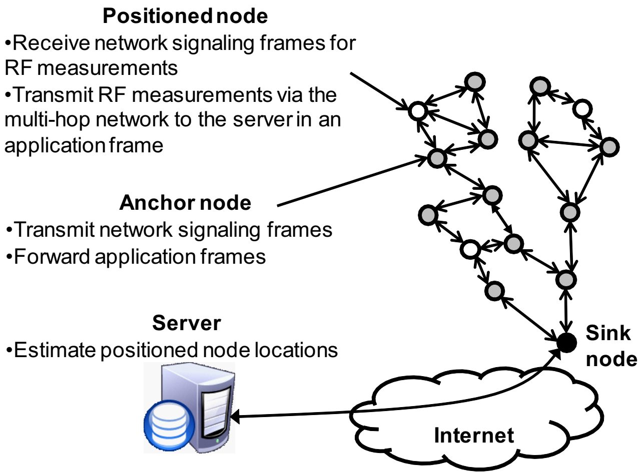

Figure 1: In centralized positioning, the positioned node locations are estimated by a server. The RF measurements are done using network signaling frames transmitted by the anchor nodes. The positioned nodes send the measured information to the server via the WSN in application frames.

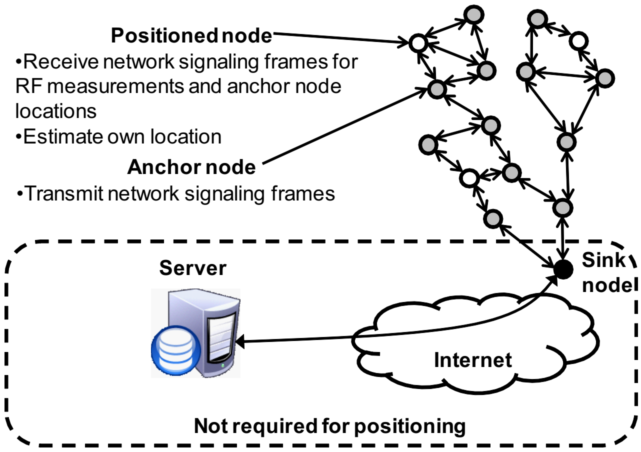

Figure 2: In distributed in-network positioning, the positioned nodes estimate their own locations using network signaling frames for RF measurements. Each anchor node knows its own location and piggybacks this information in the signaling frames. Thus, the positioned nodes receive all information required for positioning from the network signaling frames.

consumption minimize radio usage by accurately synchronizing transmissions and receptions with their neighbors. The usage of the radio transceiver for positioning is an attractive choice due to its inherent existence in the nodes. This way, no extra hardware, such as ultrasound or infrared transceivers, is required.

Typically, WNS communication protocols are designed for relatively static network environment and the energy-efficiency of mobile nodes is degraded. This is problematic in positioning point of view, since many positioned objects can be mobile. As nodes are moving, their network neighborhood changes introducing increased amount of energy consuming neighbor discovery attempts. Energy-efficient Neighbor Discovery Protocol (ENDP) (Kohvakka et al. 2009) introduces a low-power solution for neighbor discovery in synchronized WSNs by piggybacking two-hop neighborhood information in network signaling frames.

The communication protocols of synchronized low-power WSNs rely on signaling frames to achieve accurate timing of communication. In this paper, we identify how to use these signaling frames to achieve positioning of mobile nodes with minimal overhead. Then, we analyze how varying positioning parameters affect the network power consumption and lifetime. The analysis focuses on two specific cases: 1) centralized, and 2) distributed positioning. The paper extends the work presented in (Kaseva, Hamalainen & Hannikainen 2010).

In centralized positioning, illustrated in Fig. 1, the positioned node locations are estimated by a server. The positioned nodes do RF measurements using the network signaling frames transmitted by the anchor nodes. The measured information is sent to the server via the WSN in application frames. The anchor nodes form a multi-hop network for data routing and a sink node acts as a gateway to the server. The anchor node locations are stored on the server. The server estimates the positioned node locations using the RF measurement information received from the WSN and the known locations of the anchor nodes.

In distributed in-network positioning, depicted in Fig. 2, the positioned nodes estimate their own locations. Thus, only radio communication required for positioning are the network signaling frames used for RF measurements. Each anchor node knows its own location and piggybacks this information in the signaling frames. Thus, the positioned nodes receive all information required for positioning from the network signaling frames.

For the analysis, we derive mathematical models for the power consumption inflicted by the network signaling in synchronized WSN communication protocols and ENDP. These models apply for both centralized and distributed positioning architectures. Furthermore, we model the data exchanges inflicting additional power consumptions in centralized positioning. We parametrizate the models for positioned node speed, the required amount of anchor node neighbors, and the required location refresh rate. Using these models we show how power consumption and lifetime of the nodes change as the parameters vary. For each case, we derive network parameters for optimal network lifetime where the lifetime of positioned nodes and anchor nodes is mutually maximized. The presented models provide a tool for estimating network lifetimes with different positioning parameters.

As the base of the analysis results we use power consumption measurements from a real resource-constrained

Tampere University of Technology WSN (TUTWSN) node hardware platform that employs a low-power low-cost 2.4 GHz radio transceiver with no Received Signal Strength Indicator (RSSI) support. Furthermore, we present results using typical values for Texas Instruments CC2531 chip (Homepage of Texas Instruments, Inc. 2010) that integrates a low-power MCU core with IEEE 802.15.4 compliant radio including RSSI support.

The rest of the paper is organized as follows. Section 2 surveys related research in synchronized low-power WSNs and RF-based positioning. Section 3 introduces the basic network signaling operation of synchronized WSNs and ENDP, and continues to show how the network signaling can be used for positioning RF measurements. The TUTWSN node prototype hardware is presented in Section 4. Section 5 presents the mathematical power consumption models of synchronized WSNs and ENDP. In Section 6, we show the node power consumption and lifetime results when the positioning parameters are varied. Finally, Section 7 concludes the paper.

2 Related Research

Next, we survey communication protocols for synchronized WSNs and RF-based positioning techniques. In the rest of the paper we show how these can be applied to achieve positioning with minimal overhead.

2.1 Synchronized Communication in WSNs Supporting Mobile Nodes

A Medium Access Control (MAC) protocol controls radio transmissions and receptions on the shared wireless medium. Thus, it has a major effect on network performance and energy consumption (Kohvakka et al. 2009). Traditional wireless voice and data network MAC protocols try to maximize wireless medium utilization and throughput. In WSNs, the goal of a MAC protocol is to provide energy-efficient, adaptive and error tolerant operation, and adequate scalability for large and dense networks having only few kbit/s network throughput requirement (Woo & Culler 2001).

WSN MAC energy-efficiency is achieved by duty-cycling, where data is exchanged in active periods and rest of the time is spent in low-power sleep-mode. Synchronized low duty-cycle MAC protocols exchange data only in predetermined synchronized time slots resulting in even less than 1% activity. In static networks, synchronized MAC protocols can achieve even an order of a magnitude lower energy consumption compared to unsynchronized ones (Kohvakka, Hannikainen & Hamalainen 2005*b*). The synchronized low duty-cycle MAC protocols include for example IEEE 802.15.4 Low-Rate Wireless Personal Area Network (LR-WPAN) standard (IEE 2003) used in Zigbee networks and TUTWSN MAC (Kohvakka et al. 2005*b*).

As network dynamics, for example node mobility, increase neighbor discovery starts to produce significant energy overhead with synchronized MAC protocols. Network scanning, where one or multiple frequency channels are listened for an extended time period, is the the typical mechanism for neighbor discovery in current synchronized WSN MAC protocols (Kohvakka et al. 2009). It may consume energy equal to the transmission of thousands of data packets (Kohvakka, Hannikainen & Hamalainen 2005*a*).

Our previous work, ENDP (Kohvakka et al. 2009), reduces the need for costly network scans by proactively distributing node schedule information. ENDP can achieve low energy-consumption when continuously having at least one working communication link. To the best of our knowledge, ENDP is currently the most energy-efficient neighbor discovery protocol for dynamic WSNs using low duty-cycle MAC protocols.

