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Research Article

Energy-Efficient Reservation-Based Medium Access Control Protocol for Wireless Sensor Networks

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In Wireless Sensor Networks (WSNs), a robust and energy-efficient Medium Access Control (MAC) protocol is required for high energy efficiency in harsh operating conditions, where node and link failures are common. This paper presents the design of a novel MAC protocol for low-power WSNs. The developed MAC protocol minimizes the energy overhead of idle time and collisions by strict frame synchronization and slot reservation. It combines a dynamic bandwidth adjustment mechanism, multi-cluster-tree network topology, and a network channel allowing rapid and low-energy neighbor discoveries. The protocol achieves high scalability by employing frequency and time division between clusters. Performance analysis shows that the MAC protocol outperforms current state-of-the-art protocols in energy efficiency, and the energy overhead compared to an ideal MAC protocol is only 2.85% to 27.1%. The high energy efficiency is achieved in both leaf and router nodes. The models and the feasibility of the protocol were verified by simulations and with a full-scale prototype implementation.

1. Introduction

Wireless Sensor Network (WSN) is an emerging technology, which combines distributed sensing and computing with wireless communication. WSN may consist of thousands of self-configuring and self-healing nodes, which automatically form a multihop network topology [1, 2]. Data is routed to one or more sink nodes, which may operate as user interfaces or gateways to other networks. WSNs have a vast number of potential applications [3], for example monitoring of remote or hostile geographical regions, tracking of animals and objects, and surveillance [1, 4–7].

This paper focuses on very low-energy WSNs, where small, cheap, and even disposable nodes should operate up to years with small batteries, while actively performing measurements. To reach the energy, cost, and size budget, WSN nodes operate with very limited communication and computation resources. Although the advances in Radio Frequency (RF) circuits have been remarkable in recent years, a radio transceiver is still the most power-consuming component of a WSN node. The power consumption of current radios is nearly the same in the transmission and reception modes. Low power consumption is achieved only in the sleep mode, in which the radio circuitry is completely switched off. To be able to reach the energy budget, radio should be activated only when transmitting or receiving a packet that is vital for the node operation.

This paper focuses on a Medium Access Control (MAC) protocol design for presenting a solution for the energy consumption challenge. The MAC protocol manages radio transmissions and receptions on a shared wireless medium. Thus, MAC has a very high effect on network performance and energy consumption. The design objectives of low-energy WSN MAC protocols differ completely from the MAC protocols of traditional wireless computer networks, such as IEEE 802.11 wireless LAN, as presented in Table 1. While the latter pursue to maximize achieved throughput, low-energy WSN MAC protocols are aiming to maximize energy-efficiency. Other key design objectives are adaptivity for maintaining the robust and energy-efficient operation in a dynamic environment, where the network size, topology, and radio propagation conditions vary, and scalability for providing high energy efficiency and performance independently on a network size and density. WSN MAC

Table 1: Opposite MAC requirements for wireless computer networks and low-energy WSNs.

Requirement	Criticality for MAC protocols	
	Wireless computer networks	Low-energy WSNs
Energy efficiency	Lowest	Highest
Adaptivity	Low	High
Scalability	Moderate	High
Fairness	Moderate	Moderate
Latency	High	Low
Throughput	Highest	Lowest

protocol should also ensure fairness, such that sinks receive information from all sources equally. In addition, a protocol should provide adequate throughput and latency for a given application. Sufficient throughput for WSN applications may be around few kbits/s [8], while a source-to-sink latency may be even tens of seconds. Yet, one of the most important design requirements is practical feasibility, as the available computation and memory resources are very constrained.

To be able to reach adequate energy efficiency, a low-energy MAC protocol must minimize the following [5]:

(i) unnecessary listening of a Radio Frequency (RF) channel (idle listening),

(ii) frame collisions,

(iii) overhearing of frames intended to other nodes, and

(iv) network signaling traffic overhead.

In practice, the highest energy efficiency is achieved, when a source and a destination node are activated and tuned on a correct RF channel simultaneously for a frame exchange, while other nodes remain in sleep mode. This is very difficult in large and resource constrained WSNs having dynamically changing network topology.

In this paper, we present a survey of existing low-energy MAC protocols and standards for WSNs. It is shown that the existing MAC protocols lack the performance to adequately fulfill the energy efficiency and adaptivity requirements of low-energy WSNs. This motivates the design of a new low-energy MAC protocol called TUTWSN MAC. First, the energy overhead in existing MAC protocols is modeled and analyzed, and then a new protocol is designed by eliminating the most essential causes of the overhead in each radio transaction. The key principles for maximizing the energy efficiency are a collision-free slot reservation-based channel access, and a strict synchronization of transmissions and receptions. For further improving the energy efficiency, a dynamic bandwidth adjustment mechanism, and a multi-cluster-tree network topology are designed. The performance of the designed protocol is verified and compared to existing protocols and standards by performance modeling and energy analysis. Finally, the performance and feasibility of the design is validated by simulations and experimental measurements in real WSN implementations.

This paper is organized as follows. Section 2 presents the essential low-power MAC protocols proposed for WSNs. The energy overhead in wireless channel access is analyzed in Section 3. Section 4 presents the design and implementation of TUTWSN MAC. The performance of TUTWSN MAC is analyzed and compared with related proposals in Section 5. Performance simulations are presented in Section 6. Experimental power consumption measurements are carried out in Section 7. Finally, the paper is concluded in Section 8.

2. Related Research

MAC protocols have been typically categorized into contention and contention-free protocols. In contention protocols, nodes compete for a shared channel, while trying to avoid frame collisions, for example by using carrier sensing [9], and Request-To-Send-(RTS-) Clear-To-Send (CTS) handshaking [10, 11]. Examples of contention protocols are Carrier Sense Multiple Access (CSMA) [9] and MACA [10]. In contention-free protocols, nodes get unique time slots, frequency channels, or spreading codes for transmissions eliminating collisions. This simplifies the individual transmissions, but the required bandwidth must be reserved prior to data transmissions increasing signaling traffic. Examples of contention-free protocols are Time Division Multiple Access (TDMA) [12], Frequency Division Multiple Access (FDMA) [13], and Code Division Multiple Access (CDMA) [14].

The contention protocols are more flexible than contention-free protocols, as the bandwidth is divided among nodes on-demand basis. However, contention protocols suffer from collisions and high idle listening. Still, while the contention-free protocols theoretically optimize the channel usage, adjusting the correct amount of reservations is challenging and generally possible only for static networks. Even then, monitored events may generate traffic bursts, thus causing temporarily high bandwidth usage that cannot be served with rigid reservations. Therefore, in this paper, we concentrate on MAC protocols that support dynamic operation and variable traffic loads.

Due to the fundamental limitations of current low-power transceivers, the energy efficiency of the conventional MAC approaches is not adequate for the lowest energy WSN applications as such. Further energy saving is achieved by duty cycling: time is divided into a short active period and a long sleep period, which are repeated consecutively. These low duty-cycle protocols can be divided into two categories: unsynchronized and synchronized protocols, according to the synchronization of data exchanges.

2.1. Unsynchronized Low Duty-Cycle MAC Protocols. Unsynchronized low duty-cycle MAC protocols are based on a Low Power Listening (LPL) mechanism, where nodes poll channel asynchronously to test for possible traffic. Transmissions are preceded with a preamble that is longer than the channel-polling interval. Hence, the preamble part acts like a wakeup signal. If a busy channel is detected, nodes begin to listen to the channel until a data packet is received or a time-out occurs. Berkeley Media Access Control (B-MAC) [15] is a simple LPL protocol, which utilizes CSMA for collision avoidance. The energy efficiency of B-MAC is significantly limited by the transmission and reception energy costs caused by the long preamble. In addition, the overhearing of frames intended to other nodes and the idle listening caused by the frequent channel sampling reduces its energy efficiency.

Zebra-MAC (Z-MAC) [16] operates above B-MAC but utilizes TDMA for managing congestion. As a principle, each node owns a slot during which a smaller CSMA contention window is used compared to other nodes. Thus, the slot owner always has the best possibility to access the channel. Consequently, other nodes can steal the slot, if the slot owner does not have data to transmit. Under low contention, Z-MAC behaves like CSMA and under high contention more like TDMA. The utilization of slots improves the fairness and throughput of B-MAC. Yet, the improvement on energy-efficiency is only limited.

There are numerous variations of B-MAC targeting at the reduction of the preamble energy. SpeckMAC-Backoff (SpeckMAC-B) [17] replaces the long preamble with numerous short wakeup packets containing a destination address and an exact time to the actual data transmission. Thus, nodes may return to sleep mode after receiving one wakeup packet. SpeckMAC-Data (SpeckMAC-D) [17] replaces the long preamble with consecutive data packets reducing the required channel reception time. In X-MAC [18], a sender transmits multiple short preambles with the address of the intended receiver. Upon receiving a short preamble, the desired destination node sends an ACK between the short preambles. Other nodes can enter early a sleep mode for reducing overhearing. After receiving the ACK, the source node begins the transmission of a data frame. Disadvantages of these protocols are the transmission cost of a preamble and idle listening caused by CSMA mechanism, channel polling, overhearing and radio startup transients.

There are two protocols, which reduce preamble energy by combining LPL with synchronization. Wireless Sensor MAC (WiseMAC) [19] utilizes ALOHA for transmissions. A network consists of an access point and numerous sensor nodes in a star topology. The access point learns the sampling schedules of each sensor node and starts preamble transmission just prior to the channel sampling moment of a desired destination node. Major disadvantages of the protocol are very limited coverage and connectivity of the network due to the star topology. Scheduled Channel Polling MAC (SCP-MAC) [20] is a synchronized variation of B-MAC, which operates in a peer-to-peer network by synchronizing the channel polling schedules of all neighbors. Hence, only a short preamble is required to reach all neighbors. The energy consumption of preambles is reduced over one order of magnitude compared to B-MAC. Synchronization is performed by transmitting periodically synchronization (SYNC) packets containing the schedule information, or piggybacking the information in data packets. SCP-MAC is currently the most energy-efficient unsynchronized low duty-cycle protocol. Still, idle listening in contention windows, collisions, channel polling, frequent radio startup transients, and overhearing reduces its energy efficiency.

Unsynchronized protocols are relatively simple and robust, and require small amount of memory compared to synchronized protocols. Frequent channel polling increases radio startup transients causing wasted energy. A general drawback is rather high overhearing, since each node must receive at least the beginning of each frame transmitted within radio range. Thus, they suit best for relatively simple WSNs utilizing very low data rates. Unsynchronized protocols tolerate dynamics in networks, but their energy-efficiency is limited by the channel sampling and collision avoidance mechanism.

2.2. Synchronized Low Duty-Cycle MAC Protocols. Synchronized low duty-cycle MAC protocols utilize scheduling to ensure that listeners and transmitters have a regular, short active period in which to rendezvous. Due to a synchronized operation, nodes know the exact moments of active periods in advance, which eliminate the need of long preambles. As a global synchronization is very difficult in large networks [21], active periods occur typically asynchronously. Nodes signal their schedules by transmitting periodically SYCN frames. By receiving the SYNC frames, nodes maintain local synchronization with one or more neighboring nodes. Synchronization is typically obtained by a network scan, during which a node listens to an RF channel until SYNC frames from neighbors are received.

A Sensor-MAC (S-MAC) [22] is one of the first synchronized low duty-cycle MAC proposals. The protocol utilizes a fixed active period length and an adjustable, network specific wakeup period. Neighboring nodes may coordinate their active periods to occur simultaneously to form virtual clusters. An active period is divided into SYNC, RTS, and CTS phases. In SYNC phase, a node receives SYNC frames from its neighbors. In RTS phase, the neighboring nodes transmit RTS frames, from which a node selects a desired source node, and transmits a CTS frame. The CTS phase is followed by frame exchanges with the selected node until the end of the wakeup period. All frames are transmitted using CSMA. The energy nefficiency of S-MAC is reduced by long SYNC and RTS phases, and fixed active period length causing idle listening. In addition, the fixed duty cycle causes poor adaptation to changing traffic conditions. A Timeout-MAC (T-MAC) [23] protocol is a variation of the S-MAC, which utilizes a short listening window after the CTS phase. Node is in active period as long as activity occurs. Thus, the length of the active period is adjusted according to traffic. Still, the energy efficiency is limited by the idle listening in SYNC and RTS phases.

The IEEE 802.15.4 Low-Rate Wireless Personal Area Network [24] is a multipurpose standard specifying PHY layer and MAC sublayer. The ZigBee Alliance [25] builds on this foundation by providing the network layer and the framework for the application layer. IEEE 802.15.4 provides a synchronized low duty-cycle operation by optional beaconing mode, inactive period, and cluster-tree network topology. A network is formed around a PAN coordinator that is the central manager. Cluster heads (coordinators) transmit a SYNC frame (beacon) at the beginning of their active periods (superframes). Then, they listen to the channel for incoming data until the end of the superframe in a Contention Access Period (CAP). Each node maintains synchronization with a parent coordinator by receiving its beacons and transmitting data in CAP on-demand basis. Leaf nodes (devices) do not transmit beacons or route data resulting in very low energy consumption.

