

## Research Article

# Network Signaling Channel for Improving ZigBee Performance in Dynamic Cluster-Tree Networks

**Mikko Kohvakka, Jukka Suhonen, Mauri Kuorilehto, Marko Hännikäinen, and D. Hämäläinen**

*Institute of Digital and Computer Systems, Tampere University of Technology, P.O. Box 553, Tampere 33101, Finland*

Correspondence should be addressed to Mikko Kohvakka, mikko.kohvakka@tut.fi

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ZigBee is one of the most potential standardized technologies for wireless sensor networks (WSNs). Yet, sufficient energy-efficiency for the lowest power WSNs is achieved only in rather static networks. This severely limits the applicability of ZigBee in outdoor and mobile applications, where operation environment is harsh and link failures are common. This paper proposes a network channel beaconing (NCB) algorithm for improving ZigBee performance in dynamic cluster-tree networks. NCB reduces the energy consumption of passive scans by dedicating one frequency channel for network beacon transmissions and by energy optimizing their transmission rate. According to an energy analysis, the power consumption of network maintenance operations reduces by 70%–76% in dynamic networks. In static networks, energy overhead is negligible. Moreover, the service time for data routing increases up to 37%. The performance of NCB is validated by ns-2 simulations. NCB can be implemented as an extension on MAC and NWK layers and it is fully compatible with ZigBee.

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## 1. INTRODUCTION

Wireless sensor network (WSN) is an emerging technology enabling fully autonomous self-configuring ad-hoc networks [1]. WSN may consist of thousands of small nodes, which sense their environment, communicate wirelessly with each other, and share collaborative tasks. Nodes route sensed data and events to a sink node, which forms a gateway to other networks. WSN nodes may be embedded deeply in our living environment or operate under harsh conditions in outdoors or a machinery hall. Thus, a high tolerance against unreliable radio links, variable network size, and mobile nodes is required [2, 3]. Due to the large number of nodes, battery replacements are difficult. Hence, nodes may have to scavenge supply energy solely from their operation environment [4], or operate up to several years with small batteries. This necessitates very high energy-efficiency in communication protocols, algorithms, and hardware platforms. WSNs have a vast number of potential applications [5], for example monitoring and controlling in home, office, and industrial environments, monitoring of remote or hostile geographical regions, tracking of animals and objects, and surveillance.

The wireless personal area networks (WPANs) 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 [6]. The working group soon formed two other subgroups, firstly IEEE 802.15.3 focusing on high-speed WPAN [7] for multimedia applications. In December 2000, IEEE 802.15.4 [8] low-rate WPAN was initiated for providing low-complexity, low-cost, and low-power wireless connectivity among inexpensive devices, such as WSN nodes [9]. ZigBee [10] is an open specification for low-power wireless networking, which complements IEEE 802.15.4 with a network layer, security modes, and application profiles. The first version of the ZigBee specification was announced in December 2004.

IEEE 802.15.4 together with ZigBee is one of the most potential standardized technologies for enabling WSNs. As available energy is scarce, the beacon-enabled network is essential, since time synchronized sleep and wakeup mechanism can be adopted [11]. Moreover, large network size with widely located nodes is enabled by a cluster-tree network topology. By these settings, ZigBee can achieve very high energy-efficiency in static networks [12]. However, even an immobile WSN has a dynamic behavior caused by

low-transmission power levels combined with dynamic operating environment, such as opened and closed doors, moving objects, and interferences from other networks that all affect radio frequency (RF) propagation. In addition, many envisioned WSN applications, such as asset tracking and interactive games, require mobility support for nodes. In these conditions, ZigBee performance is unsatisfactory due to energy-hungry passive scan operations. Hence, techniques for reducing passive scan energy are one of the key challenges.

In this paper, we propose a network channel beaconing (NCB) algorithm for improving the performance and reducing the energy consumption of ZigBee in dynamic networks. NCB utilizes frequent beacon transmissions on a dedicated network signaling channel. A passive scan is performed by receiving these beacons resulting in dramatically reduced passive scan duration and energy consumption in low-data-rate applications. NCB can be implemented as a manufacturer specific extension on MAC and NWK layers and it is fully compatible with standard ZigBee devices.

The rest of this paper is organized as follows. The related work is discussed in Section 2. An introduction to ZigBee and IEEE 802.15.4 standard is presented in Section 3. Section 4 presents the design of NCB. The performance of NCB equipped ZigBee is analyzed and compared against standard ZigBee in Section 5. In Section 6, the beacon transmission rate of NCB is energy optimized for further energy saving. Simulations for validating the results are presented in Section 7. Finally, this paper is concluded in Section 8.

## 2. RELATED WORK

Most of researches about the IEEE 802.15.4 beacon-enabled network have been restricted to a star topology. The performance of a star network with 10 nodes has been analyzed in [13]. The analysis focused on the effect of crystal tolerance, a frame size, and the usage of guaranteed time slots (GTSs) on a node lifetime. Bougard et al. [14] have presented a mathematical analysis of a large-scale star network. 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. The performance simulations of IEEE 802.15.4 in a star network have been presented in [15]. It has been found that a significant energy saving is achieved by a low-duty-cycle operation.

An analysis and experimental measurements of IEEE 802.15.4 in a cluster-tree network has been presented in [11]. It has been found that beacon-enabled cluster-tree networks are prone to beacon collisions, which will lead to synchronization failures. The beacon collisions can be reduced by utilizing a rather long beacon interval. Clearly, another option is to use more frequency channels for the network. Yet, both of these options increase the energy consumption of passive scans proportionally.

Beacon collisions can also be reduced by scheduling. A wakeup scheduling scheme presented in [16] utilizes synchronized superframe timing such that coordinators begin beaconing at the same time, and active periods are fully overlapping. Since entire inactive period can be used for sleep-

ing, energy consumption is reduced. To reduce collisions, beacon transmission period is extended to contain a number of subslots during which beacons can be sent. Yet, the selection of a noninterfering subslot has not been specified. Another scheduling scheme presented in [17] organizes the entire active periods of different coordinators in a nonoverlapping manner. This minimizes the changes to the current IEEE 802.15.4 specification. Scheduling has also been proposed for reducing hidden node collisions that are typical for the carrier sense multiple access with collision avoidance (CSMA-CA) mechanism of IEEE 802.15.4 [18].

While the above scheduling schemes utilize software-based time synchronization; also hardware-based synchronization mechanisms exist. RT-Link [19] is a time division multiple access (TDMA) MAC protocol for multihop WSNs. The protocol employs two out-of-band synchronization sources: atomic clock broadcasts for outdoors and amplitude modulation (AM) transmissions for indoor conditions. The latter utilizes building's power grid as an antenna to radiate time sync pulses. According to experimental measurements, the hardware-based synchronization is robust, scalable, and energy-efficient option to software-based techniques. Yet, the hardware cost and complexity are increased.

In our previous work [12], we have analyzed the performance of IEEE 802.15.4 and ZigBee in large-scale WSN applications. An energy analysis on a cluster-tree multihop network indicated that the highest energy-efficiency in a low-data-rate WSN application is achieved by moderate (30.7 milliseconds) superframe duration and by scaling beacon interval according to requested throughput. According to simulations, random error situations are energy-hungry, since they usually cause the reconstruction of a complete subtree. During the reconstruction, leaf nodes may need to perform several passive scans until the above network hierarchy is initialized. Simulations also depicted that the probability that two coordinators randomize the same slot for their superframes is significant. For better scalability, it would be advantageous to divide clusters into several frequency channels.

Furthermore, our previous work [20] has proposed the use of frequent beacon transmissions to improve the performance of synchronized low-duty-cycle MAC protocols in dynamic networks. The work focused on flat networks, for which energy optimized beacon rate was determined. It has been found that optimized beacon rate results in a very significant energy saving.

In this paper, we will extend our idea of frequent beacon transmissions to ZigBee. In contrast to [20], we will utilize a cluster-tree network topology and a dedicated network signaling channel for frequent network beacons. Network beacons allow energy-efficient passive scans on the network channel, independently from the utilized IEEE 802.15.4 beacon interval and the amount of frequency channels for superframes. This enables the optimization of energy-consumption and scalability in dynamic networks. As the network beacons are transmitted on the network channel only; collisions with data and control frames are eliminated. We will also present performance analysis of the network

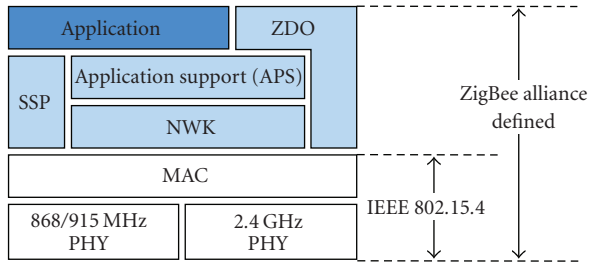


FIGURE 1: IEEE 802.15.4 and ZigBee.

channel approach. Performance models are validated by simulations.