2.2 RF-based Positioning

RF-based positioning methods can be categorized to range-based, proximity-based, and scene analysis (Hightower & Borriello 2001). Range-based methods rely on estimating distances between positioned nodes and anchor nodes. Proximity-based methods estimate locations from connectivity information. Scene analysis consists of an off-line learning phase and an online positioning phase.

The distance estimation process of range-based positioning methods is called ranging. RSSI is a common RF-based ranging technique. In (Terwilliger, Gupta, Bhuse, Kamal & Salahuddin 2004) and (Paschos, Vagenas & Kotsopoulos 2005) RSSI is replaced with multiple varying power level beacon transmissions. To reduce quantization error the amount of used transmission power levels is relatively large. Our previous research (Kohvakka, Suhonen, Hannikainen & Hamalainen 2006) presents a transmission power based path loss metering method, using only small amount of varying power level beacon transmissions to remove the need for RSSI functionality. Our work presented in (Kaseva et al. 2008) extends this method to node positioning.

Several location estimation techniques can be used in range-based positioning. These include trilateration (Hightower, Want & Borriello 2000, Paschos et al. 2005), weighted center of gravity calculation (Shi, Huang, Shao, Cheng & Chen 2006), and Kalman filtering (Kotanen, Hannikainen, Leppakoski & Hamalainen 2003). Many mathematical optimization methods, such as the steepest descent method (Kitasuka, Nakanishi & Fukuda 2003), sum of errors minimization (Terwilliger et al. 2004), and Minimum Mean Square Error (MMSE) method (An, Wang, Prasad &

Niemegeers 2006), have been used to solve range-based location estimation problems.

Proximity-based approaches exploiting RF signals (Hodes, Katz, Servan-Schreiber & Rowe 1997, Bulusu, Heidemann & Estrin 2000, Smailagic & Kogan 2002, He, Huang, Blum, Stankovic & Abdelzaher 2003) estimate locations from connectivity information. In WLANs, mobile devices are typically connected to the Access Point (AP) they are closest to. In the strongest base station method (Hodes et al. 1997, Smailagic & Kogan 2002) the location of the positioned node is estimated to be the same as the location of the AP it is connected to. In (Bulusu et al. 2000) and (He et al. 2003), the unknown location is estimated using connectivity information to several anchor nodes.

Only a coarse grained location can be estimated using the strongest base station method. The solutions presented in (Bulusu et al. 2000) and (He et al. 2003) better the granularity to some degree. Nevertheless, in order to reach small granularities the connectivity-based schemes require a very dense grid of anchor nodes. Their strength is fairly simple implementation and modest HW requirements.

Scene analysis consists of an off-line learning phase and an online positioning phase. The off-line phase includes recording RSSI values corresponding to different anchor nodes as a function of the users location. The recorded RSSI values and the known locations of the anchor nodes are used either to construct an RF-fingerprint database (Bahl & Padmanabhan 2000, Smailagic & Kogan 2002, Lorincz & Welsh 2005), or a probabilistic radio map (Elnahrawy, Li & Martin 2004*b*, Elnahrawy, Li & Martin 2004*a*, Youssef, Agrawala & Shankar 2003, Alippi, Mottarella & Vanini 2005, Roos, Myllymaki, Tirri, Misikangas & Sievanen 2002).

In the online phase the positioned node measures RSSI values to different anchor nodes. With RF-fingerprinting the location of the user is determined by finding the previously recorded reference fingerprint values that are closest to the measured one. The unknown location is then estimated to be the one paired with the closest reference fingerprint or in the (weighted) centroid of k nearest reference fingerprints. Location estimation using a probabilistic radio map includes finding the point(s) in the map that maximize the location probability.

3 Positioning in Synchronized Low-Power WSNs using Network Signaling

Next, we will present the basic network signaling operation of synchronized low-power WSNs and ENDP. Then, we show how the network signaling frames of synchronized WSNs using ENDP can be used to achieve energy-efficient positioning measurements for mobile positioned nodes with minimal interference to the WSN operation.

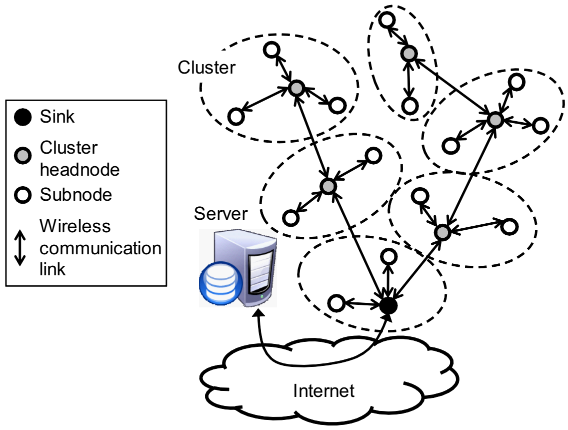

Figure 3: Example of a clustered topology and cluster tree routing.

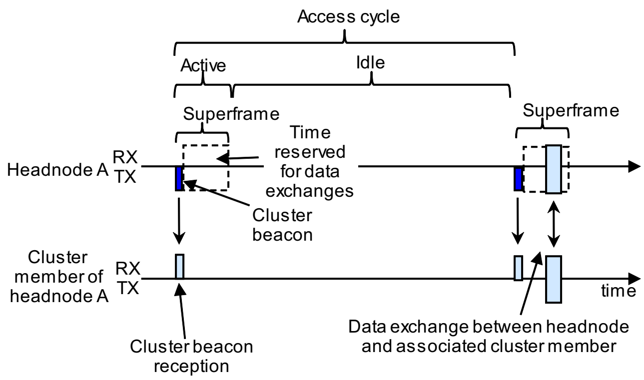

Figure 4: Network signaling and data exchange in synchronized WSN MAC protocols.

3.1 Network Signaling and Topology of Synchronized Low-Power WSNs

Fig. 3 presents an example of a clustered network topology. A clustered network topology includes cluster headnodes which are capable of data routing. The headnodes route data via multiple wireless hops to sink nodes that act as gateways to other networks, such as Internet. Subnodes act as leaf nodes and can communicate only with their designated cluster heads.

For data routing, for example a cluster tree topology can be used as depicted in Fig. 3. In a multi-cluster tree topology the nodes can have multiple parents. Thus, subnodes or headnodes acting as cluster members of other clusters may choose to associate to multiple headnodes.

In synchronized MAC protocols time is divided into access cycles as depicted in Fig. 4. Each access cycle is divided into an active period and an idle period. An active period consists of a superframe which starts with a cluster beacon

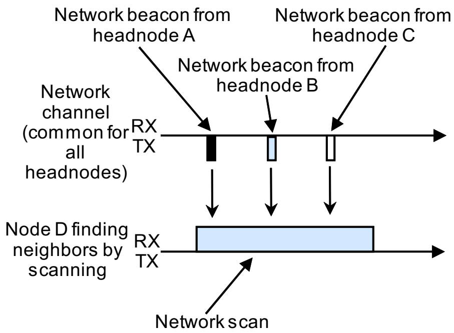

Figure 5: Example of network scanning using the network channel. Node D finds headnodes A, B, and C by listening on the network channel.

and after the beacon includes time for data exchanges.

With the cluster beacon, headnodes signal their neighbors of communication parameters, for example used frequency channel, data slot allocation in the rest of the superframe, and the time of the next active period. Using the information provided in the cluster beacons the cluster members can synchronize to the active period schedules of the headnodes and exchange data with the headnodes. A subnode does not transmit beacons but can only exchange data with its neighboring headnode in the superframe of the headnode.