Data exchanges in CAP are performed using a slotted variation of CSMA. Energy consumption is reduced by spending backoff times in a sleep mode. The number of collisions is minimized by performing carrier sensing twice. IEEE 802.15.4 supports also a Contention-Free Period (CFP) consisting of dedicated time slots for individual nodes. Yet, CFP slots can be only used for direct communication with a PAN coordinator. The cluster-tree type IEEE 802.15.4 network can provide comparably good energy efficiency in static and sparse networks. A major disadvantage is that coordinators must be active entire CAP causing significant idle listening. Since node addressing and routing schemes are based on a highly static tree network structure, achieved performance degrades rapidly in a dynamic network [26]. In addition, the hidden node problem reduces performance in dense networks, since any handshaking prior to a transmission is not used.

Several variations of TDMA are also proposed for low-energy WSN. At the best, they can provide energy-efficient, fair, and collision-free channel access. Low-Energy Adaptive Clustering Hierarchy (LEACH) [27] protocol uses TDMA with clustered network topology. LEACH utilizes a single base station, with which all cluster heads employ only direct communications. Intercluster interferences are managed by CDMA. In large networks, the energy efficiency of cluster heads is limited due to the direct communication with a base station. However, cluster members operate quite energy efficiently. For increasing network lifetime, LEACH proposes to compress data in cluster heads and to rotate of cluster heads. A drawback is that LEACH does not support dynamically changing network size. In addition, the assumption that all nodes can reach the base station with the maximum transmission power level strictly limits the coverage area and operation environment. These problems are addressed in Power Aware Clustered TDMA (PACT) [28] protocol. PACT is a variation of LEACH, which performs data relaying between clusters by intercluster gateway nodes, similar to [29]. Disadvantages of PACT are relatively high control traffic overhead and idle listening in larger networks. Relatively complex data slot scheduling algorithm performs well in static networks, but lacks support for dynamic network.

Self-Organizing Medium Access Control for Sensor Networks (SMACS) [30] protocol assigns a locally unique contention-free slot for each link. Neighbor discovery is performed at semiregular intervals by broadcasting invitation messages on a common signaling channel. Then, the channel is received for possible responses and other invitation messages. According to invitation messages, each pair of nodes mutually agrees a periodic time and frequency slot for data exchanges. A major disadvantage is the energy consumption of a neighbor discovery requiring a long-term radio reception. This severely limits energy efficiency and adaptivity in dynamic networks, where link lifetimes are short.

Traffic-Adaptive Medium Access (TRAMA) [31] is a scalable TDMA protocol designed for multihop networks. By using a distributed algorithm, only one transmitter per two-hop neighborhood is selected allowing collision-free data reception and peer-to-peer connectivity. TRAMA can command a set of neighbors to receive a given data frame providing efficient unicast, multicast, and broadcast transmissions. Nodes that are not selected to transmit or receive at a particular time slot go to a sleep mode. Neighbor information is updated during periodic and relatively long-term random access periods. TRAMA can provide collision-free medium access in a static network. Energy efficiency is reduced by signaling traffic overhead and the random access period requiring a long-term radio reception. Hence, the energy efficiency and performance decrease significantly in dynamic networks.

In current synchronized low duty-cycle protocols, the major advantage is that a sender knows a receiver's wakeup time a priori and thus transmits efficiently. In dynamic networks, synchronized links are short-lived and new neighbors need to be searched frequently, which increases energy consumption. In contention protocols, a major disadvantage is the energy cost of receiving an entire active period [15]. Contention-free protocols suffer from a poor performance in dynamic network topology. However, synchronized protocols typically have better energy efficiency than unsynchronized approaches in stationary networks.

Due to the energy efficiency, our work utilizes the synchronized low duty-cycle approach. In contrast to the above schemes, our work can minimize the idle listening of all nodes in a multihop network, and provide energy-efficient operation in dynamic networks. We will present energy-efficient solutions for channel access mechanism, dynamic bandwidth management, network topology, and RF channel utilization. The presented protocol uses hybrid approach in channel access. A contention-free method prevents collisions and minimizes idle listening, while a contention-based method supports varying traffic loads. Thus, although the protocol design itself is TDMA-based, it supports network dynamics and is therefore compared to the related contention-based protocols.

3. Energy Overhead in Channel Access

MAC protocol can be divided into channel access and networking mechanisms. The channel access mechanism defines radio utilization for maintaining synchronization and exchanging frames between nodes. The networking mechanisms perform network self-configuration and neighbor discovery operations.

Until now, low-energy channel access mechanisms have reduced energy consumption by focusing on the minimization of long-term idle listening, overhearing, and the active period length. Only a small research effort has been made to the minimization of the energy overhead in each radio operation. For finding out the most essential causes of energy overhead, a simple energy analysis of a CSMA channel access is presented. CSMA can be considered a typical channel access mechanism in WSNs, and it is used for example in IEEE 802.15.4 [24], S-MAC [22], T-MAC [23], SCP-MAC [20], and X-MAC [18]. To be able to focus purely on the data exchange between two nodes, an analyzed network contains only a source and a destination node.

At the beginning of a channel access period, a destination node activates its receiver and begins receiving the channel for possible incoming frames. The transition time from the low-energy state to the reception state is denoted as t_{ST}. Prior to a data frame transmission, the source node waits a random backoff time t_{BOT}, activates its receiver, and performs a carrier sensing t_{CCA}. For improving energy efficiency, a blind backoff is assumed, where a source spends t_{BOT} in sleep mode. If the channel is idle, the source turns the receiver off, activates its transmitter, and transmits a data frame t_{DATA}. The energy of inactivating the radio is negligible and it can be ignored. When the data frame has been received, the destination node turns off the receiver, checks the correctness of the data t_{AW}, activates a transmitter, and transmits ACK. Since the wait time t_{AW} prior to the reception of ACK is not predetermined, and depends on the frame content and data processing performance, the source node needs to be in reception mode entire t_{AW}.

The consumed energy is divided into an effective energy comprising data and ACK exchange energies, and overhead energy consisting of radio startup, backoff, and ACK wait energies. Next, models for these energies are determined.

The presented frame exchange procedure consists of three transmitter startup and two receiver startup transients (t_{ST}) during which power consumption equals to a transmitting power (P_{TX}) and a receiving power (P_{RX}), respectively. Hence, the total startup energy (E_{ST}) of a frame exchange is

$$E_{ST} = t_{ST}(2P_{TX} + 3P_{RX}). \tag{1}$$

Although the source node may sleep during the backoff delay, the destination node needs to be in reception mode. An average idle listening time consists of a half of a contention window length (t_{CW}) and a carrier sensing time (t_{CCA}). Hence, the backoff energy consumption (E_{BO}) is

$$E_{BO} = \left(\frac{t_{CW}}{2} + t_{CCA}\right)P_{RX}. \tag{2}$$

ACK wait energy consumption (E_{AW}) caused by an average ACK wait delay (t_{AW}) is

$$E_{AW} = t_{AW}P_{RX}. \tag{3}$$

The data exchange energy (E_{DATA}) consists purely of the transmission and reception energies of a data frame (L_{DATA}). As radio data rate is R, E_{DATA} is

$$E_{DATA} = \frac{L_{DATA}}{R}(P_{TX} + P_{RX}). \tag{4}$$

Similarly, the ACK exchange energy is

$$E_{ACK} = \frac{L_{ACK}}{R}(P_{TX} + P_{RX}). \tag{5}$$

Since the energy characteristics of low-power transceivers are diverse, we determine energy consumptions for two different types of generally used commercial off-the-shelf transceivers: a high data-rate (HR) Nordic Semiconductor nRF2401A [32] transceiver having 1 Mbps data rate, and a low data-rate (LR) Chipcon CC1000 [33] transceiver having 76.8 kbps data rate. The utilized parameter values are presented in Table 2. The analysis focuses on short (<128 Bytes) frame lengths, since they results the highest energy efficiency at high ($>1 \times 10^{-4}$) Bit Error Rate (BER) conditions [34, 35]. High BER is typical for WSNs due to difficult operation environment and narrow band radios [35].

The resulted energies as the function of data frame size are presented in Figure 1. Generally, the HR transceiver has nearly one order of magnitude lower effective energy consumption compared to the LR radio. The energy overhead is nearly equal for both radio types. The energy overhead is caused mostly by the backoff mechanism and carrier sensing causing idle listening. The mechanism also necessitates frequent operation mode changes causing significant startup transient energy consumption. The results clearly indicate that energy overhead is dominating the energy consumption of the HR radio. For the LR radio, the energy overhead is also significant. In practice, busy channel situations and collisions make the energy overhead even higher [36].

4. TUTWSN MAC Design and Implementation

In this section, the design of TUTWSN MAC protocol is presented, including channel access and networking mechanisms. The main objective for the channel access mechanism is the minimization of overhead energy, and thus the maximization of energy efficiency. A special focus is on the minimization of collisions, which increases energy-efficiency and reliability. The main objectives for networking mechanism are low network signaling overhead and high tolerance against unreliable radio links and node mobility. An important objective for the entire MAC protocol has been compatibility with a simple and low-power hardware allowing low-cost implementation. Neighbor discovery mechanisms are presented only briefly, since they have been published earlier in [37, 38].

4.1. TUTWSN Channel Access. The designed TUTWSN channel access mechanism pursues to maximize energy efficiency by minimizing idle listening, unnecessary startup transients, overhearing, control frame overhead, and collisions. These are minimized by two ways.

(i) Predetermined frame exchange moments: nodes maintain accurate local synchronization and exchange frames exactly at predetermined moments.

(ii) Reservation based channel access: nodes avoid collisions and the energy overhead of contention mechanism by reserving their transmission moments in advance.

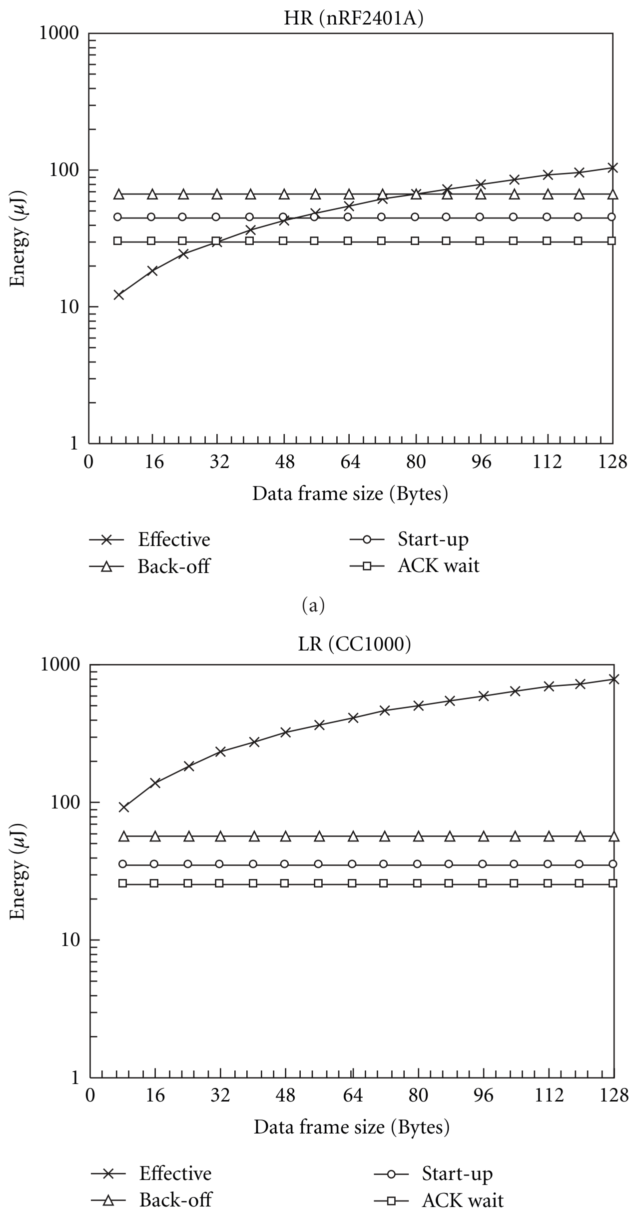

Figure 1: The effective and overhead energies of nRF2401A (HR) and CC1000 (LR) platforms.

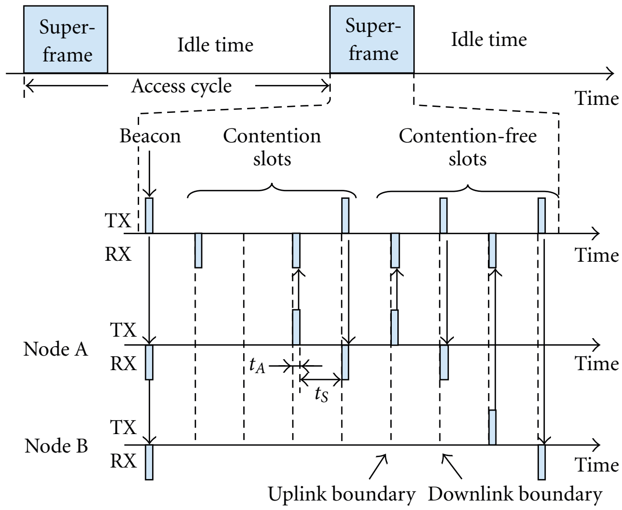

Figure 2: TUTWSN access cycle and superframe.