### 3. ZigBee AND IEEE 802.15.4 OVERVIEWS

#### 3.1. ZigBee protocol stack

A ZigBee protocol stack is presented in Figure 1 [21]. An application layer at the top of the stack determines node relationships, and supervises network initiation and association functions. Overall node management is performed by a ZigBee device object (ZDO). Application endpoints may call ZDO in order to discover other ZigBee nodes on the network and the services they offer, and to define security and network settings. A security service provider (SSP) offers security functions including encryption, key generation, key distribution, authentication, and access control lists.

A network (NWK) layer provides network self-organization and multihop routing capability. NWK performs route discovery and maintenance, and message relaying functions. NWK can initiate a new network and assign network addresses to new nodes associating with the network for the first time.

An application support (APS) sublayer connects NWK, SSP, and endpoints, and routes messages to different endpoints.

MAC and PHY layers are defined by IEEE 802.15.4. MAC is responsible for the channel access mechanism, acknowledged frame delivery, network association, and disassociation.

IEEE 802.15.4 supports two direct sequence spread spectrum (DSSS) PHY layers operating in industrial, scientific, and medical (ISM) frequency bands. A low-band PHY operates in the 868 MHz or 915 MHz frequency band and has a raw data-rate of 20 Kbps or 40 Kbps, respectively. A high-band PHY operating in the 2.4 GHz band specifies a data-rate of 250 kbps and has nearly worldwide availability. The 2.4 GHz frequency band is the most potential for large-scale WSN applications, since the high-radio data-rate reduces frame transmission time and usually also the energy per transmitted and received bit.

#### 3.2. Node types

IEEE 802.15.4 defines three types of logical devices, a personal area network (PAN) coordinator, a coordinator, and a device. ZigBee denotes them as ZigBee coordinator, ZigBee

router, and ZigBee end-device, respectively. For clearness, we utilize the naming of IEEE 802.15.4 from now on.

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 hardware. The standard designates these low-complexity nodes as reduced function devices (RFD). Nodes with the complete set of MAC services are called as full function devices (FFDs).

#### 3.3. Network topologies

The standard supports two network topologies, star, and peer-to-peer, presented in Figure 2. In the star topology, all data exchanges are controlled by a PAN coordinator that operates as a network master, while devices operate as slaves and communicate only with the PAN coordinator. This single-hop network is most suitable for delay critical applications, where large network coverage 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 multihop routed to coordinators outside its range. This enables the formation of complex self-organizing network topologies. The network may contain also RFDs as devices. 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 message relaying.

One special type of peer-to-peer topology is a cluster-tree network, defined by ZigBee. 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. This well-defined structure simplifies multihop routing and allows effective energy saving; each node maintains 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 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 grandchild nodes causing energy wasting during network reassociations [12].

#### 3.4. MAC layer

The MAC layer can operate on both beacon-enabled and nonbeacon modes. In the nonbeacon mode, a protocol is a simple CSMA-CA. This requires a constant reception of possible incoming data. The power saving features that are critical in WSN applications are provided by the beacon-enabled

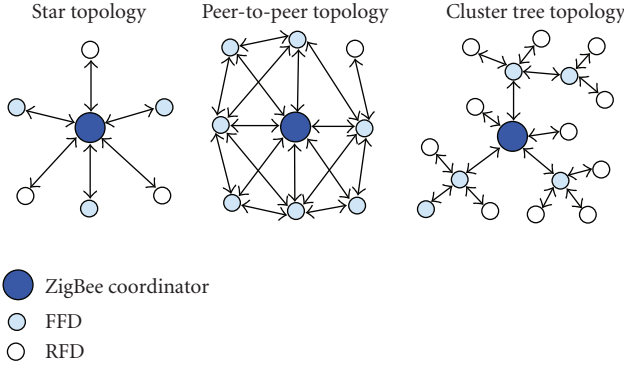


FIGURE 2: Star, peer-to-peer, and cluster-tree topology examples.

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 allows network nodes to synchronize themselves to the network. An active part of a superframe is divided into 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.

CAP is a mandatory part of a superframe during which channel is accessed using a slotted CSMA-CA scheme. Coordinators are required to listen to the channel the whole CAP to detect and receive any data from their child nodes. The child nodes may only transmit data and receive an optional acknowledgement (ACK) on demand, which increases their energy-efficiency.

CFP is an optional part of a superframe. Nodes requiring dedicated bandwidth and low-latency transmissions [22] may request GTS from a PAN coordinator. CFP does not utilize any collision avoidance mechanism. Due to inter-cluster collisions, the applicability and benefits of GTS are very limited in large peer-to-peer or cluster-tree networks. In addition, CFP can be utilized only for a direct communication with a PAN coordinator.

The beacon interval (BI) and the active superframe duration (SD) are adjustable by IEEE 802.15.4 parameters beacon order (BO) and superframe order (SO) as

$$\begin{aligned} BI &= \text{aBaseSuperframeDuration} \times 2^{BO}, \\ SD &= \text{aBaseSuperframeDuration} \times 2^{SO}, \end{aligned} \quad (1)$$

where  $0 \leq SO \leq BO \leq 14$ , and  $\text{aBaseSuperframeDuration}$  equals 960 radio symbols or 15.36 milliseconds in the 2.4 GHz band. Hence, BI and SD range between 15.36 milliseconds and 251.7 seconds. The superframe structure is maintained by a PAN coordinator. In cluster-tree networks, all coordinators transmit beacons for assisting other nodes to maintain synchronization with them.

For minimizing inter-cluster interferences, it is desirable to concatenate superframes of neighboring clusters. ZigBee specifies that BI is divided into BI/SD slots. During a start-

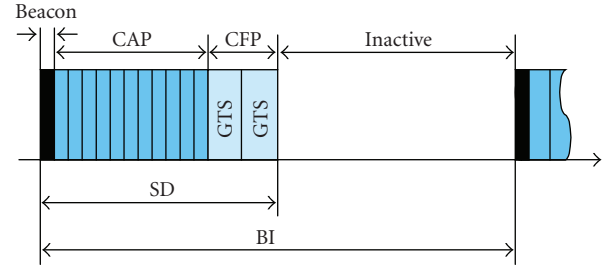


FIGURE 3: Superframe structure in beacon-enabled mode.

up, each coordinator randomizes a free slot for its superframe.

## 4. THE DESIGN OF NETWORK CHANNEL BEACONING

The designed algorithm should improve ZigBee energy-efficiency, throughput, and scalability in dynamic low-duty-cycle cluster-tree networks, while the energy overhead in static networks should be insignificant.

A starting point for the design is IEEE 802.15.4 configured to a beacon-enabled mode with inactive period. These settings provide the highest energy-efficiency in static networks. For maintaining the energy-efficiency also in dynamic networks, we focus on minimizing the energy consumption caused by link failures.

### 4.1. Network scan in IEEE 802.15.4

A network scan over a given list of channels is initiated by a *MLME-SCAN.request* primitive. The most important parameters are *ScanType*, *ScanChannels*, and *ScanDuration*. *ScanType* is used to select a suitable scan type among energy detection (ED) scan, active scan, passive scan, or orphan scan. *ScanChannels* is a bitmap indicating which channels are to be scanned. *ScanDuration* is used to calculate the length of time to spend scanning each channel. ED scan is used to determine channel usage, active or passive scan to locate beacon frames containing any PAN identifier, or an orphan scan to locate a PAN to which the device is currently associated. Passive and orphan scans are mandatory requirements for all devices. ED and active scans are optional for an RFD.

The ED scan is used by a prospective PAN coordinator to select a suitable channel for a new PAN. The ED scan estimates the received signal power within the bandwidth of a channel, while no attempt is made to identify or decode signal on the channels. Based on the detected energy, the channel with the lowest energy can be selected.

The active and passive scans allow a device to locating any coordinator transmitting beacon frames within its personal operating space (POS). These scan types are used by a prospective PAN coordinator to select a PAN identifier prior to starting a new PAN, or they could be used by a device for selecting a suitable coordinator prior to association.

