Cost-Aware Capacity Optimization in Dynamic Multi-Hop WSNs

Jukka Suhonen, Mikko Kohvakka, Mauri Kuorilehto, Marko Hännikäinen, and Timo D. Hämäläinen
Tampere University of Technology / Institute of Computer and Digital Systems
P.O.Box 553, FIN-33101 Tampere, Finland
{jukka.suhonen, mikko.kohvakka, mauri.kuorilehto, marko.hannikainen, timo.d.hamalainen}@tut.fi

Abstract

Low energy consumption and load balancing are required for enhancing lifetime at Wireless Sensor Networks (WSN). In addition, network dynamics and different delay, throughput, and reliability requirements demand cost-aware traffic adaptation. This paper presents a novel capacity optimization algorithm targeted at locally synchronized, low-duty cycle WSN MACs. The algorithm balances the traffic load between contention and contention free channel access. The energy-inefficient contention access is avoided, whereas the more reliable contention free access is preferred. The algorithm allows making cost-aware trade-off between delay, energy-efficiency, and throughput guided by routing layer. Analysis results show that the algorithm has 10% to 100% better energy-efficiency than IEEE 802.15.4 LR-WPAN in a typical sensing application, while providing comparable goodput and delay.

1. Introduction

Wireless sensor network (WSN) is an ad-hoc network that may consist of thousands of nodes. A WSN node combines environment sensing, data processing, and wireless networking with extremely low energy and cost. The applications for sensor networks range from home and industrial environments to military uses.

As WSN nodes are often powered by batteries that might be difficult or impossible to replace, network lifetime is especially important. The highest energy-efficiency can be achieved with low duty cycle operation, where channel is accessed in cycles consisting of active and idle periods. The underlying Medium Access Control (MAC) scheme is either contention or contention free. The contention channel access is flexible as nodes do not have to make reservations, yet it is energy-inefficient due to high idle listening and possible collisions. The contention free channel access reduces collisions, thus increasing reliability and throughput, but requires additional control messaging to determine slot usage.

Fixed reservations work well in constant bit rate (CBR) traffic, in which reservations match accurately the actual traffic. However, a WSN often contains extremely bursty traffic, which is triggered by environmental events. When the traffic varies, unused reservations are wasted. Further traffic variation is caused by node mobility and network dynamics due unreliable wireless communications. Still, reservations should be supported, since certain applications, such as surveillance data, require bandwidth guarantees. As there may be spatial and temporal variances in traffic, adaptation and load balancing mechanisms are required. To provide desired service level, the benefits of load balancing must be weighted against delay, throughput, and reliability cost metrics.

This paper presents a novel capacity optimization algorithm targeted at locally synchronized, low-duty cycle WSN MACs. It can be utilized in any MAC having both contention access period (CAP) and a contention free period (CFP), like in IEEE 802.15.4 LR-WPAN [1]. In the other proposed MAC algorithms, the energy-inefficient CAP is heavily utilized, while the use of contention free access requires explicit requests. Unlike the other algorithms, our algorithm significantly increases energy-efficiency and reliability by minimizing the need for CAP and preferring contention free slots. The contention free slots are assigned dynamically on-demand basis, thus supporting traffic bursts, while avoiding wasting energy with the unused reservations. As the algorithm increases both network lifetime and reliability, it is well suited for monitoring WSN applications. A cross-layer design between MAC and routing layers is used to perform cost-aware trade-off between energy and the level of service in dynamic multi-hop WSNs. The performance of the algorithm is analyzed in a large scale clustered network.

The rest of this paper is organized as follows. Section 2 describes related work. Section 3 presents the cross-layer design between routing and MAC. The capacity optimization algorithm used in MAC is presented in Section 4. Section 5 contains analytical and experimental results. Finally, Section 6 concludes the paper.

978-3-9810801-2-4/DATE07

2. Related Research

The focus of this paper is on low-duty cycle WSNs, because of their energy-efficiency. Still, the capacity optimization algorithm can be utilized in any MAC that uses both contention and contention free channel access.