Channel access is based on superframes that are repeated at regular intervals (access cycle) as shown in Figure 2. A node may act as a cluster head and maintain its own superframe and/or participate to other superframes as a member node. The rest of the time, nodes can sleep and conserve energy. For eliminating collisions, superframes have locally unique schedules such that they do not overlap with each other. The superframe interlacing mechanism is presented in the following sections.

At the beginning of each superframe, a cluster head transmits a beacon. The beacon contains crucial information for the channel access, networking, and routing. For the channel access, two fields are the most essential: time to the next superframe, which is used for maintaining synchronization, and reserved slot allocation table, which is used for granting transmission rights for associated neighbors.

The beacon is followed by a brief ALOHA-based contention period and a significantly longer contention-free period. Both channel access periods are further divided into communication slots that are large enough for a data transmission with a maximum duration of t_A, a packet processing time t_S during which radio may be on sleep state, and an acknowledgment. A communication slot is referred to as uplink when a member transmits and the cluster head acknowledges, while a downlink slot denotes that the cluster head transmits. The use of contention-free slots is preferred, while contention slots are used for control frames allowing network association and slot reservations. A node uses contention-based channel access only when it has queued data for transmission and has not been assigned with an uplink slot. This operation is detailed in Figure 3.

To ensure reliability all data transmission except broadcasts are acknowledged. The acknowledgment is transmitted in the same communication slot with the data frame. While a WSN protocol might save energy by relying on redundancy and omitting acknowledgments, taking such approach would limit the applicability of the protocol. To decrease overhead due to high redundancy, a higher layer data aggregation protocol is assumed.

Since the cluster head cannot predict which contention slots will be used, unnecessary reception of slots is unavoidable causing idle listening. This is common for all contention-based mechanisms. The reduction of the number of contention slots reduces the idle listening of cluster heads, but increases the probability of collisions reducing network energy efficiency and performance [39, 40]. In the designed contention mechanism, the energy consumption is minimized by three ways. First, the reception is always terminated as soon as an unused contention slot is detected, or at last when t_A has expired. Second, the utilization of

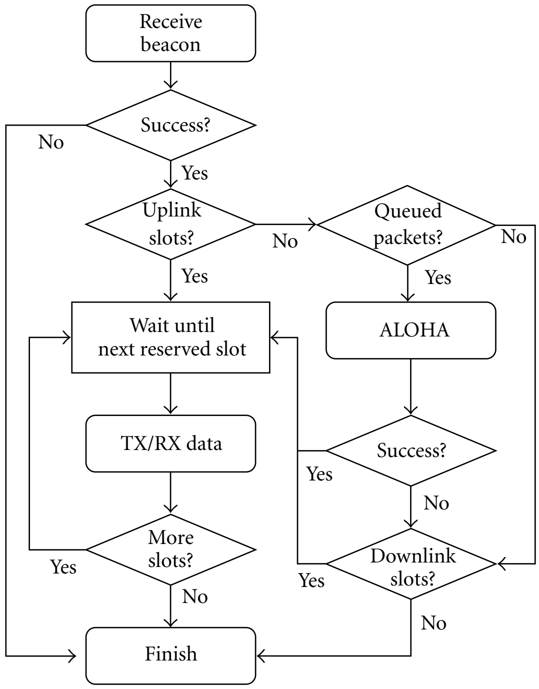

Figure 3: Operation of member node during a superframe.

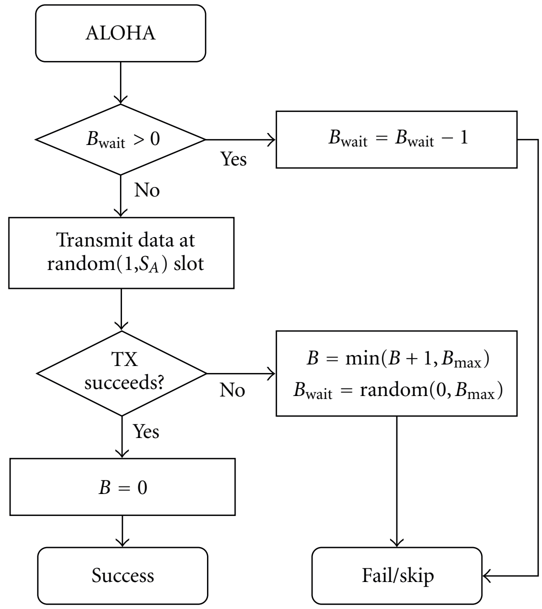

Figure 4: Contention-based channel access with ALOHA-based algorithm.

contention slots is minimized by piggybacking bandwidth adjustment signaling in data frames. Third, the number of contention slots is dynamically adjusted according load [41].

The designed contention-free mechanism is inherently energy efficient, since the utilized reserved slots in each superframe are determined in advance using bandwidth adjustment signaling and the slot allocation table. The idle listening is nearly eliminated, since only utilized slots are received. A minor idle listening is caused by the inaccuracy of time synchronization and occasional link failures causing reception failures in the contention-free slots. Since the beacon at the beginning of each superframe performs synchronization, the clock drift is negligible at the slot boundaries.

4.2. Contention-Based Channel Access. The TUTWSN design allows contention-based slot access with CSMA/CA principle. However, our design uses ALOHA-based approach to avoid the need for carrier sensing. Thus, the protocol can be implemented with a very simple and low-cost hardware.

The operation on contention-based channel access is presented in Figure 4. A cluster head indicates the number of ALOHA slots S_A in its cluster beacon. This way, a cluster head can dynamically change the number of slots if slot usage is high, for example, due to mobility. Next, a node attempts transmission at a random slot. Only one attempt per access cycle is allowed. If the transmission fails, a node assumes collision and increases its ALOHA backoff counter (B) up to B_{max}. Then, a node waits random B_{wait} access cycles before the next transmission attempt. When a transmission succeeds, node resets its backoff counter (B) thus allowing a contention-based transmission attempted on the next access cycle.

The number of ALOHA slots (S_A) and the maximum backoff value (B_{max}) have a tradeoff between energy efficiency, reliability, and channel access latency. Assuming that ALOHA transmission fails only due to collisions, the transmission success probability during CAP can be expressed as

$$P\{\text{tx succeeds}\} = \left(1 - \frac{1}{S_A}\right)^N, \tag{6}$$

where N is the number of contending nodes. As the design prefers the use of reserved slots to contention-based slots, N is usually close to zero. The use of backoff essentially increases the number of slots (or conversely, reduces the number of contending nodes per access cycle), thus reducing collisions. For energy-efficient operation, even one CAP slot would be enough with sufficiently large B_{max}. Finding optimal parameter values are outside the scope of this paper. To simplify the analysis in the remainder of this paper, we use two CAP slots and set $B_{max} = 1$ meaning that a node can attempt transmission on every access cycle. Assuming 2 CAP slots and 16 reserved slots, the CAP overhead is less than 12%.

4.3. Contention-Free Channel Access. The contention-free slot allocation mechanism has a significant effect on the efficiency of the reserved slot usage. In practice, a cluster head does not know when a member node has data to send and therefore cannot optimally assign slots. When too few reservations are granted, a node must use unreliable contention-based channel access to transmit its data, while too many reservations waste capacity and energy.

Next, we identify and examine three contention-free slot allocation methods: fixed, dynamic, and on-demand

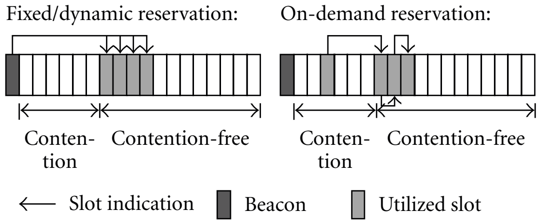

Figure 5: Fixed, dynamic, and on-demand allocation methods.

allocation. The operation of the methods is presented in Figure 5.

In the fixed allocation method, a node is granted with a predetermined amount of reserved slots. A cluster head indicates the exact slot times in its cluster beacon. The typical approach, for example, in IEEE 802.15.4, grants the same amount of reservations for each access cycle. This wastes capacity when a device does not have data to send on each access cycle. We propose that the fixed allocations are granted over a certain time referred to as a reservation period, for example, 20 slots per a minute. A cluster head distributes the reservations evenly among the access cycles within the reservation period. Thus, if node has requested only a few slots, a slot is not necessarily granted on each access cycle. A node postpones the forwarding of nondelay critical data until a slot is granted. This way, the granted slots are fully utilized, assuming that the reserved capacity matches the average traffic.

The dynamic allocation method avoids the need for determining average traffic. Instead, the allocations are adjusted to match the traffic load of a node, thus reacting to the changes in traffic load. A member node could record its own traffic and then explicitly request a matching amount of fixed reservations. However, to reduce communication overhead in TUTWSN MAC, a cluster head keeps the record of traffic received from its member nodes and adjusts dynamic reservations accordingly.

In the on-demand allocation method, a node sends an initial packet on a contention slot. If the node has more packets in its buffers, it sets a reservation flag piggybacked on the data packet. Then, a cluster head allocates another contention-free slot during the same active period. The slot is indicated to the node in the acknowledgment frame. To get more slots during an access cycle, the request is repeated on the granted slots. The problem with the on-demand allocation method is the use of contention slots, which may cause collisions. To reduce the collision probability, a node may wait for a certain time while buffering data frames. The waiting has a tradeoff between latency and reliability, as waiting decreases the collision-prone contention-based channel access.

To optimize energy-efficiency of the channel access, the proposed contention-free slot allocation scheme for TUTWSN MAC uses a combination of the allocation methods. A member node is granted with fixed allocations to guarantee certain bandwidth. The amount of fixed reservations is a deployment specific parameter and can be zero in lightly loaded networks to avoid unused slots. The dynamic allocation method provides additional capacity on top of the guaranteed bandwidth, thus allowing nodes to adjust to the traffic conditions. The fixed and dynamic slot allocations are augmented with the on-demand allocations, thus providing a method to handle traffic bursts.

4.4. Network Topology Formation. To reduce the energy consumption of frame transmissions in large networks, multihop data routing between nodes is utilized [42, 43]. Frames are routed from a source to a destination along a chain of low-energy hops. Each node along the chain receives data from a neighbor (child) one hop closer to the source, maintains synchronization with a next-hop node (parent) by periodically receiving its beacons, and transmits data according to time slot assignments.

The selection of network topology between flat and clustered affects significantly network energy consumption and bandwidth utilization [21, 41, 44]. In the flat topology, all nodes participate in data routing and consume nearly equally power and network bandwidth. In the clustered topology, a network is formed as interconnected star networks. The master of each star is a cluster head, while other nodes are leaf nodes. Cluster heads utilize a majority of energy and bandwidth by managing superframes and exchanging data with other clusters. Leaf nodes synchronize themselves with a superframe schedule and transmit data on demand without the need of their own superframes, which reduces the bandwidth utilization of a network.

The designed network topology is based on the clustered topology. Each cluster consists of a cluster head (headnode), leaf nodes (subnodes), and associated headnodes (child headnodes) from neighboring clusters. The operation of a child headnode in a next hop cluster is similar with a subnode, which receives beacons and transmits data according to time slot assignments.

The utilization of a clustered topology is rationalized by a simple analysis, which considers the energy consumptions of clustered and flat topologies using the TUTWSN channel access mechanism. The analysis assumes that the energy consumptions of frame transmissions (E_{TX}) and receptions (E_{RX}) are equal for all frame types, which is realistic for the TUTWSN channel access utilizing a low-power radio. Moreover, the density of cluster heads in the clustered topology is assumed adequate for maintaining optimal hop lengths. Therefore, the number of required data and ACK frame exchanges for flat and clustered topologies is equal, as the entire network is considered.

A router node is defined as any node in the flat topology, and a cluster head in the clustered topology. The energy overhead of the router node (E_{OR}) consists of the transmissions and receptions of beacons, and the reception of S_A contention slots. For one access cycle, the energy overhead is

$$E_{OR} = E_{TX} + (S_A + 1)E_{RX}. \quad (7)$$

The energy overhead of a leaf node (E_{OL}) using TUTWSN channel access is caused by the reception of beacons. Hence, for one access cycle, E_{OL} equals to E_{RX}.

In the flat topology, all nodes have equal energy overhead, which equals to E_{OR}. In the clustered topology, where each cluster consists of n_S leaf nodes, the average energy overhead per a node (E_{OC}) is

$$E_{OC} = \frac{E_{TX} + (S_A + 1 + n_S)E_{RX}}{n_S + 1}. \quad (8)$$

If $n_S = 0$, then $E_{OC} = E_{OR}$. This is clear, since all nodes are cluster heads and the network is similar with the flat topology. As n_S increases, E_{OC} decreases, and when $n_S \rightarrow \infty$, then $E_{OC} \rightarrow E_{RX}$, which equals to E_{OL}. Hence, the clustered topology has always lower energy overhead than the flat topology, assuming that the network has at least one leaf node. The energy efficiency of clustering is even more obvious, when cluster heads aggregate received data reducing the amount of forwarded data [44].

Network connectivity between clusters can be formed as a cluster-mesh or a cluster-tree topology. In the cluster-mesh topology, each cluster head maintains connectivity with all neighboring cluster heads resulting robust network, but higher energy consumption. In the cluster-tree topology, each cluster head maintains connectivity with one cluster head only, which is one hop closer to a sink locating at the root of the tree. This improves energy efficiency, but reduces the tolerance against link failures due to low connectivity.

