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Multihop Medium Access Control for WSNs: An Energy Analysis Model

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We present an energy analysis technique applicable to medium access control (MAC) and multihop communications. Furthermore, the technique's application gives insight on using multihop forwarding instead of single-hop communications. Using the technique, we perform an energy analysis of carrier-sense-multiple-access (CSMA-) based MAC protocols with sleeping schemes. Power constraints set by battery operation raise energy efficiency as the prime factor for wireless sensor networks. A detailed energy expenditure analysis of the physical, the link, and the network layers together can provide a basis for developing new energy-efficient wireless sensor networks. The presented technique provides a set of analytical tools for accomplishing this. With those tools, the energy impact of radio, MAC, and topology parameters on the network can be investigated. From the analysis, we extract key parameters of selected MAC protocols and show that some traditional mechanisms, such as binary exponential backoff, have inherent problems.

Keywords and phrases: energy efficiency, wireless sensor networks, medium access control, multihop communications.

1. 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 wireless sensors and therefore sensor networks are expected to operate using single-chip transceivers like the RFM TR1000 [1] or its European versions, all of which work in ISM bands. The radio parameters of the RFM TR1000 represent a typical transceiver operating in the lower-frequency ISM bands. Therefore, the RFM TR1000 is used in this paper as a representative example. Regulations in many countries impose a duty cycle [2, 3], which is normally 10% in the 434 MHz band and 1% in the 868 MHz 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 data-centric sensor networks, the performance of sink nodes in particular will often be challenged by duty-cycle constraints. Multihop communications presents another challenge to sensor networks. Tools are needed to understand the point where multihop provides real energy savings and should be applied.

The contribution of this paper is to present an analytical energy consumption evaluation technique applicable to

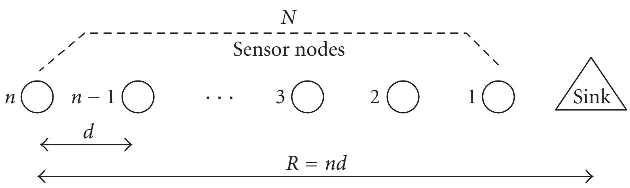

Figure 1: A simple linear sensor network of N nodes. Nodes are separated by distance d and to reach the sink node, node n's packets require n hops resulting in an overall distance of R.

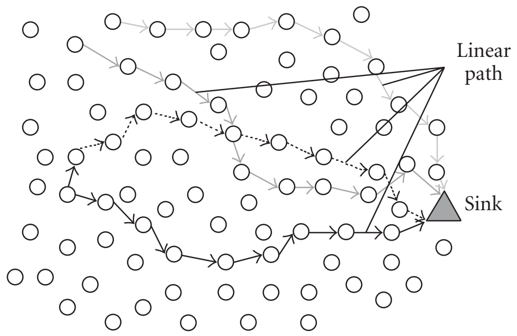

Figure 2: A simple linear multihop model in a large network producing a linear path. The large network may contain several linear paths.

MAC protocols and multihop communications. The presented technique can be applied to predict when to use multihop forwarding in wireless sensor networks. Also, applying the presented technique, we make an analysis on CSMA-based sensor MAC protocols with sleeping schemes.

We start from the simple linear multihop communications model of Figure 1 without medium access control to show the basic effects of radio parameters on the energy consumption of a network. Thereafter, we create an energy analysis technique for MAC protocols using the same radio parameters. Sleep scheduling is included in the analysis as well as multihop communications. The simple linear multihop communications model is used with the exception that MAC modelling considers the multihop forwarding model in a network with a very large number of nodes and creates background traffic for the network. The modelling in this paper uses the term "linear path" which is illustrated in Figure 2. As a result of the presented technique, we firstly perform a single-hop energy consumption comparison between three CSMA-based MAC protocols. Secondly, we compare how the basic multihop scenario without medium access control relates to the case also considering MAC protocol effects. Thirdly, a single-hop versus multihop analysis with MAC protocols is made. Lastly a few key parameters that can be extracted from the technique presented are discussed.

The linear topology model, whether uniformly or randomly spaced, represents a common network after route discovery has been accomplished. We propose an energy consumption model for the transmission and reception of MAC frames, develop a coordinated sleep group energy consumption model, and analytically investigate the effect of sleep on sensor networks. From the analysis, we show that although in an ideal scenario multihop communications performs better than single-hop communications, realistic energy models and especially the MAC design have a significant impact. The radio transceiver energy model takes into account several important radio parameters; in this paper, we use the RFM TR1000 and RFM radio designers' guide [4] as an example of realistic transceiver parameters. The main metric used is absolute energy consumption per useful successfully transmitted bit. This implies that only the MAC service data unit (MSDU), that is, the data from higher layer, will be considered useful and all the other communicated bits, headers, control frames, preambles, and so forth are considered to be overhead. For linear topology scenarios, we begin with optimum uniform spacing and optimal power control and proceed to random node spacing using more realistic four-level transmit power control. As intermediate steps, we cover non-optimum uniform spacing with optimal power control and nonuniform spacing with fixed transmission power.

The rest of the paper is organized as follows. Related work and some MAC protocols, namely, nonpersistent CSMA, S-MAC, nanoMAC, and the IEEE Std 802.15.4, are discussed in Section 2. Section 3 describes the radio propagation energy model and presents the simple linear multihop communications model without medium access control. Section 4 presents the MAC energy consumption models for the transmission and reception of data and Section 5 deals with regular sleep periods and presents the worst-case energy consumption results and the energy savings achieved by regular sleeping. Section 6 addresses the single-hop versus multihop problem and in Section 7 we present an analysis for nonoptimal and randomly spaced multihop networks using shortest-hop and longest-hop strategies. Conclusions are drawn and discussion is presented in Section 8.

2. RELATED WORK

2.1. Radio modelling

The radio model and physical layer characteristics in this paper are based on the work of [5, 6, 7]. In [5] optimal transmittable packet sizes are discussed in respect to energy efficiency over single hops. The authors present an energy consumption model and optimal packet payload sizes for various channel bit error rates (BERs) and coding schemes are determined. In [6, 7] a linear radio model is presented as seen in Figure 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. A single-hop radio energy consumption model taking into account startup energies and decoding energy was presented in [8]. The paper describes the total power consumption of a single hop and assumes a linear radio model as well as the simple linear network of Figure 1.

2.2. Topology and network protocols

There has been a lot of research on efficient wireless sensor network topologies that include LEACH [6], SPIN [9], data funnelling [10], and directed diffusion [11]. Each of them suggests 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 the data they have so that only interested nodes request the data. Data funnelling creates sensing areas with border nodes so that data from an area is gathered to border nodes that in turn find and use a multihop path to the sink node. In directed diffusion, the sink node broadcasts what data it is interested in and builds gradients to nodes that 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 Figure 1 in steady state.

2.3. Cross-layer studies

The closest related work to our paper was presented in [12]. The paper is a MAC-routing protocol cross-layer study for ad hoc networks. Although the work is on ad hoc protocols and does not take energy usage into account, it shows the importance of considering different layers when designing a new protocol. This is demonstrated with ad hoc on demand distance vector (AODV) routing and IEEE Std 802.11. AODV is designed to work specifically on top of the IEEE Std 802.11 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 the paper.

2.4. Medium access control

During the past few years, there has been an increasing amount of research on energy efficient MAC protocols specifically for use with sensor networks [13, 14, 15]. However, such protocols are usually modifications from traditional ad hoc networking and have some inherent flaws for sensor networks. The PAMAS [13] protocol was one of the first attempts to reduce unnecessary power consumption by putting 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) [14] is a protocol designed for sensor networks and its prime functionality is to reduce idle listening. S-MAC's foundations lie on IEEE Std 802.11 [16] and MACAW [17], which is the basis of IEEE Std 802.11. They both implement carrier sense multiple access with collision avoidance (CSMA/CA), a four-way handshake using binary exponential (BE) backoff and other similar functionalities. S-MAC also implements a regular sleep period and a special synchronization scheme to reduce idle listening and maintain global connectivity. The method is called virtual clustering, where irregular synchronization messages urge, but do not enforce, a common schedule. Even though S-MAC outperforms IEEE Std 802.11-like protocols in the energy perspective, it is still a traditional ad hoc protocol in many ways. The timeout MAC (T-MAC) [15] 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.

The IEEE Std 802.15.4 standard [18] is the IEEE's contribution to flexible sensor MAC protocols with a low-rate wireless personal area network (LR-WPAN). The design goal has been low-cost and very low-power short-range wireless communications. The standard provides two frequency ranges: the 868/915 MHz ISM band supporting 20/40 kbps communications and the 2450 MHz ISM band supporting a data rate of 250 kbps. Like other IEEE 802.15 protocols, the standard operates using piconets, that is, every WPAN has a central coordinator called the PAN coordinator. However, IEEE Std 802.15.4 provides more flexible topologies than the other IEEE 802.15 family protocols including star network, mesh topology, and a clustered network approach. The piconet can also operate in beacon-enabled or beaconless modes allowing more flexibility to nodes with special requirements, like advanced sleeping schemes with very low duty cycle or low delay. The channel access method for the standard is CSMA/CA except in guaranteed time slots (GTS) provided by the PAN coordinator in beacon-enabled mode where communication is reserved for a single node. The standard does not describe any specific sleep algorithms and its channel access is very similar to the other protocols we are considering in this work, therefore it is not included in the forthcoming analysis.