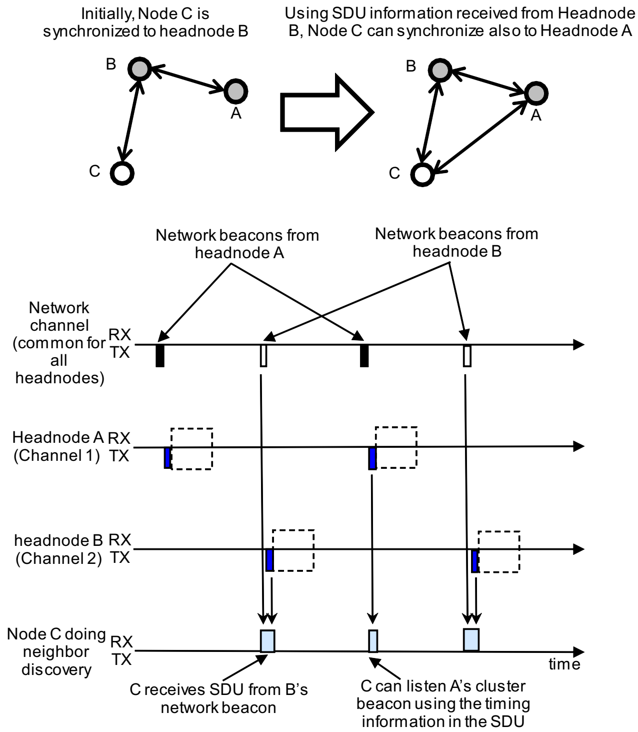

Figure 6: Example of proactive neighbor information distribution. Initially, Node C is synchronized to Headnode B. Using SDU information transmitted in B's network beacons, Node C can synchronize also to Headnode A.

3.2 Network Signaling in ENDP

Initially, nodes have to do neighbor discovery to find out active period timing information of their neighboring headnodes. Neighbor discovery is also needed when links to headnodes are lost for example due to mobility. ENDP uses energy-efficient network scanning and proactive neighbor information distribution to maintain synchronization to neighboring headnodes.

ENDP suggests the usage of a common network channel where headnodes send network beacons. In the network beacons node communicate their active period timing information with which listening nodes can synchronize to the headnodes after a network scan. Furthermore, the beacon include Synchronization Data Units (SDUs). With the SDUs, information of neighbors' neighbors active period timing is communicated for proactive neighbor information distribution.

Network scanning is needed when a node has no known communication links. Fig. 5 presents an example of a network scan using the network channel. Headnodes A, B, and C send network beacons in the network channel and Node D listens to the channel until it has found sufficient amount of neighbors or for the duration of network beacon transmission interval. The network channel makes network scanning more energy-efficient since only one frequency channel needs to be listened to for the scan duration.

With SDU information a node can synchronize to a neighbor's neighbor without the need for a network scan. Headnodes transmit network beacons during the idle periods. Furthermore, superframes are always preceded with a fixed network beacon. This allows energy-efficient network beacon reception as it is always transmitted a known time before the cluster beacon.

An example of proactive neighbor information distribution is depicted in Fig. 6. Initially, Node C has no information of headnode A. Then, it receives and SDU of Headnode A in the network beacon of Headnode B. With the timing information provided in the SDU node C can receive the next cluster beacon of Headnode A.

3.3 RF Measurements using Network Signaling for Centralized and Distributed Positioning

A clustered network topology can be used for node positioning by treating headnodes as static anchor nodes and subnodes as positioned nodes. The subnodes can use the cluster beacons transmitted by headnodes for RF measurements. Network beacons can be used to find suitable headnodes for these measurements.

RF path loss based ranging gives larger absolute errors as range increases (Patwari, Ash, Kyperountas, Hero III,

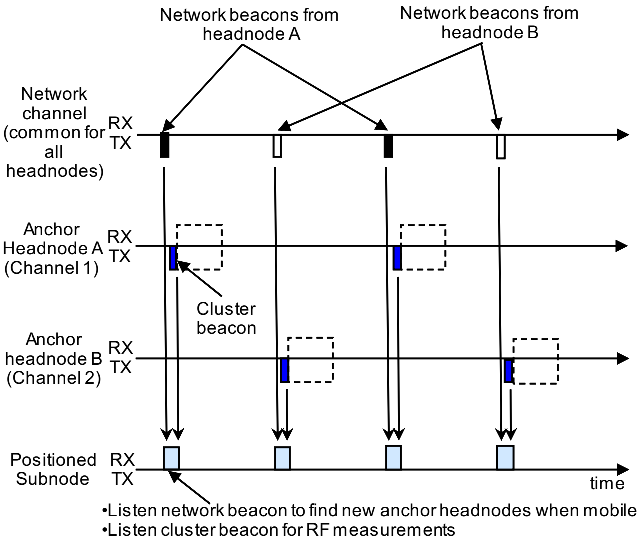

Figure 7: Example of using synchronized MAC and ENDP network signaling for positioning data gathering. Network beacons are used for finding suitable anchor headnodes during mobility. Cluster beacons are used for RF measurements.

Moses & Correal 2005). Thus, suitable headnodes may be chosen according to a signal strength threshold. This enables dynamic RF measurement quality monitoring. When there is enough anchor headnodes with 'good enough' signal strength values the positioned subnode can use these for measurements. In sparser networks the positioned subnode may choose to use also anchor headnodes above the threshold if enough good ones are not found.

Fig. 7 presents the beacon exchanges used for positioning when the positioned subnode can hear two anchor headnodes. The method extends to arbitrary number of anchor headnodes. The subnode stays synchronized to the headnodes using the access cycle timing and frequency channel information provided in the cluster beacons. Thus, the subnode always knows the exact time a cluster beacon is sent by a specific headnode and can receive it energy-efficiently. Additionally, the subnode also listens to the network beacons to find out new neighboring anchor headnodes during mobility.

With the presented method, the positioned subnode can gather RF measurement data to anchor headnodes from the cluster beacons and no additional data exchanges are needed. Furthermore, the interference to the network operation is minimized as the positioned subnode only listens in order gather the required data.

The positioned subnode can gather RF measurement data from all selected anchor nodes during one access cycle. When the used radio includes RSSI support only one cluster beacon and one network beacon per anchor headnode is required. The RF measurement and neighbor selection using

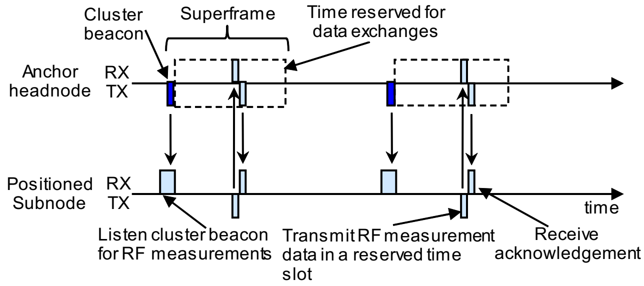

Figure 8: For centralized positioning the positioned subnodes transmit their RF measurement information via the multi-hop network. The information is transmitted during superframe reserved time slots. Acknowledgements are used for reliable communication.

the signal strength threshold can be done from the cluster beacon using RSSI. The RSSI value of the network beacon can be used for neighbor selection using the signal strength threshold when a node needs to scan.

If the used radio does not include RSSI support, the cluster and network beacons must be replaced with sets of beacons sent with varying transmission power levels. This enables transmission power based path loss metering. The amount of beacons in a cluster beacon set depends on the granularity required by the application and the amount of transmission power levels supported by the radio. The network beacon set requires two beacons. One sent at the signal strength threshold level and one sent with maximum transmission power for maximum radio coverage.

The presented RF measurement data gathering method can be used with any RF based positioning technique. For example if proximity-based closest anchor node technique is used, the positioned subnode can always stay synchronized to one anchor headnode within the chosen signal strength threshold. For finding the closest anchor node the signal strength threshold should be set to a high value. With trilateration, the positioned subnode can always stay synchronized to three anchor nodes within the chosen signal strength threshold. With RF-fingerprinting, the positioned subnode may choose to optimize power consumption and stay synchronized only to a few anchor nodes, or it may try to maximize positioning accuracy and choose to use as many anchor nodes as it can hear.