To combine the strengths of cluster-tree and cluster-mesh topologies, we present a multi-cluster-tree topology. The multi-cluster-tree topology consists of multiple superpositioned cluster-tree networks. An example multi-cluster-tree topology is illustrated in Figure 6, where arrows indicate the directions of uplink routing paths. Each subnode and headnode maintains synchronization with several (k) neighbors by receiving their beacons. This allows the adjustment of connectivity for both subnodes and headnodes allowing a tradeoff between network robustness and energy consumption. Compared to the cluster-tree topology that supports only one route to a single sink the multi-cluster-tree allows the utilization of multiple sinks, multiple routes, and load balancing between headnodes. The value of k is uniform for entire network and it is selected before a deployment according to expected network dynamics. According to measurements with TUTWSN nodes, an optimal value for k is between 2 and 4.

4.5. Superframe Interlacing. For guaranteeing contention-free channel access in a multihop network, the overlapping of superframes in two-hop neighborhood (interference range) is eliminated by interlacing. Typically, interlacing is implemented by time division, for example in IEEE 802.15.4 [24], DMAC [45], SRSA [46], and TRAMA [31]. The time division limits network density especially when the superframe length is relatively long compared to the access cycle length. In the designed superframe interlacing mechanism, scalability is improved by time and frequency division. For reasoning this, a short analysis of the maximum scalability is presented.

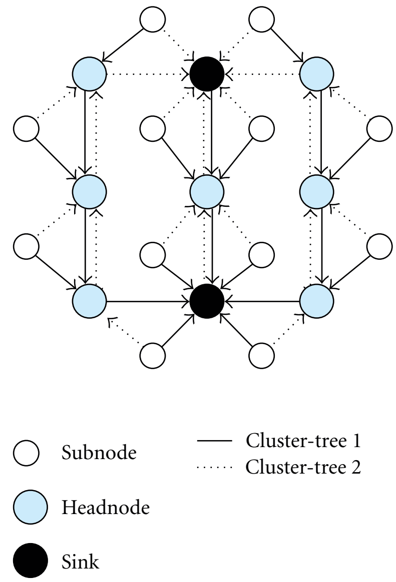

FIGURE 6: Multi-cluster-tree network topology ($k = 2$).

The maximum number (α) of nodes in an interference area can be determined by the access cycle length (T_{AC}), the superframe length, the average number of subnodes in each cluster, and the number of utilized noninterfering frequency channels (n_{CH}) as

$$\alpha = \frac{T_{AC} n_{CH}(1 + n_S)}{2(1 + S_A + S_R)(t_A + t_S) + t_{guard}}, \quad (9)$$

where S_A and S_R are the maximum number of contention and contention-free slots, t_{guard} is a short guard time between consecutive superframes. α is maximized by maximizing T_{AC}, n_{CH}, and n_S, and by minimizing t_A and t_S. It can be clearly seen in the equation that by utilizing a high data-rate radio operating at a wide frequency band provides the highest scalability.

In the current 2.4 GHz TUTWSN implementation, $T_{AC} = 4$ seconds, $n_{CH} = 20$, $n_S = 8$, $S_A = 4$, $S_R = 8$, $t_A + t_S = 10$ ms, and $t_{guard} = 100$ ms. Thus, α equals to 2000 nodes per an interference area. If only one channel is used ($n_{CH} = 1$), α would be reduced to 100 nodes per an interference area.

In the designed superframe interlacing mechanism, each headnode selects semirandomly a time slot and a frequency channel (superslot) for its superframe among the free slots detected by a network scan. The simple randomization minimizes the energy overhead of signaling traffic. The superslot is selected at a node startup and if interferences are detected by increased link error rate [41]. The energy consumption of network scans is reduced by using a network signaling channel [37] and by proactively signaling neighborhood information [38].

5. Performance Analysis of TUTWSN and Related Proposals

This chapter presents performance models for analyzing the power consumptions of the most essential low-power channel access mechanisms and comparing them against the designed TUTWSN MAC. The focus is on data and ACK frame exchanges and on the maintenance of link synchronization by a beacon or SYNC frame exchange.

The performance of TUTWSN MAC is compared against the following MAC protocols: T-MAC [23] and B-MAC [15], which are well-known synchronized and unsynchronized low duty-cycle protocols, X-MAC [18] and SCP-MAC [20], which are two interesting proposals for unsynchronized protocols, and IEEE 802.15.4 [24], which is standardized technology for WSNs. For comparison, an ideal MAC protocol is defined and modeled.

The following performance models are based on the analysis of Yoon presented in [47]. For this paper, the set of models has been extended by IEEE 802.15.4 and TUTWSN MAC protocols. In addition, the effects of startup transitions, contention windows, and crystal tolerance have been modeled more accurately. In addition, the models and their presentation have been simplified and clarified.

The performance models are derived using the following assumptions:

(i) each sensor node measures one sensor sample and forwards it to a next-hop node during one data generation interval;

(ii) each data frame is followed by an ACK for fair comparison;

(iii) there are no transmission errors nor collisions;

(iv) there is no contention, and carrier sense attempts produce an idle result;

(v) the power consumption of idle listening equals to the reception mode power;

(vi) the active time of MCU equals to the active time of radio.

Therefore, the performance models can focus on the power consumption of the channel access mechanisms, while the effects of data processing, contention, and control frame exchanges are eliminated. For contention-based protocols, obtained results are slightly better than in practice with contention. As TUTWSN MAC utilizes contention-free mechanism for data and ACK exchanges, the obtained results for TUTWSN are realistic.

5.1. Utilized Parameters. For determining the channel access models, all essential parameters describing the characteristics of a sensor node platform, application, and network topology are identified. The sensor node platform is defined by the following parameters:

ε: crystal tolerance of a wake up timer,

P_Y: the power consumed for Y, where $Y \in$ {RX (receive), S (sleep), TX (transmit)},

R: the data rate of a radio, and

t_{ST}: radio startup transient duration (crystal running).

Application and network topology are defined by the following parameters:

L_X: the length of frame X, where $X \in$ {ACK, B (beacon or SYNC), CTS, DATA, P (preamble), RTS},

n: the number of direct neighbors for a given node,

n_{DL}: the number of descendent nodes of a given node in the routing tree, that is, the number of data frames the node needs to forward during one data generation interval,

$n(i)$: the number of nodes whose transmissions can be received by node i, and

T_{DATA}: data generation interval in each node.

In addition, there are protocol implementation specific parameters. Generally utilized parameters of that kind are:

t_{CCA}: the time for a clear channel assessment or carrier sensing,

t_{CW}: contention window length in CSMA,

t_{sleep}: sleep period length,

T_{AC}: access cycle length or channel polling interval, and

T_{SYNC}: transmission interval of SYNC or beacon frames.

5.2. Modeled Network Topology. The modeled network topology describes the performance of a single link. Its parameters can be adjusted to model an arbitrary multihop topology, where each link can have different parameters. The limitation of the topology is that data is forwarded only to one hop node, which applies to networks having one data consumer (sink). Energy consumptions are analyzed for a router node (**A**), and a leaf node (**B**) presented in Figure 7. Both nodes have eight neighbors (n), which may cause overhearing and interferences for the channel access. Data generation interval (T_{DATA}) is equal for each node, and it varies from 1 second to 1000 seconds. Arrows in the figure indicate data routing directions. The traffic load is accumulated in routers, since they transmit their own data and the multihop routed data from n_{DL} nodes. For example, the router node **A** routes data from three nodes ($n_{DL} = \{\mathbf{B}, \mathbf{D}, \mathbf{E}\}$), while the router node **C** routes data from four nodes ($n_{DL} = \{\mathbf{A}, \mathbf{B}, \mathbf{D}, \mathbf{E}\}$). This increases the power consumption of these routers, but also the overhearing and interferences among other nodes in their transmission range.

Average power consumptions (P) for each protocol are calculated by transmission (t_{TX}) and reception (t_{RX}) duty cycles, and their power consumptions as

$$P = t_{TX}P_{TX} + t_{RX}P_{RX} + (1 - t_{TX} - t_{RX})P_S. \qquad (10)$$

The duty cycle is determined by dividing the duration of an activity by the interval of the activity resulting in a percentage value of the activity. Data exchanges are normalized by T_{DATA} during which all nodes in the network generate exactly one data frame. Similarly, the transmission and reception activity for maintaining synchronization is normalized by T_{SYNC}.

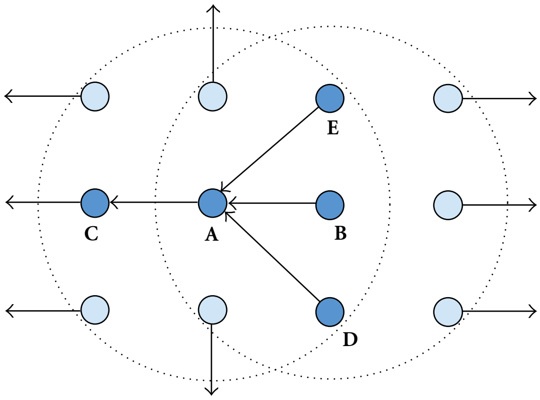

Figure 7: Network topology for channel access comparison.

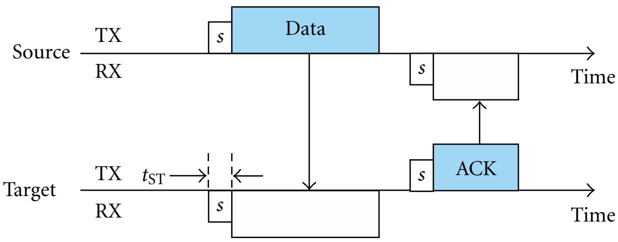

Figure 8: The activity of radio in Ideal-MAC.

5.3. Ideal-MAC. First, an ideal MAC (Ideal-MAC) protocol [47] is defined. All nodes can exchange data and ACK frames without the need of any synchronization or contention mechanism. Nodes can sleep all the time between frame exchanges. Hence, the Ideal-MAC does not cause any idle listening or control frame overhead.

The required activity for exchanging one data frame is presented in Figure 8. Although MAC is ideal and practically impossible to implement, a sensor node platform is realistic and each data transmission and reception is preceded by a radio startup transient (t_{ST}). Thus, t_{TX} and t_{RX} for a leaf node are

$$t_{TX} = \left(t_{ST} + \frac{L_{DATA}}{R}\right)\frac{1}{T_{DATA}},$$
$$t_{RX} = \left(t_{ST} + \frac{L_{ACK}}{R}\right)\frac{1}{T_{DATA}}. \quad (11)$$

The router node receives data frames from n_{DL} leaf nodes, transmits them ACKs, forwards the received and own data frames to a parent and receives ACKs.

Thus, t_{TX} and t_{RX} for the router are

$$t_{TX} = \left(t_{ST} + \frac{L_{DATA}}{R}\right)\frac{n_{DL}+1}{T_{DATA}} + \left(t_{ST} + \frac{L_{ACK}}{R}\right)\frac{n_{DL}}{T_{DATA}}. \quad (12)$$

$$t_{RX} = \left(t_{ST} + \frac{L_{DATA}}{R}\right)\frac{n_{DL}}{T_{DATA}} + \left(t_{ST} + \frac{L_{ACK}}{R}\right)\frac{n_{DL}+1}{T_{DATA}}, \quad (13)$$

5.4. Unsynchronized Low Duty-Cycle Protocols. Next, models for unsynchronized low duty-cycle protocols are defined. The unsynchronized low duty-cycle protocols allow the transmission of data frames on-demand basis without the need to wait for an active period. Yet, the nodes must poll the channel frequently for detecting the transmissions from other nodes.

5.4.1. B-MAC. B-MAC [15] uses the LPL scheme, where nodes sleep (t_{sleep}), wake up (t_{ST}) and poll channel (t_{CCA}) periodically at T_{AC} intervals. The frame exchanges of B-MAC are presented in Figure 9.