The MAC protocols used for the energy analysis in this paper, namely, nonpersistent CSMA, S-MAC, and nanoMAC, are described in the following subsections. Nonpersistent CSMA is a well-known and normally well-performing MAC protocol in almost any scenario. It gives the 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 two protocols to nanoMAC, a protocol designed to operate in a sensor networking environment.

2.4.1. Nonpersistent CSMA

Carrier sense multiple access was originally presented in [19] and has been widely referenced afterwards. The reason for considering nonpersistent CSMA (np-CSMA) in this paper is because it performs quite well under most circumstances, even though theoretically being an unstable protocol. It also functions as the 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 to be vacant for the whole duration of the CS, the node sends the data, otherwise, it does not persist in sensing the channel, but chooses a random time in the future to perform

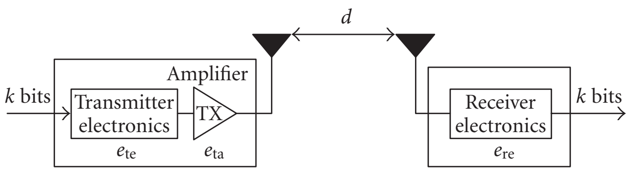

Figure 3: Typical narrowband radio energy consumption model where k bits are transmitted and e_{te} and e_{ta} are the transmitter electronics and amplifier energy consumption per bit, respectively. The transmission distance is d and the k bits are received by the receiver electronics consuming e_{rx} energy per bit.

CS again. Once the data has been sent, np-CSMA waits for an acknowledgement (ACK) frame from the intended recipient and if it 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.

2.4.2. S-MAC

The S-MAC [14] operation and frame is divided into two periods: the active period and the sleep period. During the sleep period, all nodes sharing the same schedule sleep and save energy. The sleep period is usually several times longer than the active period. The active period also consists of two subperiods: the listen for synchronization (SYNC) frame period and the listen for request-to-send (RTS) period. Nodes listen for a SYNC frame in every cycle and the SYNC frame 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 can be applied when the network layer has a packet larger than a single frame to transmit. Using message passing, S-MAC splits up the packet into smaller sized pieces and transmit them as a burst of consecutive data—ACK frames. Overhearing nodes sleep during the data transfer. Should a data transmission continue beyond the active period, the transmitting and receiving nodes using S-MAC can prolong their awake time for the duration of the data transmission.

2.4.3. NanoMAC

Because CSMA/CA is a powerful protocol for medium access control, the nanoMAC protocol also implements CSMA/CA. NanoMAC has been discussed in detail in [20, 21] and [22] presents more details of it with part of the analysis later presented in this paper. Briefly described, nanoMAC is p-nonpersistent, that is, 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 to attempt it. Nodes contending for the channel do not constantly listen for the channel, contrary to the normal binary exponential backoff mechanism, but sleep during the random contention window. When the backoff timer expires, the node wakes up to sense the channel. The CS for nanoMAC is relatively short but long enough to guarantee carrier detection on the channel with high confidence. The described feature makes the actual 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, 48-bit 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, as data is always divided into 35 octet blocks. The transmitted 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. Without forward error correction (FEC) methods, the frame train method promises to be efficient. If FEC is used, frames can be made longer. When best utilized, nanoMAC has low overhead even with low data-rate, small frame-size applications. For a 350-octet payload, the MSDU-to-packet ratio for nanoMAC is $\sim 75\%$ while for S-MAC and CSMA the values are $\sim 64\%$ and $\sim 44\%$, respectively.

3. BASELINE MULTIHOP COMMUNICATIONS MODEL

In this section, we describe the simple multihop communications model without medium access control. The analysis applies to the case where the MAC is considered to be ideal; the MAC produces no overhead, adds no delays, and the channel access never causes collisions. The analysis without medium access control provides insight into the energy consumption effects of radio parameters.

3.1. Radio power consumption

Power consumption models of the radio, illustrated by Figure 3, in embedded devices, must take both transceiver and startup 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 [5] a model for radio power consumption is given for energy per bit e_b as

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

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 energy of data is assumed to be negligible. This model takes into account the energy needed to transmit a frame from a transmitter to a receiver over a single hop. In [5] 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 used later in the paper to produce a baseline comparison for multihop MAC efficiency using the same radio parameters.

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

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

where e_{te} is the energy consumption of the transmitter electronics per bit, e_{ta} is the energy consumption of the transmit amplifier per bit over a distance of 1 meter, 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 [7] as

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

where $(S/N)_r$ is the desired signal-to-noise ratio at the receiver's demodulator, $\mathrm{NF_{Rx}}$ is the receiver noise figure, N_0 is the thermal noise floor for 1 Hz bandwidth, BW is the channel noise bandwidth, λ is the wavelength in meters, 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

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

The characteristic distance is a radio specific parameter which describes when the energy consumptions of the transmitter and receiver circuitries are in balance with the energy consumption of the transmitter amplifier. For a typical low frequency band transceiver like the RFM TR1000 with electronics values presented in Table 1, the characteristic distance is found to be 31.5 meters with a BER of 10^{-4} assuming noncoherent FSK modulation. For sensor networks, this value of d_{char} is a long link distance, but it is the most energy efficient from the point of transceiver electronics. Most communications in sensor networks can thus be completed using singlehop communications using this particular radio. In this paper, we analyze topology, traffic, and medium access control effects on multihop energy efficiency. With the parameters of Table 1, Sankarasubramaniam et al. [5] suggest that a frame size of 41 octets with a BER of 5×10^{-4} is close to optimal energy efficiency.

Table 1: Radio parameters of a typical ISM transceiver, the RFM TR1000 at 19.2 kbps, which is used in the analysis of the paper.

Parameter	Value
Transmitter circuitry e_{te}	1.066 μJ/bit
Receiver circuitry e_{rx}	0.533 μJ/bit
SNR at the receiver $(S/N)_r$	40 dB
Receiver noise figure $\mathrm{NF_{Rx}}$	10 dB
Thermal noise floor N_0	$4.17 * 10^{-21}$ J
Bandwidth BW	19 200 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}	19 200 bps
Sleep mode energy e_{slp}	120 pJ/bit

3.2. *Multihop power consumption*

In this section, an analytical model for multihop communications is introduced that takes detailed overheads into account. The linear model is used with variable spacing between nodes assuming a sink node that collects data and is not energy constrained. 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 [8] 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 [8], we can derive multihop energy per useful bit from (1) as

$$\begin{aligned} e_b = {} & \left(n\left(e_{\mathrm{te}} + e_{\mathrm{ta}}(d)^{\alpha}\right) + (n-1)e_{\mathrm{rx}}\right)\left(1 + \frac{(\beta+\tau)}{\iota}\right) \\ & + \frac{nE_{\mathrm{st}} + (n-1)(E_{\mathrm{sr}} + E_{\mathrm{dec}})}{\iota}, \end{aligned} \tag{5}$$

where n is the number of hops, β is the preamble length, τ is the coding overhead, and E_{st} and E_{sr} are startup energies from sleep to transmit and receive, respectively. The reception energy consumption of the sink node is not included because it is not considered to be energy constrained and does not affect the multihop comparison.

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 E_{MH} incurred by node n transmitting $k = \beta + \iota + \tau$ total bits over n hops to the sink is

$$\begin{aligned} E_{\mathrm{MH}} = {} & n\left(k\left(e_{\mathrm{te}} + e_{\mathrm{ta}} d^{\alpha}\right) + E_{\mathrm{st}}\right) \\ & + (n-1)\left(k e_{\mathrm{rx}} + E_{\mathrm{sr}} + E_{\mathrm{dec}}\right). \end{aligned} \tag{6}$$

The analysis used to this point has assumed an unrealistic traffic model, 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

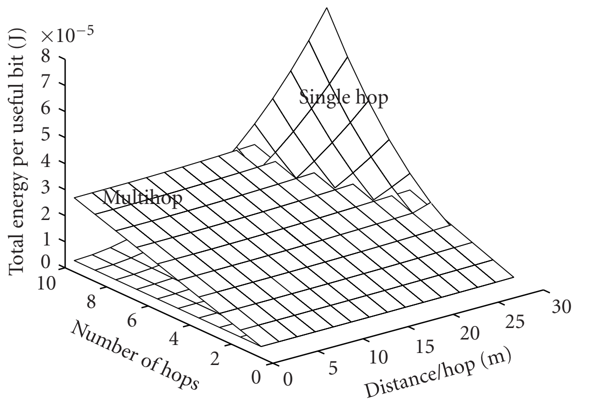

FIGURE 4: Total energy for the node n transmitting case. This plot shows the relationship between multihop and single-hop energy efficiency. Single hop is typically more efficient within the radio's transmission range. The path loss exponent α is 2.3 in this case.

