Performance Analysis of IEEE 802.15.4 and ZigBee for Large-Scale Wireless Sensor Network Applications

Mikko Kohvakka
Tampere University of Technology
Institute of Digital and Computer Systems
33720 Tampere, Finland
+358 3 3115 4702
mikko.kohvakka@tut.fi

Mauri Kuorilehto
Tampere University of Technology
Institute of Digital and Computer Systems
33720 Tampere, Finland
+358 3 3115 4567
mauri.kuorilehto@tut.fi

Marko Hännikäinen
Tampere University of Technology
Institute of Digital and Computer Systems
33720 Tampere, Finland
+358 3 3115 3837
marko.hannikainen@tut.fi

Timo D. Hämäläinen
Tampere University of Technology
Institute of Digital and Computer Systems
33720 Tampere, Finland
+358 3 3115 3385
timo.d.hamalainen@tut.fi

ABSTRACT

This paper analyses the performance of IEEE 802.15.4 Low-Rate Wireless Personal Area Network (LR-WPAN) in a large-scale Wireless Sensor Network (WSN) application. To minimize the energy consumption of the entire network and to allow adequate network coverage, IEEE 802.15.4 peer-to-peer topology is selected, and configured to a beacon-enabled cluster-tree structure. The analysis consists of models for CSMA-CA mechanism and MAC operations specified by IEEE 802.15.4. Network layer operations in a cluster-tree network specified by ZigBee are included in the analysis. For realistic results, power consumption measurements on an IEEE 802.15.4 evaluation board are also included. The performances of a device and a coordinator are analyzed in terms of power consumption and goodput. The results are verified with simulations using WIreless SEnsor NEtwork Simulator (WISENES). The results depict that the minimum device power consumption is as low as 73 μW, when beacon interval is 3.93 s, and data are transmitted at 4 min intervals. Coordinator power consumption and goodput with 15.36 ms CAP duration and 3.93 s beacon interval are around 370 μW and 34 bits/s.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design – *wireless communication.*

General Terms

Measurement, Performance, Standardization, Theory

Keywords

Wireless networks, IEEE 802.15.4, ZigBee, WPAN, cluster-tree, performance evaluation, simulation.

1. INTRODUCTION

Wireless Sensor Networks (WSN) are fully autonomous self-configuring ad-hoc networks. Typical emerging applications are monitoring and control in home, office, industrial, and outdoor environments. WSNs may consist of thousands of tiny and very energy constrained nodes, which communicate wirelessly with each other, sense their environment, and share collaborative tasks. Due to the large number of nodes, frequent battery replacements are difficult. Hence, the network lifetime should be in the order of years requiring a very careful design of communication protocols, algorithms, and hardware platforms.

The Wireless Personal Area Networks (WPAN) Working Group was initially focused on creating the IEEE 802.15.1 standard for Physical (PHY) and Medium Access Control (MAC) layers based on Bluetooth technology in 1999 [11]. In the following year the Working Group formed two other subgroups, firstly IEEE 802.15.3 for high-speed WPAN [12] for multimedia applications, and in December 2000 IEEE 802.15.4 low-rate WPAN (LR-WPAN) [13] providing low-complexity, low-cost and low-power wireless connectivity among inexpensive devices [2]. Thus, LR-WPAN has been one of the most foreseen technologies enabling WSNs.

ZigBee [16] is an open specification for low-power wireless networking, which complements the LR-WPAN standard with network and security layers, and application profiles. For security and reliability, ZigBee supports access control lists, packet freshness timers, and 128-bit Advanced Encryption Standard (AES). Different stack profiles are defined for home control, building automation, and plant control applications. The first version of ZigBee specification was announced in December 2004.

In this paper we present mathematical performance analysis and simulations of IEEE 802.15.4 LR-WPAN in a large-scale WSN application with up to 1560 nodes. The network is formed in a beacon enabled cluster-tree topology according to ZigBee specification [16]. While few studies considering only star networks exist, this is the first paper that covers a cluster-tree topology enabling low energy and large area implementations.

The performance of a device and a coordinator are analyzed in terms of the average power consumption and throughput. The analysis results are verified by simulations with WIreless SEnsor NEtwork Simulator (WISENES) [4]. These performance models form a framework that can be used as such for designing real LR-WPAN deployments.

The paper is organized as follows. Section 2 discusses the state of related research on LR-WPAN performance analysis. Section 3 gives an overview of the LR-WPAN standard. The analyzed application, network topology, and hardware platform are presented in Section 4. Section 5 presents the models for required MAC operations. The analysis results are given in Section 6 followed by

PE-WASUN'06, October 6, 2006, Torremolinos, Malaga, Spain.

the simulations results in Section 7. Finally, Section 8 concludes this paper.

2. RELATED RESEARCH

According to our best knowledge, there exist only few articles that analyze mathematically or simulate the performance of IEEE 802.15.4. The performance of IEEE 802.15.4 in a star network with 100 nodes is analyzed in [1]. The paper contains a compact mathematical analysis of average power consumption and transmission failure rate. The analysis is complemented with real measurements of steady state powers and transient energy, and switch times from a standard compliant evaluation board. A special contribution is bit error rate measurements with two evaluation boards connected through a set of calibrated attenuators. The operational analysis considers mainly the effect of path loss and packet size on energy consumption.

In [6], the performance of IEEE 802.15.4 is analyzed for medical sensor body area networking. The analysis considers quite extensively a very low data rate star network with 10 body implanted sensors transmitting data 1 to 40 times per hour. The analysis focuses on the effect of a crystal tolerance, a frame size, and the usage of IEEE 802.15.4 Guaranteed Time Slots (GTS) on a node lifetime. For analyzing the standard performance in WSN applications, further analysis with larger and more complex network topologies and other IEEE 802.15.4 MAC parameters is required.

In [5], the performance simulations of IEEE 802.15.4 in a star network are presented. The network consists of 49 nodes configured to IEEE 802.15.4 beacon-enabled mode. The evaluation considers latency and energy with different amounts of background traffic. Also, the performance of IEEE 802.15.4 GTS and beacon tracking are simulated. Still, the applicability of the results for WSN applications is insufficient, since larger network sizes with cluster-tree network topologies are required.

3. IEEE 802.15.4 OVERVIEW

An IEEE 802.15.4 network may operate in one of three Industrial, Scientific, Medical (ISM) frequency bands, presented in Table 1. The 2.4 GHz frequency band is the most potential for large-scale WSN applications, since the high radio data rate reduces the frame transmission time and thus the energy per transmitted and received bit. Also, network scalability is improved, since a higher number of nodes may communicate with each other within a given time period. In addition, the band is available in most countries worldwide. Hence, in this analysis we focus on the 2.4 GHz band.

IEEE 802.15.4 defines three types of logical devices, a Personal Area Network (PAN) coordinator, a coordinator and a device. The PAN coordinator is the primary controller of PAN, which initiates the network and operates often as a gateway to other networks. Each PAN must have exactly one PAN coordinator. Coordinators collaborate with each other for executing data routing and network self-organization operations. Devices do not have data routing capability and can communicate only with coordinators.

Due to the low performance requirements of devices, they may be implemented with very simple and low-cost platforms. The standard designates these low complexity platforms as Reduced Function Devices (RFD). Platforms with the complete set of MAC services are referred to as Full Function Devices (FFD).