The normalized channel polling time (t_{POLL}) is

$$t_{POLL} = \frac{t_{ST} + t_{CCA}}{T_{AC}}. \quad (14)$$

Each transmission is preceded by a carrier sensing (t_{CCA}) and a preamble transmission lasting T_{AC}. Thus, t_{TX} for a leaf node is

$$t_{TX} = \left(t_{ST} + T_{AC} + \frac{L_{DATA}}{R}\right)\frac{1}{T_{DATA}}. \quad (15)$$

In B-MAC, all data in a radio range is received. As a leaf node has n neighbors, and a router in a range forwards n_{DL} data frames from leaf nodes, totally $n + n_{DL}$ data frames are received during T_{DATA}. Since channel is polled randomly, average preamble reception time is a half of T_{AC}. Thus, t_{RX} for the leaf node is

$$t_{RX} = t_{POLL} + \left(\frac{T_{AC}}{2} - t_{CCA} + \frac{L_{DATA}}{R}\right)\frac{n+n_{DL}}{T_{DATA}} + \left(t_{ST} + \frac{L_{ACK}}{R}\right)\frac{1}{T_{DATA}}. \quad (16)$$

The operation of the router node is similar to the leaf node, except the amount of exchanged data. The normalized transmission and reception times for the B-MAC router are

$$t_{TX} = \left(t_{ST} + T_{AC} + \frac{L_{DATA}}{R}\right)\frac{n_{DL}+1}{T_{DATA}} + \left(t_{ST} + \frac{L_{ACK}}{R}\right)\frac{n_{DL}}{T_{DATA}},$$
$$t_{RX} = t_{POLL} + \left(\frac{T_{AC}}{2} - t_{CCA} + \frac{L_{DATA}}{R}\right)\frac{n+n_{DL}+1}{T_{DATA}} + \left(t_{ST} + \frac{L_{ACK}}{R}\right)\frac{n_{DL}+1}{T_{DATA}}. \quad (17)$$

The power consumption reaches its unique minimum at an optimal polling interval (T_{AC}^{*}) obtained by setting $\partial(t_{TX}P_{TX} + t_{RX}P_{RX})/\partial T_{AC} = 0$. Performance results are calculated using the optimal polling interval of the router, which is

$$T_{AC}^{*} = \sqrt{\frac{T_{DATA}(t_{ST} + t_{CCA})}{(n_{DL}+1)P_{TX}/P_{RX} + (n + n_R + 1)/2}}. \quad (18)$$

5.4.2. SCP-MAC. SCP-MAC [20] replaces the long preamble with a short wake-up tone by waking up the senders and the receiver at the same time.

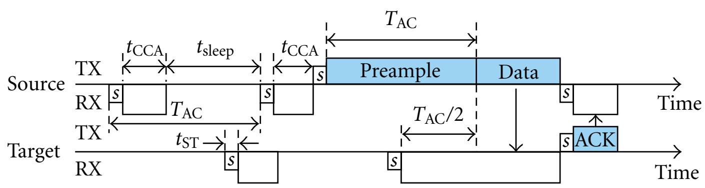

Figure 9: The activity of radio in B-MAC.

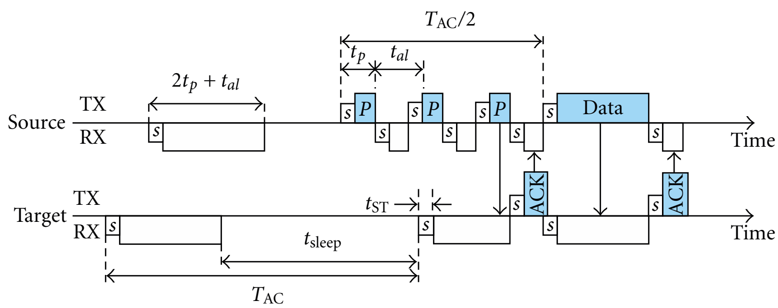

Figure 10: The activity of radio in X-MAC.

The best-case situation is considered, where all synchronization signaling is piggybacked with data frames. Thus, the synchronization does not cause control frame exchanges. SCP-MAC utilizes similar channel polling than B-MAC, and t_{POLL} equals to (13). The duration of the wake-up tone (t_{TONE}) is determined according to the clock drift (ε), the rate of frame receptions containing synchronization information, and the minimum tone duration (t_{CCA}) to detect a transmission. Thus, t_{TONE} is

$$t_{\mathrm{TONE}} = \frac{4T_{\mathrm{DATA}}\varepsilon}{n + n_{\mathrm{DL}}} + t_{\mathrm{CCA}}. \tag{19}$$

A data frame transmission consists of the wake-up tone, and the frame transmission. SCP-MAC utilizes two contention windows (CW1 and CW2) with the maximum length of $t_{\mathrm{CW}}/2$. Thus, an average backoff time in each contention window is $t_{\mathrm{CW}}/4$ during which the source node is asleep.

After a startup transient, the destination node receives on average halves of the wake-up tone and the second contention window. Data frames are piggybacked with synchronization data (SB). Thus, t_{TX} and t_{RX} of the SCP-MAC leaf node are

$$\begin{aligned}
t_{\mathrm{TX}} &= \left(2t_{\mathrm{ST}} + t_{\mathrm{TONE}} + \frac{L_{\mathrm{SB}} + L_{\mathrm{DATA}}}{R}\right)\frac{1}{T_{\mathrm{DATA}}},\\
t_{\mathrm{RX}} &= t_{\mathrm{POLL}} + \left(3t_{\mathrm{ST}} + 2t_{\mathrm{CCA}} + \frac{L_{\mathrm{ACK}}}{2}\right)\frac{1}{T_{\mathrm{DATA}}}\\
&\quad + \left(3t_{\mathrm{ST}} + \frac{t_{\mathrm{TONE}}}{2} + \frac{t_{\mathrm{CW}}}{4} + t_{\mathrm{CCA}} + \frac{L_{\mathrm{SB}} + L_{\mathrm{DATA}}}{R}\right)\\
&\quad \times \frac{n + n_{\mathrm{DL}}}{T_{\mathrm{DATA}}}.
\end{aligned} \tag{20}$$

The SCP-MAC router transmits $n_{\mathrm{DL}} + 1$ data frames to a next hop node, and ACKs to the leaf nodes. Thus, t_{TX} and t_{RX} of the SCP-MAC router node are

$$\begin{aligned}
t_{\mathrm{TX}} &= \left(2t_{\mathrm{ST}} + t_{\mathrm{TONE}} + \frac{L_{\mathrm{SB}} + L_{\mathrm{DATA}}}{R}\right)\frac{n_{\mathrm{DL}} + 1}{T_{\mathrm{DATA}}}\\
&\quad + \left(t_{\mathrm{ST}} + \frac{L_{\mathrm{ACK}}}{R}\right)\frac{n_{\mathrm{DL}}}{T_{\mathrm{DATA}}},\\
t_{\mathrm{RX}} &= t_{\mathrm{POLL}} + \left(3t_{\mathrm{ST}} + 2t_{\mathrm{CCA}} + \frac{t_{\mathrm{ACK}}}{R}\right)\frac{n_{\mathrm{DL}} + 1}{T_{\mathrm{DATA}}}\\
&\quad + \left(3t_{\mathrm{ST}} + \frac{t_{\mathrm{TONE}}}{2} + \frac{t_{\mathrm{CW}}}{4} + \frac{L_{\mathrm{SB}} + L_{\mathrm{DATA}}}{R}\right)\frac{n + n_{\mathrm{DL}} + 1}{T_{\mathrm{DATA}}}.
\end{aligned} \tag{21}$$

For achieving the best energy efficiency, a node should only poll the channel when there is a transmission from a neighbor. Performance results are calculated using the optimal polling interval of the router, which is

$$T_{\mathrm{AC}}^{*} = \frac{T_{\mathrm{DATA}}}{n_{\mathrm{DL}} + 1}. \tag{22}$$

5.4.3. X-MAC. In X-MAC [18], each data frame transmission is preceded by the strobed preamble, as presented in Figure 10. The minimum channel polling time to receive at least one entire preamble (P) equals to the lengths of two preambles (t_p) and one ACK (t_{al}). The normalized channel-polling time in X-MAC is

$$t_{POLL} = \frac{2t_p + t_{al}}{T_{AC}}, \tag{23}$$

where

$$t_p = t_{ST} + \frac{L_P}{R},$$
$$t_{al} = t_{ST} + \frac{L_{ACK}}{R}. \tag{24}$$

Assuming uniform distribution of wake-up moments, the average length of the strobed preamble is a half of the wake up period (T_{AC}), during which $T_{\text{AC}}/(2(t_p+t_{al}))$ preambles are transmitted. Overhearing is limited to the channel polling time. Hence, t_{TX} and t_{RX} the leaf node are

$$t_{\text{TX}} = \left(\frac{T_{\text{AC}}}{2\left(t_p + t_{al}\right)} t_p + t_{\text{ST}} + \frac{L_{\text{DATA}}}{R}\right) \frac{1}{T_{\text{DATA}}},$$
$$t_{\text{RX}} = t_{\text{POLL}} + \left(\frac{T_{\text{AC}}}{2\left(t_p + t_{al}\right)} + 1\right) \frac{t_{al}}{T_{\text{DATA}}}. \tag{25}$$

As the router node receives and forwards data frames from n_{DL} nodes, the normalized transmission and reception times of the X-MAC router node are

$$t_{\text{TX}} = \left(\frac{T_{\text{AC}}}{2\left(t_p + t_{al}\right)} t_p + \frac{L_{\text{DATA}}}{R}\right) \frac{n_{\text{DL}} + 1}{T_{\text{DATA}}} + \frac{2 t_{al} n_{\text{DL}}}{T_{\text{DATA}}},$$
$$t_{\text{RX}} = t_{\text{POLL}} + \left(\frac{T_{\text{AC}}}{2\left(t_p + t_{al}\right)} + 1\right) \frac{t_{al}(n_{\text{DL}} + 1)}{T_{\text{DATA}}} + \left(t_{\text{ST}} + \frac{L_{\text{DATA}}}{R}\right) \frac{n_{\text{DL}}}{T_{\text{DATA}}}. \tag{26}$$

The power consumption reaches its unique minimum at an optimal polling interval (T_{AC}^*) obtained by setting $\partial P/\partial T_{\text{AC}} = 0$.

Performance results are calculated using the optimal polling interval of the router, which is

$$T_{\text{AC}}^* = \sqrt{\frac{2T_{\text{DATA}}\left(t_p + t_{al}\right)\left(2t_p + t_{al}\right)}{\left(t_p P_{\text{TX}}/P_{\text{RX}} + t_{al}\right)(n_{\text{DL}} + 1)}}. \tag{27}$$

5.5. Synchronized Low Duty-Cycle Protocols. Next, the synchronized low duty-cycle protocols are modeled. In synchronized protocols data transmissions occur in active periods as bursts. We define n_F as the number of data transmission in each active period. For comparability, n_F is assumed to be equal for all synchronized protocols. Thus, the optimal access cycle length (T_{AC}^*) for synchronized protocols can be defined as

$$T_{\text{AC}}^* = \frac{n_F T_{\text{DATA}}}{n_{\text{DL}} + 1}. \tag{28}$$

5.5.1. T-MAC. In T-MAC [23], each node polls channel for RTS messages at T_{AC} intervals, as presented in Figure 11. If no traffic exists, radio is turned off after a period of T_A. Hence, the normalized channel polling time without traffic is

$$t_{\text{POLL}} = \frac{t_{\text{ST}} + T_A}{T_{\text{AC}}}, \tag{29}$$

where

$$T_A = t_{\text{ST}} + t_{\text{CW}} + t_{\text{RTS}}. \tag{30}$$

A data frame transmission consists of a random delay within a Contention Window (CW) being followed by an RTS - CTS - DATA - ACK frame exchange. L_B bytes long SYNC frames are transmitted at T_{SYNC} intervals using a random delay within CW. For maximum energy-efficiency, adaptive listening and virtual clusters are assumed. According to received RTS frames, nodes are in sleep mode during the transmissions intended to other nodes. Thus, t_{TX} and t_{RX} for the leaf node are

$$t_{\text{TX}} = \left(2t_{\text{ST}} + \frac{L_{\text{RTS}} + L_{\text{DATA}}}{R}\right)\frac{1}{T_{\text{DATA}}} + \left(t_{\text{ST}} + \frac{L_B}{R}\right)\frac{1}{T_{\text{SYNC}}},$$
$$t_{\text{RX}} = t_{\text{POLL}} + \left(2t_{\text{ST}} + \frac{t_{\text{CW}}}{2} + \frac{L_{\text{RTS}}}{R}\right)\frac{n + n_{\text{DL}}}{T_{\text{DATA}}} + \left(2t_{\text{ST}} + \frac{L_{\text{CTS}} + L_{\text{ACK}}}{R}\right)\frac{1}{T_{\text{DATA}}} + \left(t_{\text{ST}} + t_{\text{CW}} - \frac{L_B}{R}\right)\frac{1}{T_{\text{SYNC}}}. \tag{31}$$

The router node receives data frames from n_{DL} nodes, transmits $n_{\text{DL}} + 1$ frames to a next-hop node, and transmits and receives SYNC frames. Thus, t_{TX} and t_{RX} for the T-MAC router node are

$$t_{\text{TX}} = \left(2t_{\text{ST}} + \frac{L_{\text{RTS}} + L_{\text{DATA}}}{R}\right)\frac{n_{\text{DL}} + 1}{T_{\text{DATA}}} + \left(2t_{\text{ST}} + \frac{L_{\text{CTS}} + L_{\text{ACK}}}{R}\right)\frac{n_{\text{DL}}}{T_{\text{DATA}}} + \left(t_{\text{ST}} + \frac{L_B}{R}\right)\frac{1}{T_{\text{SYNC}}},$$
$$t_{\text{RX}} = t_{\text{POLL}} + \left(3t_{\text{ST}} + \frac{t_{\text{CW}}}{2} + \frac{L_{\text{RTS}} + L_{\text{DATA}}}{R}\right)\frac{n_{\text{DL}}}{T_{\text{DATA}}} + \left(t_{\text{ST}} + \frac{t_{\text{CW}}}{2} + \frac{L_{\text{RTS}}}{R}\right)\frac{n + n_{\text{DL}} + 1}{T_{\text{DATA}}} + \left(2t_{\text{ST}} + \frac{L_{\text{CTS}} + L_{\text{ACK}}}{R}\right)\frac{n_{\text{DL}} + 1}{T_{\text{DATA}}} + \left(t_{\text{ST}} + t_{\text{CW}} - \frac{L_B}{R}\right)\frac{1}{T_{\text{SYNC}}}. \tag{32}$$

5.5.2. IEEE 802.15.4. For obtaining the best energy efficiency, IEEE 802.15.4 [24] is analyzed in the beacon-enabled mode, with inactive time, and employing a cluster-tree network topology. Nodes maintain synchronization by receiving beacon frames from a parent at the beginning of active periods. Beacons are transmitted by cluster heads only. The required activity of radio is presented in Figure 12.