3.4 RF Measurement Information forwarding for Centralized Positioning

For centralized positioning the positioned subnodes transmit their RF measurements via the multi-hop network. Fig. 8 illustrates data transmission to next hop anchor headnode. The RF measurements and anchor node neighbor discovery are done using the network and cluster beacons as presented in previous section. The measured data is transmitted in reserved time slots following the cluster beacon

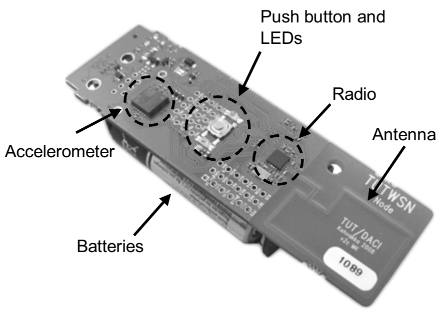

Figure 9: TUTWSN node hardware platform.

inside a superframe. All sent data is acknowledged by the receiver for reliable communication.

The data gathering inflicts uneven communication overhead to the routing anchor headnodes in the network. As data is collected using a tree-based structure the data always flows towards a sink node. Thus, routing anchor headnodes closer to the sink must forward more data.

4 TUTWSN Node Hardware Plarform

The TUTWSN node hardware platform is presented in Fig. 9. It uses a Microchip PIC18F8722 MicroController Unit (MCU), which integrates an 8-bit processor core with 128 kB of FLASH program memory, 4 kB of RAM data memory, and 1 kB EEPROM. The used clock speed the MCU is 8 MHz resulting in 2 MIPS performance.

For wireless communication the platform uses a Nordic Semiconductor nRF24L01 2.4 GHz radio transceiver having data rate of 1 Mbps and 80 available frequency channels in the Industrial, Scientific and Medical (ISM) unlicensed radio band. The radio does not support RSSI. Transmission power level is selectable from four power levels between -18 dBm and 0 dBm with 6 dBm intervals. These can be used for transmission power based path loss metering. Loop type antenna is implemented as a trace on the Printed Circuit Board (PCB). The user interface is implemented with push buttons and LEDs.

The hardware platform hosts multitude of sensors integrated to the circuit board or via an external connector. These sensors include temperature, illuminance, air humidity, accelerometer, soil humidity, carbon dioxide, sound pressure, air flow, electrical measurements (current, voltage, resistance, and power), motion detectors (passive infrared, piezo-cable), and magnetic switches. There is also support for on/off actuator control.

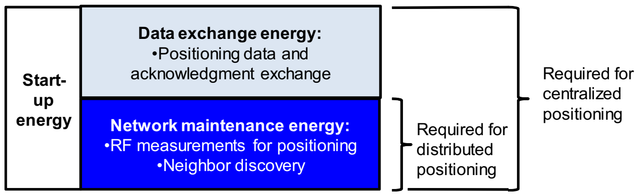

Figure 10: Node energy consumption can be divided into start-up, network maintenance, and data exchange energies. Start-up energy consumption is inflicted only at node power-up. Thus, network maintenance and data exchange energies dominate the overall energy consumption. Only the network maintenance energy consumption is inflicted in distributed positioning. Centralized positioning inflicts also additional data exchange energy consumption.

5 Power Consumption Models

Node energy consumption can be divided into start-up, network maintenance, and data exchange energies (Kohvakka et al. 2005*a*) as depicted in Fig. 10. The start-up energy consumption consists of the operations required to join the network. The start-up energy is negligible compared to the total energy consumption. After the start-up, the energy consumption consists of network maintenance and data exchange energies. The network maintenance energy includes the transmission and reception of the cluster and network beacons used for RF measurements and neighbor discovery. Thus, both the centralized and the distributed positioning architectures inflict network maintenance energy on the nodes. The data exchange energy consumption consists of the application data and acknowledgement exchanges. Thus, it is inherent only in the centralized architecture where the RF measurements need to be sent to a server.

Next, we present mathematical models for analyzing the power consumption caused by the network maintenance and the data exchanges. We start with the power consumption models for beacon exchanges needed for network link maintenance and positioning RF measurements used in both centralized and distributed positioning. This includes modeling the energy consumption of basic radio operations and power consumption of cluster and network beacon frame exchanges. Then, we derive mathematical models for data exchange power consumption inflicted by the RF measurement information forwarding in centralized positioning.

Since the radio used in the prototype platform does not include RSSI support the analysis with the platform can be done only for the transmission power based path loss metering RF measurement variant. For the RSSI based RF measurement analysis, we use power consumption and timing values for the Texas Instruments CC2531 chip (Homepage of Texas Instruments, Inc. 2010) that integrates a low-power MCU core with IEEE 802.15.4 compliant radio including

RSSI support. Since the CC2531 chip is not integrated to our current prototype platform, we use typical values provided by the datasheet.

Table 1 presents the power consumption and timing symbols and values for the hardware platform energy consumption analysis. Table 2 presents the symbols and defined values for the positioning power consumption analysis.

5.1 Radio Transmission and Reception Energy Models for RF Measurements and Neighbor Discovery

The radio frame transmission and reception energy models include the energy consumed by the radio, MCU, and the non-idealities of the physical layer. The non-idealities include radio start-up transient time, crystal inaccuracy, and synchronization inaccuracies caused by communicating timing information over one or two wireless hops.

The synchronization inaccuracies are measured from our implementation of ENDP (Kohvakka et al. 2009). The synchronization inaccuracy (t_{cbi}) for receiving periodical cluster beacons using the timing information provided in the previous cluster beacon is typically within $\pm$ 50 μs. The synchronization inaccuracy (t_{sdui}) for receiving the first cluster beacon from neighbor's neighbor using SDU information is typically within $\pm$ 250 μs.

Next, we will derive energy consumption models for

- the network beacon set transmitted during idle periods (E_{tx}^{inbs}),
- the *active network beacon* transmitted always a small constant time before the active period (E_{tx}^{anb}),
- the cluster beacon set transmission (E_{tx}^{cbs}),
- the reception of the beacon set transmitted at the start of an active period (active network beacon and cluster beacon set) (E_{rx}^{abs}),
- the successful reception of a cluster beacon set according to information provided in a SDU (E_{rx}^{sdus}), and
- the unsuccessful reception of cluster beacon set according to information provided in a SDU (E_{rxu}^{sdus}).

Note that in the RSSI variant a beacon set consists of one beacon frame whereas in transmission power based path loss metering variant the sets include multiple beacons transmitted with varying power levels. We start by defining energy consumption models for individual frame transmissions and receptions and continue to specify the transmission and reception energy consumptions of the beacon sets.

5.1.1 Energy Models for Individual Frame Transmissions and Receptions

A frame transmission consists of a radio start-up transient time (t_{st}) and the time required by the actual data transmission. The data transmission time is the ratio of frame length (L_f) and radio data rate (R). During the start-up transient the power consumption is estimated to be equal to the transmission mode power $P_{tx(n)}$, where n denotes the used transmission power. Thus, the energy consumption ($E_{tx(n)}$) of a frame transmitted using a power level n is

$$E_{tx(n)} = \left(t_{st} + \frac{L_f}{R} \right) P_{tx(n)}. \tag{1}$$

A beacon frame reception begins with the radio start-up transient and lasts until the frame has been completely received. The reception of a beacon frame using the timing information provided in the previous cluster beacon includes also idle listening caused by synchronization inaccuracy (t_{cbi}) and crystal inaccuracy (ϵ). During a frame reception the power consumption is equal to the reception mode power P_{rx}. The frame reception energy of a beacon using synchronization information provided in the cluster beacon of previous active period (E_{rx}^{cb}) is

$$E_{rx}^{cb} = \left(t_{st} + t_{cbi} + \frac{2\epsilon}{f_{ap}} + \frac{L_f}{R} \right) P_{rx}. \tag{2}$$

A beacon following immediately a small constant time after a previous beacon is assumed to have no synchronization error since the previous beacon reception synchronizes the frame exchange very accurately. Thus, this beacon reception energy is

$$E_{rx}^{pb} = \left(t_{st} + \frac{L_f}{R} \right) P_{rx}. \tag{3}$$

A cluster beacon reception according to SDU information includes more idle listening due to larger synchronization inaccuracy (t_{sdui}) caused by communicating synchronization information over two hops. Thus, a successful beacon reception energy using SDU information is (E_{rxu}^{sdu}) is

$$E_{rx}^{sdu} = \left(t_{st} + t_{sdui} + \frac{L_f}{R} \right) P_{rx}. \tag{4}$$

Since some of the two-hop neighbors signaled in SDUs are out of range, it is possible that a cluster beacon may be listened for but not received. Since both positive and negative synchronization inaccuracies are considered, the energy consumption of an unsuccessful beacon reception based on SDU information (E_{rx}^{sdu}) is

$$E_{rxu}^{sdu} = \left(t_{st} + 2t_{sdui} + \frac{L_f}{R} \right) P_{rx}. \tag{5}$$

5.1.2 Energy Models for RF Measurements with RSSI

When RSSI is in use only one cluster beacon and one network beacon needs to be sent at a time. In the analysis

Table 1: Symbols, descriptions, and defined values for hardware platform energy consumption analysis.