Table 1. IEEE 802.15.4 frequency bands and data rates.

Band	868 MHz	915 MHz	2.4 GHz
Region	EU, Japan	US	Worldwide
Channels	1	10	16
Data rate	20 kbps	40 kbps	250 kbps

3.1 Network Topology

The standard supports two network topologies, star and peer-to-peer, which are presented in Figure 1. In the star topology, communication is controlled by a PAN coordinator that operates as a network master, while devices operate as slaves and communicate only with the PAN coordinator. The devices may be either FFDs or RFDs. This single-hop network is most suitable for delay critical applications, where a large network coverage area is not required.

A peer-to-peer topology allows "mesh" type of networks, where any coordinator may communicate with any other coordinator within its range, and have messages multi-hop routed to coordinators outside its range. The network may contain also RFDs as devices. This enables the formation of complex self-organizing network topologies. Peer-to-peer topologies are suitable for industrial and commercial applications, where efficient self-configurability and large coverage are important. A disadvantage is the increased network latency due to the message relaying.

One special type of peer-to-peer topology is a cluster-tree network, which is highly static once it has been formed. The network consists of clusters, each having a coordinator as a cluster head and multiple devices as leaf nodes. A PAN coordinator initiates the network and serves as the root. The network is formed by parent-child relationships, where new nodes associate as children with the existing coordinators. A PAN coordinator may instruct a new child FFD to become the cluster head of a new cluster. Otherwise, the child operates as a device. Node operations in a cluster-tree network are specified by ZigBee [16].

An example of the cluster-tree network structure is presented in Figure 2. This well-defined structure simplifies multi-hop routing and allows considerable energy savings; each node maintains the synchronization of data exchanges with its parent coordinator only. The rest of time, nodes may save energy in a sleep mode. This is not possible in the "mesh" peer-to-peer networks, where coordinators need to receive continuously to be able to receive data from any node in the range. A disadvantage is that a coordinator failure may cause a large amount of orphaned child and grand-child nodes and energy consuming re-associations.

3.2 Medium Access Control (MAC) Layer

The MAC protocol in IEEE 802.15.4 can operate on both beacon-enabled and non-beacon modes. In the non-beacon mode, a protocol is a simple Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA). This requires a constant reception of possible

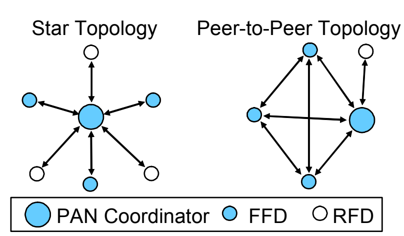

Figure 1. Star and peer-to-peer topology examples.

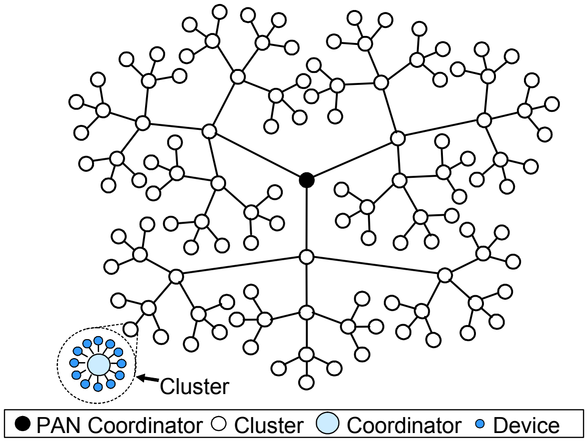

Figure 2. Analyzed cluster-tree network topology.

incoming data. The power saving features that are critical in WSN applications are provided by the beacon-enabled mode. Hence, we concentrate on the beacon-enabled mode from now on.

In the beacon-enabled mode, all communications are performed in a superframe structure presented in Figure 3. A superframe is bounded by periodically transmitted beacon frames, which allow nodes to synchronize to the network. An active part of a superframe is divided into 16 contiguous time slots that form three parts: the beacon, Contention Access Period (CAP) and Contention-Free Period (CFP). At the end of the superframe is an inactive period, when nodes may enter to a power saving mode. The Beacon Interval (I_B) and the active Superframe Duration (*SD*) are adjustable by Beacon Order (*BO*) and Superframe Order (*SO*) parameters as

$$I_B = aBaseSuperframeDuration \times 2^{BO}, \quad (1)$$

$$SD = aBaseSuperframeDuration \times 2^{SO}, \quad (2)$$

where *aBaseSuperframeDuration* = *aBaseSlotDuration* x *aNumSuperframeSlots,* and $0 \le SO \le BO \le 14$.

aBaseSlotDuration equals to 60 radio symbols resulting 15.36 ms minimum SD (*SO* = 0) at the 2.4 GHz band with 16 superframe slots. Hence, I_B and *SD* may be between 15.36 ms and 251.7 s. The superframe structure is maintained by the PAN coordinator. In cluster-tree networks, all coordinators may transmit beacons in order to maintain the synchronization with their children.

3.2.1 Contention Access Period

In addition to the beacon, CAP is a mandatory part of a superframe. Coordinators are required to listen to the channel the whole CAP to detect and receive any data from their child nodes. On the other hand, the child nodes may only transmit data and receive an optional acknowledgement (ACK) when needed, which increases their energy efficiency.

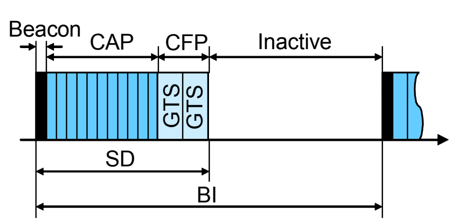

Figure 3. Superframe structure in beacon-enabled mode.

Downlink data from a coordinator to its child node are sent indirectly requiring totally four transmissions. The availability of pending data is signaled in beacons. First, a child requests the pending data by transmitting a data request message. The coordinator responds to the request with ACK frame, and then transmits the requested data frame. Finally, the child transmits ACK if the data frame was successfully received.

IEEE 802.15.4 utilizes a modified slotted CSMA-CA scheme during the CAP, except for ACK frames that are transmitted without carrier sensing. The scheme is modified from the IEEE 802.11 DCF protocol [10]. The major differences to the legacy CSMA-CA are that a channel is not sensed during a backoff time, and that a new random backoff is selected if a channel is busy during the carrier sensing. In dense networks this may lead to inefficient channel utilization and long channel access delay [3]. The protocol is prone to hidden node collisions, when two nodes outside the range of each other are transmitting data to a common coordinator. The protocol does not provide any type of protection against the hidden node problem [3].

For accessing a channel, each node maintains three variables: *NB, BE* and *CW*. *NB* is the number of CSMA-CA backoff attempts for the current transmission, initialized to 0. *BE* is the backoff exponent, which defines the number of backoff periods a node should wait before attempting a Clear Channel Assessment (CCA). *CW* is the contention window length, which defines the number of consecutive backoff periods a channel needs to be silent prior to a transmission. The backoff period length (t_{BOP}) is defined as 0.32 ms in the 2.4 GHz band. Default values for *BE* and *CW* are 3 and 2, respectively.