As the beacons are transmitted at T_{AC} intervals, the normalized beacon reception (polling) time is

$$t_{\text{POLL}} = \left(t_{\text{ST}} + 2T_{\text{AC}}\varepsilon + \frac{L_B}{R}\right)\frac{1}{T_{\text{AC}}}. \tag{33}$$

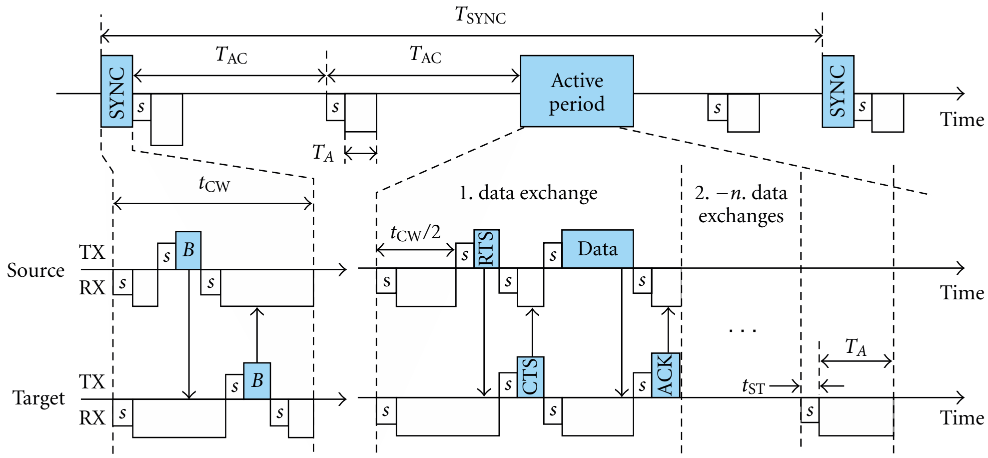

Figure 11: The activity of radio in T-MAC.

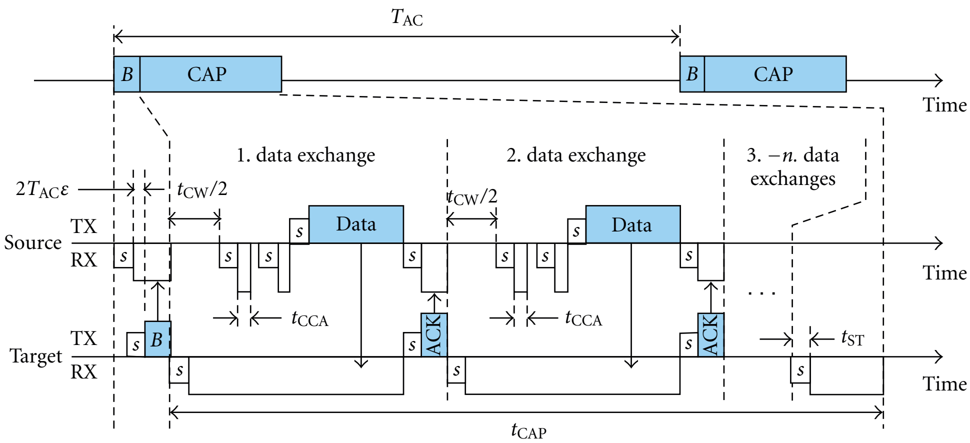

Figure 12: The activity of radio in IEEE 802.15.4.

A data frame transmission is preceded by a random backoff delay and two Clear Channel Assessment (CCA) operations [24]. IEEE 802.15.4 utilizes blind backoffs, where nodes spend the backoff delay in the sleep mode.

A data frame is followed by an ACK, which is transmitted within a maximum waiting time of 864 μs. Assuming the best case situation, where the hardware processes the received frame instantly, ACK is transmitted without a delay. Thus, t_{TX} and t_{RX} for the IEEE 802.15.4 leaf node are

$$t_{TX} = \left(t_{ST} + \frac{L_{DATA}}{R}\right)\frac{1}{T_{DATA}},$$
$$t_{RX} = t_{POLL} + \left(3t_{ST} + 2t_{CCA} + \frac{L_{ACK}}{R}\right)\frac{1}{T_{DATA}}. \tag{34}$$

The IEEE 802.15.4 router node (coordinator) transmit beacons, receives entire CAP except ACK transmissions, and forward data to a next hop node. Thus, t_{TX} and t_{RX} for the IEEE 802.15.4 router node are

$$t_{TX} = \left(t_{ST} + \frac{L_B}{R}\right)\frac{1}{T_{AC}} + \left(t_{ST} + \frac{L_{DATA}}{R}\right)\frac{n_{DL}+1}{T_{DATA}} + \left(t_{ST} + \frac{L_{ACK}}{R}\right)\frac{n_{DL}}{T_{DATA}},$$
$$t_{RX} = t_{POLL} + \frac{t_{CAP}}{T_{AC}} - \left(t_{ST} + \frac{L_{ACK}}{R}\right)\frac{n_{DL}}{T_{DATA}} + \left(3t_{ST} + 2t_{CCA} + \frac{L_{ACK}}{R}\right)\frac{n_{DL}+1}{T_{DATA}}. \tag{35}$$

For achieving the maximum energy efficiency, analysis results are determined using the minimum CAP length, where the required frame exchanges can be performed.

The minimum CAP length is

$$t_{CAP} = \left(4t_{ST} + \frac{t_{CW}}{2} + 2t_{CCA} + \frac{L_{DATA} + L_{ACK}}{R}\right)n_F. \tag{36}$$

5.5.3. TUTWSN MAC. For comparison, the energy consumption of TUTWSN MAC is modeled. Due to the stationary network, the following analysis considers the basic channel access mechanism without the networking mechanisms. Each node maintains synchronization with one parent. Superframe contains S_A contention slots and the required number of contention-free slots. The activity of radio in TUTWSN MAC is presented in Figure 13.

In TUTWSN MAC, the normalized channel polling time t_{POLL} is similar with IEEE 802.15.4. The leaf node (subnode) receives the beacons and transmits data using a contention-free slot. Thus, t_{TX} is similar with IEEE 802.15.4 leaf node, and t_{RX} for the leaf node is

$$t_{\text{RX}} = t_{\text{POLL}} + \left(t_{\text{ST}} + \frac{L_{\text{ACK}}}{R}\right)\frac{1}{T_{\text{DATA}}}. \quad (37)$$

The TUTWSN router node (headnode) receives and transmits beacons, receives S_A/T_{AC} contention slots and $n_{\text{DL}}/T_{\text{DATA}}$ contention-free slots, and transmits received and own generated data to a parent in contention-free slots. Thus, t_{TX} and t_{RX} for the TUTWSN router are

$$t_{\text{TX}} = \left(t_{\text{ST}} + \frac{L_B}{R}\right)\frac{1}{T_{\text{AC}}} + \left(t_{\text{ST}} + \frac{L_{\text{ACK}}}{R}\right)\frac{n_{\text{DL}}}{T_{\text{DATA}}} + \left(t_{\text{ST}} + \frac{L_{\text{DATA}}}{R}\right)\frac{n_{\text{DL}}+1}{T_{\text{DATA}}}, \quad (38)$$

$$t_{\text{RX}} = t_{\text{POLL}} + \left(t_{\text{ST}} + \frac{L_{\text{DATA}}}{R}\right)\left(\frac{S_A}{T_{\text{AC}}} + \frac{n_{\text{DL}}}{T_{\text{DATA}}}\right) + \left(t_{\text{ST}} + \frac{L_{\text{ACK}}}{R}\right)\frac{n_{\text{DL}}+1}{T_{\text{DATA}}}. \quad (39)$$

5.6. Results. By utilizing parameter values presented in Table 2, average power consumptions are determined for the High Rate (HR) platform utilizing Nordic Semiconductor nRF2401A transceiver and for the Low Rate (LR) platform utilizing TI CC1000 transceiver.

The results for the HR platform are presented in Figure 14. According to the results, synchronized protocols outperform clearly unsynchronized proposals in the analyzed network. For both node types, the order of power consumptions is the same. B-MAC results in the highest power, while TUTWSN MAC performs closest to the Ideal-MAC.

As data generation interval increases from 1 second to 1000 seconds, the power consumptions of the Ideal-MAC leaf and router nodes are 68 μW to 37 μW, and 270 μW to 37 μW, respectively. The power consumption of TUTWSN MAC leaf and router nodes are 23.4% to 6.54%, and 18.8% to 6.60% higher than the Ideal-MAC and the same data generation intervals. IEEE 802.15.4 performs the second best and results in 80.4% to 6.64% and 229% to 8.14% higher power consumption than the Ideal-MAC.

The utilization of LR platform increases power consumptions, as presented in Figure 15. However, TUTWSN MAC maintains its energy efficiency resulting in the lowest power consumption. The power consumptions of the Ideal-MAC leaf and router nodes are 171 μW to 37 μW, and 945 μW to 38 μW, respectively. The power consumption of TUTWSN MAC leaf and router nodes are 27.1% to 2.85%, and 20.2% to 3.18% higher than the Ideal-MAC and the same data generation intervals. IEEE 802.15.4 performs the second best and results in 42.1% to 2.92% and 66.3% to 4.33% higher power consumption than the Ideal-MAC.

Table 2: Utilized parameter values.

Parameter	Value (HR)	Value (LR)
E	20 ppm	20 ppm
$L_{\text{ACK}}, L_{\text{CTS}}, L_{\text{RTS}}, L_P$	8 B	8 B
L_B, L_{DATA}	32 B	32 B
L_{SB} (SCP-MAC)	2 B	2 B
n	8	8
n_F	8	8
n_{DL}	3	3
P_{RX}	60.2 mW	25.4 mW
P_S	37 μW	37 μW
P_{TX}	34.7 mW	29.9 mW
R	1 Mbps	76.8 kbps
S_A (TUTWSN)	2	2
T_{SYNC} (T-MAC)	90 seconds	90 seconds
t_{CCA}	128 μs	256 μs
t_{CW}	2 ms	4 ms
t_{ST}	195 μs	250 μs

The results indicate that the designed channel access mechanism achieves higher energy efficiency than the most essential existing low-power MAC protocols. Depending on the traffic loading, radio type, and data routing capability, the energy overhead of TUTWSN MAC is only 2.85% to 27.1% compared to the Ideal-MAC. The high energy efficiency is achieved in both leaf and router nodes.

6. Simulations of TUTWSN and IEEE 802.15.4

The analytical models for TUTWSN MAC and IEEE 802.15.4 were verified with Network Simulator 2 (NS2). The other protocols were not simulated as the basic versions of their models are validated in [47]. The simulations were based on the HR platform as presented in Table 2 with the exception of the data rate, which was configured to 250 kbps data rate to conform the 802.15.4 physical layer specification.

The simulation topology consisted of a sink, a router node, and three leaf nodes. TUTWSN MAC and IEEE 802.15.4 were configured to comparable performance in respect of delays and throughput. Both protocols used 2 seconds access cycle length. The active period length in 802.15.4 was 0.25 second, whereas TUTWSN MAC used 4 ms slot length and up to 18 reserved slots. The TUTWSN reservations were adjusted according to the data generation interval. For example, a node had one reservation per 10 access cycles when data interval was 20 seconds. In addition, a node could request more reservations by setting a flag in its data transmission. The cluster head indicated an allocated slot in its acknowledgment frame.

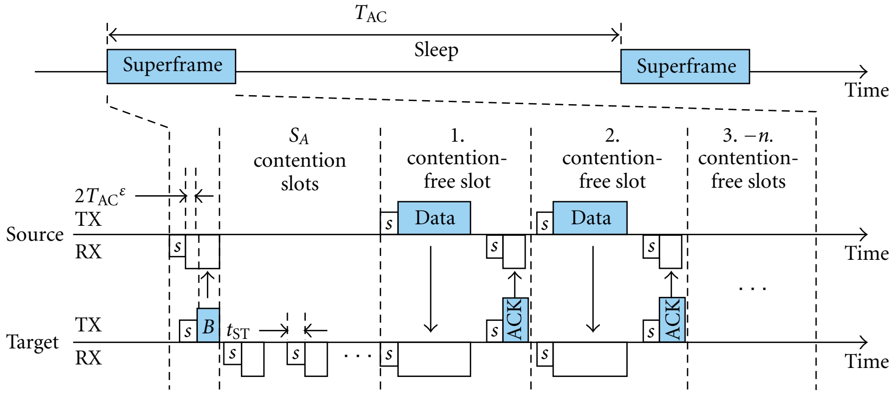

Figure 13: The activity of radio in TUTWSN MAC.

