Cross-layer Energy Analysis of Multi-hop Wireless Sensor Networks

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***Abstract*— In this paper, we propose a detailed energy survey of the physical, data link, and network layer by analytical techniques. We also show the impact of regular sleep periods on node energy consumption and present a comparison analysis of single-hop vs. multi-hop communications in the energy realm. A detailed energy expenditure analysis of not only the physical layer but also the link and network layer provides a basis for developing new energy efficient wireless sensor networks. Regular, coordinated sleeping extends the lifetime of sensor nodes, but systems can only benefit from sleeping in terms of transmitted packets if the data arrival rate to the system is low. Energy efficiency is the driving motivation for it can be considered the most important factor for wireless sensor networks because of the power constraints set by battery operation. Radio solutions in the lower ISM bands are attractive because of their relatively easy implementation and low power consumption. However, the data rates of these commercial radios are also relatively low, limiting transmittable frame sizes to a few tens of octets along with strict duty cycle requirements. From the analysis we extract key parameters of selected MAC protocols and show that some traditional mechanisms, such as binary exponential backoff, have some inherent problems. We also argue that single-hop communications has up to 40% lower energy consumption than multi-hop forwarding within the feasible transmission distances of an ISM radio.**

***Index Terms*—Energy efficiency, Wireless sensor networks, Medium access control (MAC) protocols, Multihop communications**

I. INTRODUCTION

Sensor network applications have recently become of significant interest due to cheap single-chip transceivers and microcontrollers. Sensor nodes are usually battery operated and their operational lifetime should be maximized, hence energy consumption is a crucial issue. Many single-chip transceivers and therefore sensor networks are expected to operate using radios like the RFM TR1000 [1], or its European versions all of which work in ISM bands. Regulations in many countries impose a duty cycle [2], [3], which is normally 10% for the 434MHz band and 1% for the 868MHz band. The duty cycle is defined as the ratio, expressed as a percentage, of the maximum transmitter on-time, relative to a one hour period. When a sensor network is expected to work continuously, this duty cycle has to be taken into account and it can affect the energy efficiency of a network.

In this paper we perform cross-layer analysis by presenting topology, medium access control (MAC) and radio transceiver energy consumption models that work in unison. The linear topology model represents a common network after network layer route discovery has been accomplished. We use an energy consumption model for the transmission and reception of MAC frames originally presented in [4], develop a coordinated sleep group energy consumption model, and analytically investigate the effect of sleep on sensor networks using three MAC protocols. From the analysis we show that although in an ideal scenario multi-hop communications perform better than single-hop communications, realistic energy models and especially the MAC protocol design have a significant impact. We propose a multi-group sleep model for our nanoMAC protocol, and show that regular sleep periods have a significant, energy reducing impact on node energy consumption with low traffic rates. The radio transceiver energy model takes into account several important radio parameters and we use the RFM TR1000 and RFM radio designers guide [5] for realistic transceiver parameters. The main metric used is absolute energy consumption per useful transmitted bit. This means only the MAC or the network protocol data unit (PDU) will be considered and all the other communicated bits, headers, control frames, preambles, etc. are considered as overhead.

The rest of the paper is organized as follows. Some related work is discussed in Section II and in Section III we look at the radio propagation energy model. Section IV presents the network topology and energy analysis without medium access control. In Section V, we briefly look at nonpersistent CSMA and S-MAC, and then give an introduction to a low-power sensor MAC protocol called nanoMAC. Section VI presents energy consumption models for the transmission and reception of data and Section VII deals with regular sleep periods for nanoMAC and presents the worst-case energy consumption results and the energy savings achieved by regular sleeping. Section VIII addresses the single-hop vs. multihop problem and conclusions are drawn in Section IX.

II. RELATED WORK

The radio model and physical layer characteristics in this paper are based on the original work from [6]–[8]. In [6] optimal transmittable packet sizes are discussed in respect to energy efficiency over single hops. An energy consumption model is presented and optimal packet payload sizes for various channel bit error rates (BER) and coding schemes are determined. In [7] and [8] a linear radio model is presented as seen in Fig. 1 for multihop analysis. The latter also presents an optimal hop distance characteristic for multihop communications which is a function of radio parameters and heavily dependent on the individual radio used.

During the past few years there has been some literature on energy efficient MAC protocols specifically for use with sensor networks [9]–[11]. However, such protocols are usually modifications from traditional ad hoc networking and have some inherent flaws for sensor networks. The PAMAS [9] protocol was one of the first attempts to reduce unnecessary power consumption by turning overhearing nodes to sleep. The protocol however needs a separate control channel for coordination and avoiding overhearing. It also does not take into account idle listening in any way, which accounts for a large portion of energy consumption. The sensor MAC (S-MAC) [10] is a protocol designed for sensor networks and its prime functionality is to reduce idle listening. S-MAC's foundations lie on IEEE802.11 [12] and MACAW [13], which is the basis of IEEE802.11. They both implement carrier sense multiple access with collision avoidance (CSMA/CA), a four-way RTS-CTS-Data-ACK handshake using binary exponential backoff and other similar functionality. S-MAC also implements a regular sleep period and a special synchronization scheme to reduce idle listening and maintaining global connectivity. The method is called virtual clustering, where irregular SYNC messages urge, but do not enforce a common schedule. Even though S-MAC outperforms IEEE802.11-like protocols in the energy perspective it is still a traditional ad hoc protocol in many ways. The timeout MAC (T-MAC) [11] is an evolution of S-MAC into even lower energy consumption by not only reducing idle listening, but also making the active periods of the protocol dynamic. The data communications in T-MAC is highly bursty, minimizing the active time and forcing the bursty periods to operate in a very high contention environment. It shares many of the features of S-MAC but achieves superior performance over S-MAC in certain cases.

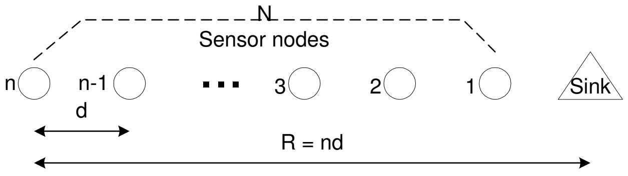

Fig. 1. Simple linear sensor network.