Symbol	**Description**	**CC2420** (Typical values)	**TUTWNS prototype platform** (Measured values)
	Radio and MCU power consumption in different modes		
$P_{tx(n)} n$=4	Power in transmission mode at -0.5/0 dBm	84 mW	42.4 mW
$P_{tx(n)} n$=3	Power in transmission mode at -6 dBm	78 mW	35.3 mW
$P_{tx(n)} n$=2	Power in transmission mode at -12 dBm	75 mW	30.8 mW
$P_{tx(n)} n$=1	Power in transmission mode at -18 dBm	72 mW	28.5 mW
P_{rx}	Power in reception	72.9 mW	48.7 mW
P_{rs}	Power in sleep mode	3 μW	39 μW
	Radio timing values		
t_{st}	Sleep to active transient time	600 μs	280 μs
	Radio data transfer parameters		
R	Data rate	250 kbps	1 Mbps
L_f	Frame length	256 bits	256 bits
	Synchronization inaccuracies		
t_{cbi}	Synchronization inaccuracy when using previous cluster beacon information	50 μs	
ϵ	Crystal inaccuracy	20 ppm	
t_{sdui}	Synchronization inaccuracy when using SDU information	250 μs	

we use the highest transmission power given in Table 1. Thus, the energy consumption of the idle network beacon set transmission (E_{tx}^{inbs}), the active network beacon transmission (E_{tx}^{anb}), and the cluster beacon set transmission (E_{tx}^{cbs}) is

$$E_{tx}^{inbs} = E_{tx}^{anb} = E_{tx}^{cbs} = E_{tx(4)}. \quad (6)$$

The active period starts with an active network beacon which is followed immediately by a cluster beacon. The reception energy consumption of the beacon set transmitted at the start of an active period (E_{rx}^{abs})

$$E_{rx}^{abs} = E_{rx}^{cb} + E_{rx}^{pb}. \quad (7)$$

The energy consumption of successful reception of a cluster beacon set consisting of one cluster beacon according to information provided in an SDU (E_{rx}^{sdus}) is

$$E_{rx}^{sdus} = E_{rx}^{sdu}, \quad (8)$$

and the energy consumption of an unsuccesful reception is

$$E_{rxu}^{sdus} = E_{rxu}^{sdu}. \quad (9)$$

5.1.3 Energy Models for RF Measurements with Transmission Power Based Path Loss Metering

With transmission power based path loss metering the idle network beacon set consists of two beacons; one sent at the threshold level, chosen to be transmission power level 3, and one sent at the highest transmission power level 4. Thus, the energy consumption of the idle network beacon set transmission (E_{tx}^{inbs}) is

$$E_{inbs} = E_{tx(3)} + E_{tx(4)}. \quad (10)$$

Since the active network beacon is used only for communicating SDU information one beacon is sufficient and the energy consumption of the active network beacon transmission (E_{tx}^{anb}) is

$$E_{tx}^{anb} = E_{tx(4)}. \quad (11)$$

The cluster beacon set consists of four beacons transmitted with varying power levels. Thus, cluster beacon set transmission energy (E_{tx}^{cbs}) is

$$E_{tx}^{cbs} = E_{tx(1)} + E_{tx(2)} + E_{tx(3)} + E_{tx(4)}. \quad (12)$$

The active period starts with an active network beacon which is followed immediately by a cluster beacon set. On average two cluster beacons need to be received from the total four beacons. The average reception energy consumption of the beacon set transmitted at the start of an active period (E_{rx}^{abs})

$$E_{rx}^{abs} = E_{rx}^{cb} + 2E_{rx}^{pb}. \quad (13)$$

Similarly, the successful reception of a cluster beacon set consisting of four cluster beacons according to information

Table 2: Symbols, descriptions, and defined values for positioning power consumption analysis.

Symbol	Description	Value
	Positioning parameters	
N_a	Required number of anchor nodes for RF measurements	1
v	Positioned node speed	Variable: 0.3 or 1 m/s
f_l	Location refresh rate	Variable: 0.03 or 1 Hz
N_s	Number of positioned subnodes in the network	100
	Beacon parameters	
f_{ap}	Active period occurrence rate	Equals f_l
f_{nb}	Network beacon transmission rate	0.01-100 Hz
	Radio range parameters	
r	Maximum radio range	25 m
ρ	Range of sufficient signal strength compared to maximum radio range	0.75
N_n	Number of nodes within radio range	10

provided in an SDU (E_{rx}^{sdus}) is

$$E_{rx}^{sdus} = E_{rx}^{sdu} + E_{rx}^{pb}, \tag{14}$$

With the unsuccesful reception according to SDU information, the time of all four cluster beacons needs to be listened giving

$$E_{rxu}^{sdus} = E_{rxu}^{sdu} + 3E_{rx}^{pb}, \tag{15}$$

5.2 Power Consumption Models for RF Measurements and Neighbor Discovery

When a positioned subnode moves out of its neighboring anchor headnode radio range (r), a link failure occurs. For a node moving at speed v and having links to N_a neighboring headnodes, the link failure rate (f_{lf}) can be approximated to be (Kohvakka et al. 2009)

$$f_{lf} = \frac{N_a v}{r}. \tag{16}$$

A positioned subnode tries to maintain links to N_a anchor headnodes. For simplicity, we assume that also the anchor headnodes maintain links to N_a other anchor headnodes. ENDP can maintain links with proactive node schedule distribution without the need for network scan as long as valid SDUs are received.

After a link failure, a positioned subnode tries to synchronize to new neighboring anchor headnodes using information provided in the SDUs. Synchronization is attempted until an attempt is successful or all N_a^2 SDUs are examined. An invalid SDU contains data about an anchor headnode that is out of radio range making synchronization to it impossible.

Assuming uniform headnode distribution, the probability (q) that the received N_a^2 SDUs from N_a neighbors are invalid and a network scan is required is (Kohvakka et al. 2009)

$$q = \prod_{a=1}^{N_a} \left(1 - \frac{N_n p_v}{N_n - (a-1)}\right)^{N_a}, \tag{17}$$

where p_v ($\approx$ 59%) is the probability that the received SDU is valid and N_n is the total amount of anchor headnodes in the radio range of a positioned subnode.