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. We consider the scenario of Figure 1 where all the nodes transmit a frame to the sink. From (6) the total energy consumed $E_{\text{MH}}^{\text{all}}$ in the network by each node transmitting their own frame and forwarding the other nodes' frames towards the sink for this scenario is

$$E_{\text{MH}}^{\text{all}} = \frac{n(n+1)}{2}\left(k\left(e_{\text{te}} + e_{\text{ta}}(d)^{\alpha}\right) + E_{\text{st}}\right) + \frac{n(n-1)}{2}\left(ke_{\text{rx}} + E_{\text{sr}} + E_{\text{dec}}\right). \tag{7}$$

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. Node n has to transmit a total distance of nd, node $n-1$ a distance of $(n-1)d$, and so forth. From (5) by summation we get the single-hop total energy consumed $E_{\text{SH}}^{\text{all}}$ in the network as

$$E_{\text{SH}}^{\text{all}} = \sum_{i=1}^{n}\left(k\left(e_{\text{te}} + e_{\text{ta}}(id)^{\alpha}\right) + E_{\text{st}}\right). \tag{8}$$

The intermediate nodes between the transmitting node and the sink in the single-hop case do not overhear the transmissions. The channel is also considered to be errorless with the parameters of Table 1. Note that in a realistic scenario, the traffic model is usually somewhere in between the two aforementioned models.

3.3. Baseline results

The parameters used for the analysis are shown in Table 1, with the exception of α being 2.3 in Figure 4 for clearer illustrative purposes. Matlab was used as a tool for producing the figures. In addition, a 350-octet payload with 4B/6B coding is assumed for comparison with the results obtained later including the MAC protocol effects. Using this model, we can compare the use of single-hop and multihop communications in low-power networks. The real question is whether transmit energy or receive and startup energy is a dominant factor, the former favoring the theory that multihop 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.

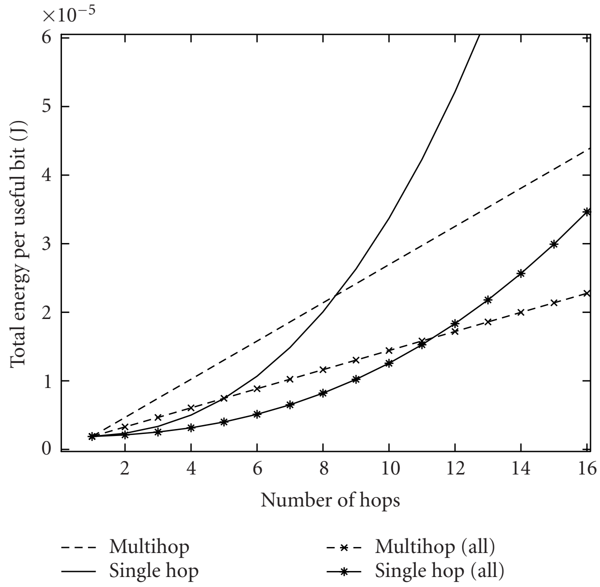

FIGURE 5: Comparison of the node n only and all node transmission traffic cases. It can be seen that the crossover point is further in the all nodes transmitting case. Node spacing d is 10 m and the path loss exponent α is 2.5.

The relationship between multihop and single-hop energy efficiency is shown in Figure 4. Here we can see how the planes of multihop and single hop intersect. Multihop is more efficient with a small number of hops over larger distances. Past the typical transmission range of the radio ($\sim$ 80 m in our case, d_{char} being less), single hop becomes less efficient because of the path loss. In Figure 5, 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, especially the path loss exponent, and thus are meant only to show the general relationship. In the next section, we develop the MAC protocol energy analysis model and later use the same radio and topology parameters as in this section in order to make a comparison of MAC effects.

4. ENERGY CONSUMPTION MODEL WITH MEDIUM ACCESS CONTROL

In this section, we describe a theoretical analysis for the energy consumption of MAC protocols and the underlying physical layer. This analysis can be used for the study of

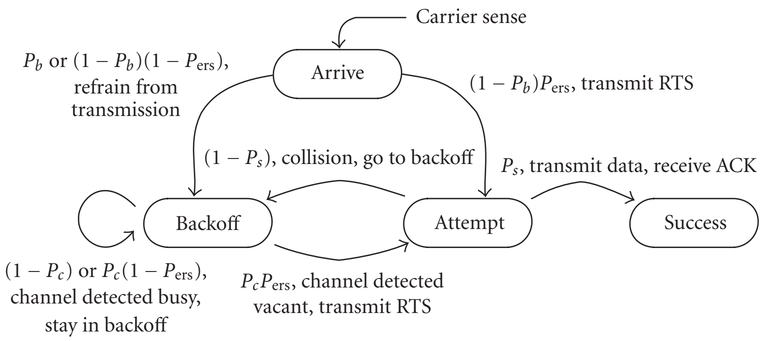

Figure 6: Transmit energy model for nanoMAC. The arrows present energy consuming transitions from one state to a new state while the states are instant and do not consume energy. P_b, P_{ers}, P_s, and P_c are transition probabilities.

networks with a large number of nodes.[1] The model consists of the energy consumed in a network in the transmission of data taking into account average contention times, average backoff times, and possible frame collisions. The model takes the reception of data into account as the average probabilities for receiving data correctly. A similar model was originally presented in [23] for the delay analysis of the FAMA-NTR protocol, but we have modified it for energy consumption calculations by investigating the probabilities of transitions from one MAC protocol state to another state and the related times consumed in transmit, receive, idle, and sleep. In the model, one consumes energy in the process of arriving to a state. The states themselves are transitory and with certain probabilities one of all possible paths is chosen to arrive to a new state (in some cases the same state as before). Usually, in the case of ISM-band transceivers, receive and idle modes can be considered as a single mode or the difference is marginal. Throughout the presentation of the analytical model, we use nanoMAC as an example, but an equivalent analysis can be applied to np-CSMA and S-MAC as well as to other MAC protocols.

4.1. Transmit energy

The energy consumption model for transmission can be found from Figure 6. There are four different states: *Arrive*, *Backoff*, *Attempt*, and *Success*. The Arrive state is the entry point to the system for a node with new data to transmit. In the case of CSMA protocols, carrier sensing is always made before arriving to the Arrive state which consumes E_{Arrive} joules of energy. To calculate the average energy consumption, we solve a system of equations implied by Figure 6. 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. On every arrival to one of the states, energy is consumed. This energy consumption consists of certain times, for example, the time needed to transmit a preamble and an RTS frame, and the time spent in a specific transceiver mode, for example, transmit (M_{Tx}) in this case. There are probabilities attached to each of the arrivals depicting a certain exponential probability to choose that path. The sum of all probabilities out of a specific state is always 1. To reach the Success state which is the exit point of the data transfer, all the possible transitions starting from the Arrive state and ending at the Success have to be calculated. 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 in general of the form

$$E_{\text{Tx}} = E_{\text{Arrive}} + P_{\text{prob}\,1}E(A) + (1 - P_{\text{prob}\,1})E(B), \quad (9)$$

$$E(A) = P_{\text{prob}\,2}E_{\text{Success}} + (1 - P_{\text{prob}\,2})E(B), \quad (10)$$

$$E(B) = P_{\text{prob}\,3}E(A) + (1 - P_{\text{prob}\,3})E(B), \quad (11)$$

where $P_{\text{prob}\{1,2,3\}}$ are different probabilities related to arriving to a certain state (each $P_{\text{prob}\{1,2,3\}}$ may contain several probabilities), E_{Arrive} is the carrier sensing energy consumption when coming to the Arrive state, and E_{Success} is the expected energy consumption upon reaching the Success state from the Attempt state. For nanoMAC, presenting the probabilities, the times, and the transceiver modes explicitly, (9) translates to

$$\begin{aligned} E_{\text{Tx}} = {} & T_{\text{CS}}M_{\text{Rx}} + P_b\left(T_{bb} + \frac{T_r}{2}\right)M_{\text{Slp}} + P_bE(B) \\ & + (1 - P_b)(1 - P_{\text{ers}})\left(T_{bp} + \frac{T_r}{2}\right)M_{\text{Slp}} \\ & + (1 - P_b)P_{\text{ers}}E(A) + (1 - P_b)P_{\text{ers}}(T_{\text{pr}} + \text{RTS})M_{\text{Tx}} \\ & + (1 - P_b)(1 - P_{\text{ers}})E(B). \end{aligned} \quad (12)$$

In (12) the notation is as follows.

(i) M_{Tx} is the transceiver transmit power consumption and is related to the time consumed arriving to a state. Similarly, M_{Rx} and M_{Slp} are transceiver reception and sleep power consumptions, respectively.

[1] We assume a Poisson process of data arrival and the number of nodes in the network approaches infinite. Therefore, the probabilities used in our analysis are exponential.

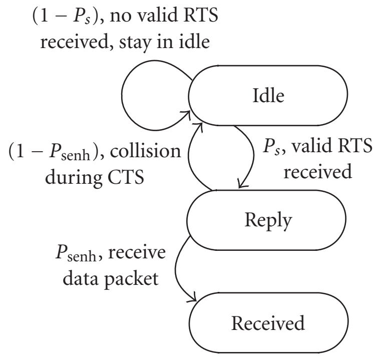

Figure 7: The receive energy model for nanoMAC. The arrows present energy consuming transitions from one state to a new state while the states are instant and do not consume energy. *Idle* is the entry point to the system and no energy is consumed before a transmission by another device is attempted. P_s and P_{senh} are transition probabilities.