There has been a lot of research on efficient wireless sensor network topologies that include LEACH [14], SPIN [15], data funnelling [16] and directed diffusion [17]. Each of them suggest a method of energy efficient network formation. LEACH builds dynamic clusters to ensure that most nodes need to transmit only small distances and SPIN sensor nodes advertise data they have so that only interested nodes can ask for the data. Data funnelling creates sensing areas with border nodes so that data from an area is gathered to border nodes that find and use a multi-hop path to the sink node and in directed diffusion the sink node broadcasts what data it is interested in and build gradients to the nodes who have the data of interest. All of the mentioned protocols are data-centric, which is a good assumption for sensor networks and implies that the data itself is the key element in the network, not the sensor nodes that sent it. Of the mentioned protocols, SPIN, data funnelling, and directed diffusion can be modelled with the linear network shown in Fig. 1 in steady state. Directed diffusion employs redundant paths for routing data infrequently causing some compatibility problems with the linear topology. In this work, we take into account the MAC protocol contention of not only the linear network but the whole network surrounding the path of the linear network. Fig. 2 illustrates this and therefore, the redundant paths can be modelled as an external traffic load affecting the contention process and consuming energy.

The closest related work to our paper was presented in

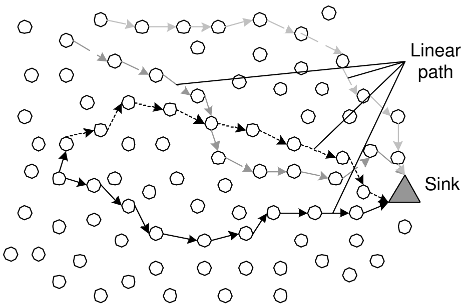

Fig. 2. Simple linear sensor network.

[18]. The paper is a MAC–routing protocol cross layer study for ad hoc communication networks. Although the work is on ad hoc protocols and does not take energy usage into account it shows the importance of considering different layer protocols when designing a new protocol. This is demonstrated with Ad Hoc On Demand Distance Vector (AODV) routing and IEEE802.11. AODV is designed to work specifically on top of the IEEE802.11 MAC protocol and achieves its best performance with that MAC and also has the best overall throughput of the MAC–routing protocol combinations presented in [18].

III. RADIO POWER CONSUMPTION

Power consumption models of the radio in embedded devices must take both transceiver and start-up power consumption into account along with an accurate model of the amplifier. The latter actually becomes dominant with small packet sizes and long transition times to receive mode because of frequency synthesizer settle-down time. In [6] a model for radio power consumption is given for energy per bit (e_b) as

$$e_b = e_{tx} + e_{rx} + \frac{E_{dec}}{\iota}, \tag{1}$$

where e_{tx} and e_{rx} are the transmitter and receiver power consumptions per bit, respectively, E_{dec} is the energy required for decoding a packet, and ι is the payload length in bits. The encoding of data is assumed to be negligible. This model takes the energy needed to transmit a frame from a transmitter to a receiver over a single hop into account. In [6] the model was used over a single hop to optimize frame sizes and coding techniques. In this paper we extend the model for multihop scenarios and with different traffic models. It is then extended later in the paper to analyze multihop MAC efficiency.

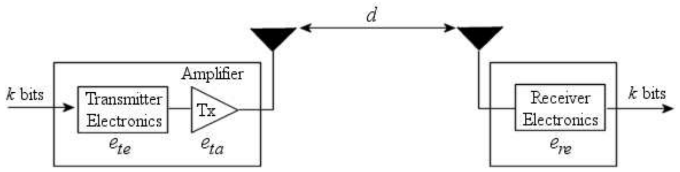

Fig. 3. Radio energy consumption model.

The term e_{tx} from (1) with optimal power control can be represented as

$$e_{tx} = e_{te} + e_{ta}d^{\alpha}, \tag{2}$$

where e_{te} is the power consumption of the transmitter electronics, e_{ta} is the consumption of the transmit amplifier, d is the transmission distance, and α the path loss exponent. Often in the literature generic approximations are used for these terms. However, an explicit expression for e_{ta} has been presented in [8] as

$$e_{ta} = \frac{(\frac{S}{N})_r(NF_{Rx})(N_0)(BW)(\frac{4\pi}{\lambda})^{\alpha}}{(G_{ant})(\eta_{amp})(R_{bit})} \tag{3}$$

where $(\frac{S}{N})_r$ is the desired signal to noise ratio at the receiver's demodulator, NF_{Rx} is the receiver noise figure, N_0 is the thermal noise floor in a 1 Hz bandwidth, BW is the channel noise bandwidth, λ is the wavelength in meters, α is the path loss exponent, G_{ant} is the antenna gain, η_{amp} is the transmitter efficiency, and R_{bit} is the raw channel rate in bits per second. This expression for e_{ta} can be used for those cases where a particular hardware configuration is being considered as in this paper. In the same paper the authors have shown that an optimal multihop distance, the *characteristic distance* d_{char} can be defined as

$$d_{char} = \sqrt[\alpha]{\frac{e_{te} + e_{re}}{e_{ta}(\alpha - 1)}}. \tag{4}$$

For the parameters shown in Table II the characteristic distance is 31.5 meters with a BER of 10^{-4} assuming non-coherent FSK modulation.

IV. MULTIHOP POWER CONSUMPTION

In this section an analytical model for multihop communications is introduced that takes detailed overheads into account. A linear model is used with variable spacing between nodes assuming a sink node that collects data and is not energy dependent. No medium access control is assumed. Energy per bit, energy efficiency and total energy are derived for various traffic cases and node distributions.

A similar analysis can be made as in [19] by extending (1) to take the linear multihop scenario shown in Figure 1 into account, assuming optimal power control. Instead of total power derived in [19] we can derive multihop energy per useful bit from (1) as

$$e_b = (n(e_{te} + e_{ta}(d)^{\alpha}) + (n-1)e_{re})(1 + \frac{(\beta+\tau)}{\iota}) + \frac{nE_{st} + (n-1)(E_{sr} + E_{dec})}{\iota}, \quad (5)$$

where e_{te} is the energy per bit needed by the transmitter electronics, e_{re} for the receiver electronics, E_{st} and E_{sr} are startup energies, e_{ta} is the power needed to successfully transmit one bit over one meter, α is the path loss exponent, β is the preamble length, τ is the coding overhead and n is the number of hops.

