Multi-radio Medium Access Control Protocol for Wireless Sensor Networks

Junaid Ansari, Xi Zhang and Petri Mähönen
Department of Wireless Networks
RWTH Aachen University, Kackertstrasse 9, D-52072 Aachen, Germany
Email: {jan, xzh, pma}@mobnets.rwth-aachen.de

Abstract— **In this paper, we propose a new dual radio medium access control (MAC) protocol for wireless sensor networks. Our MAC protocol design combines the advantages of low and high frequency bands in different modes of MAC operations in order to result in energy efficiency. Our prototype also supports spectrum agility, which is becoming important due to ever crowding wireless spectrum. We present the detailed design rationale and individual micro-level experimental performance evaluation of the MAC protocol on our prototype sensor node platform. We also make comprehensive empirical performance comparisons with the widely used B-MAC protocol and show the performance gains that our MAC protocol is able to achieve under various traffic loads and duty cycles.**

I. Introduction

Wireless Sensor Networks (WSNs) are widely used in many application areas such as environmental and habitat monitoring, health-care applications, home automation, traffic control, etc. Sensor nodes are generally battery operated and keeping the network alive over extended periods of time just by changing batteries is either highly cumbersome or impractical. Since radio communication consumes most of the available energy resource, power-aware networking in general and especially the MAC protocols bear a peculiar importance in this context.

Owing to the severe energy constraints, we designed a MAC protocol that combines the advantages of high and low frequency radios to yield an energy efficient operation. The use of low frequency band for carrier sensing and high frequency band for burst data transmission results in an overall power optimal operation [1]. Multi-radio MAC (MR-MAC) protocol is a p-persistent carrier sense multiple access protocol with collision avoidance (CSMA/CA). It is designed for sensor node platforms supporting dual frequency bands. It aims at providing an energy efficient solution for the varying traffic requirements of WSN applications and at the same time intelligently utilizing the ever crowding frequency spectrum.

We have developed a prototype sensor node platform, which is capable of operating in two different frequency bands simultaneously. The basic idea behind this approach is to achieve energy consumption gains as compared to many other contemporary solutions by exploiting the benefits of the two frequency bands. This is achieved by using appropriate radios in different modes of MAC operations as we will describe in this article. Our hardware platform also provides support for spectrum agility, which we believe will be an important feature in the future wireless systems. Because of the low transmission power, sensor nodes suffer the most in competing with other less power-constrained wireless networks operating in the same frequency band. We have developed an algorithm for determining the degree of interference in high frequency band so that our multi-radio MAC protocol is able to decide which data transmission channel should be used.

The rest of the paper is organized as follows: we give a state-of-the-art overview of the existing WSN MAC solutions in Section II. Section III describes the design and implementation details of MR-MAC on our prototype sensor node platform. In Section IV, a detailed experimental performance evaluation of the MR-MAC is presented and empirical performance comparison with B-MAC [2] is carried out. Finally, in Section V, the article is concluded and future work directions are outlined.

II. Related Work

Sensor network MAC protocols exercise a duty cycle scheme for energy conservation and there are two main streams of contention based protocols. One class of MAC protocols is the IEEE 802.11 inspired protocols such as S-MAC [3], T-MAC [4], nanoMAC [5], etc., which try to synchronize the nodes at a common wake-up schedule. These protocols exercise RTS/CTS/DATA/ACK handshake, which is also used for synchronization purposes. Finding a common synchronized schedule by exchanging RTS/CTS frames results in high control packet overhead and is one of the major sources of energy wastage. This can be effectively addressed in another set of MAC protocols such as [2], [6], [7], which are based on preamble sampling or channel polling methods. Apart from contention based MAC protocols, conflict free TDMA based protocols such as BMA [8], LMAC [9] etc. are also quite popular. However, these protocols suffer from scalability problems and under-utilization of the available time slots. There are a few hybrid protocols, e.g. Funneling-MAC [10] and Z-MAC [11], which behave as CSMA or TDMA depending upon the traffic conditions. These protocols are shown to out-perform B-MAC in high traffic load scenarios but have a fairly complex signalling overhead.