(ii) T_{CS} is the time required for carrier sensing.
(iii) T_{bb} and T_{bp} represent the average values of binary exponential backoff. T_{bb} is the incremented backoff time and T_{bp} is the base backoff time.
(iv) P_b is the probability of finding the channel busy during CS.
(v) $T_r/2$ is the average random delay obeying uniform distribution.
(vi) P_{ers} is the nonpersistence value of nanoMAC.
(vii) T_{pr} and RTS are times to transmit a preamble and an RTS frame, respectively.

From *Backoff*, (11), and *Attempt*, (10), we make the same analysis as from the *Arrive*, (9), state and solve a system of equations. For nanoMAC, $E(B)$ of (11) after algebra translates to

$$E(B) = (\omega + P_c P_{\text{ers}} \delta)(P_{\text{ers}} P_c P_s)^{-1}, \tag{13}$$

where P_c is the probability of finding no transmissions during time e and P_s is the probability of no collision during an RTS frame. The symbol ω represents the energy model's transition from Backoff state to Attempt state or Backoff state. The explicit form of ω is presented in Appendix A and by form it is similar to (12). Similarly, δ represents the model's transition from Attempt state to Backoff state or Success state and the explicit form can be found in Appendix A. After algebra, $E(A)$ of (10) for nanoMAC can also be found and is

$$E(A) = \delta + (1 - P_s)(\omega + P_c P_{\text{ers}} \delta)(P_{\text{ers}} P_c P_s)^{-1}, \tag{14}$$

where the term $E(A)$ gives a constraint: the probability of no collision with retransmit RTS $P_c > 0$ and the probability of successful data transmission $P_s > 0 \rightarrow G \in [0, \infty]$. Note that we are not modelling the BE backoff with a Markov chain here. We are using average values of BE backoff modified by G, where G is the normalized, average traffic offered to the channel. This assumption does not affect the energy consumption result.

For np-CSMA and S-MAC, a state machine similar to Figure 6 can be drawn but with different probabilities and values. Equations (9), (10), and (11) apply and the transmit energy consumption of np-CSMA and S-MAC is of the form $E_{\text{Tx}} = \gamma + \sigma E(B) + \phi + (1 - \sigma) E(A)$, where γ and ϕ are sums of products of probabilities, times, and transceiver modes (similar to ω and δ) and σ is a probability based on the value of the congestion window.

4.2. Receive energy

The reception energy consumption model of a packet for nanoMAC can be found in Figure 7. Idle listening is not taken into account in the model of Figure 7, instead the next section provides it. For analysis the reception energy model is similar to the transmit energy model 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

$$E_{\text{Rx}} = E(I) = (\mu + P_s \theta)(P_s P_{\text{senh}})^{-1}, \tag{15}$$

where the notation is as follows.

(i) $E(I)$ is the energy incurred in each visit to state *Idle*.
(ii) μ represents the energy model's transitions from state *Idle* and is explicitly described in Appendix B. It is similar to ω of the previous subsection.
(iii) θ represents the energy model's transitions from state *Reply* and is explicitly described in Appendix B. It is also similar to ω of the previous subsection.
(iv) P_s and P_{senh} are the probabilities of no collision during RTS or CTS, respectively.

Details for receive energy consumption can be found in Appendix B. For reception, the constraint $P_s P_{\text{senh}} > 0 \rightarrow G < \infty$ is introduced. The energy consumption for np-CSMA and S-MAC for reception can be calculated using Figure 7 and replacing the probabilities, times, and transceiver modes with appropriate ones.

The average energy per useful bit for transmission and reception is depicted in Figure 8. A network with a very large number of nodes using a Poisson process is assumed. The radio parameters can be found in Table 1 and we can see that np-CSMA transmission energy consumption is the highest as expected and about 40% higher than with nanoMAC and 7% higher than with S-MAC. Surprisingly, the reception energy consumption of S-MAC is the highest of 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. Thirdly, S-MAC has a cyclic listen for SYNC period, in which the

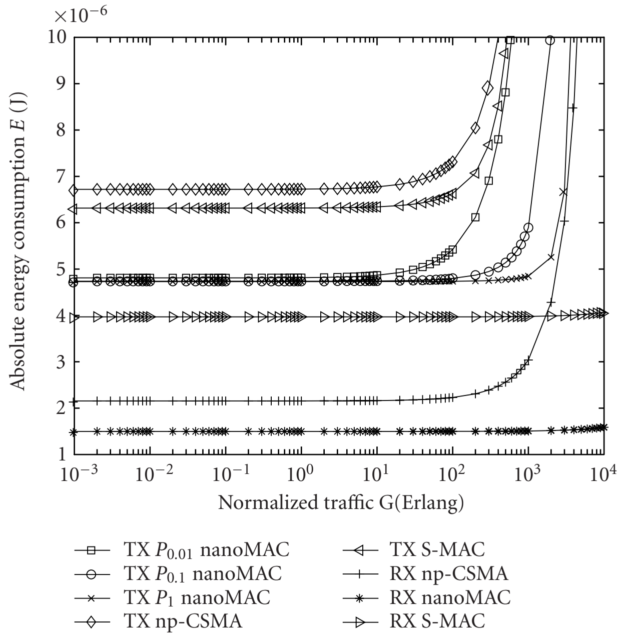

Figure 8: Transmission and reception energy consumption of np-CSMA, S-MAC, and nanoMAC per MSDU bit. The traffic assumes a Poisson process over a single hop, and a fully connected network with a very large number of nodes.

transceiver has to be in RX mode. No actual data can be communicated during that time, so a potential transmitter and receiver has to spend extra time in RX mode. In nanoMAC, the synchronization is handled in RTS, CTS, and ACK frames, so no extra listening is required per transmitted data packet. NanoMAC reception therefore consumes only two fifths of the energy in reception per useful bit compared to S-MAC.

5. REGULAR SLEEP PERIODS

In the previous section, we presented a MAC energy model for the transmission and reception of data. In a more realistic analysis of wireless sensor MAC protocols, we have to include periods when there is no data communication ongoing as well as sleeping to save energy. These issues are addressed in this section by including idle listening and describing a sleep mechanism which are appended to the model of the previous section. A comparison of energy consumption with and without sleep is also made.

We evaluate the average, maximum, single-hop power consumption for a node using the RFM TR1000 and nanoMAC with and without sleep periods as well as np-CSMA without sleep. Because S-MAC has an inherent sleep cycle, we use a similar model for evaluation. A legal duty cycle of 10% common to ISM channels is used implying that a node is allowed to transmit only one tenth of its active time. That is, 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 in Table 2 we can see the relevant parameters for the data packet communications. We consider a 350-octet MSDU A_{pkt} arriving from an upper layer process for nanoMAC and S-MAC and a 25-octet MSDU for np-CSMA. In this way, the least overhead is used by each of the protocols. The length of the data transmitted on the channel C_{pkt} in octets is known after appending the necessary control frames, headers, and preambles. Of C_{pkt}, S_{Tx} octets are transmitted by the data originator transmitter and R_{Tx} octets are transmitted by the receiver transmitter as control frames and acknowledgements. Protocols have their own frame structure and communications method and therefore the values are different for each protocol.

Table 2: MAC protocol specific frame sizes, MSDU size, communicating MSDU on the channel, and transmitted portions by the data originator and the recipient in octets.

Parameter (octets)	NanoMAC	CSMA	S-MAC
Control frame size	18	1	10
Data frame size	41	41	43
Data frame payload	35	25	35
MSDU 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, called the worst-case scenario 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 packets it transmits.

5.1. *Worst-case scenario*

Whenever a node transmits data, control frames, or acknowledgements, it has to obey duty-cycle constraints. Because of the duty-cycle constraints, a node can transmit a packet every T_{tp} seconds,

$$T_{\text{tp}} = \frac{S_{\text{Tx}}}{R_d C_d} + \text{MAX}(r)\left(\frac{R_{\text{Tx}}}{R_d C_d}\right) G_{\text{mod}}, \tag{16}$$

where R_d is the data rate (bps), C_d the duty cycle, and r 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, normalized traffic with a limit that when $G > 1 \rightarrow G_{\text{mod}} = 1$. The value of MAX($r$) can be defined as the maximum number possible r in a T_{tp} at $G = 1$ by

$$\text{MAX}(r) = \left(\frac{S_{\text{Tx}}}{C_d\left(C_{\text{pkt}} + T_{\text{proc}}\right)} - 1\right)\left(1 - \frac{R_{\text{Tx}}}{C_d\left(C_{\text{pkt}} + T_{\text{proc}}\right)}\right)^{-1}. \tag{17}$$

The processing delay T_{proc} is expressed in bits. We use a 1-octet ACK for np-CSMA because using a 15-octet-long ACK frame (ACK frame with IEEE sender/recipient MAC addresses) with np-CSMA leads to a deadlock. The deadlock is expressed by $\text{MAX}(r)$ reaching negative values. Negative values correspond to a situation where a node first transmits a data frame. While refraining from transmission until the duty cycle is satisfied, the node receives data frames and by acknowledging those frames the ACK frame transmissions delay the next data transmission indefinitely.