For this same topology we can also calculate the total energy consumed in the network. Using the same notation as in (5) total multihop energy consumption is

$$E_{MH} = n(k(e_{te} + e_{ta}(d)^{\alpha}) + E_{st}) + (n-1)(ke_r + E_{sr} + E_{dec}), \quad (6)$$

where k is the number of bits transmitted. The analysis used to this point has taken an unrealistic traffic assumption into account, that is, only node n (furthest from the sink) transmits data. This was necessary for calculating energy per bit and energy efficiency, which are frame-centric metrics. However, in most useful scenarios all nodes will transmit data. We can take that into account by assuming that all nodes have a single frame to transmit towards the sink. Total energy for this scenario is

$$E^{all}_{MH} = \frac{n(n+1)}{2}(k(e_{te} + e_{ta}(d)^{\alpha})) + E_{st}) + \frac{n(n-1)}{2}(ke_r + E_{sr} + E_{dec}). \quad (7)$$

We can compare this multihop case to the single-hop case where each node transmits its frame directly to the sink node, that is, no forwarding is performed. This is calculated as

$$E^{all}_{SH} = \sum_{i=1}^{n}(k(e_{te} + e_{ta}(id)^{\alpha}) + E_{st}). \quad (8)$$

In addition, we can calculate energy consumption from a node-centric point of view, that is, how much power does a particular node n consume. This is useful when balancing the power consumed in packet forwarding. For the multihop case this is calculated as

$$E^{all}_{MH}(i) = (n-i+1)(k(e_{te} + e_{ta}(d)^{\alpha}) + E_{st}) + (n-i)(ke_r + E_{sr} + E_{dec}), \quad (9)$$

and for the single-hop case as

$$E^{all}_{SH}(i) = k(e_{te} + e_{ta}(id)^{\alpha}) + E_{st}. \quad (10)$$

V. MAC PROTOCOLS

In this section the MAC protocols to be used for energy analysis in this paper, namely nonpersistent CSMA, S-MAC and nanoMAC, will be described. Nonpersitent CSMA is a well known, relatively well performing MAC protocol in almost any scenario. It gives worst-case energy performance that any sensor MAC protocol should outperform. S-MAC is the current sensor MAC benchmark protocol which is used to highlight some of the faults of traditionally designed sensor MAC protocols. We compare these to nanoMAC, a protocol designed to operate in a sensor networking environment.

A. Nonpersistent CSMA

Carrier sense multiple access (CSMA) was originally presented in [20] and has been widely referenced afterwards. The reason for using the energy consumption model with nonpersistent CSMA (np-CSMA) in this paper is that np-CSMA is a protocol which performs quite well under most circumstances, even though theoretically it is an unstable protocol. It also functions as a worst-case model for sensor MAC protocols. When a node using np-CSMA has data to send it first uses carrier sensing (CS) to sense the channel. If the channel is found vacant for the whole duration of the CS the node sends the data, otherwise it does not persist on sensing the channel, but chooses a random time in the future to do CS again. Once the data has been sent, np-CSMA waits for an acknowledgement (ACK) frame from the intended recipient and if the ACK is received before a timeout, the data is known to be successfully received. Otherwise, the data has to be retransmitted at a later time. As a deviation from the original paper, the ACK frame is transmitted on the same channel as data.

B. S-MAC

The S-MAC [10] operation and frame is divided into two periods; the active period and the sleep period. During the sleep period all nodes that share the same schedule sleep and save energy. The sleep period is usually several times longer than the active period and in our analysis we use 1 second sleep times. The active period also consists of two subperiods; the listen for SYNC packet period and the listen for RTS period.

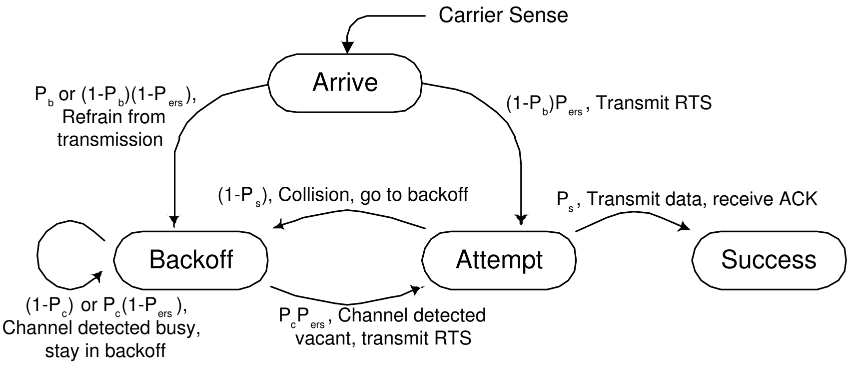

Fig. 4. NanoMAC TX energy model.

Nodes listen for a SYNC packet in every frame and the SYNC packet is transmitted by a device infrequently to achieve and maintain virtual clustering. In the listen for RTS part the nodes can communicate using a CSMA/CA channel access method with binary exponential backoff. S-MAC also implements a technique called message passing which means that if the networks layer has a larger than MPDU packet to transmit, S-MAC can split up the packet into smaller MPDU sized pieces and transmit them as a burst of consecutive Data–ACK frames. Overhearing nodes sleep during the data transfer. The active period is 300 ms in our analysis and listen for RTS is 115 ms.

C. NanoMAC

Because CSMA/CA is a powerful tool for medium access control, the nanoMAC protocol also implements this feature which has been discussed in detail in [21], [22]. Briefly described, nanoMAC is a p-nonpersistent, i.e., with probability p, the protocol will act as nonpersistent and with probability $1-p$ the protocol will refrain from sending even before CS and schedule a new time for CS. Nodes contending for the channel do not constantly listen for the channel, but sleep until the contention window value is low. Then the node wakes up to sense if the channel is busy for a short but high confidence period before transmitting if the channel is detected vacant. This feature makes the carrier sensing time short, even though the backoff mechanism is binary exponential and saves energy. In the request-to-send/clear-to-send (RTS/CTS) frames nanoMAC does virtual carrier sensing in addition to informing overhearing nodes of the time they are required to refrain from transmission. Virtual carrier sensing enables overhearing nodes to sleep during that period. Unlike S-MAC, IEEE MAC addresses are supported as well as sleep information for virtual clustering and the number of data frames to be transmitted are also included in the RTS and CTS frames.