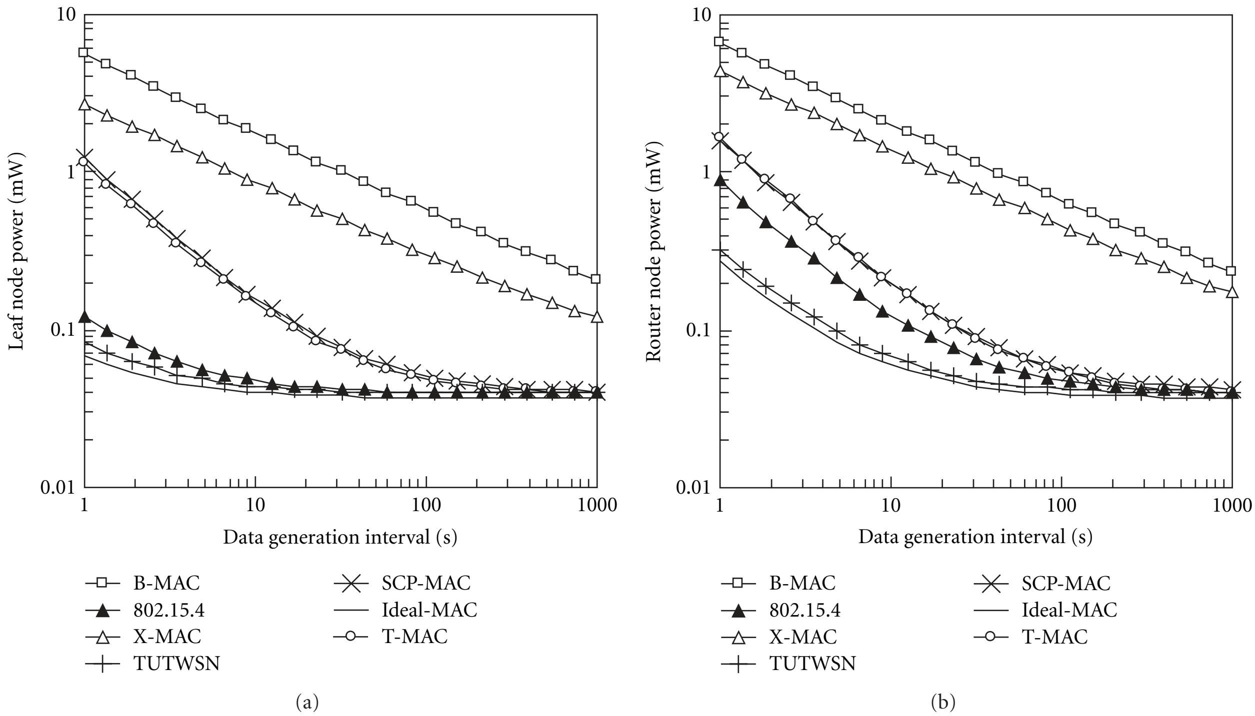

Figure 14: Power consumption comparison using the High Rate (HR) platform.

6.1. Model Verification. The difference between simulated and modeled power consumptions as the function of data generation interval is shown in Figure 16. To determine the energy efficiencies of the MAC schemes, the power consumptions were measured after network construction and therefore network scans and route construction messaging are excluded.

According to simulations, the power consumption of TUTWSN is significantly lower than IEEE 802.15.4. As the data generation interval ranges from 1 to 1000 seconds, the power consumption of a leaf node is 0.12 mW–0.068 mW in TUTWSN and 0.33 mW–0.078 mW in IEEE 802.15.4. In a router node, the power consumption of TUTWSN is 0.55 mW–0.15 mW, which is over one order of magnitude lower than in IEEE 802.15.4 being 7.78 mW–7.5 mW.

The difference between modeled and simulated power consumptions in an IEEE 802.15.4 router is below 1%. In a leaf node, the simulated power consumption is 12%–63% higher than modeled, because the models do not consider collisions. As several nodes compete over the medium, collision probability and therefore retransmissions and energy consumption increase as data generation interval decreases.

The simulated power consumption of the TUTWSN MAC is within 5% of the modeled values. Slight variation in the simulation results is caused by the suboptimal amount of reservations.

6.2. Slot Allocation Methods. The slot allocation methods were tested with the configuration listed in Table 3. When

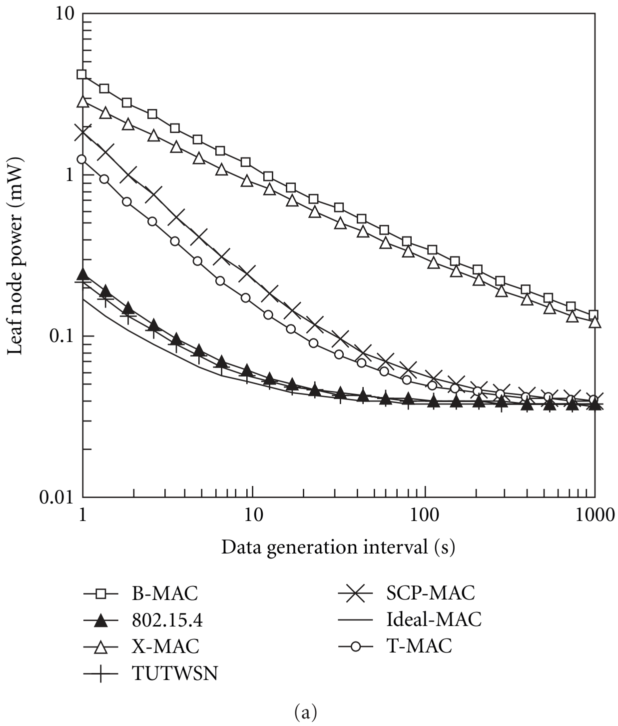

Figure 15: Power consumption comparison using the Low Rate (LR) platform.

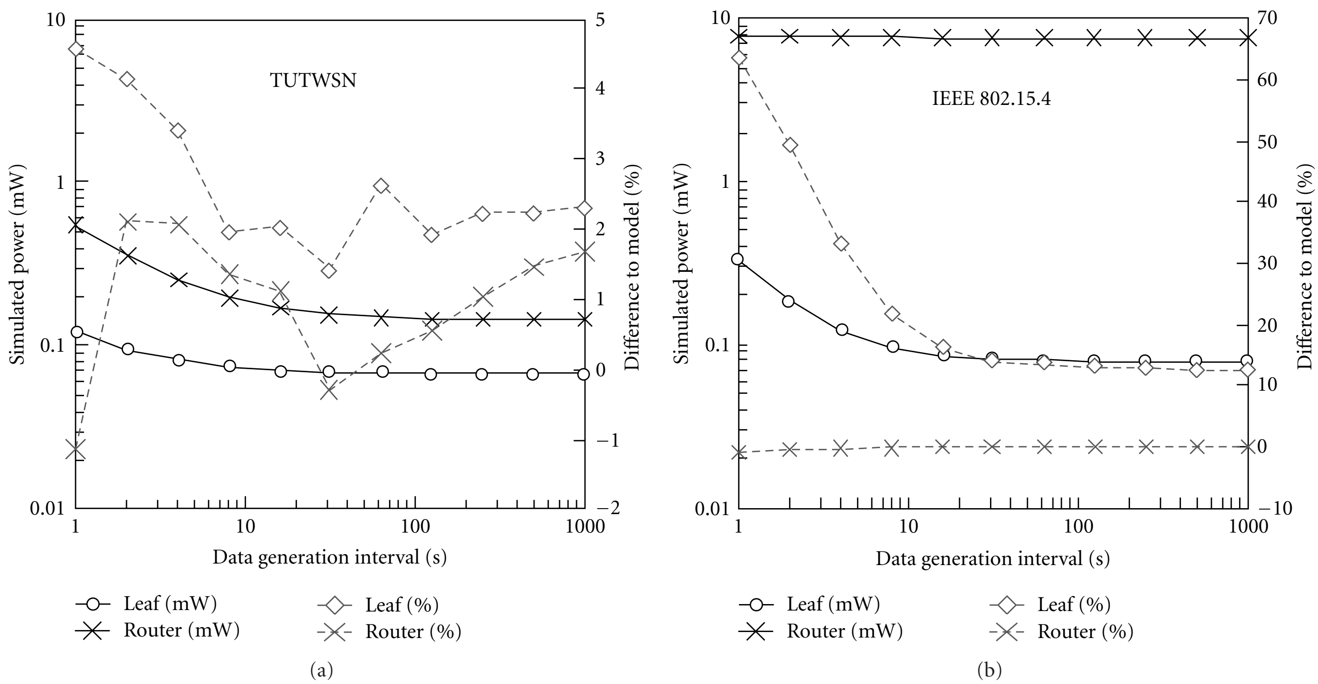

Figure 16: Difference between simulated and modeled power consumptions in TUTWSN and IEEE 802.15.4.

fixed reservations were used, each leaf node was granted one contention-free slot at every second access cycle, equaling to 64 bps bandwidth. If a node was granted with a slot, but had nothing to send, the node yielded its reservation by sending a control frame to the cluster head. The cluster head did not reply to the control frame. A node used the contention-based channel access to send data and to request on-demand reservations if a reserved slot was not granted within two access cycles (4 seconds). To obtain a realistic traffic pattern, nodes generated Poisson distributed traffic.

Table 3: Configurations used in the slot allocation method simulations.

Configuration	Fixed allocations	On-demand reservations	Dynamic reservations
On-demand	not used	Yes	no
On-demand + fixed	64 bps	Yes	no
Dynamic	not used	Yes	yes

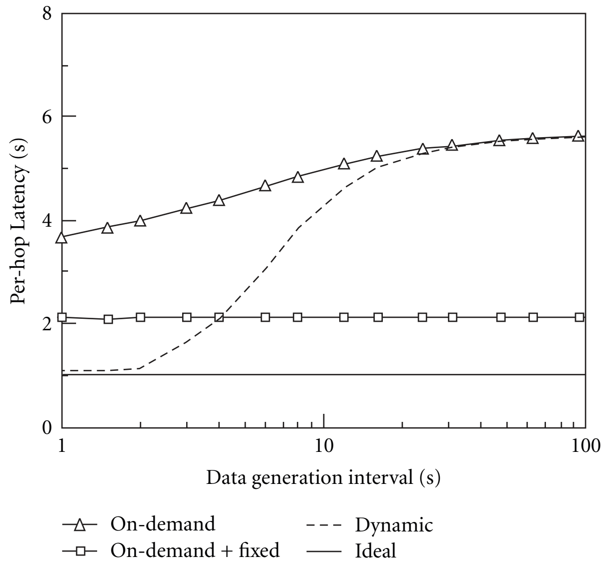

Figure 17: One-hop latency with different contention-free slot allocation methods.

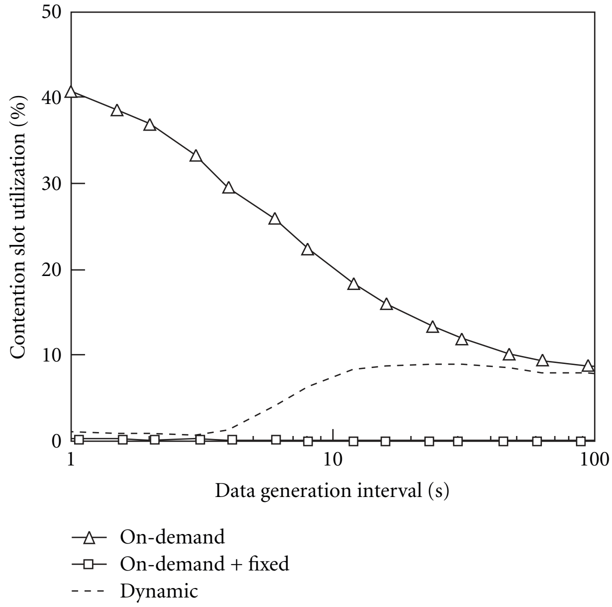

Figure 18: Contention slot utilization with different contention-free slot allocation methods.

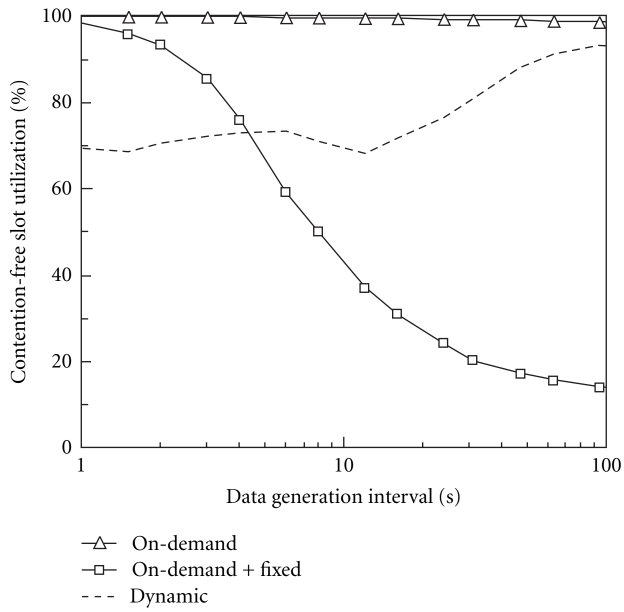

Figure 19: Utilization of granted contention-free slots with different contention-free slot allocation methods.