ZigBee [2] defines a network layer and application framework on top PHY layer and MAC sublayer specified in IEEE 802.15.4 LR-WPAN [1]. LR-WPAN provides a synchronized low duty-cycle operation by optional beaconing mode, cluster-tree network topology, and a superframe structure consisting of a beacon, CAP, and CFP. During CAP, a coordinator receives data from the associated nodes using a slotted variation of Carrie Sense Multiple Access (CSMA). CFP contains dedicated time slots for individual nodes that can be used only for direct communication with a PAN coordinator. Although cluster-tree LR-WPAN has a good energy-efficiency, highly static node addressing and routing schemes do not work well in dynamic networks, in which link failure may cause the re-formation of a large part of the network.

S-MAC [3] is a low duty cycle MAC that uses contention channel access. Neighboring nodes form virtual clusters to get a common sleep schedule, thus allowing a node sleep longer. Sleep and listen periods are constant, which decreases the efficiency. T-MAC [4] enhances S-MAC under variable traffic load by ending active period when traffic has not been received within a defined time threshold. Dynamic Sensor MAC (DSMAC) [5] is another S-MAC variant, in which nodes shorten their sleep time if their traffic load is high. S-MAC and its variants use request to send (RTS) / clear to send (CTS) procedure to prevent hidden node problem. However, RTS/CTS messages cause high overhead as most of the packets sent in sensor networks are small.

Traffic-adaptive MAC protocol proposed in [6] increases the utilization of time division multiple access (TDMA) in an energy-efficient manner by dividing time into random and scheduled access periods It uses a contention random access to establish a two-hop topology, while the obtained priority information is used to assign scheduled slots. Z-MAC [7] is another traffic-adaptive MAC that behaves under low load the protocol like CSMA, while preferring TDMA under high load TDMA. The problem with the both traffic-adaptive approaches is that time slot assignment requires information covering two-hop neighborhood.

DMAC [8] is a traffic adaptive MAC protocol that is based on slotted ALOHA. Transmission slots are assigned to a set of nodes based on a data gathering tree. When a target node has receive slot, all of its children can transmit, thus contending over the medium. As slots are successive in the data transmission path, the end-to-end latency is low. The problem in DMAC is that collisions between nodes in the same level of the tree are common. Also, as the knowledge of the data transmission path is required, DMAC is not suitable for dynamic networks.

The capacity optimization allocation algorithm proposed in this paper is compatible with but not limited to the LR-WPAN. Unlike S-MAC and its variants, the algorithm targets at minimizing idle listening. The additional messaging used in the proposed traffic adaptive MACs is not required. In addition to the dynamic adjustment, explicit reservation allowing guaranteed traffic are supported.

3. Cost-Aware Capacity Optimization

In this paper, a clustered network topology as shown in Fig. 1 is used. A cluster consists of a cluster head and one or more member nodes referred to as subnodes. Routing is performed in the cluster heads, whereas the subnodes communicate only with the nodes within their cluster. The nodes sent their data to one or more data collectors referred to as *sinks*.

A cross-layer capacity optimization architecture is presented in Fig. 2. The capacity optimization algorithm is located in the MAC layer, in which it controls channel access and slot usage. An application defines its desired service level with delay, reliability, and throughput requirements. The routing layer uses these requirements to guide the operation of the MAC layer. On each step of the route, a next hop is selected by weighting the application requirements against energy consumption. For example, when the application requires reliability, the routing layer selects next hop links that minimize the link error rate. In addition, each frame is assigned locally with a retransmission count and a delay (T_A) parameters that allow service differentiation within traffic using a same link. The retransmission count affects reliability, while the delay determines the priority of the frame.