Preamble sampling protocols such as B-MAC [2] and WiseMAC [12] transmit a long continuous preamble to ensure that all the potential receivers, sniffing the channel periodically, are able to detect the carrier. In Micro-Frame Preamble MAC [7], the continuous preamble is replaced by a series of micro-frames. Each micro-frame contains the full set of information regarding the upcoming data frame. Only the destined node receives the data frame and the rest of the nodes go into the sleep mode. This scheme also saves energy by avoiding the reception of the rest of the preamble sequence.

All the above mentioned protocols are designed to use single channel in a particular frequency band. Schurgers *et al.* have proposed in STEM (Sparse Topology and Energy Management) [13] an idea of using two radios operating in separate frequency bands to completely separate data transfer from wake-up. In the tone based approach of STEM, a long wake-up tone is sent to make sure that the destined receiver has awoken once. It is similar to certain extent to the preamble sampling approach used in MR-MAC. However, since MR-MAC uses meaningful fields in the preamble in contrast to the meaningless wake-up tone, the non-addressed nodes can avoid receiving irrelevant data and preamble sequence. Furthermore, MR-MAC nodes are able to know the time duration until when the channel is going to be busy.

DCMA/AP (Dual Channel Multiple Access with Adaptive Preamble) [14] is a dual channel MAC protocol designed especially for WSNs and uses two separate channels in the same frequency band, which can be used simultaneously. The main idea is to conserve energy consumption by avoiding RTS/CTS control frames. The data channel is used for preamble and data-packet transmissions while the control channel may indicate reception in progress for avoiding hidden terminals and packet overhearing. In MR-MAC, besides using two channels we also combine the advantages of the two different frequency bands and offset their constraints.

III. Design and Implementation

In this section we describe the architectural details of the MR-MAC protocol, the various functionalities and rationale behind the design. We also describe the implementation details of the protocol and the design of the prototype sensor node platform, which simultaneously supports dual frequency bands.

A. Overview

MR-MAC is a *p*-persistence CSMA/CA micro frame preamble sampling MAC protocol which uses dedicated high and low frequency bands for data and control, respectively. There are several advantages, which can be gained from a dual frequency band supported MAC protocol. Generally, higher frequency bands have more bandwidth, which allow faster and bursty radio transmissions. Oppermann *et al.* [1] showed that the per bit energy consumption for high frequency bands is lower than for low frequency bands. This is so because having more bandwidth in the high frequency bands allows high data rates to be achieved. At the same time, for a given receiver sensitivity, less energy is spent in low frequency bands while idle listening to the medium. Furthermore, a lower transmit power level is required to achieve the same transmit range in the low frequency band as that of a higher frequency band.

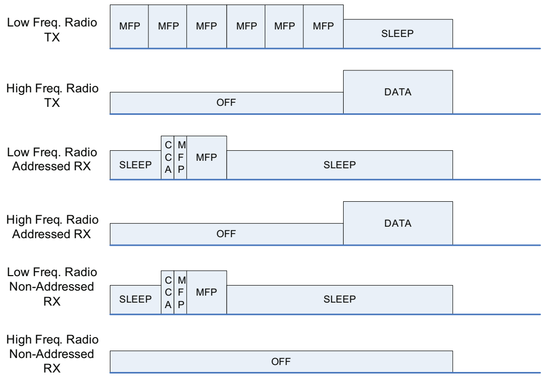

Fig. 1. Operational cycle of the radio channels of a transmitting node, an addressed node and a non-addressed node.

Sensor networks are characterized by long idle times and the actual data transmission is typically very scarce. Preamble sampling protocols periodically poll the channel for a certain short duration to be able to detect the presence of the carrier. In the duty cycle operation, the transmitting nodes need to send a long enough preamble, equals to the check interval, so that it can be heard by the receiving nodes which perform periodic listening. This preamble sequence transmission/reception for a particular check interval generally consumes higher energy for radios operating in higher frequency band. Based on the above mentioned premise, MR-MAC uses an extremely low power sniffer radio, operating in low frequency band for control/preamble transmission while it uses a high frequency radio for bursty data transmission. MR-MAC performs the preamble sampling operation only in low frequency band, while the high frequency transceiver is turned on only during the data transmission/reception. This overall leads to highly energy optimized utilization of radio resources.