The active scan is performed by sending a beacon request command and then by receiving for possible beacon frames in return. Upon receiving the beacon request, each node in



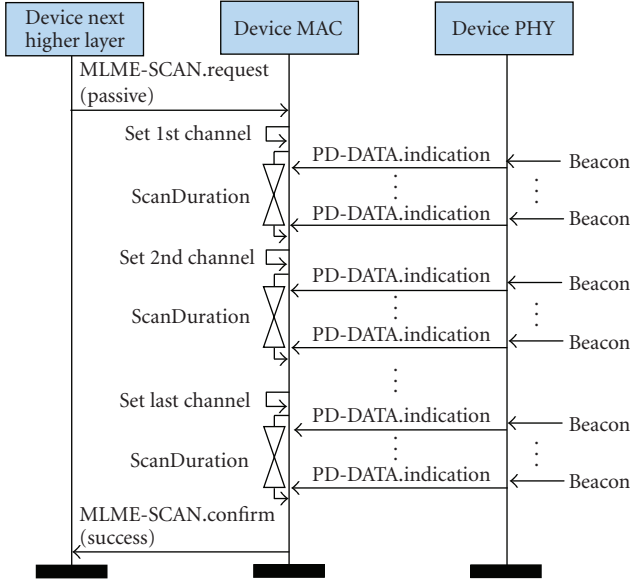


FIGURE 4: Passive scan message sequence chart of ZigBee.

a range transmits a beacon. This necessitates that each coordinator is continuously in reception mode.

The passive scan is performed by receiving beacons without transmitting any requests. This necessitates that all coordinators transmit beacons at predetermined intervals in some of the specified frequency channels. However, coordinators are not required to be constantly in reception mode allowing the inactive time, which is crucial for energy-efficiency. The message sequence chart of the IEEE 802.15.4 passive scan is presented in Figure 4. For detecting all coordinators in POS, passive scan should be conducted on each selectable channel at least a beacon transmission interval. In ZigBee, passive scan duration equals  $BI + aBaseSuperframeDuration$ .

The orphan scan allows a device to attempt to relocate its coordinator following a loss of synchronization. The scan is performed in each of specified set of channels by sending an orphan notification command and then by receiving for a possible coordinator realignment command until a *macResponseWaitTime* (491.2 milliseconds at 2.4 GHz band) expires. The scan is terminated, if the realignment command is received, or all the specified channels have been scanned.

The orphan scan is suitable for networks, where coordinators are constantly in reception mode. In energy-efficient networks utilizing the inactive period, coordinators are typically most of time in sleep mode, and the reception of the orphan notification command cannot be guaranteed. Thus, the orphan scan should be replaced by a MAC sublayer reset followed by a passive scan, and a network reassociation, as specified by IEEE 802.15.4.

As the focus of this paper is on networks where all nodes utilize the inactive period, only ED scan and passive scan are applicable. Since ED scan is utilized only at the startup of a PAN coordinator, we can focus purely on the minimization of passive scan energy consumption.

#### 4.2. Minimization of passive scan energy

Passive scan energy consumption is a product of transceiver power consumption in reception mode and passive scan duration. Since it is difficult to affect the transceiver power characteristics, we focus on minimizing the scanning time.

As found in [19], the energy consumption of a one second long network (passive) scan equals the energy of nearly 3000 beacon transmissions by a typical low-power transceiver. One can easily conclude that it is worthwhile to increase beacon transmissions rate by reducing BI. Yet, the cost of a shorter BI is increased beacon reception energy due to beacon synchronization. Due to time drift, the synchronized reception of beacons is also more energy hungry than the transmission of them.

For eliminating this drawback, the designed NCB algorithm utilizes additional beacon transmissions on a dedicated network signaling channel. These *network beacons* are transmitted without collision avoidance independently from the IEEE 802.15.4 specified beacons (*standard beacons*) and received during passive scans only. Since the dedicated network channel eliminates collisions with data transmissions, the transmission rate of network beacons can be significantly higher than the rate of standard beacons. This effectively minimizes the required passive scan duration reducing both energy consumption and data routing breaks. Moreover, the passive scan duration is independent from BI and the number of utilized channels for superframes, which is a major improvement for the standard passive scan. Thus, the scalability can be improved by increasing BI length and the number of utilized frequency channels, while maintaining rapid and low-energy passive scans. As the 2.4 GHz and 915 MHz, frequency bands have 16 and 10 selectable channels, respectively, the use of a separate network signaling channel is feasible.

In principle, the network beacons are used for searching a suitable coordinator with which to associate. Then, the association is performed on the *cluster channel* of a desired coordinator, where standard beacon, data, and control frames are exchanged. In practice, occasional collisions between beacons are possible. However, they do not interfere with data and control frame exchanges, or the standard beacon synchronization. Assuming that the transmission interval of network beacons is around two orders of magnitude longer than a beacon length, the probability of collisions is very low in sparse networks. In dense networks, we can assume that adequate number of beacons can be received correctly even though some collisions occur.

Due to frequency selective channel fading, the link quality of the network and cluster channels may differ [23]. This causes two consequences: all coordinators in the range of the cluster channel are not detected, or the signal strength of a selected coordinator is too low for communication, when operation is switched to the cluster channel. However, we can assume that an adequate number of network beacons can be received during the passive scan for ensuring network connectivity. According to the schedule and frequency channel information of received network beacons, a node attempts to receive the standard beacons, one after another, until

a suitable coordinator with adequate signal strength is found. Standard beacons are received accurately at the specified moments minimizing the energy consumption of idle listening.

If the network beacons of two coordinators collide, collisions are also probable with beacons transmitted later on, because beacons are sent periodically at constant intervals. To prevent beacon collisions without the need of network beacon scheduling, we propose delaying network beacon transmission by a random jitter ( $J$ ), defined as

$$J = \varphi[0 \cdots J_{\text{MAX}}] \cdot t_{\text{TXB}}, \quad (2)$$

where  $\varphi[a, b]$  is a random function on the interval  $[a, b]$ ,  $J_{\text{MAX}}$  is the maximum jitter, and  $t_{\text{TXB}}$  is the time required to send a network beacon.

As presented in Figure 5, network beacons are broadcasted by all coordinators during inactive periods. This is easily managed by a single radio transceiver. Normally, network beacons are transmitted at rate  $f_N$ . However, assuming one radio per station, a coordinator may not send a network beacon, while maintaining an active period or communicating with another coordinator. Then, the transmission of a beacon must be delayed until the end of the active period, causing at most  $1/f_N + \text{SD}$  interval between network beacons. While it is possible to avoid delaying the transmission by selecting suitable network beacon interval and active period boundaries, the presented interval is considered as a practical network scan time with NCB.

The algorithm operates similarly on PANs operating on a single channel and PANs, where coordinators are divided into several frequency channels. Additional information carried in network beacons in respect to IEEE 802.15.4 beacons are an exact time to the beginning of the next superframe, and the frequency channel of the coordinator. The presented design does not have any effect on the standard beacons transmitted at the beginning of superframes.

The message sequence chart of a passive scan utilizing NCB is presented in Figure 6. As network beacons are transmitted at rate  $f_N$ , passive scan is performed by the MLME-SCAN.request primitive by setting: *ScanType* = passive, *ScanChannels* = network channel, and *ScanDuration* =  $1/f_N + \text{SD}$ .

If the network will be deployed in an environment having high-RF interferences, some frequency channels may be locally jammed [23]. The robustness of network channel can be improved by defining two network channels, where network beacons are transmitted consecutively. Correspondingly, a passive scan is conducted on the both channels. The network channels should be selected before deployment according to RF spectrum measurements. It should also be noted that it is always possible to fall back into the standard passive scan. However, in the rest of this paper we assume rather low-RF interferences and utilize one network channel.

### 4.3. Implementation guidelines

The management functions of NCB algorithm should be implemented on the NWK layer. In addition, IEEE 802.15.4 MAC should be modified by adding functionality for network beacon transmissions. The format of network beacons

is a slight variation of an IEEE 802.15.4 beacon frame. We suggest replacing the fields *GTS fields* and *pending addresses* of the IEEE 802.15.4 beacon frame with *time to next superframe* and *coordinator channel*, as illustrated in Figure 7. For adequate resolution, the space allocated for these fields are 4 B and 1 B, respectively. The initialization and transmissions of network beacons are very similar to standard beacons.

For maintaining all the benefits of standardized technology, interoperability with standards is essential. In principle, a ZigBee node should be able to find a NCB equipped coordinator by a passive scan and to associate with it and vice versa.

We suggest adding a NCB specification field in the payload of standard beacons specifying the utilized network channel, and the transmission rate of network beacons. The NCB field that can be utilized for determining is NCB supported in the PAN.

At a startup, a new PAN coordinator should perform active/passive and an ED scans, as specified by IEEE 802.15.4. According to the scans, free channels for the PAN and network beacons are selected, and beacon transmissions are initiated.

At a startup, other nodes perform a passive scan and select a suitable PAN to associate with, as specified in IEEE 802.15.4. According to the NCB specification field, nodes determine the usage of network channel in PAN. If NCB is supported, network beacon transmissions are initiated. For allowing compatibility with nodes lacking the NCB functionality, the standard specified passive scan should be performed each time the NCB passive scan cannot find suitable parents. Since the NCB algorithm does not affect standard beacon transmissions, the ordinary passive scan easily finds all nodes resulting in cross-compatibility with ZigBee.