The data frames carry only temporary, short, random addresses to minimize the data frame overhead. With one RTS/CTS reservation a maximum of 10 data frames can be transmitted using a frame train ideology The idea is similar to message passing in S-MAC, but it is a default characteristic in nanoMAC and the data frames are acknowledged by a single, common ACK frame that has a separate acknowledgement bit reserved for each data frame. The ACK frame is therefore an acknowledgement/negative acknowledgement (ACK/NACK) combination. In this way only the corrupted frames need to be retransmitted and not the whole packet. When forward error correction (FEC) methods are not used, the frame train method promises to be efficient. If FEC should be used, frames can be made longer. When best utilised, nanoMAC has low overhead even with low data-rate, small frame size applications. For example, a data-rate of 19.2 kbps with 4B/6B encoding provides a 12.8 kbps data-rate for the MAC layer. According to [6] a frame of 41 octets with a BER of 5×10^{-4} is close to optimal energy efficiency. With 41 octet data frames and 18 octet RTS/CTS/ACK frames the MPDU-to-packet ratio is $\sim$75% while for np-CSMA the same efficiency with a 41 octet data frame and 15 octet ACK is $\sim$44%. For S-MAC, the data frame is 43 octets and control frames are 10 octets and produce an MPDU-to-packet ratio of $\sim$64% with 350 octet MPDU and message passing.

VI. ENERGY CONSUMPTION MODEL

In this section we briefly describe the theoretical energy consumption of MAC protocols and the underlying physical layer. The energy consumption model was presented by the authors in [4] and consist of energy consumed in the transmission and reception of data, but we have extended our analysis in all directions. The model used was originally presented in [23] for a delay analysis of the FAMA-NTR protocol, but we have modified it to be used for energy consumption calculations by investigating the probabilities of transitions from one state to another state and the related times consumed in transmit, receive, idle and sleep. Usually, in ISM transceivers, receive and idle modes can be considered as a single mode or the difference is marginal.

The energy consumption model for transmission can be found from Fig. 4. There are four different states: *Arrive*, *Backoff*, *Attempt* and *Success*. The *Arrive* state is the entry point to the system for a node getting new data to transmit. To calculate the average energy consumption, we solve a system of equations implied by Fig. 4. Let E_{TX} equal the expected energy consumption by a node with new data at the *Arrive* state until the node reaches the *Success* state. Let $E(A)$ equal the average energy consumption on each visit by the node to the *Attempt* state, and let $E(B)$ equal the energy consumption on each visit to the *Backoff* state. The average energy consumption upon transmission from the point of packet arrival from the upper layer to the point of receiving an ACK frame is

$$\begin{aligned} E_{TX} =& T_{CS}M_{RX} + P_b\left(T_{bb} + \frac{T_r}{2}\right)M_{Slp} + P_bE(B) \quad (11)\\ &+(1-P_b)(1-P_{ers})\left(T_{bp} + \frac{T_r}{2}\right)M_{Slp}\\ &+(1-P_b)P_{ers}E(A) + (1-P_b)P_{ers}(T_{pr} + RTS)M_{TX}\\ &+(1-P_b)(1-P_{ers})E(B). \end{aligned}$$

- M_{TX}, M_{RX}, and M_{Slp} are transceiver modes TX, RX, and sleep, respectively,
- T_{CS} is the time required for carrier sensing,
- T_{bb} and T_{bp} are incremented and un-incremented backoff times, respectively,
- P_b is the probability of finding channel busy during CS,
- $T_r/2$ is the average random delay,
- P_{ers} is the non-persistence value of nanoMAC, and
- T_{pr} and RTS are times to transmit a preamble and an RTS frame, respectively.

From $E(B)$ and $E(A)$ we make the same analysis as from the *Arrive* state and solve a system of equations. The term $E(A)$ gives a constraint: the probability of no collision with retransmit RTS $P_c \neq 0$ and probability of successful data transmission $P_s \neq 0 \rightarrow G \in \ ]0, \infty[$.

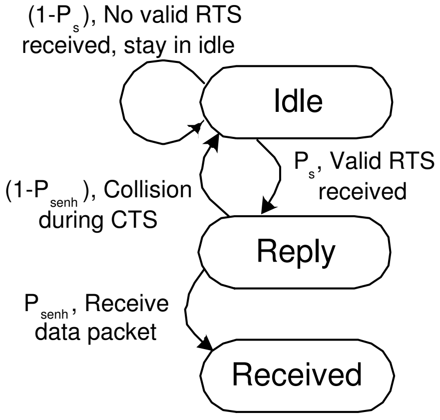

Fig. 5. NanoMAC RX energy model.

For np-CSMA and S-MAC a state machine similar to Fig. 4 can be drawn but with different probabilities and values. The transmit energy consumption of np-CSMA and S-MAC is of the format $E_{TX} = \gamma + \sigma E(B) + \phi + (1-\sigma)E(A)$, where γ and ϕ are sums of products of probabilities, time, and transceiver modes and σ is a probability based on the value of the congestion window.

The reception energy consumption model of a packet can be found from Fig. 5 and the average receive energy consumption E_{RX} from listening for a transmission to detecting and receiving a valid packet and being the proper destination can be found to be

$$E_{RX} = E(I) = (\mu + P_s\theta)(P_sP_{senh})^{-1}. \qquad (12)$$

- $E(I)$ is the time incurred in each visit to state *Idle*,
- μ and θ are functions of different probabilities multiplied by times spent in different transceiver modes,
- P_s and P_{senh} are the probabilities of no collision during RTS or CTS, respectively.

For reception, the constraint $P_sP_{senh} > 0 \rightarrow G < \infty$ is introduced. The energy consumption for np-CSMA and S-MAC on reception can be calculated using Fig. 5 and replacing the probabilities, times, and transceiver modes with appropriate ones. The average energy per useful bit on transmission and reception of the protocols is depicted in Fig. 6. From the figure we can see that np-CSMA transmission energy consumption is the highest, as expected and about 40% higher than with nanoMAC, but only 7% higher than with S-MAC. Surprisingly, S-MAC receive energy consumption is the highest of