Fig. 1 shows the operational cycle of the two radios in MR-MAC while transmitting and receiving data. MR-MAC's preamble consists of a series of back to back micro frames with a custom defined frame structure, containing the necessary control information. It is composed of the radio byte sequence for PLL locking. Followed by this, are the synchronization bytes for the receiver to calculate and to make the bit offset adjustments so as to receive the rest of the micro frame bytes correctly. By including the destination address into a micro frame, only the target node receives the upcoming data bytes. All the non-addressed receiving nodes go to sleep and avoid overhearing the rest of the preamble and the data following it.

Since the effective energy consumption gains for high frequency radio are achieved when the data size is large, we implement data frame preambles [15] for smaller data sizes. When the size of the data to be transmitted is smaller than a pre-selected threshold, data bytes are included in each micro preamble frame to form a data frame preamble and transmitted over the control channel. In this case, the data transmission in the high frequency band is not carried out at all and the effective extra energy overhead caused by high frequency radio for transmitting/receiving very short data packets is avoided. The maximum number of bytes allowed for data frame preamble is found out experimentally for the best power consumption performance.

In the micro frame structure, a single bit is included to indicate whether the frame is a normal micro preamble frame or a data preamble frame. In the case of a data preamble frame, data packet which concludes the data frame, is transmitted immediately after the indicator bit. Otherwise, the micro frame includes the fields described in the following.

The total number of frames to be transmitted and the sequence number of the current frame are the two fields, which are used by the receiving nodes to calculate the duration of the rest of the preamble transmission. The addressed nodes sleep during this duration in order to avoid the preamble overhearing. Similarly, the non-addressed nodes can calculate the time when the medium is going to be busy and go to sleep. MR-MAC protocol supports spectrum agility. Since higher frequency band has generally more available bandwidth, there are usually more than one communication channel available. At the same time, because of having more bandwidth in the high frequency band, more devices/networks are likely to operate and therefore spectrum agility is desired for the high frequency band. We design a scheme to scan the high frequency spectrum on need-basis and choose the available channel for data communication. The information of high frequency channel selection is exchanged through low frequency radio using micro frame preamble. Channel number is included in the micro frame for this purpose. There is also a 12-bit field which indicates the size of the data packet that follows the preamble sequence. This field enables any non-addressed receiver to extend its sleeping time to the end of the data transmission.

Our MAC protocol exposes a number of tunable parameters, which contribute to the flexibility and on-the-fly (re)-configuration of the protocol. This feature is desirable for many cross-layer optimization schemes. These parameters include local duty cycle, preamble length, optional gap duration between micro preamble frames, CCA thresholds, CCA duration, enable/disable CCA, maximum size of a data packet, initial backoff window size, radio transmission power, radio channels and persistency values. Some of the parameters are interrelated and a re-configuration of these leads to the re-adjustments of the dependent ones.

B. Hardware Platform

Our prototype sensor node platform (as shown in Fig. 2) consists of Moteiv Inc.'s TelosB sensor node with an on-board Texas Instrument's MSP430 series microcontroller and CC2420 radio transceiver. We interfaced an external CC1000 radio module to the microcontroller. Both the configuration and signalling interface of the radio chip are interfaced through the extension connectors on TelosB.

The IEEE 802.15.4 compliant radio chip, CC2420, operates in 2.4 GHz band. This packetized radio acts as the burst radio while CC1000 radio, operating in 433 MHz band, acts as the low frequency sniffer radio. CC1000 provides byte level interface and has lower power consumption in idle mode and is therefore suitable for transmission of customized micro frame preambles.

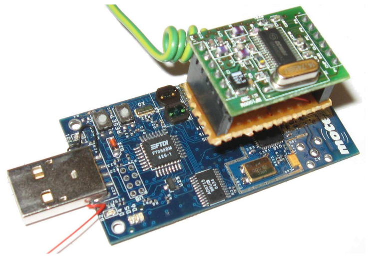

Fig. 2. Snapshot of the prototype sensor node platform.