For the highest energy-efficiency, it is important to energy to optimize network beacon rate according to the level of network dynamics [19]. A successful operation of NCB necessitates that the network beacon rate is uniform and globally known in entire network. It is possible to predetermine the network beacon rate according to presumable network dynamics in a given application. However, a more efficient option is to adjust the network beacon rate dynamically. We suggest that each node observes and maintains a record of an average link lifetime. The maintained values are transmitted to a PAN coordinator in data frames upon a request. It is suggested that the PAN coordinator broadcasts the request at regular intervals, for example once per hour. According to the gathered link lifetimes, the PAN coordinator determines an energy optimal network beacon rate for the PAN. The network beacon rate is flooded through the network by utilizing the NCB specification field of standard beacons minimizing a control frame overhead.

## 5. PERFORMANCE ANALYSIS

To be able to analyze purely the effect of NCB on the energy of network maintenance operations, we first divide the energy consumed by the wireless communication into three classes [19]: *node startup*, *network maintenance*, and *data exchange* energies, as illustrated in Figure 8. Node startup

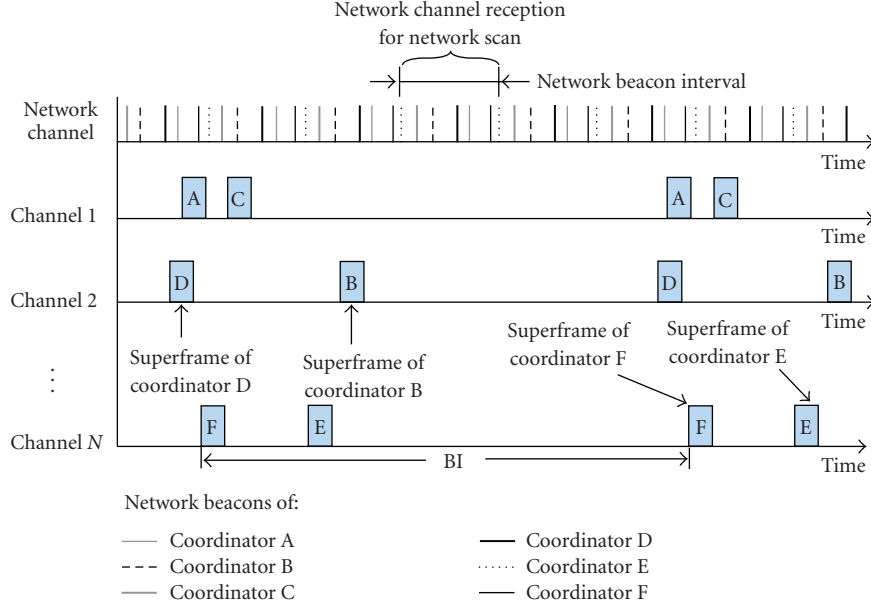


FIGURE 5: Principle of frequent network beacons.

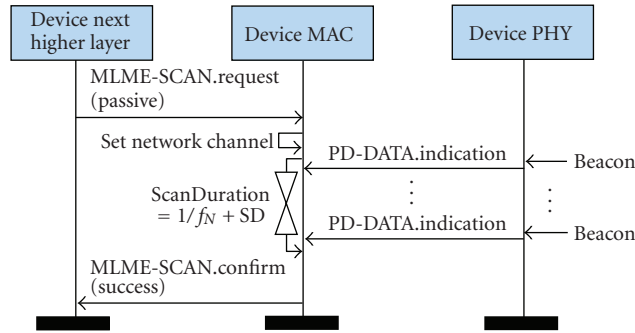


FIGURE 6: Passive scan message sequence chart of NCB equipped ZigBee.

energy is composed of a passive scan for detecting coordinators in a range, and a network association for connecting the node to the network. The network association consists of control packet exchange according to the IEEE 802.15.4 specification. Network maintenance and data exchange operations are executed after the startup period. Network maintenance energy consists of beacon transmissions and reception, passive scans, and network reassociations according to occurred link failures. Data exchange energy is consumed by upper-layer payload data and acknowledgement transmissions and receptions. We define that network beacon transmissions have lower priority than data exchanges. Hence, network beacon broadcasts do not affect data exchange energy. From now on, we can focus on the minimization of network maintenance energy.

Next, the performance analysis of NCB algorithm in a WSN application will be presented. The analysis begins by an energy analysis of a reference hardware platform, and proceeds to network maintenance power analysis through MAC operation models.

### 5.1. Hardware platform

To obtain realistic results, steady-state power consumptions of a commercial IEEE 802.15.4 compliant Chipcon CC2420EM/EB [24] transceiver evaluation board are measured. In addition, the power consumption of a PIC18LF8722 [25] microcontroller is measured to estimate the energy consumption of a low-power MAC protocol processor. The measured power consumptions of the platform in different operation modes are presented in Table 1. Highest power of 56.5 mW is consumed in reception mode ( $P_{RX}$ ). In transmission mode, power consumption varies from 26.6 mW to 48.0 mW. We define that frames are always transmitted with the highest transmission power level resulting in 48.0 mW transmission power ( $P_{TX}$ ). Sleep mode power consumption is 30  $\mu$ W. Table 2 presents the measured transient times as the transceiver switches from sleep to idle mode and from idle to active (RX or TX) mode. The transient times from active to idle and from idle to sleep mode are negligible.

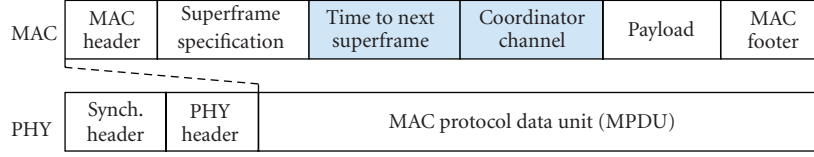


FIGURE 7: Suggested format of an NCB network beacon frame.

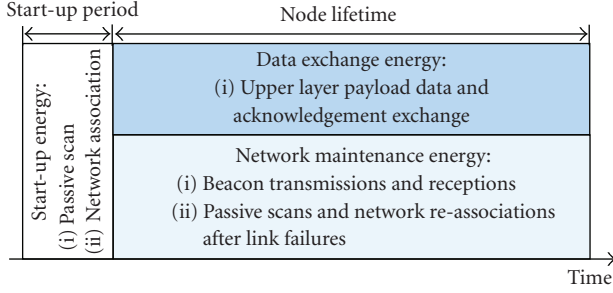


FIGURE 8: Node energy consumption classification.

TABLE 1: Measured static platform power consumptions at 3 V supply voltage.

Symbol	MCU mode	Radio mode	Power consumption
$P_{TX}$	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
$P_I$	Active	Idle	2.79 mW
$P_S$	Sleep	Sleep	30 $\mu$ W

TABLE 2: Measured chipcon CC2420 transient times.

Symbol	Description	Time ( $\mu$ s)
$t_{ST}$	Sleep to idle	970
$t_{IA}$	Idle to active	192

### 5.2. Network configuration

We analyze the energy-efficiency of NCB in a cluster-tree network, where each cluster contains  $n_D$  (11) devices and  $n_C$  (2) child coordinators. Network depth ( $d$ ) is 4 levels of hierarchy. Coordinators broadcast standard beacons once per BI resulting a standard beacon rate  $f_C = 1/BI$ , where BI gets values between 0.246 second and 15.7 seconds. Network beacon rate  $f_N$  is varied from 0.1 Hz to 100 Hz. The network operates on  $n_{CH}$  channels. The utilized parameters and their values are presented in Table 3.

### 5.3. MAC operation models

To be able to analyze the network maintenance energy, MAC operation models are defined for a beacon transmission, a beacon reception, and a passive scan.

A beacon frame transmission consists of a sleep-to-idle ( $t_{SI}$ ) transient, idle-to-active ( $t_{IA}$ ) transient, and actual data transmission defined as the ratio of beacon frame length ( $L_B$ ) and radio data-rate ( $R$ ). No CCA analysis is needed for a beacon frame. During the sleep-to-idle transient, radio power consumption equals  $P_I$ , after which power consumption rises to  $P_{TX}$ . The beacon transmission energy ( $E_{TXB}$ ) is

$$E_{TXB} = t_{SI}P_I + (t_{IA} + L_B/R)P_{TX}. \quad (3)$$

The resulting energy consumption per transmitted frame is  $E_{TXB} = 39.6 \mu$ J, which equals 190 nJ per a PHY layer data bit.

A beacon reception begins with radio startup transients. The radio is in reception mode until a beacon frame has been received including a time margin required due to synchronization inaccuracy ( $t_I$ ), and the time drift between a transmitting and a receiving node. As synchronization is obtained by standard beacon receptions; the time drift caused by crystal tolerance ( $\epsilon$ ) is directly proportional to BI. The beacon reception energy ( $E_{RXB}$ ) is

$$E_{RXB} = t_{SI}P_I + (t_{IA} + 2\epsilon BI + t_I + L_B/R)P_{RX}. \quad (4)$$

The resulting energy consumption per received frame is  $E_{RXB} = 70.2 \mu$ J ( $BI = 0.96$  second). This equals 338 nJ per a PHY layer data bit.