The performance of the capacity optimization algorithm is affected by the lengths of CAP and CFP. Too short CAP causes collisions, while too long CAP uses too much idle listening. If the network characteristics are known on deployment time, the ratio can be fixed based on expected number member nodes. However, a cluster head can also dynamically adjust the ratio. If the underlying radio supports carrier sensing, the cluster head determines possible

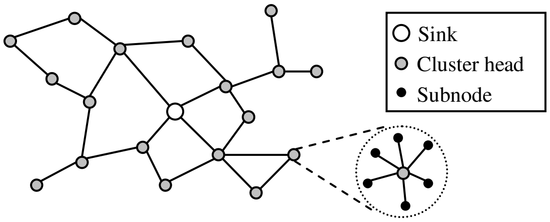

Figure 1. Clustered network topology.

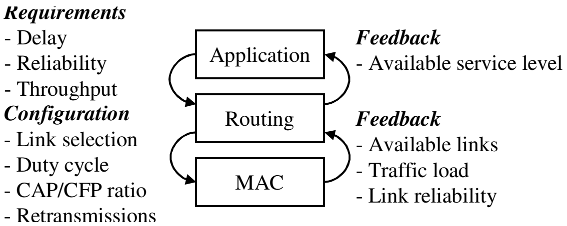

Figure 2. Cross-layer capacity optimization.

collisions and enlarges its CAP if needed.

In low duty cycle MACs, a significant delay is caused by buffering frames until the active period. Thus, an access cycle length determines forwarding delay. Short access cycle length allows small delay, but it also consumes more energy as control beacons are sent more often. In the capacity optimized architecture, the access cycle length is dynamically adjusted as multiples of the base access cycle length. This has the benefit of allowing the increase or the decrease of the access cycle length without forcing nearby clusters to change their cluster timings.

In this paper, the channel or TDMA timing selection algorithms are not discussed. It is assumed that nodes can select non-conflicting TDMA timing. Also, clusters that do not communicate with each other may have overlapping timings, if they operate on separate channels.

4. Capacity Optimization Algorithm

Capacity optimization algorithm consists of two parts that control CFP usage on the MAC layer, an on-demand and a traffic adaptive CFP slot allocation. These slot allocation methods complement each other by using different approaches to minimize the need for energy-inefficient CAP, but can also be used independently.

The on-demand slot allocation supports unpredictable and bursty traffic by allowing a node to request for several dedicated CFP slots within an access cycle. In traffic adaptive slot allocation, CFP slots are assigned to member nodes based on their long-term reservations (guaranteed traffic) and traffic patterns (adapted traffic) as shown in Fig. 3. This method is used with stable links and is targeted at continuous traffic. The traffic guarantees are obtained with a separate handshake, in which a node asks for certain capacity. Although the guaranteed traffic is not analyzed in this paper, it is important as it allows a resource reservation algorithm to provide end-to-end throughput guarantees by reserving capacity on each hop. The adapted traffic avoids using the CAP by granting CFP slots without explicit request.

To reduce contention channel access, a node may transmit only one frame during each CAP. Also, a node does not use the CAP, if it has a CFP slot. Cluster head signals the guaranteed and adapted slot usage in a cluster beacon at the beginning of each access cycle. The contention free slot assignment may be different on every access cycle.

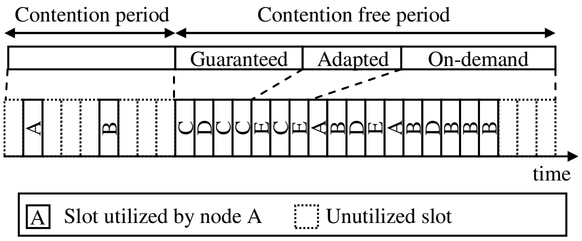

Figure 3. Superframe and slot allocation between nodes A-E.

4.1. On-Demand Slot Allocation

In on-demand slot allocation, a node requests for a CFP slot from the cluster head by setting a reservation flag in its transmitted frame. This allows a node to use collision free transmissions. The cluster head replies with an acknowledgment frame that contains the slot index of the granted slot. As the required information is carried in headers, the reservation is performed within a normal data transmission and no additional signaling is required.