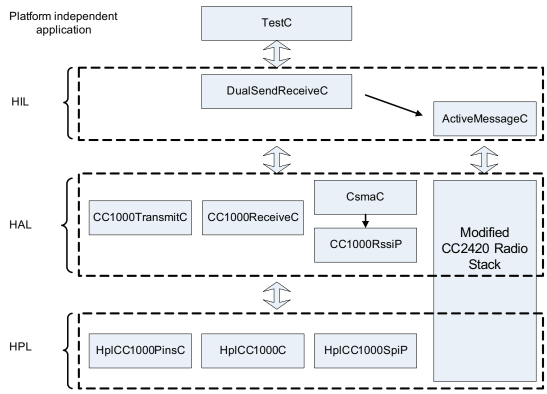

Fig. 3. Hardware abstraction architecture followed in our MAC protocol implementation.

C. Implementation Details

MR-MAC protocol is implemented using nesC programming language and TinyOS 2.x operating system. Fig. 3 shows our hardware abstraction architecture. Our protocol is implemented following the strict design philosophy as presented in [16]. This allows easy portability of the MAC protocol to other platforms. Hardware Presentation Layer (HPL) provides the extended driver level interface. Hardware Adaptation Layer (HAL) provides the resource control and contains the core platform functionality. Finally, the Hardware Interface Layer (HIL) gives the MAC protocol abstraction to the application. We keep the advantages of the layering approach and at the same time expose various set of configuration parameters from different levels to the application.

IV. Performance Evaluation

The power consumption of MR-MAC running on our prototype sensor node platform (c.f. Fig. 2) are measured and presented in comparison to the widely used B-MAC protocol, running on MICA2 and TelosB platforms at different duty cycles and under various traffic loads. In order to have a fair comparative analysis of the MAC protocols, the transmission power of the radio chips were set to be the same for all the nodes.

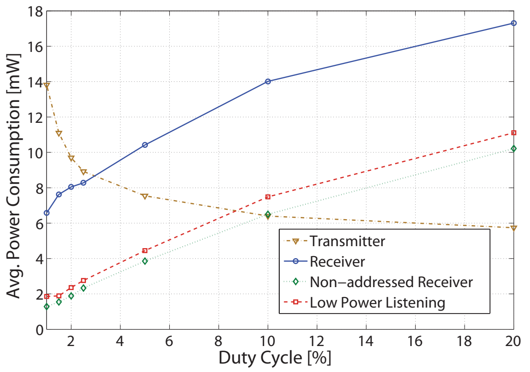

Fig. 4. Power consumption performance of Multi-radio MAC running on the prototype platform at different duty cycles. The transmission rate was chosen to be 1Hz and the data packet size was taken to be 1000 bytes.

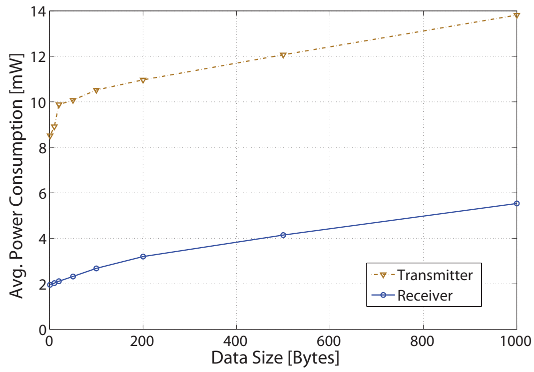

Fig. 5. Power consumption performance of Multi-radio MAC running on the prototype platform at different data sizes. The frequency of transmission is 1 Hz and the duty cycle is 1 %.

A. *Multi-radio MAC Performance*

MR-MAC uses the maximum supported baud rate of the CC1000 radio chip (76.8 kbps) by default. All the measurements in this section are carried out at this baud rate. Later on, for fair comparison with B-MAC, we lower down the baud rate of CC1000 chip on our prototype sensor node to 19.2 kbps to be consistent with that of B-MAC running on MICA2.