A passive scan begins with the startup transients. Then, a radio is in RX mode during passive scan duration ( $t_{NS}$ ). The energy required for message exchanges during a reassociation is negligible compared to the energy of the passive scan, and thus it is ignored in the following analysis. Thus, the passive scan energy ( $E_{NS}$ ) is

$$E_{NS} = t_{SI}P_I + (t_{IA} + t_{NS})P_{RX}. \quad (5)$$

The passive scan duration depends on the utilization of NCB. For ZigBee, the duration is a function of the number of scanned cluster channels and a beacon order as

$$t_{NS} = n_{CH} \cdot \text{aBaseSuperframeDuration} (2^{BO} + 1). \quad (6)$$

As defined above, practical network scan duration for NCB equipped ZigBee is

$$t_{NS} = 1/f_N + SD. \quad (7)$$



TABLE 3: Utilized parameters and their values.

Symbol	Parameter	Value
$f_C$	Standard beacon rate	63.8 mHz–16.4 Hz
$f_N$	Network beacon rate	0.1 Hz–100 Hz
$L_B$	Beacon frame length	26 B
$n_D$	Number of devices associated with each coordinator	12
$n_C$	Number of child-coordinators associated with each coordinator	3
$n_{CH}$	Number of cluster channels	1 or 10
$R$	Radio data-rate	250 Kbps
$r$	Radio range	20 m
$t_I$	Synchronization inaccuracy	0.10 ms
$v$	Node mobility	0.01–10 m/s
$\epsilon$	The crystal tolerance	20 ppm

#### 5.4. Network maintenance power analysis

Network maintenance operations are performed continuously during entire network lifetime. Hence, it is most convenient to consider a long-time energy consumption divided by the elapsed time resulting in average power consumption. Average network maintenance power  $P_M$  is defined as a sum of passive scan power  $P_{NS}$  and beacon exchange power  $P_B$ .

The interval of passive scans depends on the average link lifetime ( $t_{LF}$ ). It should be noted that a link failure somewhere along the routing path between a given node and a sink may cause a passive scan and network reassociation. For simplicity, we omit these link failures in this analysis, and the interval between passive scans equals a link lifetime. We also omit occasional frame errors, and determine link lifetime according to node mobility. Assuming a random mobility for all nodes, average link lifetime can be approximated by a radio range ( $r$ ) and node mobility ( $v$ ) as

$$t_{LF} = r/v. \quad (8)$$

The resulted link lifetime as a function of node mobility is plotted in Figure 9. As mobility increases, node quickly moves out of the communication range of its coordinator, and the lifetime of a link drops rapidly. According to the link lifetime, the average power consumption of network scans ( $P_{NS}$ ) is obtained as

$$P_{NS} = E_{NS}/t_{LF}. \quad (9)$$

We determine average beacon exchange power according to beacon transmission and reception energies. All nodes receive beacons, but they are transmitted by coordinators only. In standard ZigBee, beacons are transmitted and received from a parent at rate  $f_C$ . As beacon exchange power is averaged over all the nodes of a cluster; beacon exchange power consumption ( $P_B$ ) for ZigBee is

$$P_B = \frac{f_C}{n_D + 1} E_{TXB} + f_C E_{RXB}. \quad (10)$$

When NCB is utilized, beacon transmissions are increased. Besides the standard beacons, each coordinator

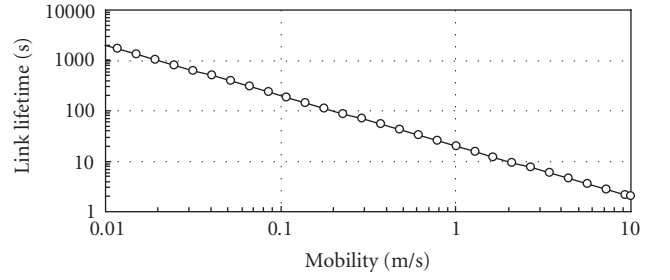


FIGURE 9: The effect of mobility to link lifetime in the simulated scenario.

transmits network beacons on the network channel at rate  $f_N$ . For NCB equipped ZigBee, average beacon exchange power consumption is

$$P_B = \frac{f_N + f_C}{n_D + 1} E_{TXB} + f_C E_{RXB}. \quad (11)$$

#### 5.5. Energy analysis results

The network maintenance powers are compared between standard ZigBee and NCB equipped ZigBee. BI and  $v$  are fixed to 3.96 seconds and 0.01 m/s, respectively. As the network operation is divided into 1 and 10 channels, the maintenance power of the standard ZigBee equals 132  $\mu$ W, and 1.13 mW, respectively, as presented in Figure 10. When NCB is used, the network maintenance power  $P_M$  (the sum of  $P_B$  and  $P_{NS}$ ) has a minimum of 42  $\mu$ W at 2.6 Hz network beacon rate. At low-beacon rates below 1 Hz,  $P_M$  typically doubles as the beacon rate halves and the power consumption are dominated by the passive scan power. The effect is reversed at high-beacon rates above 10 Hz, when the beacon transmissions dominate the power consumption. At the energy optimum 2.6 Hz network beacon rate, NCB algorithm reduces the network maintenance power up to 96%. Yet, the BI may also be energy optimized reducing the network maintenance power of standard ZigBee.

For finding an energy optimal value for BI, the network maintenance power of ZigBee is analyzed as the function of BI. From now on, the number of channels is fixed to 1.

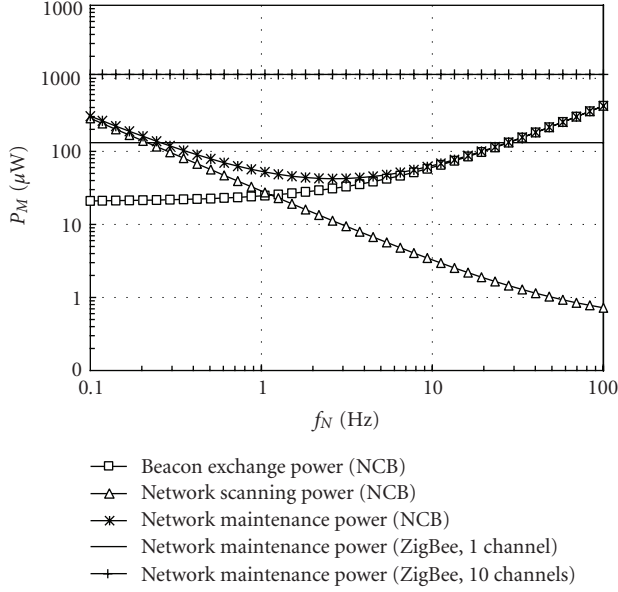


FIGURE 10: Average beacon exchange, passive scan, and network maintenance power consumptions as the function of network beacon transmission rate.

Average node mobility gets values 0.01 m/s, 0.1 m/s, and 1 m/s, ranging from a nearly static network to a quite dynamic network, respectively. The results are presented in Figure 11. At shorter values of BI, network maintenance power is dominated by beacon exchange power consumption. At longer BI values, passive scans dominate the power consumption. An energy optimal BI depends on the node mobility. The energy optimal values of BI at 0.01 m/s, 0.1 m/s, and 1 m/s mobility levels are 1.97 second, 0.49 second, and 0.12 second, respectively. The resulted minimum network maintenance power consumptions at these points are 94  $\mu$ W, 288  $\mu$ W, and 936  $\mu$ W, respectively.

Next, the network maintenance power of NCB equipped ZigBee is analyzed as the function of network beacon transmission rate. Node mobility gets values 0.01 m/s and 1 m/s, and BI is varied from 0.246 second to 15.7 seconds. The results are presented in Figure 12. In contrast to ZigBee, the network maintenance power is minimized by maximizing BI. This is logical, since passive scans are performed by receiving network beacons independently of the transmission rate of standard beacons. Hence, the increase of BI reduces beacon transmission and reception power consumption. The minimum network maintenance power is achieved by optimizing network beacon transmission rate. At 0.01 m/s and 1 m/s node mobility levels, energy optimal network beacon rates are 2.6 Hz and 28 Hz, respectively. Achieved network maintenance power consumptions at these points are 28.1  $\mu$ W and 220  $\mu$ W, respectively, as BI = 15.7 seconds. Compared to ZigBee at these link lifetimes, NCB equipped ZigBee achieves 70%–76% lower-network maintenance power. The results also indicate that NCB algorithm operates most efficiently in dynamic networks, and an energy optimal network beacon rate depends significantly on a link lifetime. A shorter link

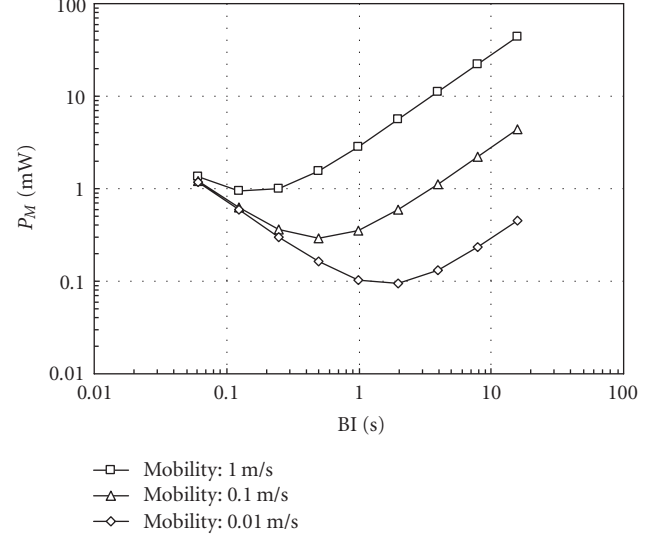


FIGURE 11: Average network maintenance power of ZigBee as the function of BI, while node mobility varies.