When having no neighbors, a positioned subnode needs to scan until a network beacon with sufficient signal strength is received. The range of sufficient signal strength in proportion to maximum radio range (r) is defined to be ρ. The probability that the anchor headnode from which the first network beacon is received is within sufficient signal strength is ρ^2. If the attempt fails, the number of anchor headnodes outside the sufficient radio range decreases. The expected number of network beacon receptions (N_{nb}) until a beacon with sufficient signal strength is received is (Kohvakka et al. 2009)

$$N_{nb} = \rho^2 + \sum_{a=2}^{N_n-1} a \left(\prod_{b=1}^{a-1} \left(1 - \frac{N_n \rho^2}{N_n - (b-1)}\right)\right) \frac{N_n \rho^2}{N_n - (a-1)} + N_n \prod_{a=1}^{N_n-1} \left(1 - \frac{N_n \rho^2}{N_n - (a-1)}\right). \tag{18}$$

The required network scan duration (t_{ns}) can be derived to be (Kohvakka et al. 2009)

$$t_{ns} = \frac{N_{nb}}{f_{nb} N_n}. \tag{19}$$

The long-time average power of network scans (P_{ns}) using ENDP is (Kohvakka et al. 2009)

$$P_{ns} = f_{lf} q \left(t_{st} + t_{ns}\right) P_{rx}. \quad (20)$$

When a node loses a neighbor it tries to synchronize to a new headnode by listening its cluster beacons at the time provided in the received SDUs. When using SDU information, the probability of finding a neighboring anchor headnode with sufficient signal strength in the first attempt is $p_v \rho^2$. Similarly to (18), the expected number of cluster beacon receptions (u) until a neighboring anchor headnode with sufficient signal strength is found is (Kohvakka et al. 2009)

$$u = p_v \rho^2 + \sum_{a=2}^{N_a^2 - 1} a \left(\prod_{b=1}^{a-1} \left(1 - \frac{N_n p_v \rho^2}{N_n - (b-1)} \right) \right) \frac{N_n p_v \rho^2}{N_n - (a-1)} + N_a^2 \prod_{a=1}^{N_a^2 - 1} \left(1 - \frac{N_n p_v \rho^2}{N_n - (a-1)} \right). \quad (21)$$

The anchor headnodes transmit network and cluster beacon sets at rates f_{nb} and f_{ap}, respectively. A positioned subnode receives active network beacons and cluster beacons at the starts of anchor headnodes' active periods from the N_a neighboring anchor headnodes to which it maintains synchronization. The active periods occur at rate f_{ap}. After every link failure, which occur at rate f_{lf}, on average u cluster beacon set reception attempts is needed when using SDU information. Thus, the average power (P_{bp}) consumed by a positioned subnode on beacon receptions is

$$P_{bp} = N_a f_{ap} E_{rx}^{abs} + f_{lf}((u-1) E_{rxu}^{sdus} + E_{rx}^{sdus}). \quad (22)$$

The total neighbor maintenance and RF signal measurement power consumption of a positioned subnode consists of the network scan power (P_{ns}) and the beacon reception power (P_{bp}). The rest of the time is spent in sleep mode so also the radio and the MCU sleep power consumptions need to be included. This gives a total power consumption of

$$P_{mp} = P_{ns} + P_{bp} + P_s. \quad (23)$$

For the anchor headnodes, also the beacon transmission consume energy. However, as the anchor headnodes are static their link failure rate is assumed to be zero. Thus, the average power (P_{ba}) consumed by an anchor headnode on beacon exchanges is

$$P_{ba} = f_{nb} E_{tx}^{inbs} + f_{ap}(E_{tx}^{anb} + E_{tx}^{cbs}) + N_a f_{ap} E_{rx}^{abs}. \quad (24)$$

As anchor headnodes require a network scan only at start-up, its power consumption is negligible. Thus, the total power consumption of anchor headnodes is given by

$$P_{ma} = P_{ba} + P_s. \quad (25)$$

5.3 Power Consumption Models for Application Data Exchanges

For centralized positioning the positioned subnodes transmit their RF measurements to the server in application data frames. A data transmission includes exchanging a data frame and an acknowledgement frame. A frame transmission is assumed to happen at the maximum transmission power level to maximize link budget and minimize packet error rate. Thus, the energy consumed by a data frame (E_{tx}^{data}) or an acknowledgement frame (E_{tx}^{ack}) transmission is

$$E_{tx}^{data} = E_{tx}^{ack} = E_{tx(4)}. \quad (26)$$

A frame transmission inside a superframe is accurately synchronized by the cluster beacon. Thus, required reception margins are assumed to be zero and the energy consumed by a data frame (E_{rx}^{data}) or an acknowledgement frame (E_{rx}^{ack}) reception is

$$E_{rx}^{data} = E_{rx}^{ack} = \left(t_{st} + \frac{L_f}{R} \right) P_{rx}. \quad (27)$$

The positioned subnodes transmit their RF measurements with a rate equaling the location refresh rate f_l. A positioned subnode acts as a leaf node in the network. For each data exchange it needs to transmit the RF measurement data frame to a neighboring anchor headnode and receive an acknowledgement frame. Thus, a positioned subnode data exchange power consumption (P_{dp}) is

$$P_{dp} = f_l(E_{tx}^{data} + E_{rx}^{ack}) \quad (28)$$

An anchor headnode routing the data receives application data frames from N_{dl} positioned subnodes that are in the downlink direction of it in the routing tree. For each of the N_{dl} positioned subnodes, data is received with rate f_l. Also, an anchor headnode acknowledges the received data packets. The data is generated by a direct neighboring positioned subnode or received from another anchor headnode routing the data. Furthermore, an anchor headnode has to forward the received data resulting in N_{dl} data frame transmission and acknowledgement frame receptions with a rate of f_l. Thus, an anchor headnode data exchange power consumption (P_{da}) is

$$P_{da}(N_{dl}) = N_{dl} f_l (E_{rx}^{data} + E_{tx}^{ack} + E_{tx}^{data} + E_{rx}^{ack}). \quad (29)$$

Anchor nodes neighboring a sink have to forward most data frames. Thus, the network lifetime is dictated by these nodes as they're batteries deplete first and after this connectivity to the sink is lost. It is assumed that the forwarded data is evenly balanced between the N_n anchor nodes in the sink's radio range. Thus, the worst case anchor node data exchange power consumption (P_{da}^{wc}) is

$$P_{da}^{wc} = \frac{P_{da}(N_s)}{N_n} \tag{30}$$

with N_s positioned subnodes in the network.

6 Analysis Results

Using the presented models we have calculated the positioned subnode and anchor headnode power consumptions with localization to closest anchor node. The positioned subnode speed, and required location refresh rate are varied. The main parameter affecting the tradeoff between positioned subnode and anchor headnode power consumption while positioned subnodes are mobile is the network beacon transmission rate. The parameter values used in the analysis are given in Table 2.

Furthermore, we have calculated the optimal network power consumption, where positioned subnode power and anchor headnode power are mutually minimized, for each case. With the optimal power consumption we have estimated the network lifetime when two AA lithium batteries are used as the power source for the nodes. According to our measurements the effective capacity of two AA lithium batteries with our prototype platform is 2850 mAh.

6.1 Analysis Results for RF Measurements with RSSI - Distributed Positioning

Figs. 11-12 present the power consumptions for positioned subnode and anchor headnode when RSSI-based RF measurements are used in distributed positioning architecture. The results are obtained using values for the CC2531 from Table 1.

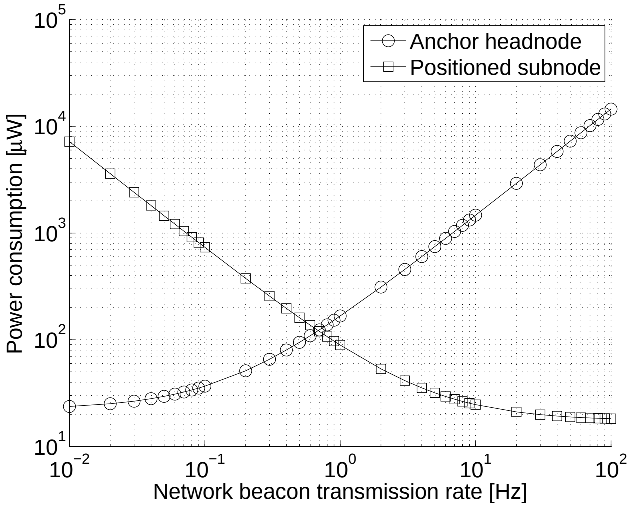

Figure 11: Positioned subnode and anchor headnode power consumption in distributed positioning. RSSI is used for RF measurements. Positioned subnode speed is is 0.3 m/s (≈1 km/h), location refresh rate is 0.03 Hz (≈30 min location update interval), and required number of anchor nodes is 1. The network beacon transmission rate varies from 0.01 Hz to 100 Hz. CC2531 power consumption and timing values used.