Table I lists the energy and power consumption break-down for the basic operations of both the CC1000 and the CC2420 radio chips on our platform working at 3 V. In active mode, the power consumption of CC2420 chip is approximately twice that of CC1000 radio. This strongly supports our idea of using the CC1000 radio chip in low frequency band for control packets and high frequency band for data.

Fig. 4 shows a typical preamble sampling MAC behaviour. The average power consumption for transmitter decreases with increasing duty cycle due to shortening of preamble length while the power consumption for receiver increases because of the need for more frequent channel polling. The above argument is supported by the fact that the increasing slopes of the addressed receiver, non-addressed receiver and low power listening node (without any transmitter in the vicinity) are approximately the same. The difference between the power consumption of the addressed receiver and the non-addressed receiver indicates the additional energy consumed in the data reception for the addressed receiver. Interestingly, the power consumption of the non-addressed receiver is lower than that of the node performing just the low power listening because the non-addressed receiver can calculate the time for the on-going transmission and thereby prolongs its sleeping time till the end of data transmission. This allows the non-addressed node to further save energy by avoiding undesired overhearing. This result confirms the extended energy saving mechanism provided in our design.

TABLE I
ENERGY AND POWER CONSUMPTION BREAK-DOWN FOR OUR PROTOTYPE SENSOR NODE PLATFORM.

Operation break-down	*Energy Cost [μJ]*
CCA	200
Turning on CC1000 to Tx mode	109
Turning on CC1000 to Rx mode	65.2
Turning off CC1000	6.22
Turning on CC2420 to Tx mode	15.6
Turning on CC2420 to Rx mode	15.7
Turning off CC2420	0.313
Operation break-down	*Power Cost [mW]*
CC1000 in Transmission Mode	31
CC1000 in Reception Mode	25
CC2420 in Transmission Mode	52.4
CC2420 in Reception Mode	55.4

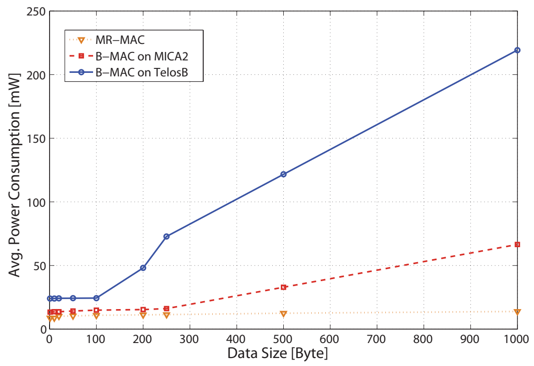

Fig. 6. Power consumption performance of transmitters running MR-MAC, B-MAC on MICA2 and TelosB at different data sizes. The transmission rate is chosen to be 1 Hz and the duty cycle to be 1 %.

MR-MAC also supports burst data transmission by transmitting multiple back-to-back data frames. In Fig. 5 there is a sudden increase in the transmit energy consumption when the data size is 20 bytes. This is due to the fact that the transmission mode has been switched from data frame preamble to micro frame preamble at data size greater to equal to 20 bytes. This figure has been found by empirical studies in order to ensure the lowest receiver power consumption possible. The receiver-oriented design is considered instead

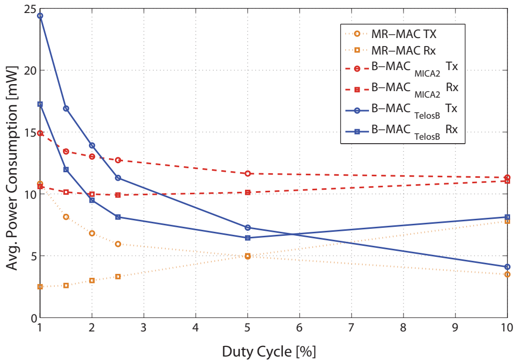

Fig. 7. Power consumption performance of transmitters and receivers running MR-MAC, B-MAC on MICA2 and TelosB at different duty cycles. The transmission rate is chosen to be 1 Hz and data size to be 100 bytes.