5.2. NanoMAC sleep groups

We implement four-level sleep scheduling for nanoMAC. The sleep scheduling operates in cycles of 9.6 seconds after which all of the nodes in the network resynchronize themselves. After the resynchronizing timer expires in a node, the node turns its radio to listen mode. The node then only listens for the channel for a period of time to confirm that every node in its area of influence is awake. After this period, the node starts a random timer after which it broadcasts a special synchronization preamble to resynchronize all of the nodes. Should the node receive the special synchronization preamble before its own transmission, it synchronizes with that preamble and resumes normal operation. A new cycle of 9.6 seconds begins from the end of transmission of the special preamble. If the node has data to transmit, it can piggyback the data. In the case that a node cannot resynchronize with the network, it has to immediately change its sleep group to SG 00, always awake until it receives a valid resynchronization preamble. On the average, nodes have to spend 500 milliseconds in receive mode to resynchronize producing an extra energy cost of 5.1 mJ in 10.1 (9.6 + 0.5) seconds corresponding to 28 nJ/bit in a cycle.

The sleep group information in nanoMAC is transmitted in the control frames which every node awake can overhear: RTS, CTS, and ACK. Each control frame has a 1-octet sleep field which is divided into two parts.

(i) *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 second, SG 10 with 0.96-second wake-ups, and SG 11 with 1.6-second wake-ups.

(ii) *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*.

The above values are just carefully selected examples and one could use other values. After wake-up, the nodes stay awake for an *active period* of 85 milliseconds and in addition a period of $\{0 - C_{\text{pkt}}/R_d\}$ (the time of a data packet communication) seconds. The additional period is spent awake only in the case that a valid packet is being transmitted or received. Any node overhearing one of the control frames can calculate the times when the source node will be awake. Every node keeps the schedules of all its immediate neighbors, or at least the schedules of the neighbors it wishes to communicate with if the additional memory consumption of keeping track of all nodes is not justified.

5.3. Energy consumption with sleep groups

In the last two subsections, we defined the scenario and presented a sleep group model for analysis with the MAC energy model derived before. Next all these are added together to consider single-hop communications, MAC energy consumption with idle listening and sleeping, taking into account the radio characteristics.

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 process. The total worst-case energy consumption with sleep E_{WCS} consists of the energy consumed in transmission E_{Tx}, reception E_{Rx}, sleeping, and idle listening. The exact derivation of E_{WCS} is presented in Appendix C and the resulting formula is

$$E_{\text{WCS}} = \frac{mT_{\text{aw}}G_{\text{imod}}}{T_{\text{tp}}}\left(\frac{1}{C_{\text{pkt}}} - \frac{1}{R_d T_{\text{tp}}}\right) \times \left(1 - \frac{A_{\text{pkt}}}{R_d T_{\text{tp}} G_{\text{inc}}}\right)E_{\text{Rx}} + \frac{m(T_{\text{wup}} - T_{\text{aw}})}{A_{\text{pkt}}}M_{\text{Slp}} + E_{\text{Tx}} + \frac{mT_{\text{aw}}(1 - G_{\text{imod}})}{T_{\text{tp}}}T_{\text{idleRX}}\frac{M_{\text{idleRX}}}{A_{\text{pkt}}}, \tag{18}$$

where $m = T_{\text{tp}}/T_{\text{wup}}$ 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 due to sleeping with a maximum value of 1, G_{inc} the increased traffic due to sleeping, T_{idleRX} is the time in one T_{tp} a node spends in idle mode, and M_{idleRX} is the transceiver in idle receive mode (here, the same as M_{Rx}). Traffic offered to the channel is increased because there are arrivals when nodes are sleeping and when the nodes wake up, there will be increased contention.

The radio parameters are listed in Table 1. The total energy consumption per useful transmitted bit in the worst-case scenario with and without sleep groups is depicted in Figure 9. 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 with a nonpersistence of 1 performs very well for a wide range of G,

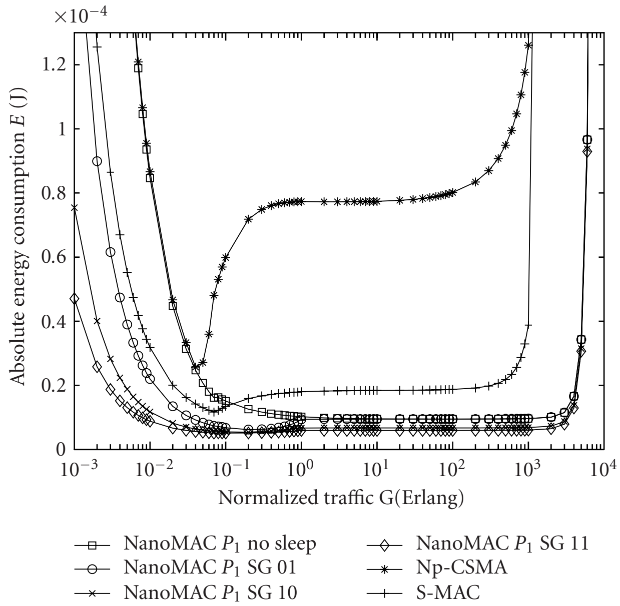

Figure 9: Energy consumption of nanoMAC with sleep groups, np-CSMA, and S-MAC per transmitted MSDU bit in the worst-case scenario with respect to G. A node transmits as often as possible with a 10% duty-cycle constraint and is the recipient for all the other transmissions in the channel.

but eventually in extremely high bursts of G the energy consumption increases exponentially. NanoMAC accomplishes this by being passive and sleeping. The low energy consumption tradeoff is an increase in delay as our work in [21] implies (with throughput-delay calculations). 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 $G = 0.07$. At this point 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 exponentially.

The performance of np-CSMA on the other hand seems quite interesting, but upon closer inspection 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 beyond the point of 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 np-CSMA is a simple protocol, high bursts of traffic lead to a rapid increase in energy consumption per useful bit.

The energy saving effect of regular sleeping can be observed with low values of G and occurs 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.

6. MULTIHOP ANALYSIS

We have described an analytical model for MAC energy evaluation in the previous sections, but up till now we have only considered a single-hop model. From here on we extend our analysis to include the multihop topologies of Figures 1 and 2. In Figure 1 N is the total number of nodes in the multihop chain with uniform optimum spacing d. With multihop, one hop is d meters and node N's packets make N hops reach the sink node whereas for single hop, node N transmits the same data with one hop of distance Nd.

We assume that sleep scheduling similar to nanoMAC's can be made for np-CSMA. ACK frames for np-CSMA are 1 octet long. Three different scenarios are investigated: one with perfect sleep scheduling, one with the multigroup sleep scheduling described in the previous section, 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 multigroup sleep scheduling, we 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 awake during a transmission will overhear it if they are within the range of the transmission. When common sleep scheduling is used, we assume that all N nodes in the linear network are awake at the same time, so all the nodes within the transmission radius will overhear the transmissions. The MAC model produces background traffic in the network resulting in the scenario of Figure 2.

Figure 10 illustrates the energy consumption behavior of the modified np-CSMA with optimum spacing,[2] where d is the characteristic distance d_{char} of (4) and $G = 0.22$. We observe the following: with d_{char}, the optimum multihop power consumption distance, multihop communications always has lower energy consumption than single-hop communications. This behaviour is independent of the MAC protocol even though only np-CSMA is shown in Figure 10. The lower energy consumption performance of multilevel (SG 01) and perfect sleep can only be seen in MAC protocols like np-CSMA because the overheard frames are long. In S-MAC and nanoMAC, the overheard frames are limited to small control frames implying that even perfect sleep

[2]By optimum spacing we mean all the nodes in the chain are equidistant and the separation of nodes d is exactly the radio characteristics dependent characteristic distance d_{char}.

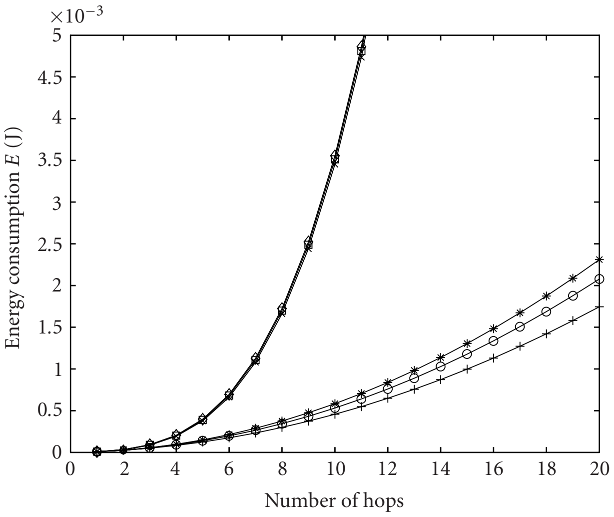

Figure 10: Nonpersistent CSMA with a linear topology. Comparison of single-hop versus multihop communications with characteristic distance d_{char}. All nodes are transmitting and different sleep groups are utilized ($d = 31.5$ m times multiplier N, path loss exponent $\alpha = 2.5$).