Fig. 11 presents the positioned subnode and anchor headnode power consumption when positioned subnode speed is 0.3 m/s (≈1 km/h), location refresh rate is 0.03 Hz (≈30 min location update interval), required number of anchor nodes is 1, and the network beacon transmission rate varies from 0.01 Hz to 100 Hz. The optimal power consumption of 122 μW is achieved with 0.68 Hz network beacon transmission rate. This results in estimated network lifetime of 97 months.

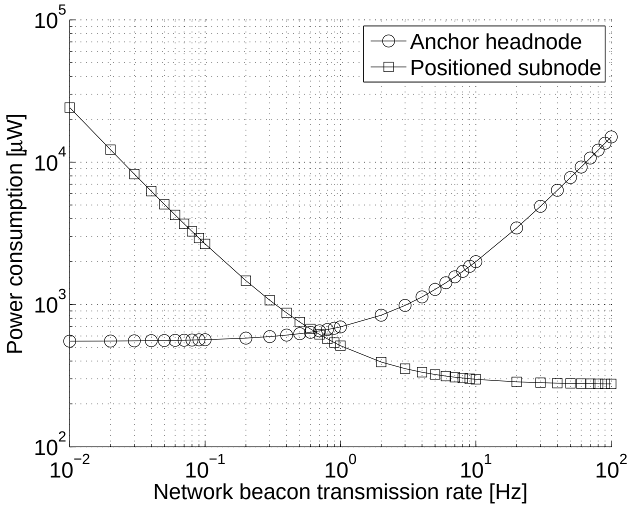

Figure 12: Positioned subnode and anchor headnode power consumption in distributed positioning. RSSI is used for RF measurements. Positioned subnode speed is 1 m/s (3.6 km/h), location refresh rate is 1 Hz (1 s location update interval), and required number of anchor nodes is 1. The network beacon transmission rate varies from 0.01 Hz to 100 Hz. CC2531 power consumption and timing values used.

Fig. 12 presents the positioned subnode and anchor headnode power consumption when positioned subnode speed is 1 m/s (3.6 km/h), location refresh rate is 1 Hz (1 s location update interval), required number of anchor nodes is 1, and the network beacon transmission rate varies from 0.01 Hz to 100 Hz. The optimal power consumption of 644 μW is achieved with 0.65 Hz network beacon transmission rate. This results in estimated network lifetime of 18.4 months.

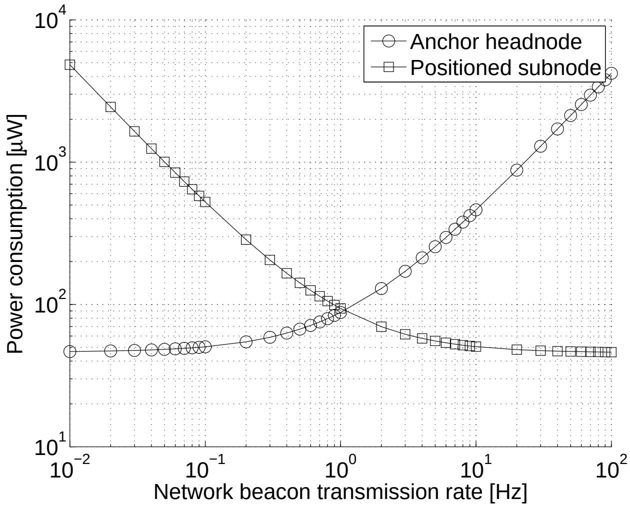

Figure 13: Positioned subnode and anchor headnode power consumption in distributed positioning. Transmission power based path loss metering is used for RF measurements. Positioned subnode speed is is 0.3 m/s (≈1 km/h), location refresh rate is 0.03 Hz (≈30 min location update interval), and required number of anchor nodes is 1. The network beacon transmission rate varies from 0.01 Hz to 100 Hz. TUTWSN prototype platform power consumption and timing values used.

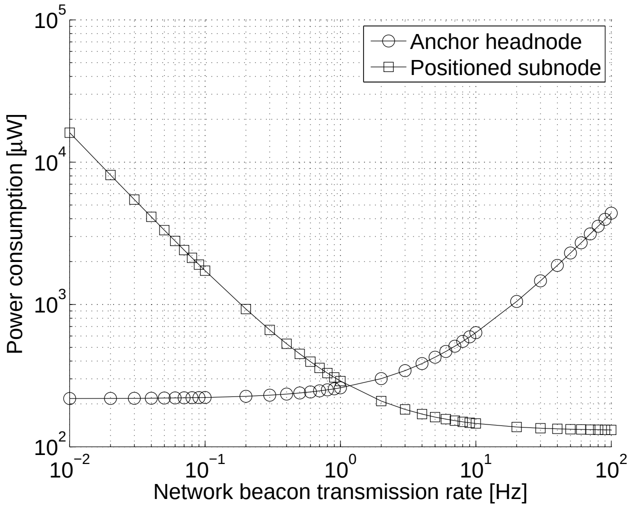

Figure 14: Positioned subnode and anchor headnode power consumption in distributed positioning. Transmission power based path loss metering is used for RF measurements. Positioned subnode speed is 1 m/s (3.6 km/h), location refresh rate is 1 Hz (1 s location update interval), and required number of anchor nodes is 1. The network beacon transmission rate varies from 0.01 Hz to 100 Hz. TUTWSN prototype platform power consumption and timing values used.

6.2 Analysis Results for RF Measurements with Transmission Power based Path Loss Metering - Distributed Positioning

Figs. 13-14 present the power consumptions for positioned subnode and anchor headnode when transmission power based path loss metering is used for RF measurements in distributed positioning architecture. The results are obtained using values for the prototype platform from Table 1.

Fig. 13 presents the positioned subnode and anchor headnode power consumption when positioned subnode speed is 0.3 m/s (≈1 km/h), location refresh rate is 0.03 Hz (≈30 min location update interval), required number of anchor nodes is 1, and the network beacon transmission rate varies from 0.01 Hz to 100 Hz. The optimal power consumption of 91 μW is achieved with 1.07 Hz network beacon transmission rate. This results in estimated network lifetime of 131 months.

Fig. 14 presents the positioned subnode and anchor headnode power consumption when positioned subnode speed is 1 m/s (3.6 km/h), location refresh rate is 1 Hz (1 s location update interval), required number of anchor nodes is 1, and the network beacon transmission rate varies from 0.01 Hz to 100 Hz. The optimal power consumption of 266 μW is achieved with 1.17 Hz network beacon transmission rate. This results in estimated network lifetime of 44.5 months.

6.3 Analysis Results for RF Measurements with RSSI - Centralized Positioning

Figs. 15-16 present the power consumptions for positioned subnode and anchor headnode when RSSI-based RF measurements are used in centralized positioning architecture. The results are obtained using values for the CC2531 from Table 1.

Fig. 15 presents the positioned subnode and anchor headnode power consumption when positioned subnode speed is 0.3 m/s (≈1 km/h), location refresh rate is 0.03 Hz (≈30 min location update interval), required number of anchor nodes is 1, and the network beacon transmission rate varies from 0.01 Hz to 100 Hz. The optimal power consumption of 234 μW is achieved with 0.34 Hz network beacon transmission rate. This results in estimated network lifetime of 51 months.

Fig. 16 presents the positioned subnode and anchor headnode power consumption when positioned subnode speed is 1 m/s (3.6 km/h), location refresh rate is 1 Hz (1 s location update interval), required number of anchor nodes is 1, and the network beacon transmission rate varies from 0.01 Hz to 100 Hz. The optimal power consumption of 6.0 mW is achieved with 0.04 Hz network beacon transmission rate. This results in estimated network lifetime of 2.0 months.