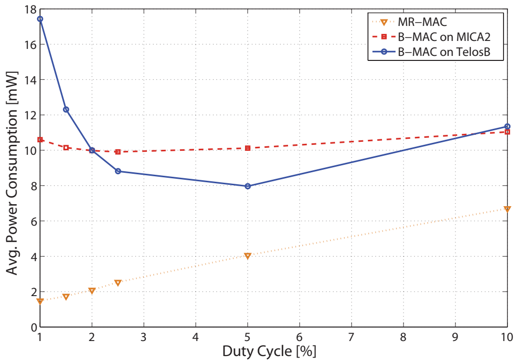

Fig. 8. Power consumption performance of non-addressed receivers running MR-MAC, B-MAC on MICA2 and TelosB at different duty cycles. The data size is 100 bytes.

of transmitter-oriented because in general WSN applications nodes are densely deployed and have a higher possibility of operating in reception mode rather than in transmission mode.

B. Performance Comparison

In order to quantify the advantages of the dual radio MAC protocol more effectively, we carried out the performance comparison of MR-MAC with B-MAC protocol using both the radios as used by MR-MAC. Furthermore, comparison results against the widely used B-MAC protocol as the reference will help the sensor network community to understand the energy conservation gains of the MR-MAC design in a better way. The experimental performance comparison is carried out from two aspects: by analyzing the power consumption at different data sizes while keeping the duty cycle constant, and vice versa.

Fig. 6 shows the power consumption comparison at various data sizes while keeping the duty cycle fixed at 1%. Since the maximum supported data size for B-MAC on both MICA2 and TelosB is smaller than that of MR-MAC, it has to transmit multiple packets for the same amount of data, thus increasing the overhead significantly. It may be observed from Fig. 6 that the benefit of using MR-MAC is more evident when the data size becomes larger. Although the maximum data size for MR-MAC used in this experiment is 1000 bytes, MR-MAC can support up to 4095 bytes and we expect to observe further gains at higher data sizes. At the same time, MR-MAC still out-performs B-MAC when the data size is smaller mainly due to the energy saved by using micro frame preamble instead of a continuous long preamble. If the data size becomes very small, MR-MAC uses data frame preamble. In comparison to B-MAC running on TelosB, the use of DFPs in MR-MAC is beneficial because turning on the high frequency radio can be avoided and the data can be piggy-backed into the necessary preamble. The power consumption performance graph of the receiver has the same energy saving characteristics as that of the transmitter owing to the same reasons.

Fig. 7 shows better power consumption performance of MR-MAC as compared to B-MAC. There is a higher degree of savings as the duty cycle decreases, which shows the significance of energy spent in preamble transmission. Fig. 7 shows the power consumption efficiency at low duty cycles of MR-MAC as compared to B-MAC. Fig. 8 shows the power savings of non-addressed receiver running MR-MAC in comparison to B-MAC. This is the most significant feature among all the operational cases because it is a very likely case in a typical WSN.

The operational cycle of MR-MAC resembles that of the MFP-MAC to a certain degree. However, in contrast to MFP-MAC, MR-MAC uses two radios in such a way that the slower radio with much less energy consumption is used for preamble transmission and faster bursty radio is used for data transmission. Although the current consumption of the bursty radio is high, the transmission/reception duration is so small that the effective energy consumption in MR-MAC is much lower than the case of MFP-MAC. The preamble transmission is carried out for a fixed duration depending upon the operating duty cycle. MR-MAC uses a slower radio with less current consumption for preamble and can save energy in both preamble and data transmission/reception. Table I containing the current consumption measurements confirms the energy gains of the MR-MAC against MFP-MAC. Apart from the benefits of using the radio resources efficiently, MR-MAC design has additional features like support of DFPs and multiple back-to-back data packet transmissions, which has additional gains.

V. Conclusions and Future Work

In this paper, we have presented and analyzed a multi-radio MAC protocol, which combines the advantages of both the high and the low-frequency bands by using the appropriate radios. We have also comprehensively described the protocol design and the underlying rationale of various aspects of the protocol. An in-depth experimental performance evaluation of the MR-MAC protocol running on our prototype sensor node platform is presented. It is shown empirically that MR-MAC protocol performs remarkably well in both reception and transmission at various traffic loads and duty cycles in comparison to the widely used B-MAC protocol running on both TelosB and MICA2. We particularly emphasize the advantage of MR-MAC in case of non-addressed receiving nodes because it is a very common case in sensor networks, especially in dense deployments. Our MAC protocol also supports spectrum agility for the ever crowding high frequency spectrum and a high degree of flexibility through the list of its exposed reconfigurable parameters as we demonstrated in [17].