Before a transmission, a node locates a backoff period boundary by the received beacon, waits for a random number of backoff periods (0 to $2^{BE} - 1$), and senses the channel by CCA for *CW* times. If the channel is idle, a transmission begins. Otherwise *NB* and *BE* are increased by one and the operation returns to the random delay phase. When *NB* exceeds *macMaxCSMABackoffs* (default is 4), transmission terminates with a channel access failure. A node may try to retransmit the frame at maximum *aMaxFrameRetries* (default is 3) times before MAC issues a frame transmission failure.

The standard defines that each frame is followed by an interframe spacing. The spacing depends on the length of a MAC Protocol Data Unit (MPDU). A Long InterFrame Spacing (LIFS) defined as 640 μs is used for frames containing longer than 18 B MPDU. Shorter frames are followed by a Short InterFrame Spacing (SIFS) defined as 192 μs.

3.2.2 Contention-Free Period

CFP is an optional feature of IEEE 802.15.4 MAC, in which a channel access is performed in allocated time slots. A node may reserve bandwidth for delay critical applications by requesting GTS from a PAN Coordinator. The GTS allocations are signaled in beacon frames. In star networks, a device may obtain better Quality-of-Service (QoS) by the use of GTS, since contention and collisions are avoided. Yet, the applicability of GTS in peer-to-peer or cluster-tree networks is poor, since GTS may be used only between the PAN Coordinator and its one-hop neighbors. Moreover, inter-coordinator collisions degrade QoS in GTS, since no collision avoidance mechanism is used in CFP.

3.2.3 BatteryLifeExtension

IEEE 802.15.4 supports a *BatteryLifeExtension* option, which may reduce coordinator energy consumption. When the option is selected, *BE* is initialized to 2, and any transaction should begin during *macBattLifeExtPeriods* backoff periods (default is 6 equaling 1.92 ms at 2.4 GHz band) after the beacon. This allows the coordinator to sleep the rest of CAP and conserve energy. In practice, only one uplink or downlink transmission attempt is possible per CAP, which significantly reduces available throughput. In addition, a collision probability is high due to the shorter backoff time. Thus, this option is suitable only for small and very low data rate networks.

4. ANALYSIS SETUP

4.1 Network Parameters

We analyze IEEE 802.15.4 MAC performance in a large-scale WSN application. In order to obtain the lowest power consumption, a cluster-tree type beacon-enabled network topology is selected. In addition, CFP option is not used and all data exchanges are performed during CAP. Thus, the CAP length (t_{CAP}) is approximated to be equal to the superframe length. In the following analysis *SO* and *BO* are varied between 0 - 2 and 6 - 10, resulting 15.36 ms - 61.44 ms CAP length, and 0.96 s - 15.73 s beacon interval. This setting corresponds to a very low duty cycle operation.

The selected cluster-tree network, where each coordinator has three child coordinators (n_C) and 12 devices (n_D) is presented in Figure 2. The depth of the network is four resulting totally 1560 nodes. Each node transmits data frames, which are routed through the network to a PAN coordinator (uplink data). The transmission interval of data frames is normalized to the beacon interval. In the analysis, the uplink transmission interval is varied between 1 and 100 beacon intervals. For updating data gathering settings, the PAN coordinator broadcasts downlink data frames to the network at the intervals of 100 beacons. In the beacon-enabled network, the broadcasts are implemented by indirect unicast transmissions for each parent-child link.

Inter-cluster interferences are minimized by interlacing superframes of neighboring nodes. According to ZigBee [16] specification time is divided into periodic slots, the length of which equals to the superframe length. During start-up each coordinator performs a passive scan for searching neighbors and free slots for periodic superframes. A slot is selected randomly from founded free slots for reducing collisions with sibling coordinators. Due to the interlacing, inter-cluster interferences are ignored in the analysis.

In the following analysis, each node transmits 6 B sensing item (L_I) consisting of 16-bit sensor sample and 32-bit timestamp. In addition, each data frame contains 2 B application layer, 8 B network layer, 9 B data link layer, and 8 B physical layer headers. A 33 B short frame length (L_S) is used for transmitting sensing items separately from devices to coordinators, and for transmitting downlink data. Coordinators aggregate received sensing items, and utilize 105 B long frames (L_L) containing totally 12 sensing items. Data aggregation requires the use of a 6 B aggregate header. ACK frame length (L_A) is 11 B.

4.2 Reference Hardware Platform

To obtain realistic results, the IEEE 802.15.4 performance analysis is combined with the real measurements of a commercial IEEE 802.15.4 compliant Chipcon CC2420EM/EB [8] transceiver evaluation board. To estimate the energy consumption of a low power MAC protocol processor, the power consumption of a Microchip PIC18LF8720 [9] nanoWatt series microcontroller is also measured. The measurements include static power consumptions and switch times between various operation modes. The results are presented in Table 2 and Table 3.

5. PERFORMANCE MODELS

The LR-WPAN protocol is modeled according to IEEE 802.15.4 standard and ZigBee specification. All the significant run time operations are defined for a device and a coordinator operating in a cluster-tree network by analytical models. The models are presented in Table 4. Due to the long expected network lifetime, models concerning node start-up operations are outside of this analysis.

The models are grouped into CSMA mechanism (contention models), MAC layer operations (MAC operation models), and node operations. Realistic results are obtained by combining these models with the measurements from the hardware platform.

5.1 Contention Models

The contention models are used for analyzing the CSMA-CA mechanism including backoff time, collisions and retransmissions. For simplification, the slotted structure is not considered in the equations. Hence, the following equations utilize CAP more efficiently than in reality, giving also slightly higher performance. The following models are based on the analysis of IEEE 802.15.4 in a star network, presented in [6]. The utilized parameters and their values are summarized in Table 5.

Table 2. Measured platform power consumptions.

Symbol	MCU mode	Radio mode	Power @ 3 V
P_{TX}	Active	TX (0 dBm)	48.0 mW
	Active	TX (-1 dBm)	45.0 mW
	Active	TX (-3 dBm)	42.1 mW
	Active	TX (-5 dBm)	39.1 mW
	Active	TX (-7 dBm)	36.0 mW
	Active	TX (-10 dBm)	32.9 mW
	Active	TX (-15 dBm)	29.8 mW
	Active	TX (-25 dBm)	26.6 mW
P_{RX}	Active	RX	56.5 mW
P_{CCA}	Active	CCA	55.8 mW
P_I	Active	Idle	2.79 mW
P_{MCU}	Active	Sleep	1.50 mW
P_S	Sleep	Sleep	30 µW

Table 3. Measured Chipcon CC2420 transient times.

Symbol	Description	Time (µs)
t_{SI}	sleep to idle	970
t_{IT}	idle to transmit	192
t_{IR}	idle to receive	192
t_{RT}	receive to transmit	220
t_{TR}	transmit to receive	200

Table 4. IEEE 802.15.4 operation models.