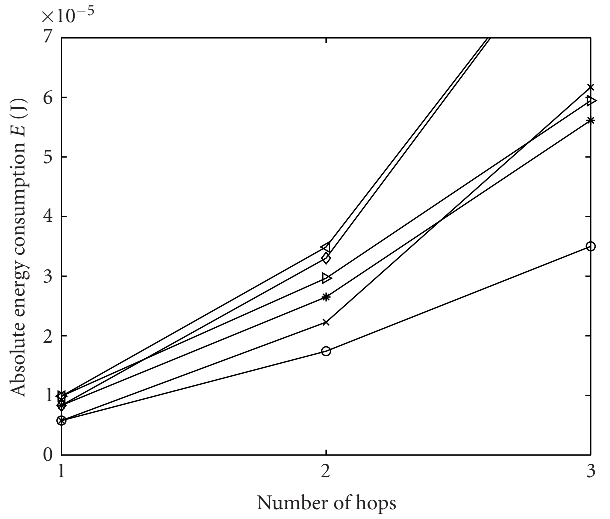

Figure 11: Optimal spacing with characteristic distance d_{char}. Common sleep group for single-hop versus multihop communications. With d_{char}, multihop forwarding always outperforms single-hop communications but, for example, nanoMAC single-hop communications outperform np-CSMA and S-MAC multihop forwarding with 2 hops ($d = 31.5$ m times multiplier N, path loss exponent $\alpha = 2.5$).

scheduling does not provide better energy performance to that of common sleeping. The benefits of an advanced sleep algorithm therefore help only in situations where the channel is lightly loaded as seen in Figure 9. Figure 11 illustrates all three MAC protocols for uniform optimum spacing d_{char} and a common sleep group. We observe the MAC protocols having different energy consumptions even for a small number of hops, but nanoMAC single-hop communications is more energy efficient than np-CSMA and S-MAC multihop communications by up to 2 hops.

Next we make the same analysis as above, but change from uniform optimum spacing to uniform nonoptimal spacing. We choose d to be 10 meters and calculate Figure 12. In the legend the first three curves are for the single-hop case and the latter are for multihop. All of the MAC protocols' single-hop and multihop energy consumption curves cross. Each of the crossing points is outside the feasible single-hop transmission distances of our ISM radio and the protocols illustrate similar behavior to that of Figures 4 and 5 which are calculated without medium access control. The differences between Figures 5 and 12 are mainly in the energy consumption showing that medium access control consumes almost 2 orders of magnitude more energy than in the analysis without medium access control. Therefore, a simpler analysis can illustrate equivalent behavior in some cases even though the absolute values differ. From the figures we deduct that the use of single-hop communications is more energy efficient in wireless sensor networks, where the offered traffic is usually low or moderate and node separation is small. When we compare the protocols with one another, we can see the importance of proper design of the MAC protocol with its neighboring layers; nanoMAC as a sensor MAC protocol achieves over 50% energy savings compared to np-CSMA.

7. MULTIHOP WITH RANDOM SPACING

Lastly, we use the developed analysis technique in realistic wireless sensor networks. To this point we have assumed the node separation in sensor networks to be uniform, but in reality this is generally not achievable due to, for example, the terrain or deployment method. Usually, nodes are scattered around randomly causing certain minimum and maximum separation thresholds. Also, in the case of spatially large sensor networks, single-hop communications can become impossible due to too long node-sink distances. Therefore, we adopt new communication styles: shortest hop and longest hop corresponding to the former multihop and single-hop communications, respectively. Shortest-hop communications applies to many routing protocols, where one chooses a close or closest neighbor towards the sink and routes the data via that neighbor. In the longest-hop strategy, a node tries to transmit to the furthest neighbor it can within the feasible transmission distance of the radio. We use the radio characteristics provided by Table 1 and based on measurements choose 100 meters to be the maximum feasible transmission radius of a node with legal transmission power. We also discard the usage of optimal power control and apply a four-level discrete power control achievable by

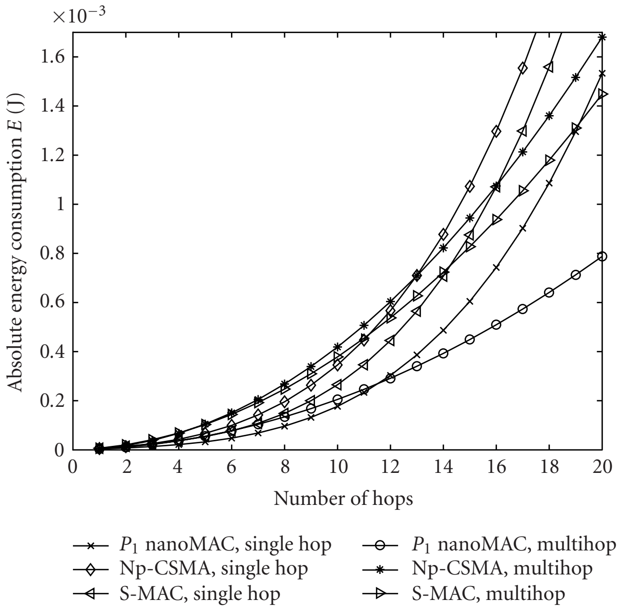

Figure 12: Np-CSMA, S-MAC, and nanoMAC energy consumption with nonoptimal spacing of $d = 10$ meters. Common sleep group applied for all the protocols comparing single-hop versus multihop communications. All the protocols' curves cross implying single-hop communications outperform multihop communications up to the crossover point ($d = 10$ m times multiplier N, path loss exponent $\alpha = 2.5$).

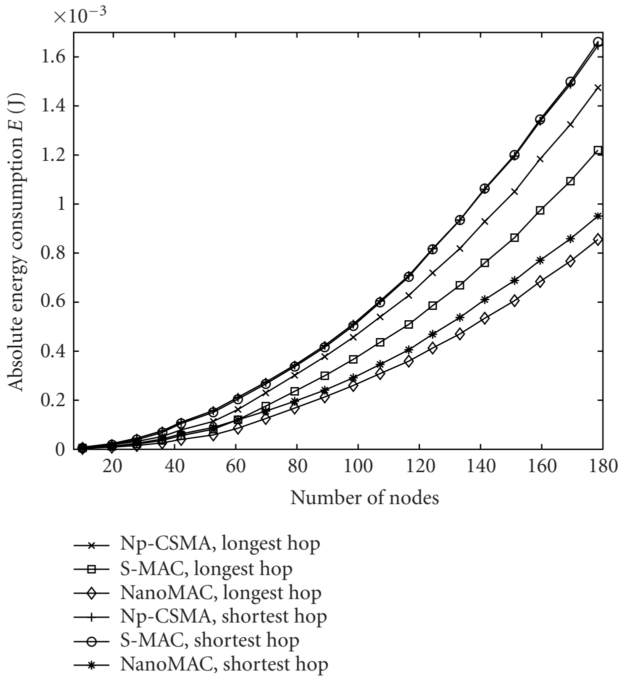

Figure 13: Np-CSMA, S-MAC, and nanoMAC with random [3, 15] meter node spacing. The MAC protocols use common sleep groups and longest-hop versus shortest-hop communications are compared. Note that there is no crossing of curves and longest-hop communications clearly outperform the shortest-hop strategy (total distance (m) with random length hops, $N = 20$, path loss exponent $\alpha = 2.5$).

cheap sensor nodes. The power levels enable transmission to full range and 3/5, 1/3, and 1/10 of full range.

7.1. Short node distances

We set up the network with hop distances randomly chosen between 3 to 15 meters. All the nodes in the network are transmitting data to the sink. An average of 20, d bounded random scenarios are run and the results are illustrated in Figure 13. When we compare the figure to Figure 12, we see that there is no crossing point and the longest-hop method outperforms the shortest-hop method. The behavior is explained by two factors: a discrete step power control causes more overhearing by the shortest-hop communications as well as higher than necessary transmission power. Secondly, although the shortest-hop method could occasionally reach two hops away, it always communicates with the closest node like many traditional ad hoc routing protocols do. Therefore, the shortest-hop method wastes energy and causes the difference in the figures.

7.2. Large node distances

First, we take a look at a special case where there is no power control and nodes always transmit at their set power, full power. We use random hop distances with 5 to 70 meter hops and again average over 20 independent networks. The path loss exponent α is given values between 2 and 4. Figure 14 presents the case of $\alpha = 4$ and we argue that the longest-hop communications mode outperforms the shortest-hop method even with a very harsh radio propagation environment. The results are not unexpected since the shortest-hop method transmits at the same power as the longest-hop method, but always to the nearest neighbor. When α is lower, S-MAC energy performance achieves better results than the modified np-CSMA. We expect that communications using the shortest-hop method occurs within a longer period of time and therefore multiple packet forwarding does not increase G significantly.