In the future, we plan to present our performance evaluation related to throughput and latency over single and multiple hops. The protocol has a potential to support high throughput and low latency owing to its burst radio design approach. We will also extend the analysis to co-existence with other MAC solutions owing to the increasing popularity of various sensor network applications. We expect to utilize the tunable parameters of the MR-MAC in order to have a symbiotic co-existence with other networks in heterogenous environments.

ACKNOWLEDGMENT

We would like to thank financial support from E.U. (project IST-034963-WASP), Deutsche Forschungsgemeinschaft through the UMIC-excellence cluster and RWTH Aachen University.

REFERENCES

[1] I. Oppermann et al., "UWB wireless sensor networks: UWEN-a practical example," *IEEE Comm. Mag.*, vol. 42, pp. 527–532, December 2004.

[2] J. Polastre, J. Hill, and D. Culler, "Versatile low power media access for wireless sensor networks," in *SenSys*, Nov. 2004.

[3] W. Y. et al., "An energy-efficient mac protocol for wireless sensor networks," in *Proceedings of the IEEE Infocom*. IEEE, 2002, pp. 1567–1576.

[4] T. van Dam and K. Langendoen, "An adaptive energy-efficient MAC protocol for wireless sensor networks," in *SenSys*, 2003, pp. 171–180.

[5] J. Ansari and J. Riihijärvi and P. Mähönen and J. Haapola, "Implementation and Performance Evaluation of nanoMAC: A Low-Power MAC Solution for High Density Wireless Sensor Networks," *Int. J. of Sensor Networks*, vol. 2, no. 5, pp. 341–9, 2007.

[6] A. El-Hoiydi and J.-D. Decotignie, "Wisemac: an ultra low power MAC protocol for the downlink of infrastructure wireless sensor networks," in *ISCC '04: Proceedings of the Ninth International Symposium on Computers and Communications 2004 Volume 2 (ISCC"04)*, 2004, pp. 244–251.

[7] A. Bachir et al., "Micro-frame preamble MAC for multihop wireless sensor networks," in *In Proc. Of ICC'06*, Istanbul,Turkey.

[8] J. Li and G. Y. Lazarou, "A bit-map-assisted energy-efficient MAC scheme for wireless sensor networks," in *IPSN '04*, 2004, pp. 55–60.

[9] L. v. Hoesel and P. Havinga, "A lightweight medium access protocol (LMAC) for wireless sensor networks," in *INSS*, 2004.

[10] Gahng-Seop Ahn et al., "Funneling-MAC: a localized, sink-oriented MAC for boosting fidelity in sensor networks," in *SenSys*, 2006.

[11] I. Rhee et al., "Z-MAC: a hybrid MAC for wireless sensor networks," in *SenSys*, 2005.

[12] A. El-Hoiydi et al., "Poster abstract: WiseMAC, an ultra low power MAC protocol for the WiseNET wireless sensor network," in *SenSys*, 2003.

[13] C. Schurgers et al., "Optimizing sensor networks in the energy-latency-density design space," *IEEE Transactions on Mobile Computing*, pp. 70–80, Jan.-Mar. 2002.

[14] A. G. Ruzzelli et al., "Advantages of dual channel MAC for wireless sensor networks," in *COMSWARE*, 2006.

[15] S. Mahlknecht and M. Boeck, "CSMA-MPS: A minimum preamble sampling MAC protocol for low power wireless sensor networks," in *IEEE Int. Workshop on Factory Communication Systems*, 2004.

[16] TinyOS 2.0 TEP 2, "http://www.tinyos.net," Last visited: 15.01.2008.

[17] J. Ansari, X. Zhang and P. Mähönen, "Demo abstract: Multi-radio medium access control protocol for wireless sensor networks," in *SenSys*, 2007.