	Model	Symbol
Node operation models	Device power consumption	P_{DEV}
	Coordinator power consumption	P_{COOR}
	Maximum throughput	T_{MAX}
	Goodput	G
MAC operation models	Data frame transmission	E_{TXD}, t_{TXD}
	Indirect data reception	E_{RXDD}, t_{RXDD}
	ACK transmission	E_{TXA}, t_{TXA}
	ACK reception	E_{RXA}, t_{RXA}
	Beacon transmission	E_{TXB}, t_{TXB}
	Beacon reception	E_{TXB}, t_{TXB}
	Network scanning	E_{NS}, t_{NS}
Contention models	Avg. number of retransmissions	u
	Transmission success rate	v
	Backoff energy and time	E_{BOT} , t_{BOT}

5.1.1 Backoff Time and Energy

The probability (q) that a single data transmission with the consecutive ACK is detected by CCA at any time in CAP is estimated by the RF transmission times of data and ACK frames. q is modeled separately for short (q_S) and long (q_L) data frames as

$$q_S = \frac{L_S + L_A}{t_{CAP} R}, \tag{3}$$

$$q_L = \frac{L_L + L_A}{t_{CAP} R}. \tag{4}$$

For estimating the average CSMA backoff time and energy, we first model the amount of data transmissions during CAP. As a uniform cluster-tree network structure is used, the number of nodes (n_{DL}) hierarchically below an analyzed coordinator is calculated as

$$n_{DL} = \sum_{a=1}^{a=k} n_C{}^a \left(1 + n_D\right), \tag{5}$$

where k is the network depth below the analyzed coordinator. The devices associated directly with the coordinator are excluded. As k increases from 1 to 4, n_{DL} gets values from 39 to 1560.

The average amount of data transmissions during CAP (d) is modeled by the number of nodes whose data is routed through the coordinator, the number of retransmissions (u), and the interval of uplink (I_U) and downlink (I_D) data transmission normalized to a beacon interval (I_B). For approximating the effect of indirect communication, I_D is divided by 2. As downlink data utilizes flooding through the cluster tree, downlink data transmissions are not increased proportionally to n_{DL}. d is modeled separately for short (d_S) and long (d_L) data frames as

$$d_S = \left(\frac{n_D}{I_U} + \frac{2\left(n_D + n_C\right)}{I_D} \right) u, \tag{6}$$

$$d_L = \frac{n_{DL} L_S u}{I_U L_L}. \tag{7}$$

The equations (3), (4), (6) and (7) are further used for modeling the probability (p_C) of a clear channel by CCA. According to [7], the probability that two randomly deployed nodes in the range of a coordinator have a hidden node relationship (h) is around 41%. This affects significantly the performance of CCA, since a portion of ongoing transmissions are not detected. With the two consecutive CCA analyses, as specified in IEEE 802.15.4 standard, p_C can be modeled as

Table 5. Utilized parameters and their values.

Symbol	Parameter	Value
A	Sensing items transmitted in a long frame	12
BO	MAC beacon order	6 - 10
h	Probability of a hidden node relationship	41 %
I_D	Downlink data transmission interval (I_B)	100
I_{NS}	Network scanning interval	3 h
I_U	Uplink data transmission interval (I_B)	1 - 100
k	Network depth below analyzed coordinator	1 - 4
L_A	ACK frame length	11 B
L_B	Beacon frame length	26 B
L_I	Sensing item length	6 B
L_L	Long data frame length	105 B
L_O	Data frame overhead (PHY, MAC, NWK)	25 B
L_S	Short data frame length	33 B
n_C	Number of child coordinators	3
n_D	Number of devices	12
n_{DL}	Number of the nodes hierarchically below a coordinator	39 - 1560
R	Radio data rate	250 kbps
SO	MAC superframe order	0 - 2
t_A	ACK frame RF time	352 µs
t_{AW}	ACK wait duration	864 µs
t_{BOP}	Backoff period length	320 µs
t_{CCA}	CCA analysis time	128 µs
t_I	Synchronization inaccuracy	100 µs
t_{LIFS}	Long InterFrame Spacing	640 µs
t_{RES}	Response time for data request	19.52ms
t_{SIFS}	Short InterFrame Spacing	192 µs
ε_{RX}	The crystal tolerance of a receiving node	20 ppm
ε_{TX}	The crystal tolerance of a transmitting node	20 ppm

$$p_C = (1 - q_S)^{2 d_S (1-h)} (1 - q_L)^{2 d_L (1-h)} . \tag{8}$$

In case of unsuccessful CCA, the CSMA-CA backoff algorithm is repeated at maximum b times (*macMaxCSMABackoffs,* default is 4) before declaring a channel access failure. The probability (s) of a successful CCA with b backoff attempts, and the average number of backoffs (r) for each frame are modeled as

$$s = \sum_{a=1}^{a=b} p_C (1 - p_C)^{a-1}, \tag{9}$$

$$r = (1 - s) b + \sum_{a=1}^{a=b} a p_C (1 - p_C)^{a-1} . \tag{10}$$

By combining r with average backoff time, total backoff time and energy for each transmission attempt are estimated. The average backoff time (t_{BO}) as a function of a backoff exponent is given as

$$t_{BO}(BE) = \frac{2^{BE} - 1}{2} t_{BOP} . \tag{11}$$

After each unsuccessful backoff attempt, BE is incremented by one until *aMaxBE* (default is 5) is reached. The total backoff time (t_{BOT}) is obtained by summing the average backoff and CCA analysis (t_{CCA}) times of each attempt. As CCA is performed twice only if the channel is assessed to be clear on the first attempt, we approximate that averagely 3/2 CCA analyses are performed for each backoff attempt. Hence, the total backoff time can be modeled as

$$t_{BOT} = \frac{3}{2} r\left(t_{IR} + t_{CCA}\right) + \sum_{a=0}^{a=r-1} t_{BO}\left(\min\left(macMinBE + a, aMaxBE\right)\right). \quad (12)$$

It is assumed that a radio is in the idle mode during the backoff time. The idle mode is used instead of the sleep mode, since radio start-up time from sleep mode is almost 1 ms. Hence, total backoff energy (E_{BOT}) can be approximated as

$$E_{BOT} = \frac{3}{2} r(t_{IR} + t_{CCA})\left(P_{CCA} - P_I\right) + t_{BOT} P_I \, . \quad (13)$$

5.1.2 Collision Probability

Collisions causing transmission failures are common in a highly loaded network. The CSMA-CA MAC is prone to two types of collisions; collisions caused by the hidden node phenomenon, and collisions caused by the selection of the same backoff slot with another node. Neither of these collisions can be avoided by the standard, since handshaking before a transmission is not used. The probability (p_h) that two nodes in a hidden node position transmit simultaneously and collide is modeled as

$$p_h = 2\frac{\left(q_L d_L + q_S d_S\right)}{d_S + d_L} \, . \quad (14)$$

Due to the relatively long inactive part of superframes, nodes most probably gather data during the inactive time and start a backoff procedure simultaneously at the beginning of CAP. Since *BE* is initialized with *macMinBE* (default is 3) for each new transmission, nodes randomize backoff delays using a relatively low backoff exponent. The probability (p_d) that two nodes select the same backoff delay and collide can be modeled as

$$p_d = \frac{1}{2^{BE} - 1} \, . \quad (15)$$

5.1.3 Retransmission Probability

For approximating the amount of traffic in CAP, we determine the average number (C) of contenting nodes in CAP as

$$C = \min\left[\left(\frac{1}{I_U} + \frac{2}{I_D}\right)u, 1\right] n_D + \min\left[\left(\frac{2}{I_D} + \frac{n_{DL} L_S}{I_U n_C L_L}\right)u, 1\right] n_C . \quad (16)$$