Last, we consider a case of random 5 to 50 meter hops with four-level power control. The radio parameters are found in Table 1, but we vary α from 2 (free space) upward. Figure 15 illustrates the energy consumption of nanoMAC with the longest- and shortest-hop communication methods and varying path loss. In a free space environment, the longest-hop communications method has superior energy performance compared to the shortest-hop method. In open fields, where α is usually close to 2.2, the longest-hop method still clearly outperforms the shortest-hop method, but already with light woods ($\alpha \sim 2.4$) the shortest-hop communication achieves better energy performance per bit than the longest hop. Therefore, we deduct that choosing the proper communications method depends heavily on the environment the sensor network is supposed to work in. In large opens spaces one should favor longest-hop communications whereas in large industrial halls where the path loss can be high (close to 4) the shortest-hop communications method is the best choice. The MAC protocol chosen

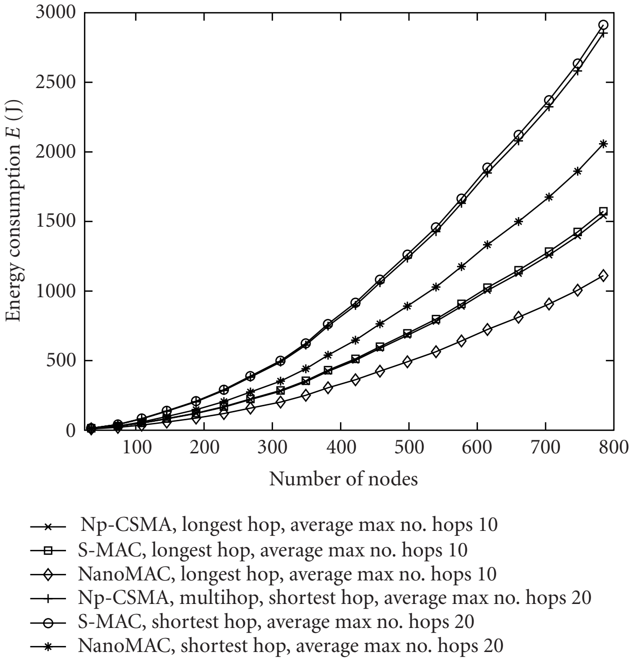

FIGURE 14: Np-CSMA, S-MAC, and nanoMAC with no power control and random [5, 70] meter spacing. Nodes transmit with full power and a common sleep group is applied. Longest-hop versus shortest-hop communications are compared and the longest-hop strategy performs better even with harsh radio environments (total distance (m) with random length hops, $N = 1 - 20$, path loss exponent $\alpha = 4$).

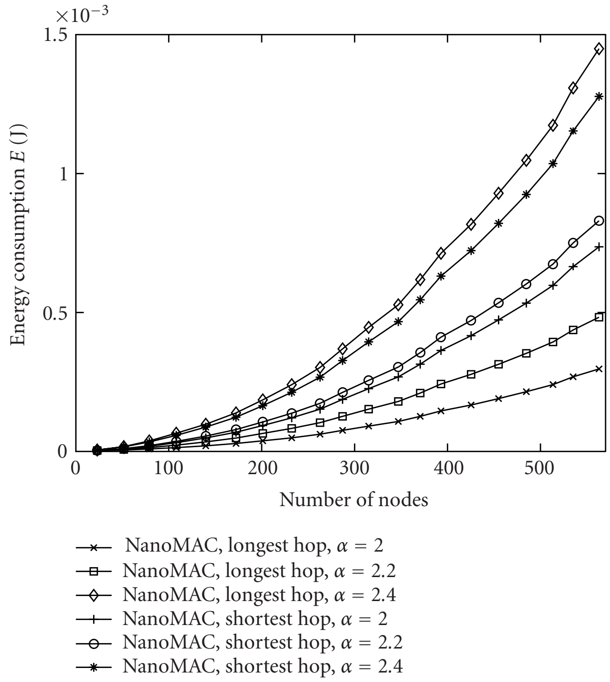

FIGURE 15: The effect of path loss on nanoMAC energy consumption with random [5, 50] meter spacing. A common sleep group for longest-hop versus shortest-hop communications is used. The path loss heavily affects which of the communication styles performs better, with high path loss favoring shortest-hop communications (total distance (m) with random length (5 – 50 m) hops, $N = 20$).

has some importance because in the presented scenario the nanoMAC longest-hop method still has a marginally better behavior than S-MAC shortest-hop methods with $\alpha = 2.5$ (not shown). The individual differences between MAC protocols are still great, for example, resulting in over 35% better energy performance per useful bit from nanoMAC to modified np-CSMA with common sleep mode for both the shortest- and longest-hop methods with $\alpha = 2.5$.

8. CONCLUSIONS AND DISCUSSION

In this paper, we have presented an energy analysis technique applicable to medium access control and multihop communications. By applying this technique, we have gained insight for when to use single-hop communications instead of multihop forwarding. As an application of the presented technique, we have made an energy analysis on np-CSMA, S-MAC, and nanoMAC protocols with sleeping schemes. Based on the analysis, we have discovered many important results that relate 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 multihop from an energy perspective. This phenomenon applies to uniform hop distances of less than the radio-specific optimum transmission distance d_{char} with optimal power control, nonuniform random short and long (long with $\alpha < 2.4$) link distances with discrete four-level power control, and in cases where no power control can be exercised. 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 one magnitude.

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 publications, such as [14, 15], but also any listening that is not absolutely necessary, like listening for the SYNC in S-MAC, decreases the energy performance of a sensor MAC. Binary exponential backoff causing nodes to 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 (see Figures 8 and 9). 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), ACKs should be combined. On the other hand, combining ACK frames makes the common ACK more important and communications more vulnerable to losing the frame. ACK combining is implemented in nanoMAC and proves more energy efficient in our analysis.

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, however, increase the delay, but they can be justified because of the energy savings. Regular, coordinated multigroup sleeping also decreases the energy consumption in both single-hop and multihop communications per transmitted useful bit because it limits the number of overhearing nodes. The energy savings depend heavily on the MAC protocol used as well as whether single-hop or multihop communications is used. The energy saving effect is most effective with MAC protocols where the overheard frames are long, like np-CSMA (see Figure 10).

When designing sensor networks, several factors are required to be taken into account. Firstly, the environment the sensor network is going to operate in suggests whether communications with longest possible links or shortest possible links is more energy efficient. In small areas and large open areas, utilizing longest feasible links is most energy efficient and in large indoor areas shortest link communications is best suited. Secondly, the availability of power control on the transmitter amplifier is an important consideration. If no power control is available, longest feasible hops are recommended no matter the environment. The more adjustable power levels there are, the better short link multihop communication performs. With optimal power control a range of communications where using longest possible hops is more beneficial generally exist, but if the sensor nodes can be placed with the radio-specific characteristic distance d_{char} apart, shortest-hop communications will perform best. Thirdly, if delay is not an important factor, minimize the amount of time the MAC protocol consumes in listening. Periodic listen times after a sleep period should be made as short as possible with functionality to dynamically extend the listening time if data is being received. The listening includes backoff periods, network synchronization periods, and contention for the channel. Finally, the used transceiver's radio parameters highly influence the system energy performance. For example, if the reception circuitry of a radio consumes more energy than transmission at full power as in Bluetooth, single-hop communications becomes much more favorable than multihop communications. The same behavior is observed if the power consumption of the transmitter electronics is dominant. When the transmitter amplifier energy consumption is highly dominant multihop communications is better.

9. FUTURE WORK

In order to continue the analysis, further analytical results will be compared with real measurements. We have implemented nanoMAC on TinyOS for the Berkeley MICA2-mote nodes 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 modifications to the MAC energy model or a switch to Markov chains and a finite number of nodes and the use of energy saving error control codes for low BER values. Different sensor network traffic models influence the energy consumption and the types of protocols used, so the definition of traffic models other than data-centric nodes transmitting to the sink is also needed. Finally, the problem needs to be considered also from the transport and application layer. Different schemes for packet forwarding in sensor networks should be compared using a similar cross-layer analysis.

APPENDICES

A. TRANSMIT ENERGY

From Figure 6 for nanoMAC,

(1)

$$\begin{aligned} E_{\text{Tx}} = {} & T_{\text{CS}} M_{\text{Rx}} + P_b\left(T_{bb} + \frac{T_r}{2}\right) M_{\text{Slp}} + P_b E(B) \\ & + (1 - P_b)(1 - P_{\text{ers}})\left(T_{bp} + \frac{T_r}{2}\right) M_{\text{Slp}} \\ & + (1 - P_b) P_{\text{ers}} E(A) + (1 - P_b) P_{\text{ers}} (T_{\text{pr}} + \text{RTS}) M_{\text{Tx}} \\ & + (1 - P_b)(1 - P_{\text{ers}}) E(B). \end{aligned} \tag{A.1}$$

M_{Tx}, M_{Rx}, and M_{Slp} are transceiver power consumptions in TX, RX, and sleep modes, respectively. Whereas T_{CS} is the time required for carrier sensing, T_{bb} and T_{bp} are weighted average and base backoff times, respectively. Symbol P_b denotes the probability of finding channel busy during CS, $T_r/2$ is the average random delay, P_{ers} is the nonpersistence value of nanoMAC, and T_{pr} and RTS are times to transmit a preamble and an RTS frame, respectively.

(2)

$$\begin{aligned} E(A) = {} & P_s(\Delta) M_{\text{Rx}} + P_s(\Psi) M_{\text{Tx}} + (1 - P_s) P_{nf} (T_f) M_{\text{Rx}} \\ & + (1 - P_s) P_{nf} E(B) + (1 - P_s)(1 - P_{nf}) E(B) \\ & + (1 - P_s)(1 - P_{nf})\left(\frac{T_f}{2} + T_{\text{pr}} + \text{RTS}\right) M_{\text{Rx}} \\ & + (1 - P_s)(1 - P_{nf})(T_{\text{pkt}} - T_{\text{pr}} - \text{RTS}) M_{\text{Slp}}, \end{aligned} \tag{A.2}$$

where $\Delta = 2 \times T_{\text{pr}} + \text{CTS} + \text{ACK} + T_{\text{to}}/2$, $\Psi = T_{\text{pr}} + 9 \times (T_{\text{prs}} + T_{\text{sym}}) + 10 \times \text{Data}$, and P_{nf} is the probability of not having a new data transmission by another device during failed period T_f. $T_{\text{pkt}} = 4 \times T_{\text{pr}} + \text{RTS} + \text{CTS} + 9 \times (T_{\text{prs}} + T_{\text{sym}}) + 10 \times \text{Data} + \text{ACK} + T_{\text{to}}$, where T_{prs} is a short preamble, T_{sym} is the time of 1 symbol, CTS, Data, and ACK are the corresponding times to transmit those frames, and T_{to} is the timeout delay.