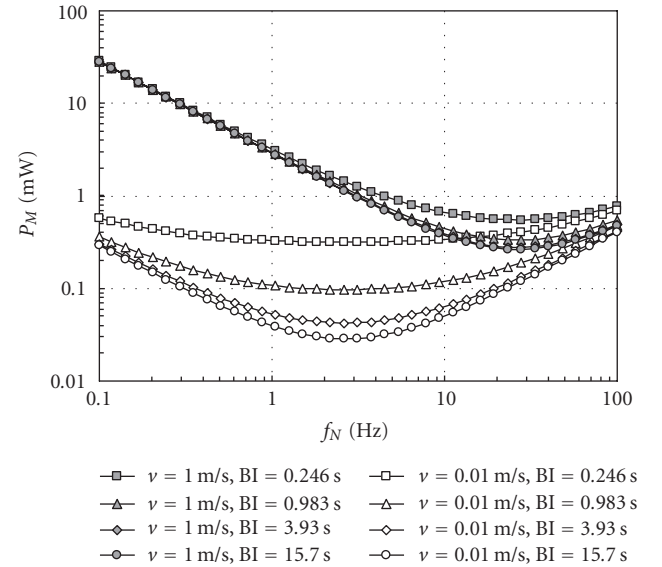


FIGURE 12: Average network maintenance power of NCB equipped ZigBee as the function of network beacon rate, as BI, and node mobility varies.

lifetime increases passive scan power consumption and thus, shifts the  $P_M$  minimum to higher-network beacon rates. According to [12], the typical power consumption of a ZigBee node in a static low-data-rate network is below 1 mW. Hence, network maintenance power has a very significant effect on entire network lifetime and the optimization of network beacon rate is very important.

## 6. NETWORK BEACON RATE OPTIMIZATION

An optimal network beacon rate ( $f_N^*$ ) is determined by minimizing the network maintenance power with respect to the

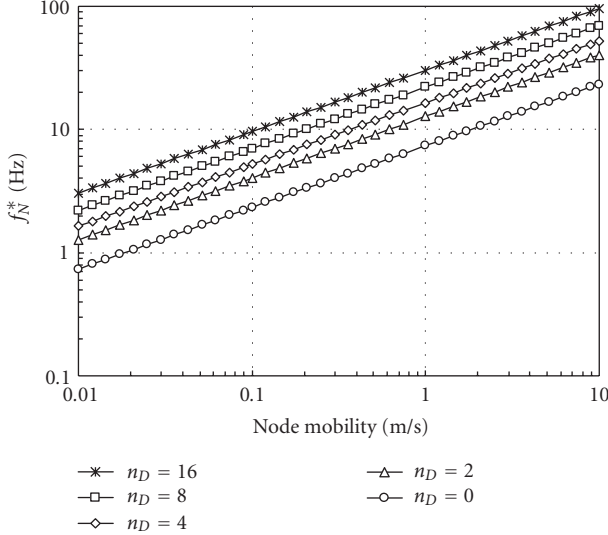


FIGURE 13: Network maintenance power of NCB equipped ZigBee at  $f_N^*$  as the function of node mobility, and comparison with standard ZigBee.

network beacon rate. An optimization function can be written as

$$P_m = \frac{f_N + f_C}{n_D + 1} E_{TXB} + f_C E_{RXB} + \frac{t_{SI} P_I + (t_{IA} + 1/f_N + SD) P_{RX}}{r} v. \quad (12)$$

It can be shown that there exists a unique minimum at  $f_N^*$  that is obtained by setting  $dP_m/df_N = 0$  in (12). This yields

$$f_N^* = \sqrt{\frac{P_{RX} v (n_D + 1)}{E_{TXB} r}}. \quad (13)$$

The optimal network beacon rate is determined by radio parameters  $E_{TXB}$ ,  $P_{RX}$ , and  $r$ , and network parameters  $n_D$  and  $v$ .

The effect of a link lifetime and a cluster size on the optimal network beacon rate is presented in Figure 13. The optimal rate is nearly directly proportional to node mobility. As the number of devices per cluster ( $n_D$ ) increases from 0 to 16, the energy optimal network beacon rate increases 312%. Although, a higher-network beacon rate increases  $P_B$  in coordinators, overall network maintenance power consumption is reduced due to shorter passive scans.

The network maintenance powers of ZigBee and NCB equipped ZigBee are compared as the function of node mobility. In the comparison, BI varies from 0.246 second to 15.7 seconds, and NCB is operating at the energy optimal network beacon rate. The results are presented in Figure 14. In static networks with very low mobility, obtained network maintenance powers are nearly the same. Hence, the energy overhead of NCB is small. The energy saving of NCB compared to standard ZigBee increases rapidly with higher-node mobility. At 1 m/s node mobility, achieved energy saving using NCB is from 44% to 99.5%.

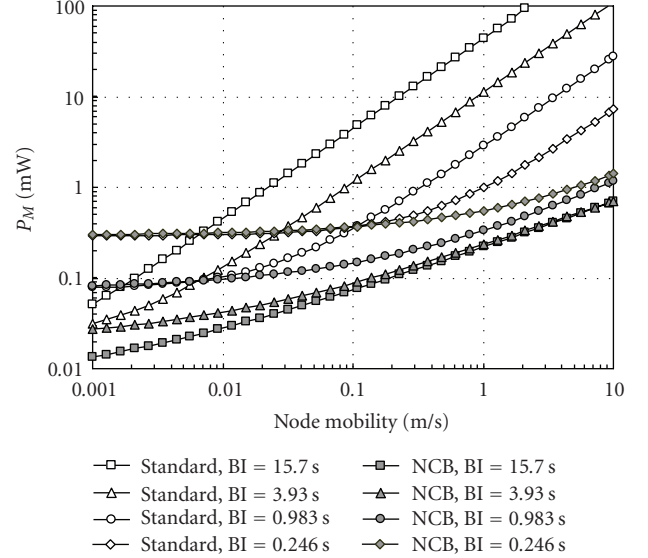


FIGURE 14: Energy optimal network beacon rate as the function of node mobility, and as the number of devices per a cluster varies.

Finally, we analyze the effect of NCB on a service time, during which a node is connected to a network and capable for routing data. We consider a time period equaling to  $t_{LF}$ . The active operation time between passive scans equals  $t_{LF}$  reduced by the durations of a passive scan ( $t_{NS}$ ) and network association ( $t_A$ ) operations. After a passive scan, a node selects a suitable parent and waits for the beginning of parent's next superframe requiring on average a half BI. Then, the node transmits an association request and waits for a response to the next superframe. Hence, on average  $t_A = 1.5BI$ . The service time ( $S$ ) is determined as the percentual duration of active operation time in proportion to the entire period as

$$S = \frac{t_{LF} - t_{NS} - t_A}{t_{LF}}. \quad (14)$$

The resulted service time as the function of a link lifetime is plotted in Figure 15. Due to the time required for association, the service time depends significantly on BI. However, NCB algorithm improves the service time of ZigBee up to 37%. The improvement is the most significant at node mobility levels above 0.1 m/s.

## 7. SIMULATIONS

The performance of the network channel beaconing was compared against standard ZigBee using ns-2 simulation tool (version 2.31) [26]. Next, the NCB implementation for ns-2 and obtained performance results are discussed.

### 7.1. Implementation

For enabling simulations in ZigBee network, few modifications for the IEEE 802.15.4 implementation provided by ns-2 were made. First, the code was modified to support a cluster-tree topology with inactive time and to perform synchronization to the coordinator prior to each association attempt.