The simulation results of one-hop latency with the three slot allocation methods are presented in Figure 17. As 2 seconds access cycle length was used, the ideal average latency per hop is 1 second. The on-demand method has the highest latency, since the node buffers packets for two access cycles before sending a packet in a contention slot. The average latency decreases on shorter data generation intervals, as several packets can be forwarded at the same access cycle. When the on-demand method is combined with fixed allocations, the latency remains the same regardless of data generation interval, since the node receives a slot on every other access cycle. The dynamic allocation method has nearly optimal latency, when traffic load is high. Yet, the latency increases on low traffic loads, since the probability that a cluster head grants a reserved slot just after the node has new data to send decreases. The reason is that the interval of granting data slots increases with the data generation interval.

The contention-based slot utilization and the efficiency of the contention-free slot usage, measured as ratio between utilized and wasted slots, are shown in Figures 18 and 19. The on-demand method does not waste capacity, as reservations are requested only when needed. However, the drawback of the method is the high contention slot usage that can cause collisions. The contention-based channel access is eliminated, when the on-demand allocation method is used with fixed reservations. Yet, the contention-free slot utilization is lower, as some granted slots are wasted on low-rate traffic because a node does not always have data to send. The dynamic allocation method combines low contention slot usage with good contention-free slot utilization.

Based on the results, the reservation-based approach of TUTWSN MAC is feasible in WSNs. The presented slot allocation methods can be used with both high-rate and low-rate traffic, and they allow a tradeoff between latency, energy efficiency, and capacity.

Table 4: TUTWSN protocol stack resource utilization.

	Program memory		Data memory	
Module	Bytes	% of total	Bytes	% of total
MAC	33.0 kB	25.1%	566 B	13.8%
Routing	13.5 kB	10.3%	318 B	7.8%
Applications	14.9 kB	11.4%	386 B	9.4%
Node management	13.5 kB	10.3%	385 B	9.4%
Device drivers	12.1 kB	9.2%	239 B	5.8%
Miscellaneous	13.0 kB	9.9%	342 B	39.6%
Free space	31.1 kB	23.8%	1859 B	14.2%

7. Experimental Measurements with TUTWSN

For verifying the practical feasibility of the TUTWSN MAC protocol, the power consumptions of TUTWSN subnode and headnode are experimentally measured using TUTWSN prototype platforms. The prototype platform is presented in Figure 20. It consists of Microchip PIC18F8722 MCU operating at 8 MHz (2 MIPS), 2.4 GHz Nordic Semiconductor nRF24L01 transceiver, and temperature, acceleration, and luminance sensors. The power consumption of the platform is 35.5 mW in RX mode and 51 μW in sleep mode. The TX power consumption is 33.9 mW (0 dBm), 27 mW (-6 dBm), 22.5 mW (-12 dBm), or 21 mW (-18 dBm) depending on the transmission power level. The platform is powered by two AA batteries.

The protocol stack contains the MAC protocol and an interest-based routing protocol [48]. Since the utilized radio transceiver does not support Received Signal Strength Indication (RSSI) functionality, the RF attenuation between nodes is estimated by the successfully received beacons transmitted at different power levels, as presented in [49]. The mechanism doubles the number of beacon transmissions. In addition, a separate network channel is used for neighbor discovery. Headnodes transmit periodic network beacons every 500 ms. Also, the network beacons are transmitted with different power levels. Thus, a headnode transmits 10 beacons every 2 second access cycle. The MAC was configured with 20 ms slot length, 4 ALOHA slots, and 12 reserved slots.

The protocol stack with required peripheral device drivers consumes 131 kB program memory and 2.2 kB data memory. The remaining data memory is used for packet buffers. The size of the MAC protocol with network management and error control algorithms is 33.0 kB. The program memory utilization of TUTWSN protocol stack is summarized in Table 4. Node management includes self-diagnostics, role, and neighbor selection procedures, while miscellaneous category includes shared library functions.

7.1. Duty Cycle and Power Consumption. To evaluate the energy efficiency of the prototype platform, nodes recorded the duty cycles of MCU and radio and forwarded the information to the sink in the data packets. The network was small, consisting of a sink, a headnode, and three subnodes, which enabled fully controllable topology formation. The subnodes forwarded their traffic through the headnode. MAC was configured similarly to the analysis and simulations. The access cycle length was fixed to two seconds and each access cycle contained two contention slots.

Table 5: Measured duty cycle of MCU and radio.

Node	Interval	MCU	Radio TX	Radio RX
Subnode	2 seconds	2.7%	0.024%	0.089%
Subnode	60 seconds	1.5%	0.017%	0.085%
Headnode	2 seconds	7.2%	0.33%	0.33%
Headnode	60 seconds	4.1%	0.22%	0.15%

Table 6: Modeled power consumption against measured power derived from radio duty cycles.

Node	Interval	Modeled	Measured
Subnode	2 seconds	0.086 mW	0.091 mW
Subnode	60 seconds	0.069 mW	0.087 mW
Headnode	2 seconds	0.29 mW	0.28 mW
Headnode	60 seconds	0.17 mW	0.18 mW

The activities measured in 2 seconds and 60 seconds data generation intervals are listed in Table 5. The duty cycle of radio is 0.1%–0.5%, which verifies the efficiency of the TUTWSN channel access mechanism. The MCU duty cycle at 2 MIPS speed is 1.4%–6.3%. Most of the MCU activity is caused by the operating system that polls frequently the status of running processes.

The power consumption of the prototype was calculated based on the measured duty cycles and known static power consumption of the nRF24L01 radio. MCU power consumption was not considered in the calculation because it contains other activities beside MAC (e.g., task managing). The measured power is compared against modeled results in Table 6. The models were modified slightly to match the protocol implementation. First, the modeled transmission time (t_{TX}) was increased due to the additional beacon transmissions. Second, the beacon reception time (t_{POLL} variable) was increased due to the additional beacon receptions used for RF attenuation estimation. On average, nodes received 1.3 cluster beacons per access cycle. Third, a 250 μs reception margin was added to each reception in (39). The margins are used to compensate practical inaccuracies in synchronization and time measurement.

7.2. Real World Performance. The practical feasibility of the TUTWSN MAC protocol was tested in a 16 nodes network with 10 seconds data generation interval. Results were obtained over two days measurement period. Due to practical reasons, the measured network was rather small. However, indicative results of the network energy efficiency are well obtained. To allow alternative routes and faster recovery on a link break, each node maintained synchronization up to two neighbors. The network topology is presented in Figure 21. Arrows in the TUTWSN user interface indicate current data routing paths. The network has one sink that is shown as the largest circle (ID: 300), three subnodes that are shown as the smallest circles having the lightest

Table 7: Average contention and contention-free slot usages and end-to-end latencies.

	Contention slot usage (%)			Contention-free slot usage (%)			End-to-end latency (s)		
Data interval (s)	5	10	30	5	10	30	5	10	30
On-demand	10.6	7.08	4.45	11.8	5.22	1.87	28.0	23.7	18.1
On-demand + fixed	2.75	1.60	0.812	14.4	9.55	7.21	17.6	11.2	9.61
Dynamic	1.58	2.31	2.54	14.4	6.75	3.11	6.54	8.29	12.4

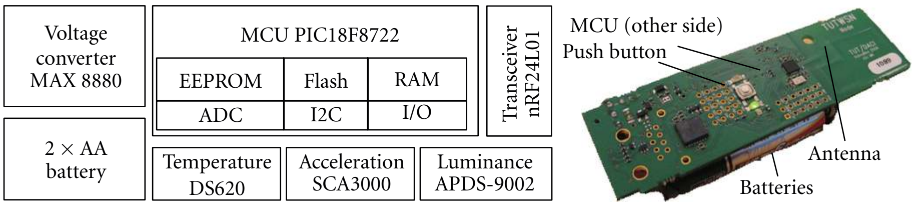

Figure 20: TUTWSN prototype platform.

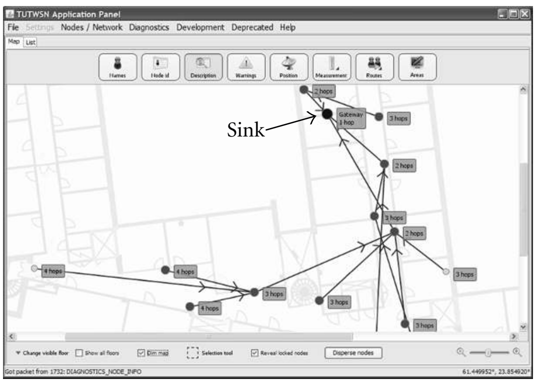

Figure 21: Measured network topology as shown by TUTWSN user interface.

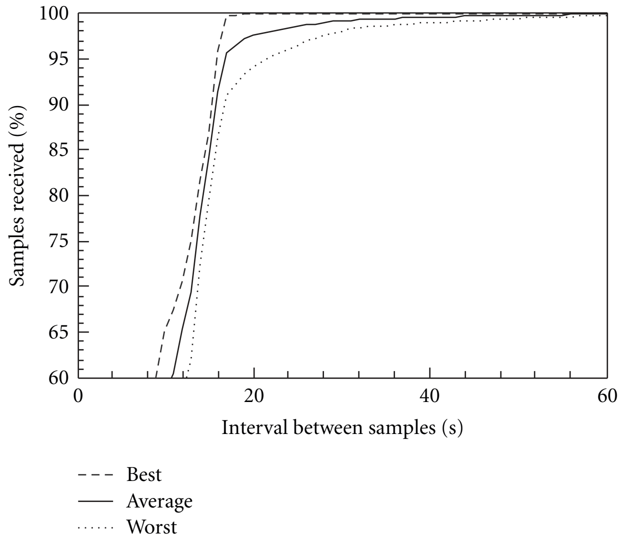

Figure 22: Availability of best, average, and worst case nodes in measurement network.

color, 12 headnodes presented as the medium sized dark circles. The network topology changed dynamically to adapt to varying RF propagation conditions and for balancing energy consumption between nodes. The maximum number of hops to the sink was 5.

In a headnode, the average MCU, TX, and RX duty cycles were 6.4%–7.5%, 0.22%–0.26%, and 0.35%–0.64%, respectively. In a subnode, the average MCU, TX, and RX activities were 2.2%–2.4%, 0.020%–0.021%, and 0.18%–0.27%, respectively. RX duty cycle was higher than in the power consumption measurements because a node synchronized to several neighbors and the measurement period included network scans that were used to discover neighbors. On average, nodes performed two network scans per hour, each causing 700 ms channel listening time. Still, the duty cycle was well below 1% in all nodes, verifying the energy efficiency of the TUTWSN MAC protocol.

The network reliability was evaluated with availability metric that denotes the probability that a sample is received from a node within a certain time interval. Ideally, the packet reception interval equals to the data generation interval, but beacon misses, retransmissions, and broken links increase the packet forwarding time and thus the time between successive receptions. The measured availabilities in best, average, and worst case nodes are presented in Figure 22. Nodes reached 99% availability in 16 seconds–42 seconds intervals indicating that the data forwarding was consistent and the operation was reliable.

Different slot allocation methods were tested with the practical network to verify the simulations. Table 7 shows the average slot usages and end-to-end latencies. The measurements confirm the simulation results. On-demand allocation optimizes contention-free slot usage but has high contention-slot usage and latencies. Fixed allocations allow controllable latency but waste capacity when traffic load is low. Finally, dynamic allocations scale according to the traffic and present a compromise between on-demand and fixed allocations.

8. Conclusions

This paper presented a survey, performance models, and analysis of existing low-energy MAC protocols. It was shown that existing MAC protocols lack the performance to adequately fulfill the energy efficiency and adaptivity requirements of low-energy WSNs. This motivated the design of a new MAC protocol called TUTWSN MAC. The focus has been on ultra-low duty-cycle frame exchanges and scalable network self-configuration. The performance of the TUTWSN MAC has been proven by performance analysis and comparison against the current state-of-the art MAC protocols and the Ideal-MAC protocol. The analysis results indicated that the energy efficiency of the designed MAC protocol is better than existing protocols in various traffic conditions, and using low and high data-rate transceivers. According to the analysis, the energy consumption of TUTWSN MAC is only 2.85% to 27.1% higher than the Ideal-MAC, and the high energy efficiency is achieved in both leaf and router nodes. Simulations verified that the power consumption of a leaf node follows closely the analyzed values, whereas the energy efficiency of a router node depends on the used contention-free allocation method. The simulations with the fixed, on-demand, and dynamic allocation methods indicate a tradeoff between latency and energy efficiency. The practical feasibility of the TUTWSN MAC protocol was verified with a prototype implementation on resource constrained MCU and measurements in a real WSN deployment. The measured activity time of nRF24L01 radio was 0.06%–1% depending on network load, which corresponds the power consumption of 0.01 mW–0.3 mW. This provides the lifetime of several years with a low-power MCU. Experiments indicated that the protocol is reliable and energy efficient in real WSN applications.

In future work, the presented models should be extended to allow multiple sinks. While the relative performance between modeled protocols would not change, the extension would allow more modeling other than tree-based routing protocols. Future work also includes examining new reservation policies and researching optimal switching points between the presented policies. While several slot allocation policies were presented, none of them were optimal for each type of traffic. Thus, changing the policy, for example, depending traffic load could reduce contention slot utilization and wasted reservations.

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