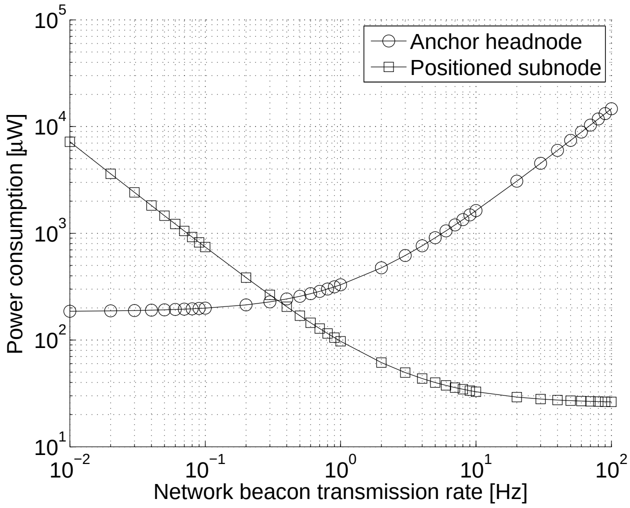

Figure 15: Positioned subnode and anchor headnode power consumption in centralized positioning. RSSI is used for RF measurements. Positioned subnode speed is is 0.3 m/s (≈1 km/h), location refresh rate is 0.03 Hz (≈30 min location update interval), and required number of anchor nodes is 1. The network beacon transmission rate varies from 0.01 Hz to 100 Hz. CC2531 power consumption and timing values used.

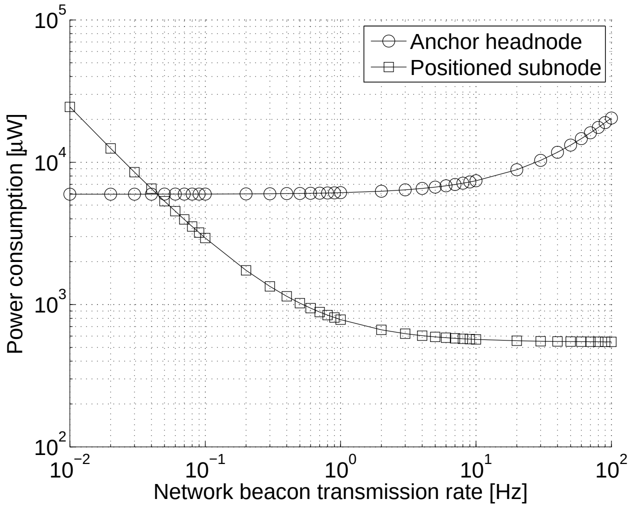

Figure 16: Positioned subnode and anchor headnode power consumption in centralized positioning. RSSI is used for RF measurements. Positioned subnode speed is 1 m/s (3.6 km/h), location refresh rate is 1 Hz (1 s location update interval), and required number of anchor nodes is 1. The network beacon transmission rate varies from 0.01 Hz to 100 Hz. CC2531 power consumption and timing values used.

6.4 Analysis Results for RF Measurements with Transmission Power based Path Loss Metering - Centralized Positioning

Figs. 17-18 present the power consumptions for positioned subnode and anchor headnode when transmission power based path loss metering is used for RF measurements in

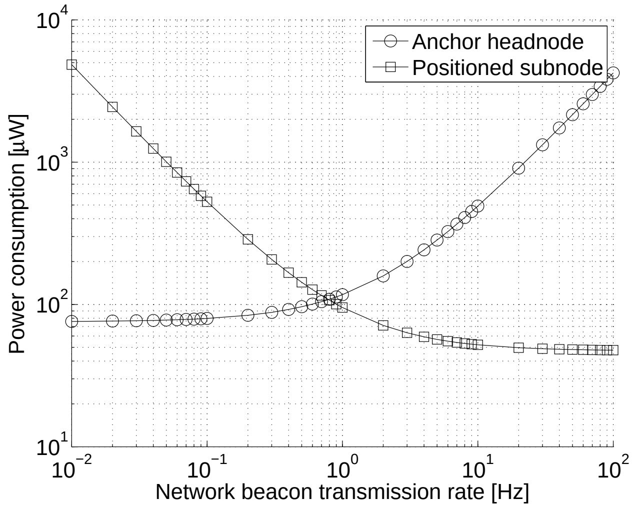

Figure 17: Positioned subnode and anchor headnode power consumption in centralized positioning. Transmission power based path loss metering is used for RF measurements. Positioned subnode speed is is 0.3 m/s (≈1 km/h), location refresh rate is 0.03 Hz (≈30 min location update interval), and required number of anchor nodes is 1. The network beacon transmission rate varies from 0.01 Hz to 100 Hz. TUTWSN prototype platform power consumption and timing values used.

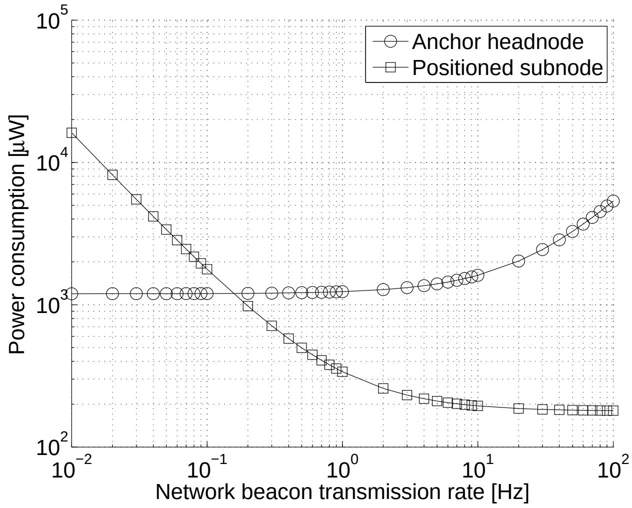

Figure 18: Positioned subnode and anchor headnode power consumption in centralized positioning. Transmission power based path loss metering is used for RF measurements. Positioned subnode speed is 1 m/s (3.6 km/h), location refresh rate is 1 Hz (1 s location update interval), and required number of anchor nodes is 1. The network beacon transmission rate varies from 0.01 Hz to 100 Hz. TUTWSN prototype platform power consumption and timing values used.

centralized positioning architecture. The results are obtained using values for the prototype platform from Table 1.

Fig. 17 presents the positioned subnode and anchor headnode power consumption when positioned subnode speed is 0.3 m/s (≈1 km/h), location refresh rate is 0.03 Hz (≈30 min location update interval), required number of anchor nodes is 1, and the network beacon transmission rate varies from 0.01 Hz to 100 Hz. The optimal power consumption of 108 μW is achieved with 0.79 Hz network beacon transmission rate. This results in estimated network lifetime of 110 months.

Fig. 18 presents the positioned subnode and anchor headnode power consumption when positioned subnode speed is 1 m/s (3.6 km/h), location refresh rate is 1 Hz (1 s location update interval), required number of anchor nodes is 1, and the network beacon transmission rate varies from 0.01 Hz to 100 Hz. The optimal power consumption of 1.2 mW is achieved with 0.16 Hz network beacon transmission rate. This results in estimated network lifetime of 9.9 months.

7 Conclusions

In this paper, we presented a method for positioning data gathering using synchronized MAC and ENDP signaling frames. The presented method inflicts minimal overhead on the WSN operation. Furthermore, we presented mathematical analysis models for estimating the network lifetime when average positioned node speed, the amount of anchor nodes required by the location estimation algorithm, and the location refresh rate required by the application are known. Models for both distributed in-network positioning and centralized positioning were presented.

Using the models we calculated results for network lifetime when the nodes use two AA lithium batteries as power source. The presented results based on two kinds of node hardware: real TUTWSN node hardware prototypes having no RSSI support and node hardware using an IEEE 802.15.4 compliant radio with RSSI.

Using RSSI measurements and CC2531 chip, the network lifetime ranged from 97 to 18.4 months in distributed positioning and from 51 to 2 months in centralized positioning. Using transmission power based path loss metering measurements and TUTWSN prototype platform, the network lifetime ranged from 131 to 44.5 months in distributed positioning and from 110 to 9.9 months in centralized positioning.

The results show that the positioning parameters and the energy-efficiency of the used hardware have significant impact on node power consumption and lifetime. This should be taken into consideration when estimating the feasibility of the positioning application. The presented models provide a tool for estimating network lifetimes with different positioning parameters and hardware.

Our future work includes the implementation of the presented positioning method in TUTWSN which already uses a synchronized low-power MAC protocol for communication and ENDP for neighbor discovery and integrating it with positioning algorithms developed in our previous work.

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