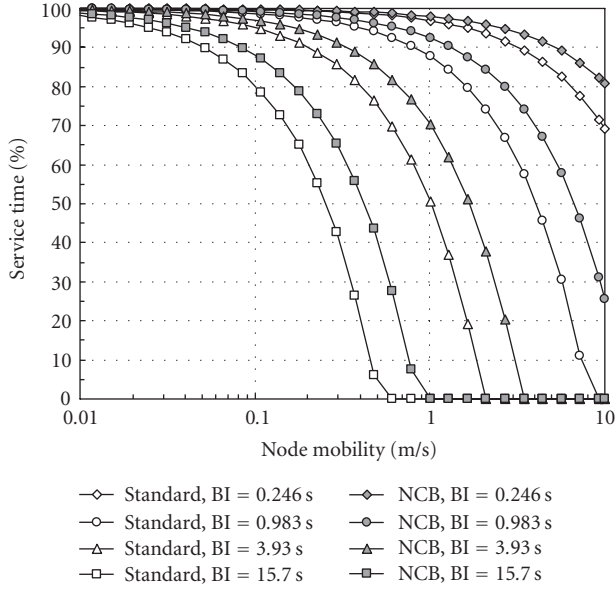


FIGURE 15: Service time versus node mobility at  $f_N^*$  and comparison with ZigBee.

Otherwise, the synchronization procedure would have included a long-term idle listening. Second, a beacon scheduling was implemented, as required by the ZigBee. Because the standard does not specify the exact method to determine the beacon schedules, a custom algorithm was used. The algorithm utilizes precalculated beacon transmission times to ensure unique time slots for each coordinator within an interference range. It should be noted that while end-to-end delay varies in different schedules, the energy, throughput, and reliability results are the same, assuming that a nonconflicting schedule is found.

Moreover, the simplest version of ZigBee routing was implemented by omitting the optional routing tables and route discovery procedure. Instead, the packets were routed along the formed cluster tree. While the route discovery procedure allows communication between two arbitrary nodes in the network, it causes high-initial delay, since a node must communicate with its destination. Therefore, the route discovery is impractical for networks having high degree of mobility.

For NCB, the NWK layer was modified to issue the passive scan command with the network channel instead of the usual channel range. The received network beacon frames were distinguished from other frames by a unique frame type value. The received beacons were handled similarly to the standard beacons, except for the time of next superframe which was calculated with *time to next superframe* field. Each station was preconfigured with network channel and network beacon interval, thus the beacon interval was the same during a simulation run. Coordinator transmitted network beacons periodically by briefly switching to the network channel. For these simulations, network beacon transmission jitter  $J_{MAX}$  was set to the value of eight, which was found to reduce collisions adequately.

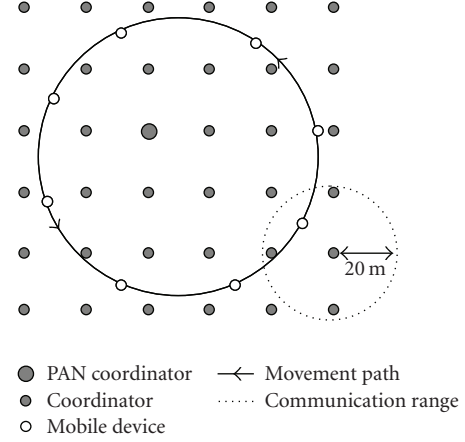


FIGURE 16: Simulated network topology. Coordinators are located on a grid around a PAN coordinator, while devices move around the grid.

The simulated scenario consisted of 36 stationary coordinators and 8 mobile devices. The coordinators were formed on a grid around a PAN coordinator, while mobile devices moved along a circle having a radius of 45 m, as illustrated in Figure 16. Each coordinator was within the communication range of its adjacent nodes. That is, the coordinators in the center had four neighbors. Maximum hop count (network depth) to the PAN coordinator was six. The simulation utilized a two-ray ground propagation model allowing communication range of 20 m. This was enough for reliable communication between immediate neighbors, but prevented interference from other nodes. To simulate normal network operation, each mobile device transmitted 40 B packets periodically to the PAN coordinator with 30 s as a period. Simulation time was one hour.

IEEE 802.15.4 was simulated without CFP and battery life extension options. During CAP, channel access mode was slotted CSMA-CA. For evaluating power consumption, the measured power consumption and transient times of Chipcon CC2420 were used, as presented in Tables 2 and 3. Frames were always sent with the highest transmission power level (0 dBm).

## 7.2. Simulation results

The simulations produced power consumption and service time results for each node in the network. The obtained results are averaged among all nodes of the same type resulting in average node behavior. It should be noted that the power consumption results include also the power consumptions of a startup and all data exchanges. Thus, the presented power consumptions are higher than that in the analysis.

We present first the simulated service time as the function of node mobility. The results are presented in Figure 17. In the results, the maximum relative error with 95% confidence is 7%. The service time depends heavily on the beacon interval, as long interval increases association delays. Because shorter network scan time allows faster neighbor discovery and thus, minimizes the time in which a node is not



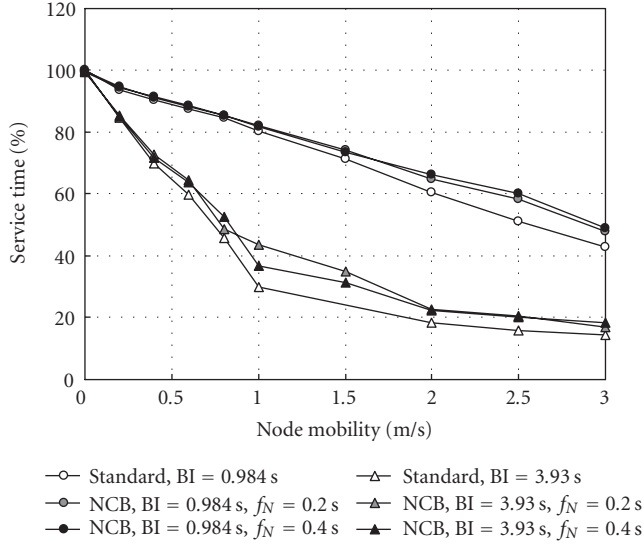


FIGURE 17: Simulated service time of a mobile device (SO = 1).

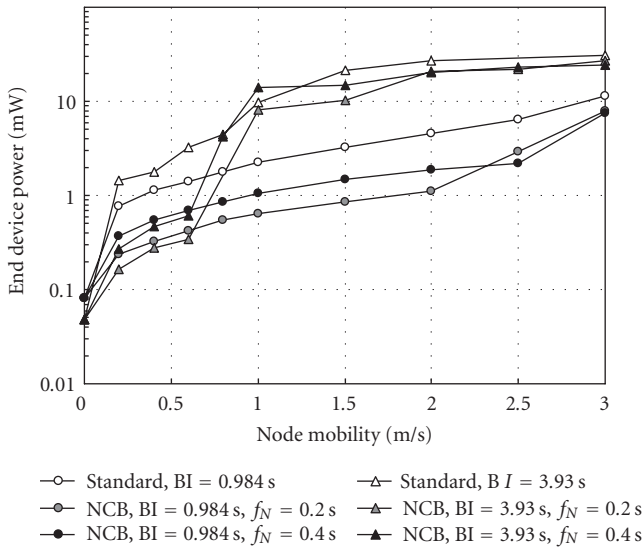


FIGURE 18: Simulated power consumption of mobile devices (SO = 1).

connected to the network, NCB increases service time up to 14%. The simulations results slightly lower service time than the analysis. This is mostly caused by occasional unsuccessful associations.

Power usage of a mobile device is presented in Figure 18. In the results, the maximum relative error with 95% confidence is 12%. When a device is stationary, only an initial network scan is performed. As the normal operation is identical between standard ZigBee and NCB, the difference on energy usage is minimal. When mobility increases, links break often and more network scans are required. Then, NCB performs significantly better than standard due to its short network scan time.

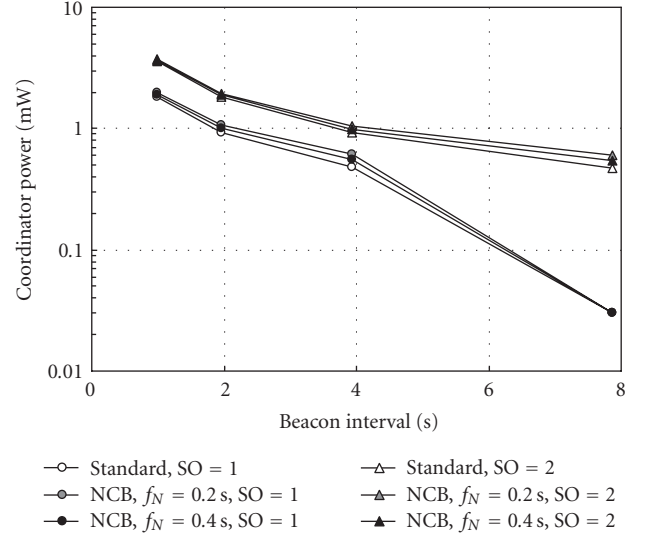


FIGURE 19: Simulated coordinator power consumption.