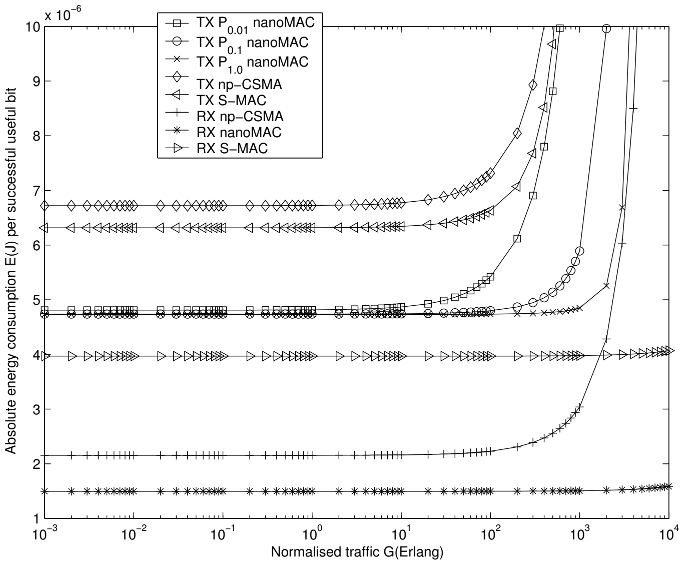

Fig. 6. Transmission and reception energy consumption per MPDU bit.

the three protocols. This is due to three factors: In the calculations done in Matlab, artificially small ACK frames of 1 octet were used for np-CSMA. This is due to the fact that longer ACK frames for np-CSMA would lead to a deadlock situation in the worst-case energy consumption scenario presented in the next chapter. Secondly, binary exponential backoff causes S-MAC and also np-CSMA to spend on the average a relatively long time in transceiver RX mode before data transmission. Third, S-MAC has a cyclic listen for SYNC period, in which the transceiver has to be in RX mode. No actual data can be communicated during that time, so a potential transmitter has to spend extra time in RX mode. In nanoMAC the synchronisation is handled in RTS, CTS and ACK frames, so no extra listening is required per transmitted data packet. NanoMAC reception therefore consumes less than $\frac{2}{5}$ of the energy in reception per useful bit compared to S-MAC.

VII. REGULAR SLEEP PERIODS

We can now calculate the average maximum power consumption for a node using the European version of the RFM TR1000, the 433.92 MHz ISM transceiver RFM TR3000 and nanoMAC with and without sleep periods or np-CSMA without sleep. Because S-MAC has an inherent sleep cycle, we use a similar model. The 433 MHz band has a legal duty cycle of 10% implying that a node is allowed to transmit only one tenth of its active time, i.e., whenever a node sends a packet to some other node it has to refrain from transmission for a period of 9 times the time it took to transmit the packet. The data arrival rate to the system is Poisson distributed and from Table I we can see relevant parameters for the data packet communication.

TABLE I
COMMUNICATION PACKET SIZES

Parameter (octets)	*nanoMAC*	*CSMA*	*S-MAC*
Arrival packet size, A_{pkt}	350	25	350
Packet on the channel, C_{pkt}	507.25	49	627
C_{pkt}; Sender transmitter, S_{TX}	464.25	44.5	478.5
C_{pkt}; Receiver transmitter, R_{TX}	43	4.5	148.5

We consider a maximal usage case in which a node(i) transmits a packet as often as possible, without buffering and it is the recipient for *all* of the packets sent in the channel, except the one packet it transmits.

A. Worst-case Scenario

A node can transmit a packet every T_{tp} seconds,

$$T_{tp} = \frac{S_{TX}}{R_d C_d} + MAX(n)\left(\frac{R_{TX}}{R_d C_d}\right) G_{mod}, \tag{13}$$

where R_d is the data rate (bps), C_d the duty cycle, and n the number of packets addressed to node(i) that node(i) receives during a wait between packet transmissions T_{tp}. G_{mod} is the average, normalised traffic with a limit that when $G > 1 \rightarrow G_{mod} = 1$. The value of MAX($n$) can be defined as the maximum number possible (n) in a T_{tp} at $G = 1$ by

$$MAX(n) = \left(\frac{S_{TX}}{C_d(C_{pkt} + T_{proc})} - 1\right)\left(1 - \frac{R_{TX}}{C_d\,(C_{pkt} + T_{proc})}\right)^{-1} \tag{14}$$

The processing delay T_{proc}, is expressed in bits. We use a 1 octet ACK for np-CSMA because should one use a 15 octet long ACK frame (ACK frame with IEEE sender/recipient MAC addresses) for np-CSMA, the value of *MAX(n)* would take negative values, i.e., a deadlock in which a node first transmits a data frame and then by sending ACK frames corresponding to received data frames would consume all the time available for new data transmissions.

In nanoMAC RTS, CTS and ACK frames, the sleep field is divided into two parts:

- *Sleep Group*: This field announces the sleep group the node is currently following. There are four different sleep groups: SG 00 with no sleep periods, SG 01 in which nodes wake-up every 0.4 s, SG 10,

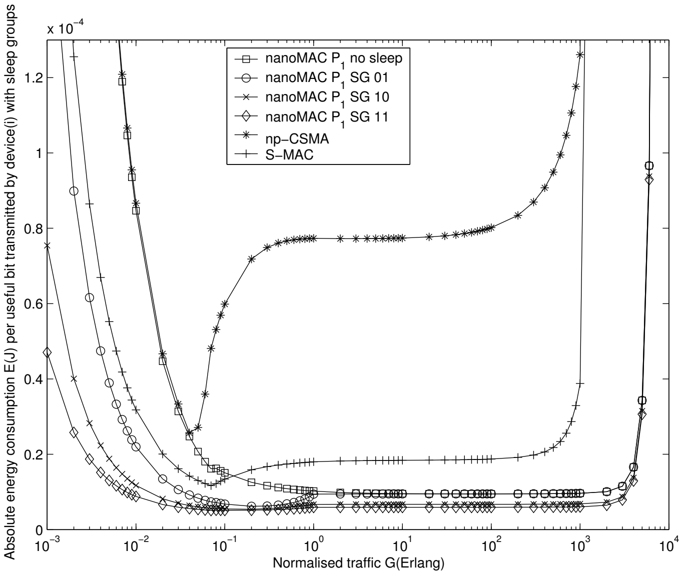

Fig. 7. Worst-case energy consumption per MPDU bit.

TABLE II

RADIO PARAMETERS

Parameter	*Value*
Transmitter circuitry, e_{te}	1.066 μJ/bit
Receiver circuitry, e_{re}	0.533 μJ/bit
SNR at the receiver, $(\frac{S}{N})_r$	40 dB
Receiver noise figure, NF_{Rx}	10 dB
Thermal noise floor, N_0	$4.17 * 10^{-21}$ J
Bandwidth, BW	19200 Hz
Wavelength, λ	0.327 m
Path loss exponent, α	2.5
Antenna gain, G_{ant}	-10 dB
Transmitter efficiency, η_{amp}	0.2
Raw bit rate, R_{bit}	19200 bits/s
Sleep mode energy	120 pJ/bit

with 0.96 s wake-ups, and SG 11, with 1.6 s wake-ups.