For modeling the probability (p_s) of a successful transmission, C is combined with p_h and p_d as

$$p_s = s\left(1 - p_h\right)^{h(d_S + d_L)}\left(1 - p_d\right)^C \, . \quad (17)$$

A frame is transmitted c times before declaring a transmission failure. c is defined as *aMaxFrameRetries* (default is 3)+1. The probability of a successful transmission (v) after a attempts is

$$v = \sum_{a=1}^{a=c} p_s\left(1 - p_s\right)^{a-1} \, . \quad (18)$$

Finally, the average number of transmission attempts per frame (u) can be modeled as

$$u = \left(1 - v\right)c + \sum_{a=1}^{a=c} a p_s\left(1 - p_s\right)^{a-1} \, . \quad (19)$$

5.2 MAC Operation Models

MAC operation models are used for analyzing energy and time required for the transmission and reception of data, ACK and beacon frames, and the network scanning. A frame transmission in IEEE 802.15.4 consists of a backoff time and the actual data transmission. The time and energy of a data transmission are modeled separately for short (t_{TXDS}, E_{TXDS}) and long (t_{TXDL}, E_{TXDL}) frames according to the above defined backoff models, radio transient times and power consumptions, frame lengths, and radio data rate (R) as

$$t_{TXDS} = t_{SI} + t_{BOT} + t_{IT} + \frac{L_S}{R} \, , \quad (20)$$

$$E_{TXDS} = t_{SI} P_I + E_{BOT} + \left(t_{IT} + \frac{L_S}{R}\right) P_{TX} \, , \quad (21)$$

$$t_{TXDL} = t_{SI} + t_{BOT} + t_{IT} + \frac{L_L}{R} \, , \quad (22)$$

$$E_{TXDL} = t_{SI} P_I + E_{BOT} + \left(t_{IT} + \frac{L_L}{R}\right) P_{TX} \, . \quad (23)$$

In indirect communication the maximum response time (t_{RES}) for a data request is 19.52 ms. Hence, the data reception time and energy may be significantly higher than in direct communication. The coordinator response time is assumed to be an average of t_{BOT} and t_{RES}. In this analysis, indirect communication utilizes only short frames. The time (t_{RXDD}) and energy (E_{RXDD}) for an indirect data transmission after a data request are modeled as

$$t_{RXDD} = t_I + \frac{t_{RES} + t_{BOT}}{2} + \frac{L_S}{R} + t_{LIFS} \, , \quad (24)$$

$$E_{RXDD} = \left(t_{RXDD} - t_{LIFS}\right) P_{RX} + t_{LIFS} P_I \, . \quad (25)$$

The ACK reception time (t_{RXA}) and energy (E_{RXA}) are modeled by assuming the wait duration for ACK being a half of the maximum allowed (t_{AW}). The time and energy are modeled as

$$t_{RXA} = t_{TR} + \frac{t_{AW}}{2} + \frac{L_A}{R} + t_{SIFS} \, , \quad (26)$$

$$E_{RXA} = \left(t_{RXA} - t_{SIFS}\right) P_{RX} + t_{SIFS} P_I \, . \quad (27)$$

Moreover, ACK transmission time (t_{TXA}) and energy (E_{TXA}) are modeled as

$$t_{TXA} = t_{RT} + \frac{t_{AW}}{2} + \frac{L_A}{R} \, , \quad (28)$$

$$E_{TXA} = \left(t_{RT} + \frac{L_A}{R}\right) P_{TX} + \frac{t_{AW}}{2} P_I \, . \quad (29)$$

Due to relatively long beacon intervals, beacon reception models consider the synchronization inaccuracy and crystal tolerances in receiving and transmitting nodes (ε_{RX}, ε_{TX}). In addition, a node is typically in a sleep mode before the beacon reception. The beacon reception time (t_{RXB}) and energy (E_{RXB}) can be modeled as

$$t_{RXB} = t_{SI} + t_{IR} + \left(\varepsilon_{RX} + \varepsilon_{TX}\right) I_B + t_I + \frac{L_B}{R} + t_{LIFS} \, , \quad (30)$$

$$E_{RXB} = \left(t_{RXB} - t_{SI} + t_{LIFS}\right) P_{RX} + \left(t_{SI} + t_{LIFS}\right) P_I \, . \quad (31)$$

Finally, beacon transmission time (t_{TXB}) and energy (E_{TXB}) are modeled without CCA analysis as

$$t_{TXB} = t_{SI} + t_{IT} + \frac{L_B}{R}, \tag{32}$$

$$E_{TXB} = t_{SI} P_I + \left(t_{IT} + \frac{L_B}{R} \right) P_{TX} . \tag{33}$$

If a node looses the contact with its associated coordinator (orphans) due to mobility or a radio link failure, it may perform either an orphaned device realignment procedure, or reset the MAC sublayer and re-associate with the network. In beacon-enabled networks the latter performs best and a node performs a passive channel scan on a single channel prior to the re-association (the operating channel of the network is known). The energy required for the message exchange during the association is negligible compared to network scanning energy, and thus it is ignored in the following analysis. The network scanning time (t_{NS}) and energy (E_{NS}) can be modeled as follows:

$$t_{NS} = t_{IR} + aBaseSuperframeDuration\left(2^{BO} + 1\right), \tag{34}$$

$$E_{NS} = t_{NS} P_{RX} . \tag{35}$$

6. ANALYSIS RESULTS

In this section the performances of a LR-WPAN device and a coordinator are analyzed in terms of power consumption, requested throughput and achieved goodput.

6.1 Device Power Consumption

To be able to operate in a beacon-enabled IEEE 802.15.4 network, a device receives beacons and exchanges data with a coordinator. If a communication link to the coordinator is lost a device performs a network scanning. The rest of time a device is in the sleep mode. The duty cycle of a device (DC_{DEV}) is calculated with beacon receptions, uplink and downlink data exchanges, and network scanning. The average network scanning interval (I_{NS}) depends on device speed and radio link quality. DC_{DEV} can be modeled as

$$DC_{DEV} = \frac{t_{RXB}}{I_B} + \frac{t_{TXDS} + t_{RXA}}{I_U I_B} u + \frac{\left(t_{TXDS} + t_{RXA} + t_{RXDD} + t_{TXA}\right)u}{I_D I_B} + \frac{t_{NS}}{I_{NS}}. \tag{36}$$

Similarly, the device power consumption is modeled as

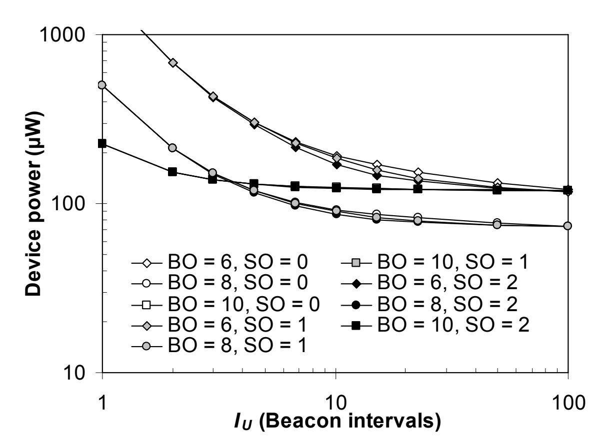

Figure 4. Device power consumption as a function of data transmission interval (k = 3).