A member can make the slot request in any frame sent during the CAP or in its last reserved slot, which allows the efficient use of excess capacity. For example, in Fig. 3 node B first asks for a contention free slot first during the CAP. Then, it asks for an additional reservation three times in the contention free slots. If a cluster head cannot assign contention free slot during the same access cycle, it will grant it on the next access cycle. This way, a member does not need contention access on the next access cycle.

On-demand reservation can also be used with variable length frames, allowing compatibility with several WSN MACs, such as LR-WPAN. Variable length frames allow efficient bandwidth usage, because the frame length can be optimally adjusted to the required data length. In on-demand allocation request, a member uses an estimate of its transmission time instead of setting the reservation flag. The cluster head replies with an exact time stamp of the transmission.

4.2. Traffic Adaptive Slot Allocation

In traffic adaptive slot allocation, a cluster head keeps a record of average throughput sent by its member nodes. The CFP slots are assigned to each member according to the recorded throughput. Because a node might not get a CFP slot every access cycle, the sending of a frame is postponed until the slot is granted or T_A access cycles elapses. This way, a node can benefit from the adapted traffic and avoid sending in CAP. The use of delay T_A prevents postponing to cause too long delays. The value of T_A can be configured per frame basis, thus allowing service differentiation. If a node has delay critical data or the cluster head does not grant a reservation in time, CAP is used to send the frame. As other frames might be buffered during the postponing, the on-demand slot allocation is used to request for additional slots. While the postponing introduces an additional delay, it reduces the usage of CAP and allows nodes to use more reliable CFP transmissions.

The allocations in CFP are managed as reservation periods that consist of R_A access cycles. The total number of slots r granted to a node during a reservation period is expressed as $r = r_a + r_c$, where r_a is the number of adapted slots and r_c is the number of requested guaranteed slots. These slots are divided equally between access cycles. This keeps average delay low, since a node does not have to wait long for the next reserved slot. The average delay caused by the postponing of a frame transmission to the next granted CFP slot is

$$delay = min\left(\frac{R_A}{r}, T_A\right) \cdot t_{ac}, \tag{1}$$

where t_{ac} is the access cycle length. If $r > R_A$, an additional delay penalty does not occur.

If a node does not have data to send on its contention free slot, it transmits an empty frame. The cluster head does not reply, but frees all the remaining reserved slots during the access cycle. Because the slots are alternated, other nodes have better chance to benefit from the freed slots. For example, if the node C in Fig. 3 sends an empty frame on its first transmission, the node D could utilize the guaranteed slots originally reserved for the node C.

5. Performance Analysis

In this analysis, the performance of the proposed capacity optimization algorithm is compared against 802.15.4 LR-WPAN. LR-WPAN is used with superframe order (SO) set to 2 and beacon order (BO) parameter set to 8, which result to 61.44 ms superframe and 3.932 s access cycle. These values are selected to achieve comparable results in respect of throughput, energy, and delay. The LR-WPAN results are calculated with the model and parameters based on real equipment that are found in [9]. The performance of the proposed capacity optimization algorithm is analyzed with a similar model, frame lengths, and radio power consumption.

In the proposed algorithm, 30% of the active period is reserved for the CAP. CAP uses slotted ALOHA, because it is energy-efficient with a small payload. ALOHA has an additional benefit of reducing radio complexity as energy measurement required in CSMA is not necessary. For comparison, results with traditional slotted ALOHA are provided.

This analysis does not consider hidden nodes, network maintenance (network scans), or data aggregation. In general, hidden nodes have the greatest impact on contention channel access, especially on CSMA-based algorithms where the failure of a clear channel assessment leads to collision. Therefore, it is expected that the presented algorithm will perform better in respect to LR-WPAN on the presence of hidden nodes.