- *Next Wake-Up*: This field indicates the next time the node will be awake for communication. The resolution of the field depends on the *Sleep Group*.

After wake-up the nodes stay awake for an *active period* plus a period $\{0 - C_{pkt}\}$. Any node overhearing one of the control frames can calculate the times when the source node will be active. An overhearing node can synchronize with the overheard frame source. For mutual synchronization issues, after a 9.6 s *synch. period*, a node first transmitting a frame will send a long preamble so that every overhearing node in every *Sleep Group* can synchronize their relative times to it. Every node keeps the schedules of all its immediate neighbors, or at least the schedules of the neighbors it wishes to communicate with.

B. Energy Consumption with Sleep Groups

When considering sleep groups, we assume that the sender and recipient are synchronized in time so that when the sender transmits, the recipient is awake to receive data. Because the transmitter and receiver are synchronized in time, sleeping mainly reduces idle listening. Sleeping also increases the traffic offered to the channel because some arrivals occur during the sleep period and every new arrival can be allocated for a new node to satisfy the Poisson distribution. The total worst-case energy consumption with sleep is found to be

$$E_{slp} = \frac{mT_{aw}G_{imod}}{T_{tp}} \left(\frac{1}{C_{pkt}} - \frac{1}{R_d T_{tp}} \right) \left(1 - \frac{A_{pkt}}{R_d T_{tp} G_{inc}} \right) E_{RX} \qquad (15)$$
$$+ E_{TX} + \frac{m(T_{wup} - T_{aw})}{A_{pkt}} M_{Slp} + \frac{mT_{aw}(1 - G_{imod})}{T_{tp}} T_{idleRX} \frac{M_{idleRX}}{A_{pkt}}$$

Here $m = T_{tp}/T_{wup}$ is the number of wake ups during T_{tp}, T_{wup} the wake up period defined by sleep groups, T_{aw} the period a node is awake, G_{imod} the increased traffic offered to the channel with a maximum value of 1, and G_{inc} the increased traffic.

The radio parameters are listed in Table II and the total energy consumption per useful transmitted bit in the worst-case scenario with and without sleep groups is depicted in Fig. 7. The behavior of the curves needs some explanation. The high energy consumption per bit at low values of G is explained by the fact that the offered traffic to the channel is very low and nodes spend most of their time in idle listening. The actual energy consumed in the transmission of a packet is negligible compared to the energy consumed in idle listening between successive data packet transmissions. This behavior is common to all of the MAC protocols we consider. We can see that the introduction of sleep groups and S-MAC's inherent sleep schedule help to compensate for the idle listening, but it can be seen that one needs at least a 15:1 sleep:awake cycle (nanoMAC SG 11) to keep the energy per useful bit value low. When G increases, nanoMAC performs very well for a wide range of G, but eventually in extremely high bursts of G the energy consumption becomes exponentially increasing. NanoMAC accomplishes this by solving most of the problems of being passive and sleeping. The low energy consumption trade-off is increased delay as our work in [22] implies (with throughput–delay calculations).

When nodes are passive, the actual traffic offered to the channel increases as new arrival occur. The contention is therefore higher and the delay increases rapidly after G becomes higher than 1. The good performance of nanoMAC is also due to the fact that overhearing nodes sleep for the duration of data transmission as well as for the duration of the backoff times.

Similar behavior can be seen for S-MAC, but there is a clear energy consumption minimum seen around $G = 0.07$. This is the point where there is exactly one data packet arrival per T_{tp}. When the traffic load increases node(i) begins to receive data packets in addition to its own transmissions. Idle time is reduced, but the high energy consumption of receiving increases energy consumption. The energy consumption per useful transmitted bit soon reaches a steady state or a saturation point, where extra traffic no longer increases the amount of data node(i) receives per T_{tp} because T_{tp} has reached its maximum value no more traffic can be communicated in the channel. When the instantaneous traffic offered to the channel reaches very high values, the number of collisions effectively block communications on the channel and energy per useful transmitted bit grows first linearly, then exponentially.

The performance of np-CSMA on the other hand is quite interesting, but the behavior is exactly the same as for S-MAC. At low values of G the performance of np-CSMA is similar to that of nanoMAC without sleep for the same reasons as for nanoMAC. When G increases to the point where there is more than one arrival (during T_{tp}) to the system, the energy consumption starts increasing linearly because the number of received packets per T_{tp} grows linearly. The increase of reception continues for a while until the channel starts to saturate with data packets. Because of np-CSMA's simplicity high instantaneous bursts of traffic lead to a rapid increase in energy consumption per useful bit.

The energy saving effect of regular sleeping is mainly with low values of G. This is because the amount of idle listening is reduced by a large factor. We expect that the same energy saving behavior is not limited to this worst-case scenario, but is applicable whenever G is low.

VIII. MULTI-HOP ANALYSIS

A. Cross-layer Results

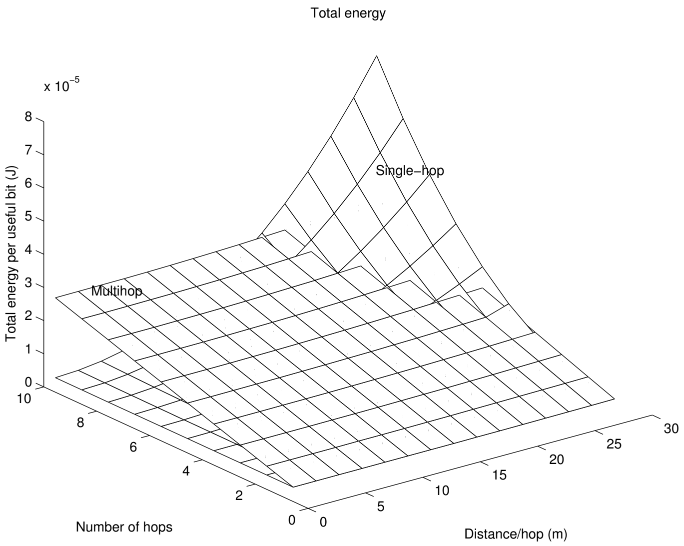

Fig. 8. Total energy for the node n transmitting case. This plot shows the relationship between multihop and single-hop energy efficiency. Single-hop is typically more efficient within the radio's transmission range. The path loss exponent α is 2.3 in this case.