$$\begin{aligned} P_{DEV} = {} & \frac{E_{RXB}}{I_B} + \frac{\left(E_{TXDS} + E_{RXA} + E_{RXDD} + E_{TXA}\right)u}{I_D I_B} \\ & + \frac{E_{TXDS} + E_{RXA}}{I_U I_B} u + \frac{E_{NS}}{I_{NS}} + \left(1 - DC_{DEV}\right) P_S . \end{aligned} \tag{37}$$

The average device power consumption as a function of the uplink data transmission interval with various I_B and SO is plotted in Figure 4. The network scanning interval is approximated to be averagely 3 hours, which corresponds to a deployment with low dynamics and good link qualities. In general, the power consumption decreases with longer beacon and uplink data transmission intervals, since the energy required for beacon receptions and data transmissions diminishes. At longer beacon intervals, the network scanning power becomes significant, since the network scanning energy increases directly proportionally to the beacon interval. Hence, the device power consumption with BO = 10 is higher than when BO equals to 8. Moreover, small SO increases device power consumption slightly due to the increased contention and retransmissions.

6.2 Coordinator Power Consumption

In order to operate as a coordinator in a beacon-enabled cluster-tree network, a node has to transmit beacons and receive the CAP for communicating with the nodes associated with it. In addition, a coordinator maintains synchronization with its parent by receiving beacons from it. The activity of a coordinator depends significantly on its location in the network and hence, the requested throughput. As the power consumptions of radio transmission and reception modes are quite similar, we estimate that the power consumption of a coordinator during CAP equals to the reception mode power consumption. The data flow to the uplink direction is performed by long MAC payloads containing A sensing items per each frame. In this analysis A is 12. The duty cycle of a coordinator (DC_{COOR}) is modeled as

$$\begin{aligned} DC_{COOR} = {} & \frac{t_{TXB} + t_{RXB}}{I_B} + \frac{\left(t_{TXDL} + t_{RXA}\right)\left(n_{DL} + n_D + 1\right)u}{I_U I_B A} \\ & + \frac{\left(t_{TXDS} + t_{RXA} + t_{RXDD} + t_{TXA}\right)u}{I_D I_B} + \frac{t_{CAP}}{I_B} + \frac{t_{NS}}{I_{NS}}. \end{aligned} \tag{38}$$

Similarly, the average power consumption of a coordinator is

$$\begin{aligned} P_{COOR} = {} & \frac{E_{TXB} + E_{RXB}}{I_B} + \frac{t_{CAP} P_{RX}}{I_B} + \frac{\left(E_{TXDL} + E_{RXA}\right)\left(n_{DL} + n_D + 1\right)u}{I_U I_B A} \\ & + \frac{\left(E_{TXDS} + E_{RXA} + E_{RXDD} + E_{TXA}\right)u}{I_D I_B} + \frac{t_{NS}}{I_{NS}} + \left(1 - DC_{COOR}\right) P_S . \end{aligned} \tag{39}$$

The average coordinator power consumption as a function of the uplink data transmission interval with various I_B and SO is plotted in Figure 5. As in the case of the device power consumption analysis, the network scanning interval equals to 3 hours. With very low data rate network, coordinator power consumption can go below 200 µW. In typical applications coordinator power consumption is between 1 and 10 mW.

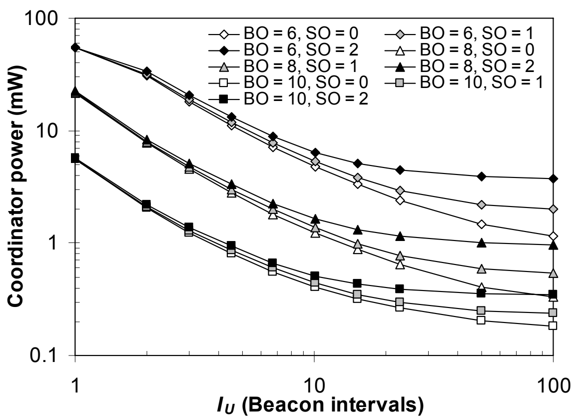

Figure 5. Coordinator power as a function of data transmission interval (k = 3).

6.3 Goodput

The throughput (T_{REQ}) requested by the sensor application depends on the data transmission intervals (I_U, I_D), beacon interval (I_B) and the number of nodes (children, grand-children etc.) that route data through the coordinator (n_{DL}). The requested throughput can be determined as:

$$T_{REQ} = \left(\frac{n_D + n_{DL} + 1}{I_U} + \frac{2(n_D + n_C)}{I_D} \right) \frac{L_I}{I_B} . \qquad (40)$$

The requested throughput as a function of the uplink data transmission interval is plotted in Figure 6 in different depths (k) of the network. For generalizing the results the throughput is normalized to the beacon interval.

Furthermore, the achieved goodput (G) of a coordinator is modeled with the requested throughput and the probability of a successful transmission (v), as follows:

$$G = T_{REQ} v . \qquad (41)$$

The achieved goodput versus requested throughput with different CAP lengths (*SO*) is plotted in Figure 7. The results are presented both as a percentage of the requested throughput and in absolute values. Again the results are normalized to the beacon interval. The results indicate that a goodput of about 200 bits per a superframe

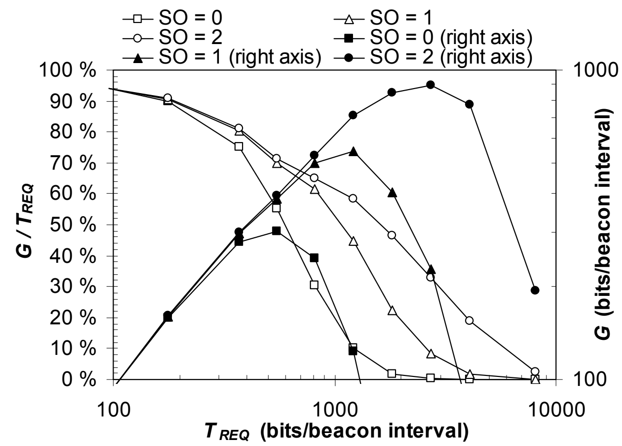

Figure 7. Coordinator goodput as a function of requested throughput (*k*=2).

can be achieved with 90 % transmission success rate. As *SO* varies from 0 to 2, the maximum goodputs are 302, 545 and 897 bits per a beacon interval. These are obtained with goodput percanteges between 33% - 55%. With higher requested throughputs, the increased contention reduces goodput rapidly. A longer CAP length reduces contention and improves the goodput.

Network energy efficiency is analyzed by dividing the achieved goodput by the coordinator power consumption, which results to the energy per successfully transmitted bit of payload data over one hop. The achieved energy efficiency is presented in Figure 8. As seen in the figure, the energy efficiency depends on the requested throughput, *SO*, and *BO*. The highest energy efficiency is achieved, as *SO* gets value 1, and is around 5 μJ/bit. The figure also shows that for the energy efficiency, the optimization of *BO* and *SO* parameters is very important.