Nodes do not make reservations, but slot allocation algorithm allows dynamic capacity adjustment and a request for CFP slots on-demand basis. The presented analysis uses a fixed data frame length of 105 B (L_L) and acknowledgment frame length of 33 B (L_S), both values include 25 B header overhead. Slots are large enough to allow frame reception, processing, and sending of an acknowledgment. The parameters used in the analysis are presented in Table 1.

5.1. Network Setup

The analysis is performed with a cluster-tree multi-hop network, in which n^i_{dl} defines all nodes that are hierarchically below the node n_i and each cluster head has two child cluster heads (n^i_c) and 5 members (n^i_m). The network depth is four, resulting to 186 nodes in total. Each node is synchronized exactly to one next hop cluster and transmits data frames to the root of the cluster-tree topology (sink).

The performance is evaluated with a commercial Chipcon CC2420EM/EM [10] transceiver board. Power consumption in idle mode is evaluated with Microchip PIC18LF8720 [11] series microcontroller. The static power consumption in different states is presented in Table 2. Active mode power consumptions do not include sleep power, as the sleep energy is calculated over the whole access cycle

Table 1. Parameters used in analysis.

Symbol	Parameter	Value
I_u	Uplink data transmission interval	1..100 s
L_s	Beacon/ACK frame length	33 B
L_l	Data frame length	105 B
R	Radio data rate	250 kbps
t_{ac}	Access cycle length	4 s
t_{ap}	Active period length	0.25 s
t_{cap}	CAP length	$0.3 \cdot t_{ap}$
t_{cfp}	CFP length	$0.7 \cdot t_{ap}$
t_I	Synchronization inaccuracy	100 μs
t_s	Slot length	10 ms
ε	Crystal tolerance	20 ppm

Table 2. Static power consumptions.

Symbol	MCU	Radio	Power (3 V)
P_{tx}	Active	TX (-5 dBm)	39.1 mW
P_{rx}	Active	RX	56.5 mW
P_{id}	Active	Idle	2.79 mW
P_s	Sleep	Sleep	30 μW

5.2. Goodput

Probability p_s of successful transmission during CAP depends on collision probability as

$$p_s = \prod_{n_i \in n_c \cup n_m} \left(1 - \frac{min\left(T_o^i, 1\right)}{t_{cap}/t_s} \right), \qquad (2)$$

where T_o^i denotes the load in frames per access cycle offered by node n_i.

The probability that sending a frame succeeds (v) after C_r retransmission attempts is

$$v = \sum_{i=0}^{C_r} p_s (1 - p_s)^i, \qquad (3)$$

from which the average number of transmission attempts per each frame (u) is obtained as

$$u = (1 - v)(C_r + 1) + \sum_{i=0}^{C_r} (i+1) p_s (1 - p_s)^i. \qquad (4)$$

Traffic send to a cluster head consists of the traffic generated by a node itself and the traffic of its child nodes. Offered frames per the access cycle by a member node (n_i) is

$$T_o^i = \frac{(|n_{dl}^i| + 1) t_{ac}}{I_u} u, \qquad (5)$$

where u models the increased transmission attempts due to retransmissions.

The expected number of transmissions (T_{cap}^i) of node n_i during a CAP is

$$T_{cap}^i = min(T_o^i, 1), \qquad (6)$$

where taking minimum ensures that node competes at maximum one slot. The expected number of transmission in CFP (E_R^i) is calculated as

$$T_{cfp}^i = T_o^i - T_{cap}^i. \qquad (7)$$

If the network is saturated (sum of T_{cfp}^i is greater than the capacity), contention free capacity is divided evenly between nodes. From the expected number of transmissions we obtain goodput G^i in bytes as

$$G^i = (T_{cap}^i \cdot v + T_{cfp}^i) \frac{L_l}{t_{ac}}. \qquad (8)$$

As CFP does not involve collisions, it assumed that transmission on CFP always succeeds.