On low mobility and at 3.93 seconds beacon interval, NCB has order of magnitude lower power consumption than the standard. Yet, the power consumption increases significantly between 0.6 m/s and 0.8 m/s due to increased failures during synchronization. As beacon interval is long, a device may try to synchronize to a neighbor that has already moved outside its communication range. The device tries to track beacons and enables its radio for several beacon intervals before failing. Thus, after 0.6 m/s, NCB results are nearly the same with the standard. At shorter, at 0.98 second beacon interval, the same effect occurs after 2.5 m/s mobility.

Figure 19 shows the average power usage on a stationary ZigBee coordinator. The increased power requirement of NCB is only 2%–4% higher. This is expected, as network beacons are short and do not require CSMA-CA mechanism. Thus, the transceiver receptions dominate the power consumption. This is evident in Figure 19, as the super-frame length (beacon order) has the most profound effect on power.

Generally, the simulations show higher-power consumption than the analysis. The reason is that simulations included also power consumption due to data exchange, while analysis focused on the network maintenance power only. However, the results and findings are comparable and prove the energy-efficiency of proposed network channel beacons.

## 8. CONCLUSIONS

The design and performance analyses of the NCB algorithm for ZigBee are presented. A dedicated frequency channel for frequent network beacons reduces the energy consumption of IEEE 802.15.4 passive scans. Energy-efficiency is further improved by optimizing the network beacon transmission rate according to observed link lifetimes.

According to the energy analysis, NCB algorithm reduces the network maintenance power of ZigBee in dynamic networks 70%–76%. This equals even milliwatts absolute power

saving using low-power hardware platforms. As coordinator power consumption in a static network and a low- data-rate application is typically below 1 mW [12], achieved power saving is dramatic. In addition, the NCB algorithm improves network performance by increasing the service time for data routing up to 37%. Simulations validate the energy-efficiency of NCB, although the energy saving is slightly lower than in the analysis.

As the NCB algorithm minimizes passive scan energy regardless the number of utilized PAN channels, the division of clusters into several frequency channels becomes feasible and energy-efficient. This would improve ZigBee scalability and performance especially in dense and large WSNs by even eliminating inter-cluster interferences. It should be also noted that the network beacons provide an efficient way to signal network maintenance, neighborhood, and routing information for additional algorithms and protocols. NCB can be implemented as an extension on MAC and NWK layers, and it is fully compatible with ZigBee.

## REFERENCES

- [1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: a survey," *Computer Networks*, vol. 38, no. 4, pp. 393–422, 2002.
- [2] J. Polastre, R. Szewczyk, A. Mainwaring, D. Culler, and J. Anderson, "Analysis of wireless sensor networks for habitat monitoring," in *Wireless Sensor Networks*, C. S. Raghavendra, K. M. Sivalingam, and T. Znati, Eds., pp. 399–425, Springer, New York, NY, USA, 2004.
- [3] J. Suhonen, M. Kohvakka, M. Hännikäinen, and T. D. Hämäläinen, "Design, implementation, and experiments on outdoor deployment of wireless sensor network for environmental monitoring," in *Proceedings of the 6th International Workshop on Embedded Computer Systems: Architectures, Modeling, and Simulation (SAMOS '06)*, pp. 109–121, Samos, Greece, July 2006.
- [4] S. Roundy, P. K. Wright, and J. Rabaey, "A study of low-level vibrations as a power source for wireless sensor networks," *Computer Communications*, vol. 26, no. 11, pp. 1131–1144, 2003.
- [5] M. Haenggi, "Opportunities and challenges in wireless sensor networks," in *Handbook of Sensor Networks: Compact Wireless and Wired Sensing Systems*, M. Ilyas and I. Mahgoub, Eds., pp. 1.1–1.14, CRC Press, Boca Raton, Fla, USA, 2004.
- [6] IEEE Std 802.15.1-2002, wireless medium access control (MAC) and physical layer (PHY) specifications for wireless personal area networks (WPANs).
- [7] IEEE Std 802.15.3-2003, wireless medium access control (MAC) and physical layer (PHY) specifications for high rate wireless personal area networks (WPANs).
- [8] IEEE Std 802.15.4-2006, wireless medium access control (MAC) and physical layer (PHY) specifications for low-rate wireless personal area networks (WPANs).
- [9] J. A. Gutierrez, E. H. Callaway Jr., and R. L. Barrett Jr., *Low-Rate Wireless Personal Area Networks—Enabling Wireless Sensors with IEEE 802.15.4*, IEEE Press, New York, NY, USA, 2003.
- [10] "ZigBee Alliance Document 053474r06; ZigBee Specification, Version 1.0," December 2004.
- [11] J. Ha, W. H. Kwon, J. J. Kim, Y. H. Kim, and Y. H. Shin, "Feasibility analysis and implementation of the IEEE 802.15.4 multi-hop beacon enabled network," in *Proceedings of the 15th Joint Conference on Communications & Information (JCCI '05)*, pp. 1–5, Korea, April 2005.
- [12] M. Kohvakka, M. Kuorilehto, M. Hännikäinen, and T. D. Hämäläinen, "Performance analysis of IEEE 802.15.4 and ZigBee for large-scale wireless sensor network applications," in *Proceedings of the 3rd ACM International Workshop on Performance Evaluation of Wireless Ad Hoc, Sensor and Ubiquitous Networks (PE-WASUN '06)*, pp. 48–57, Terromolinos, Spain, August 2006.
- [13] N. F. Timmons and W. G. Scanlon, "Analysis of the performance of IEEE 802.15.4 for medical sensor body area networking," in *Proceedings of the 1st Annual IEEE ICommunications Society Conference on Sensor and Ad Hoc Communications and Networks (SECON '04)*, pp. 16–24, Santa Clara, Calif, USA, October 2004.
- [14] B. Bougard, F. Catthoor, D. C. Daly, A. Chandrakasan, and W. Dehaene, "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)*, vol. 1, pp. 196–201, Munich, Germany, March 2005.
- [15] G. Lu, B. Krishnamachari, and C. S. Raghavendra, "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)*, pp. 701–706, Phoenix, Ariz, USA, April 2004.
- [16] D. Mirza, M. Owrang, and C. Schurgers, "Energy-efficient wakeup scheduling for maximizing lifetime of IEEE 802.15.4 networks," in *Proceedings of the 1st International Conference on Wireless Internet (WICON '05)*, pp. 130–137, Budapest, Hungary, July 2005.
- [17] A. Koubaa, A. Cunha, and M. Alves, "A time division beacon scheduling mechanism for IEEE 802.15.4/Zigbee cluster-tree wireless sensor networks," in *Proceedings of the 19th Euromicro Conference on Real-Time Systems (ECRTS '07)*, pp. 125–135, Pisa, Italy, July 2007.
- [18] L.-J. Hwang, S.-T. Sheu, Y.-Y. Shih, and Y.-C. Cheng, "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)*, pp. 26–32, Budapest, Hungary, July 2005.
- [19] A. Rowe, R. Mangharam, and R. Rajkumar, "Rt-link: a time synchronized link protocol for energy constrained multi-hop wireless networks," in *Proceedings of the 3rd Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON '06)*, vol. 2, pp. 402–411, Reston, Va, USA, September 2006.
- [20] M. Kohvakka, M. Hännikäinen, and T. D. Hämäläinen, "Energy optimized beacon transmission rate in a wireless sensor network," in *Proceedings of the 16th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC '05)*, vol. 2, pp. 1269–1273, Berlin, Germany, September 2005.
- [21] B. Heile, "Wireless sensors and control networks: enabling new opportunities with ZigBee," ZigBee Alliance Tutorial, December 2006, <http://www.zigbee.org>.
- [22] A. Koubaa, M. Alves, and E. Tovar, "GTS allocation analysis in IEEE 802.15.4 for real-time wireless sensor networks," in *Proceedings of the 14th International Workshop on Parallel and Distributed Real-Time Systems (WPDRTS '06)*, pp. 1–8, Rhodes, Greece, April 2006.

- [23] D. Sexton, M. Mahony, M. Lapinski, and J. Werb, "Radio channel quality in industrial wireless sensor networks," in *Proceedings of the Sensors for Industry Conference (SIcon '05)*, pp. 88–94, Houston, Tex, USA, February 2005.
- [24] Data Sheet for CC2420 2.4 GHz IEEE 802.15.4/ZigBee RF Transceiver, <http://focus.ti.com/lit/ds/symmlink/cc2420.pdf>.
- [25] Data Sheet for PIC18LF8722 Microcontroller, <http://focus.ti.com/lit/ds/symmlink/cc2420.pdf>.
- [26] The Network Simulator - ns-2, version 2.31, <http://www.isi.edu/nsnam/ns>.

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