7. SIMULATIONS

Provided models are verified by simulating complete ZigBee [16] protocol stack in WISENES [4]. WISENES is targeted for large-scale simulations of long-term WSN deployments. In WISENES, protocols are designed in high abstraction level with Specification and Description Language (SDL) [14]. SDL design tools allow the use of graphical notation in the implementation [15].

The characteristics of environment and sensor nodes are defined for

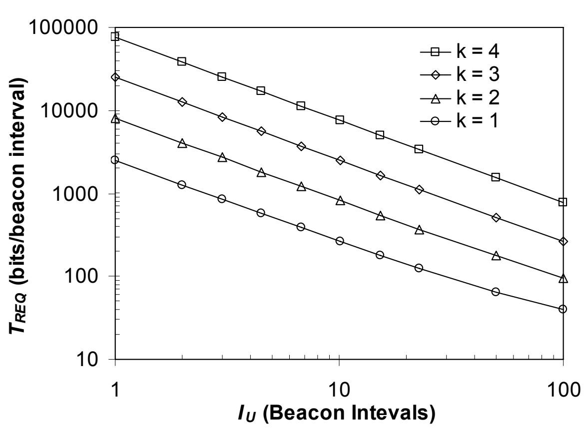

Figure 6. Requested throughput versus uplink data transmission interval (I_U) as *k* varies.

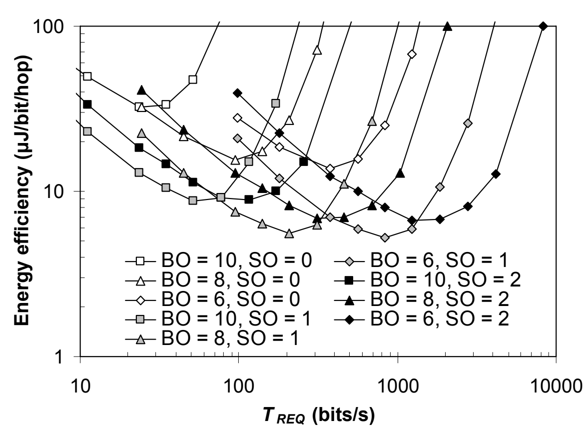

Figure 8. Coordinator energy efficiency as a function of requested throughput (*k* = 2).

WISENES using eXtensible Markup Language (XML). The detailed parameterization and the realistic modeling of wireless transmission medium, physical phenomena, and sensor node hardware capabilities result to accurate performance information of simulated protocols, nodes, and networks [4]. The output information is stored to logs, which provide detailed event information for post-processing. During runtime, the progress of the simulation is visualized through a graphical user interface.

7.1 Simulation Case Description

For the WISENES simulations a node platform similar to the one in the analysis is parameterized, protocols initialized, and an application implemented. The application implemented for the simulations consists of three tasks: *sensing, aggregation*, and *sink*. The sensing task on the devices measures a temperature reading periodically (I_U) and sends it to the parent coordinator. At the coordinators, the buffered temperature readings from the children are combined to an aggregate packet, which is sent to the PAN coordinator within I_U time intervals. At the PAN coordinator, the sink task stores received aggregate packets. Further, it initiates the periodic (I_D) downlink control packets. The network topology for the simulations is forced to follow that of analysis.

The IEEE 802.15.4 LR-WPAN MAC protocol implementation in WISENES conforms the standard. The synchronization inaccuracy among the nodes is balanced by a simple algorithm. The algorithm tracks the time drift between consequent beacons and compensates the drift with the averaged inaccuracy over ten last beacons. The functional parameters of the MAC protocol are set by the upper protocol layers. However, unlike specified by the standard, in the association a child device waits for the association response for *macTransactionPersistenceTime* instead of *aResponseWaitTime* symbols. The latter is not valid timeout in the beacon-enabled mode with BO values of five or higher.

In the presented simulations, WISENES ZigBee NWK implementation uses hierarchical addressing and routing scheme (*nwkUseTreeAddrAlloc* and *nwkUseTreeRouting* are set to 1), which is suitable for static cluster-tree topologies [16]. Each coordinator initiating its own superframe selects a random slot for its superframe among the free slots found out during the passive scan. The WPAN MAC is configured to the beacon-enabled mode with case dependent *BO* and *SO* values. The *nwkTransactionPersistenceTime* is set so that it results to 16 I_B. Other parameters are set to the default values of IEEE 802.15.4 standard and ZigBee specification.

7.2 Simulation Results

The simulations are done with I_U value 60. Only one value of I_U is simulated due to the long running time of simulations caused by the large-scale, long simulated network lifetime, and the amount of different parameters. Thus, the simulations show the validity of analysis, which extends to larger number of parameters.

7.2.1 Power Consumption

Power consumption is evaluated separately for devices and coordinators. The simulated and analyzed power consumptions for devices with different CAP lengths (*SO*) are depicted in Figure 9 as a function of I_B. The presented simulation results are averaged over randomly selected nodes. Similarly, the power consumptions for coordinators are depicted in Figure 10.

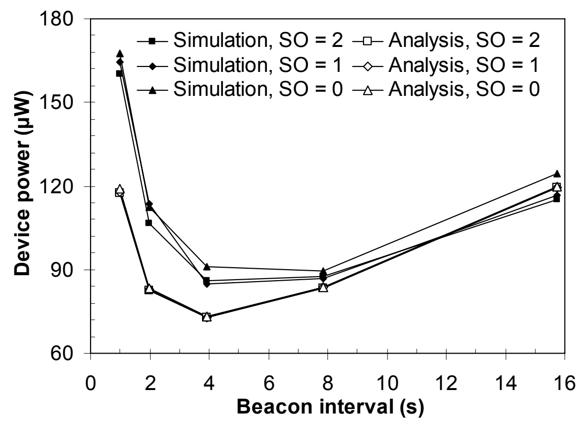

Figure 9. Simulated and analyzed device power consumption as a function of beacon interval.

Both analysis and simulation results indicate that *SO* has only minimal effect on the device power consumption. The difference between the analysis and simulation results is mainly due to the higher dynamics of the simulations. Furthermore, due to the longer frames, a coordinator is able to send several frames during CAP more likely than a device after the first successful send. The overall average difference is 14.7%, which indicates that analysis gives accurate results. In the coordinator power consumption the validity of analysis results is also clearly visible. The main reasons for the deviation are similar to those of device power consumption. The overall average difference is 13.9 %.

7.2.2 Goodput

As the uplink data transmissions are relative to I_B, the goodput does not depend on the beacon interval. The simulated and analyzed goodputs for coordinators at depth 2 ($k = 4$) are given in Table 6 for different CAP lengths (*SO*). The simulated goodput results are averaged over *BO* values from 6 to 10. As shown, the analyzed and simulated goodputs are quite similar. Unlike in the analysis, *SO* has a minor effect on the goodput in simulations. As mentioned above, the coordinators tend to be able to send several frames during the CAP. With larger *SO* this is more beneficial.