5.3. Energy Consumption

The energy consumption is

$$E^i = E_s + E_{txb} + E_{rxb} + E_{cap}^i + E_{cfp}^i + E_{fwd}^i, \qquad (9)$$

where $E_s = P_s \cdot t_{ac}$ energy in sleep mode, E_{txb} and E_{rxb} are the energies required to send and receive a cluster beacon, energy consumed during CAP (E_{cap}^i) is

$$E_{cap}^i = \frac{t_{cap}}{t_s} E_{rxd} + \sum_{n_j \in n_c^i \cup n_m^i} T_{cap}^j \cdot p_s \cdot E_{txa}, \qquad (10)$$

energy consumed during CFP (E_{cfp}^i) is

$$E_{cfp}^i = (E_{rxd} + E_{txa}) \sum_{n_j \in n_c^i \cup n_m^i} T_{cfp}^j, \qquad (11)$$

and required energy for forwarding received data is

$$E_{fwd}^i = (E_{txd} + E_{rxa})(T_{cap}^i \cdot p_s + T_{cfp}^i). \qquad (12)$$

E_{txd}, E_{rxd} are the energies required to transmit and receive a data frame, and E_{rxd}, E_{rxa} are the energies required to transmit and receive an acknowledgment.

Frame transmission energy (E_{txb}, E_{txd}, and E_{txa}) is

$$E_{tx*} = P_{tx} \cdot L/R, \qquad (13)$$

and frame reception energy (E_{rxb}, E_{rxd}, and E_{rxa}) is

$$E_{rx*} = P_{rx}(L/R + t_I + \varepsilon \cdot t_{ac}), \qquad (14)$$

where t_I is represents synchronization inaccuracies and ε clock drift between nodes. ε is used only for beacon receptions (E_{rxb}), because the clock drift is negligible within an active period.

5.4. Analysis Results

Two variants of the capacity optimization algorithm, denoted as $R(T_A)$, are considered. Variant R(0) tries to transmit all buffered frames immediately, while R(2) waits two access cycles for a reserved slot. Adjusted reservations are not considered, thus the benefit of waiting in R(2) is that a node can send a frame during the CAP and other buffered frames with requested, on-demand contention free slots.

The achieved goodput with 3 retransmissions at sink is presented in Fig. 4. R(2) variant performs slightly better than R(0), because frames are buffered when delaying sending. When the T_A is exceeded, a node sends one frame in CAP and the rest of the buffered frames in CFP, which decreases the traffic and collision probability in CAP. The goodput of 802.15.4 decreases as channel becomes congested and backoff times increase. Traditional slotted

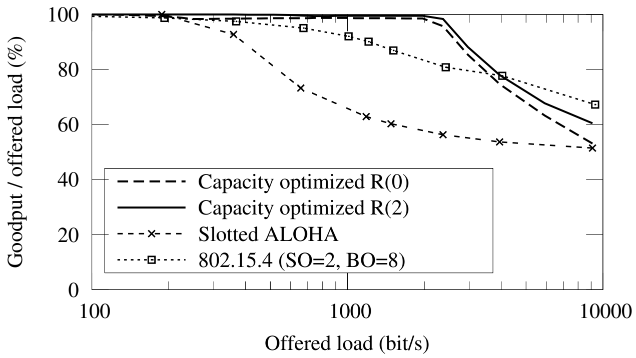

Figure 4. Goodput at a sink as a function of total offered load.

ALOHA performs poorly, because collisions are common and a node can send only one frame per access cycle.

Cluster head power consumption at 3 V operating voltage is presented in Fig. 5. Depending on traffic, both variants have 10%-100% smaller power consumption than a LR-WPAN coordinator. After network gets congested, the power consumption of the capacity optimization algorithm evens. The nearly constant power consumption of traditional slotted ALOHA is not comparable at high traffic loads, as its goodput is bad.