The results presented in this section were collected using Matlab. The parameters used are shown in Table II (Fig. 8 has $\alpha = 2.3$). In addition a 350 byte payload with 4B/6B coding is assumed for comparison with results in the next section. Using this model we can compare the use of single-hop and multi-hop communications in low-power networks. The real question is whether transmit energy or receive and startup energy are dominant factors, the former favoring the theory that multi-hop is always more efficient. However, when accurately taking startup energies and other overheads into account, it can be shown that in most practical cases single-hop techniques are preferred for energy efficiency.

The relationship between multi-hop and single-hop energy efficiency is shown in Fig. 8. Here we can see how the planes of multi-hop and single-hop intersect. Multi-hop is more efficient with a small number of hops over larger distances. Past the typical transmission range of the radio (around 80 m in this case) single-hop becomes less efficient because of path loss. In Fig. 9 we can see how the traffic model affects this intersection. The all nodes transmitting case increases the range under which single-hop is more efficient. Note that in both cases the intersection is beyond the practical range of the radio. These results are highly influenced by radio and channel parameters, and thus are meant only to show the general relationship.

B. Cross-layer Results with Medium Access Control

We use the linear topology of Fig. 1 where N is the total number of nodes with uniform optimum spacing d. When using multi-hop, one hop is d and one makes N hops to reach the sink node whereas for single-hop,

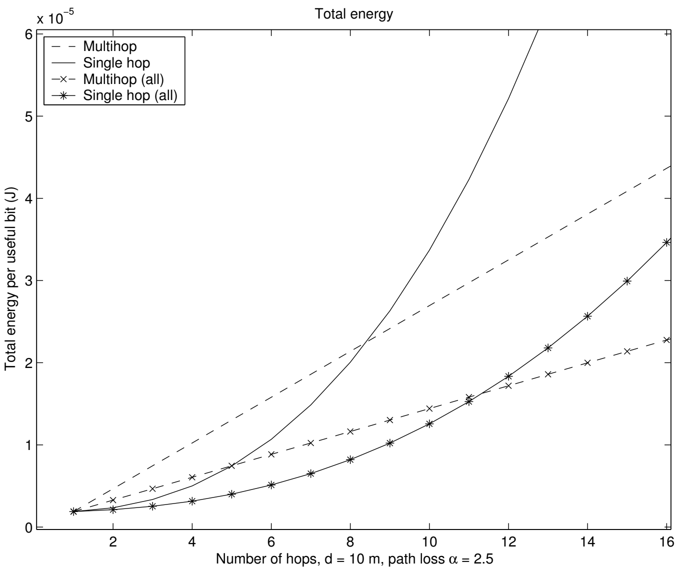

Fig. 9. Comparison of the node n and all node transmission traffic cases. It can be seen that the crossover point is further in the all nodes transmitting case.

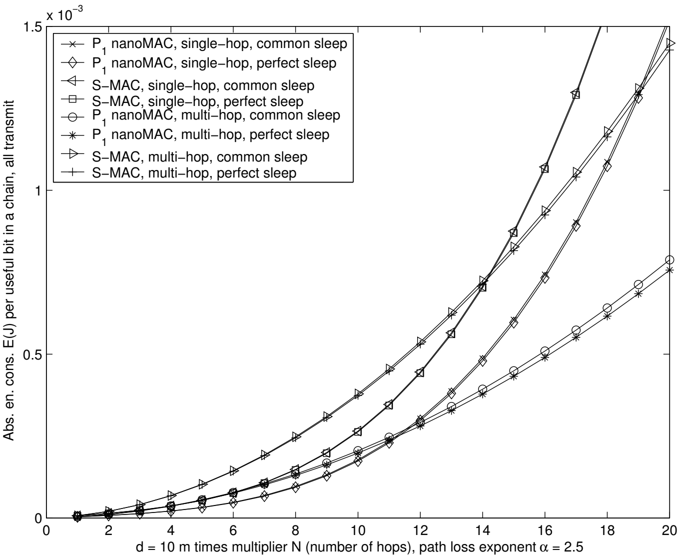

Fig. 10. NanoMAC and S-MAC with a linear topology, non-optimal spacing.

node N transmits the same data for one hop with the distance Nd. Three different scenarios are investigated: one with perfect sleep scheduling, one with realizable multi-group sleep scheduling, and one with common sleep scheduling. In perfect sleep scheduling only the source and the immediate destination are awake during any given transmission and there are no overhearing nodes. With multi-group sleep scheduling we use the four level sleep scheduling presented earlier in the paper and assume that 25% of nodes obey each sleep schedule. Notice that all of the sleep schedules overlap in certain wake periods to keep the network fully connected and all the nodes that are awake during a transmission will overhear the transmission if they are within the range of the transmission. When common sleep scheduling is used we assume that all the n nodes in the linear network are awake at the same time, so all the nodes within the transmission radius will overhear the transmissions. When using the transceiver specific characteristic distance, d_{char} (31.5 m in this case), we note that the multi-hop communication always outperforms the single-hop strategy. The phenomenon is independent of the MAC protocol and presents an optimum separation of nodes. However, when the distance, d, is not optimum the single-hop communications can outperform the multi-hop strategy. A distance, d, of 10 meters per hop is chosen and the following is observed.

Fig. 10 presents nanoMAC and S-MAC with common and perfect sleep scheduling. The figures are calculated at $G = 0.22$ and it is assumed that multi-hop communications occur within a longer period in order not to increase the offered traffic due to forwarding. There is little difference in energy consumption per useful bit between common sleep group and perfect sleeping with CSMA/CA type MAC protocols. The multi-group sleep algorithm falls in between the two cases. The energy expenditure of nanoMAC however, is considerably less than S-MAC with both single-hop and multi-hop communications. Fig. 11 illustrates the behaviour of the modified np-CSMA. It is assumed np-CSMA uses similar sleep scheduling to nanoMAC and the ACK frame length is 1 octet. The energy consumption difference of the sleep groups can be observed with MAC protocols like CSMA where the length of overheard frames are long and the multi-group sleep algorithm provides $10 - 20\%$ better performance than common sleeping.