7.2.3 Considerations

In general, the analysis results correspond accurately to those obtained from the simulations. The main reason for the slight

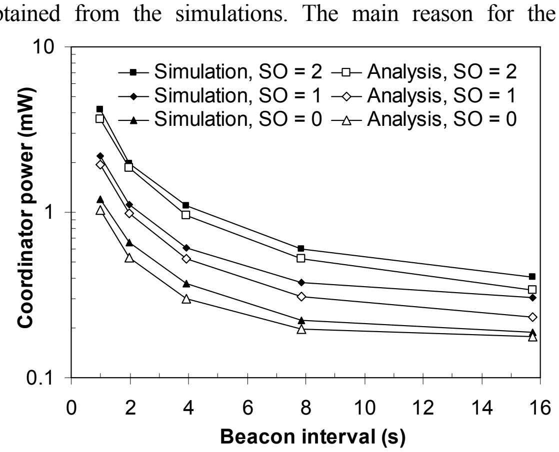

Figure 10. Simulated and analyzed coordinator power consumption as a function of beacon interval ($k = 2$, $I_U = 60\ I_B$).

Table 6. Analyzed and simulated goodputs of a coordinator (k = 2, I_U = 60 I_B).

SO	Analysis (bits/ I_B)	Analysis (%)	Simulation (bits/ I_B)	Simulation (%)
SO = 0	135.6	91.3	132.5	89.2
SO = 1	136.4	91.9	142.0	95.6
SO = 2	136.7	92.0	147.1	99.1

deviation is the higher dynamics of the simulations. Random error situations and the reconstruction of the complete sub-tree is typically energy consuming. The leaf nodes may need to initiate several scan operations due to the time required to reinitialize the above network hierarchy. Further, as several nodes are attempting the association simultaneously, association failures are common.

Another cause for the goodput result deviation is the saturation of data throughput at the lower levels of the network hierarchy. This is not considered in the analysis, but in the simulations the goodputs of child coordinators affect to that of the parent coordinators. This is more evident with the small values of I_U.

Some issues considering ZigBee specification should be noted based on the simulations. First, the hierarchical addressing and routing scheme is prone to errors due to its assumption of static network. The address space is exhausted, if there are nodes with random mobility pattern. Further, during associations duplicate addresses occur, if a coordinator removes the neighbor table entry of a device, association of which fails. However, if the device successfully received the association response but the acknowledgement was lost, duplicate addresses realize.

Another typical cause for errors is the time slot selection when a coordinator is started. The decision for the own time slot has to be made based on the information obtained during the passive scan. However, in dense networks the delay between the passive scan and the starting of own superframe may be considerable. Thus, a coordinator may not be aware of the time slots of its neighbors, especially if a complete sub-tree is reinitialized after an error situation. Thus, the possibility of the selection of a same time slot is high, if the slot randomization is limited to certain subset of slots, or if *BO* is small (e.g. 6) and *SO* large (e.g. 2).

8. CONCLUSIONS

The performance of IEEE 802.15.4 standard MAC protocol is analyzed in a large-scale cluster-tree network. The analysis consists of models for MAC and node operations, and CSMA mechanism. According to the analysis, *BO* and *SO* parameters have a very significant effect on the network performance and energy efficiency. The results depict that minimum device power consumption is as low as 73 µW, when the beacon interval is 3.93 s, and uplink data are transmitted at 4 min intervals. With the shortest 15.36 ms CAP length and 3.93 s beacon interval achieved coordinator goodput and power consumption are around 34.4 bits/s (135 bits/I_B) and 370 µW. Simulations show that the performance models are generally accurate, but some inaccuracy is caused by the random error situations detected by simulations, but which are not included in the analysis. In the future, the operation of IEEE 802.15.4 will be modeled and simulated in a dynamic WSN with error prone nodes and slight mobility.

9. REFERENCES

[1] Bougard, B., Catthoor, F., Daly, D.C., Chandrakasan, A., Dehaene, W., Energy efficiency of IEEE 802.15.4 standard in dense wireless microsensor networks: modeling and improvement perspectives, in *Proceedings of Design, automation and test in Europe (DATE'05)* (Munich, Germany, March 7-11, 2005). IEEE, 2005, Vol. 1, 196-201.

[2] Gutierrez, J.A., Callaway, Jr, E.H., Barrett, Jr, R.L., *Low-Rate Wireless Personal Area Networks – Enabling Wireless Sensors with IEEE 802.15.4*, IEEE Press, NY, 2004.

[3] Hwang, L.-J., Sheu, S.-T., Shih, Y.-Y., Cheng, Y.-C., Grouping strategy for solving hidden node problem in IEEE 802.15.4 LR-WPAN, in *Proceedings of the 1st IEEE international conference on Wireless Internet (WICON'05)* (Budabest, Hungary, July 10-15, 2005). IEEE, 2005, 26-32.

[4] Kuorilehto, M., Kohvakka, M., Hännikäinen, M., Hämäläinen, T.D., High Level Design and Implementation Framework for Wireless Sensor Networks, In *Proceedings of Embedded computer systems: architectures, modeling, and simulation (SAMOS V)* (Samos, Greece, July 18-20, 2005). Springer Verlag, 2005, 384-393.

[5] Lu, G., Krishnamachari, B., Raghavendra, C.S., Performance evaluation of the IEEE 802.15.4 MAC for low-rate low-power wireless networks, in *Proceedings of the 23rd IEEE international Performance computing and communications conference (IPCCC'04)* (Phoenix, AZ, USA, April 15-17, 2004). IEEE, 2004, 701-706.

[6] Timmons, N.F., Scanlon, W.G., Analysis of the performance of IEEE 802.15.4 for medical sensor body area networking, in *Proceedings of the 1st IEEE international conference. on Sensor and ad hoc communications and networks (SECON'04)* (Santa Clara, CA, USA, 4-7. October, 2004). IEEE, 2004, 16-24.

[7] Tseng, Y.-C., Ni, S.Y., Shih, E.Y., Adaptive approaches to relieving broadcast storms in a wireless multihop mobile ad hoc network, *IEEE Trans. on Computers, 52, 5* (May 2003), 545-557.

[8] Data Sheet for CC2420 2.4 GHz IEEE 802.15.4/ZigBee RF Transceiver, available online at http://www.chipcon.com/files/CC2420_Data_Sheet_1_3.pdf

[9] Data Sheet for PIC18LF8720 Microcontroller, available online at: http://ww1.microchip.com/downloads/en/DeviceDoc/39609b.pdf

[10] IEEE Standard 802.11-1997, Wireless Lan Medium Access Control (MAC) And Physical Layer (PHY) Specifications.

[11] IEEE Standard 802.15.1-2002, wireless medium access control (MAC) and physical layer (PHY) specifications for wireless personal area networks (WPANs).

[12] IEEE Standard 802.15.3-2003, wireless medium access control (MAC) and physical layer (PHY) specifications for high rate wireless personal area networks (WPANs).

[13] IEEE Standard 802.15.4-2003, wireless medium access control (MAC) and physical layer (PHY) specifications for low-rate wireless personal area networks (WPANs).

[14] ITU-T Recommendation Z.100, Specification and description language (SDL), Aug 2002, available online at: http://www.itu.int/ITU-T/studygroups/com17/languages/

[15] Telelogic TAU SDL Suite, http://www.telelogic.com/corp/products/tau/sdl/index.cfm

[16] ZigBee Alliance Document 053474r06; ZigBee Specification, Version 1.0, Dec 2004.