As most of the delay in low duty cycle WSNs is caused by periodic communications, it is expected that LR-WPAN and the proposed algorithm with R(0) have similar delay characteristics. However, R(2) variant will have up to $2 \cdot t_{ac}$=4 s worse delay. Since R(2) has best goodput characteristics, it is possible to make trade-off between delay and energy-efficiency by adjusting the value of T_A.

6. Conclusions

This paper presents a cost-aware capacity optimization algorithm targeted at synchronized, low-duty cycle WSN MACs. The algorithm uses a novel method to make on-demand and traffic adaptive slot allocations on CFP, which allows minimizing the energy inefficient CAP, while still providing flexible capacity usage. Analysis results show that the algorithm has 10-100% smaller energy consumption than IEEE 802.15.4 LR-WPAN in typical sensing application, while providing better goodput and comparable delay. The algorithm allows making trade-off between delay and energy-efficiency by defining how long a frame transmission can be delayed (T_A), therefore controlling the experienced service.

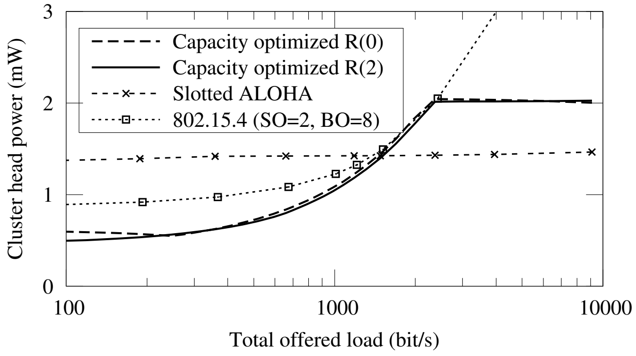

Figure 5. Cluster head power consumption.

References

[1] IEEE Std 802.15.4-2003. *Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs).* IEEE, October 2003.

[2] ZigBee Alliance. *ZigBee Specification, Version 1.0*, December 2004.

[3] W. Ye, J. Heidemann, and D. Estrin. Medium access control with coordinated adaptive sleeping for wireless sensor networks. *IEEE/ACM Transactions on Networking*, 12(3):493–506, June 2004.

[4] T. van Dam and K. Langendoen. An adaptive energy-efficient MAC protocol for wireless sensor networks. In *Proc. 1st ACM Conf. Embedded Networked Sensor Systems*, pages 171–180, November 2003.

[5] I. Rhee, A. Warrier, M. Aia, and J. Min. Medium access control with a dynamic duty cycle for sensor networks. In *Proc. Wireless Communications and Networking Conference (WCNC)*, volume 3, pages 1534–153, March 2004.

[6] V. Rajendran, K. Obraczka, and J. J. Garcia-Luna-Aceves. Energy-efficient, collision-free medium access control for wireless sensor networks. *ACM Wireless Networks*, 12(1):63–78, February 2006.

[7] I. Rhee, A. Warrier, M. Aia, and J. Min. Z-MAC: a hybrid MAC for wireless sensor networks. In *Proc. 3rd ACM Conf. Embedded Networked Sensor Systems*, pages 90–101, November 2005.

[8] G. Lu, B. Krishnamachari, and C. S. Raghavendra. An adaptive energy-efficient and low-latency MAC for data gathering in wireless sensor networks. In *Proc. Parallel and Distributed Processing Symposium*, pages 224–231, April 2004.

[9] 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 *Proc. The Third ACM International Workshop on Performance Evaluation of Wireless Ad Hoc, Sensor, and Ubiquitous Networks*, pages 48–57, October 2006.

[10] CC2420 2.4 GHz IEEE 802.15.4 / ZigBee-ready RF Transceiver. Chipcon AS. [Online]. Available: http://www.chipcon.com/files/CC2420_Data_Sheet_1_3.pdf.

[11] PIC18F8720 Data Sheet. Microchip. [Online] Available: http://ww1.microchip.com/downloads/en/DeviceDoc/39609b.pdf.