Fig. 12 illustrates the energy consumption behavior of nanoMAC, np-CSMA, and S-MAC with common sleep group. The protocols exhibit similar behavior to that of Figs. 8 and 9 which are calculated without medium access control. The energy difference per useful bit is almost two orders of magnitude greater when the MAC is taken into account. All of the MAC protocols have an intersection point with single-hop and multi-hop communications, but the intersection point is above the feasible transmission radius of our transceiver. Therefore, single-hop communications should be preferred when the path loss is moderate or less. The energy savings can

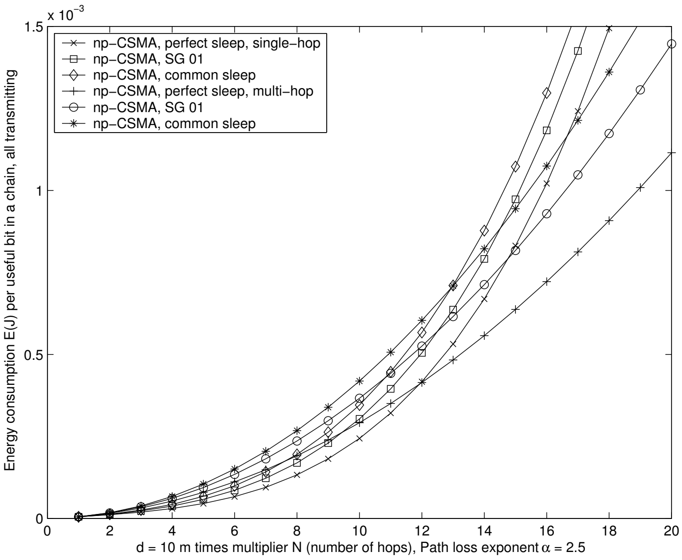

Fig. 11. Nonpersistent CSMA with a linear topology and non-optimal spacing.

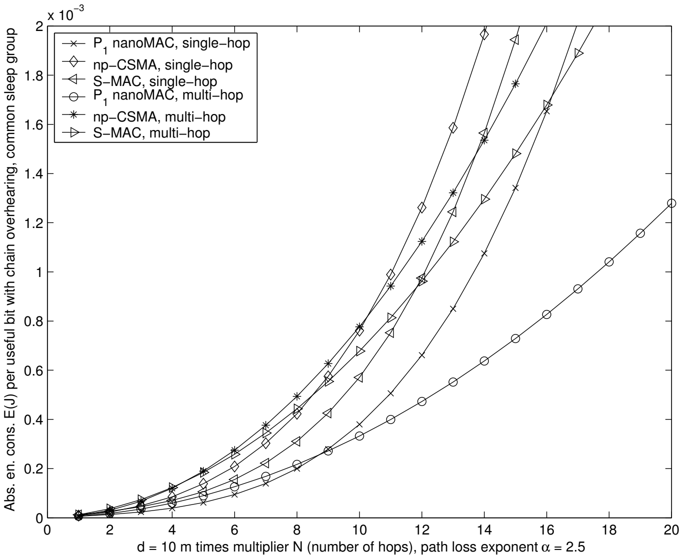

Fig. 12. Linear topology for the MAC protocols using common sleep group and link distances, d of 10 m.

range up to $30 - 40\%$ depending on the MAC protocol. and implies that the use of single-hop communications is more energy efficient in wireless sensor networks, where the offered traffic is usually low or moderate. The differences in energy consumption between the MAC protocols are high and show the importance of proper design of a MAC protocol for sensor networks.

IX. CONCLUSIONS

In this paper, we have analytically investigated a cross-layer energy consumption model with realistic radio transceiver characteristics, three MAC protocols and a linear network model suitable for many sensor network protocols in steady state. Based on the analysis we have discovered many interesting results that relate to single-hop vs. multihop communications and MAC protocol features. Firstly, when a realistic radio model is applied for a sensor network, we discovered that with feasible transmission distances single-hop communications can be more efficient than multi-hop in the energy perspective. The conditions are the multi-hop hop distances, d, are less than the radio-specific optimal multi-hop transmission distance d_{char} and that the path loss exponent is less than 2.7. Secondly, a well designed sensor MAC protocol has similar behavior to the case where the MAC protocol can be considered ideal; only the absolute value energy consumption is higher, on the order of two magnitudes.

Thirdly, there are some inherent flaws in adapting existing ad hoc MAC protocols to sensor networks. Idle listening and overhearing avoidance are important factors as already discussed in other publications, such as [10], [11], but also any listening that is not absolutely necessary, like listening for the RTS in S-MAC, decreases the energy performance of a sensor MAC. Binary exponential backoff, where nodes listen for the channel for the duration of the contention window before transmitting also increases energy consumption, especially when the offered traffic to the channel increases. If message passing techniques are used, transmitting an ACK frame and the related turnaround times consume a large amount of energy and occupy the channel for a longer time, then ACKs should be combined. Of course combining ACK frames make the larger ACK more important and might need methods for ensuring integrity.

It has been shown that introducing regular sleep periods can have a major impact on the energy consumption of a node, especially with low traffic loads. The low duty cycle of ISM bands also demands regular sleep periods. Sleep periods increase the delay, however it can be justified because of the energy savings. Regular, coordinated multi-group sleeping also decreases the energy consumption in both single-hop and multi-hop communications. This applies to CSMA like protocols where the overheard frames are long because multi-group sleeping limits the number of overhearing nodes. The energy saving depends heavily on the MAC protocol used as well as whether single-hop or multi-hop communications is used. From the analysis we can conclude, however that with an energy efficiently designed MAC protocol, like nanoMAC, up to 40% energy savings can be achieved by using single-hop communication within the transmission range of a low frequency ISM transceiver.

X. FUTURE WORK

In order to continue the analysis further analytical results will be compared with real measurements. We have developed nanoMAC on TinyOS for the Berkeley MICA2 motes and on the CWC's WIRO sensor platform to make measurements. Also, we have assumed an error-free or nearly error-free (BER 10^{-4}) channel and need to analyze the energy behavior with different bit error rates. This implies major modifications to the MAC energy model or a switch to Markov chains and a finite number of nodes. Different sensor network traffic models influence the energy consumption and the types of protocols to use, so the definition of traffic models other than data-centric nodes to the sink are also needed. Finally, this problem needs to be considered also from the transport and application layer. Different schemes for packet forwarding in sensor networks should be compared using this a similar cross-layer analysis.

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