(3)

$$\begin{aligned} E(B) = {} & (1 - P_c)(T_{\text{CS}} + \text{RTS}) M_{\text{Rx}} + (1 - P_c) E(B) \\ & + (1 - P_c)(T_{\text{pkt}} - T_{\text{pr}} - \text{RTS}) M_{\text{Slp}} + P_c (1 - P_{\text{ers}}) E(B) \\ & + P_c (1 - P_{\text{ers}})\left(T_{bp} + \frac{T_r}{2} + e\right) M_{\text{Slp}} \\ & + P_c P_{\text{ers}} (M_{\text{Rx}} T_{\text{CS}} + M_{\text{Tx}} (T_{\text{pr}} + \text{RTS})) + P_c P_{\text{ers}} E(A), \end{aligned} \tag{A.3}$$

where P_c is probability of finding no transmissions during time e. Inserting $E(A)$ into the above equation of $E(B)$, we can solve $E(B)$ and get

$$E(B) = (\omega + P_c P_{\text{ers}}\delta)(P_{\text{ers}} P_c P_s)^{-1}, \tag{A.4}$$

where

$$\begin{aligned}
\omega &= P_c P_{\text{ers}}(M_{\text{Rx}} T_{\text{CS}} + M_{\text{Tx}}(T_{\text{pr}} + \text{RTS})) \\
&\quad + P_c(1 - P_{\text{ers}})\left(M_{\text{Slp}}\left(T_{bp} + \frac{T_r}{2} + e\right)\right) \\
&\quad + (1-P_c)(M_{\text{Rx}}(T_{\text{CS}}+\text{RTS}) + M_{\text{Slp}}(T_{\text{pkt}} - T_{\text{pr}} - \text{RTS})), \\
\delta &= P_s(M_{\text{Rx}}(\Delta) + M_{\text{Tx}}(\Psi)) + (1 - P_s)P_{nf}(M_{\text{Rx}}(T_f) \\
&\quad + M_{\text{Slp}}(T_{\text{pkt}} - T_{\text{pr}} - \text{RTS})) \\
&\quad + (1 - P_s)(1 - P_{nf})\left(M_{\text{Rx}}\left(\frac{T_f}{2} + T_{\text{pr}} + \text{RTS}\right)\right).
\end{aligned} \tag{A.5}$$

Now we can solve $E(A)$ as follows:

$$E(A) = \delta + (1 - P_s)(\omega + P_c P_{\text{ers}}\delta)(P_{\text{ers}} P_c P_s)^{-1}. \tag{A.6}$$

The term $E(A)$ gives a constraint: the probability of no collision with retransmit RTS $P_c > 0$ and the probability of successful data transmission $P_s > 0 \rightarrow G \in [0, \infty]$.

B. RECEIVE ENERGY

Based on Figure 7 we can solve the average reception energy consumption E_{Rx} of nanoMAC by analyzing *Idle* $E(I)$ and *Reply* $E(R)$ states:

(1)

$$\begin{aligned}
E(I) &= (1-P_s)(1-P_{nf})\left(2T_{\text{CSRX}} + 2\text{RTS} + T_{\text{pr}} + \frac{T_f}{2}\right)M_{\text{Rx}} \\
&\quad + (1 - P_s)(1 - P_{nf})(T_{\text{pkt}} + \text{RTS} + T_{\text{pr}})M_{\text{Slp}} \\
&\quad + (1 - P_s)(1 - P_{nf})E(I) + (1 - P_s)P_{nf}E(I) \\
&\quad + (1 - P_s)P_{nf}\left(T_{\text{CSRX}} + \text{RTS} + \frac{T_f}{2} + e\right)M_{\text{Rx}} \\
&\quad + P_s(T_{\text{CSRX}} + \text{RTS} + T_{\text{proc}} + e)M_{\text{Rx}} + P_s E(R),
\end{aligned} \tag{B.1}$$

where T_{CSRX} is receive carrier sense delay and T_{proc} is the processing delay in the MAC protocol.

(2)

$$\begin{aligned}
E(R) &= P_{\text{senh}}(2T_{\text{pr}} + \text{CTS} + \text{ACK})M_{\text{Tx}} \\
&\quad + P_{\text{senh}}(T_{\text{pr}} + 9(T_{\text{prs}} + T_{\text{sym}}) + 10\text{Data} + T_{\text{proc}})M_{\text{Rx}} \\
&\quad + (1-P_{\text{senh}})(2T_{\text{pr}} + 9(T_{\text{prs}} + T_{\text{sym}}) + 10\text{Data} + T_{\text{to}})M_{\text{Rx}} \\
&\quad + (1-P_{\text{senh}})(2T_{\text{pr}} + \text{CTS} + \text{ACK})M_{\text{Tx}} + (1-P_{\text{senh}})E(I),
\end{aligned} \tag{B.2}$$

where P_{senh} is the enhanced probability of not having a collision during CTS transmission and CTS and Data are times needed to transmit a CTS frame and a data frame, respectively. From the above equations we can solve E_{Rx} and get

$$E_{\text{Rx}} = E(I) = (\mu + P_s\theta)(P_s P_{\text{senh}})^{-1}, \tag{B.3}$$

where

$$\begin{aligned}
\mu &= (1 - P_s)(1 - P_{nf})\Big[(T_{\text{pkt}} - T_{\text{pr}} - \text{RTS})M_{\text{Slp}} \\
&\qquad + \left(2T_{\text{CSRX}} + 2\text{RTS} + T_{\text{pr}} + \frac{T_f}{2}\right)M_{\text{Rx}}\Big] \\
&\quad + (1 - P_s)P_{nf}\left(T_{\text{CSRX}} + \text{RTS} + \frac{T_f}{2} + e\right)M_{\text{Rx}} \\
&\quad + P_s(T_{\text{CSRX}} + \text{RTS})M_{\text{Rx}}, \\
\theta &= P_{\text{senh}}[(2T_{\text{pr}} + \text{CTS} + \text{ACK})M_{\text{Tx}} \\
&\qquad + (T_{\text{pr}} + 9(T_{\text{prs}} + T_{\text{sym}}) + 10\text{Data} + T_{\text{proc}})M_{\text{Rx}}] \\
&\quad + (1 - P_{\text{senh}})[((2T_{\text{pr}} + \text{CTS} + \text{ACK})M_{\text{Tx}}) \\
&\qquad + (T_{\text{pr}} + 9(T_{\text{prs}} + T_{\text{sym}}) + 10\text{Data} + T_{\text{to}})M_{\text{Rx}}].
\end{aligned} \tag{B.4}$$

For reception, the constraint $P_s P_{\text{senh}} > 0 \rightarrow G < \infty$ is introduced.

C. ENERGY CONSUMPTION WITH SLEEP GROUPS

The total energy consumption and sleep has to be expressed in parts as a function of G, the average, normalized traffic offered to the channel. When $G = 1$ (the capacity of the channel) and we denote R_d as the data rate, A_{pkt} as the MSDU size, and T_{tp} of (16) as the minimum period between two consecutive packet transmissions by node(i), $(R_d/A_{\text{pkt}})T_{\text{tp}}$ new packets arrive to the system in T_{tp} period. When $G = (A_{\text{pkt}}/(R_d T_{\text{tp}}))$, only one packet is generated for transmission every T_{tp}. When $G \leq (R_d/A_{\text{pkt}})T_{\text{tp}}$, the transceiver of the node(i) stays in idle listening T_{idleRX} for

$$T_{\text{idleRX}} = \frac{A_{\text{pkt}}}{R_d T_{\text{tp}} G}\left(T_{\text{tp}} - \frac{C_{\text{pkt}}}{R_d}\right) \tag{C.1}$$

seconds for every packet transmitted.

When $(R_d/A_{\text{pkt}})T_{\text{tp}} \leq G \leq 1$, at least one packet is generated every T_{tp} and one of the generated packets can be assigned for transmission by node(i). In this worst case scenario, all the other generated packets during the period T_{tp} will be assigned for reception by node(i). So, for total energy consumption E_{tot}, we get

$$\begin{aligned}
E_{\text{tot}} &= E_{\text{Tx}} + \left(\frac{1}{C_{\text{pkt}}} - \frac{1}{R_d T_{\text{tp}}}\right)\left(1 - \frac{A_{\text{pkt}}}{R_d T_{\text{tp}} G}\right)E_{\text{Rx}} \\
&\quad + T_{\text{idleRX}}\frac{M_{\text{idleRX}}}{A_{\text{pkt}}},
\end{aligned} \tag{C.2}$$

where the energy consumption is per successfully transmitted useful bit by node(i), E_{Tx} is found from (12) and divided by A_{pkt}, E_{Rx} is found from (15) and divided by A_{pkt}, and M_{idleRX} is the power consumption for listening for empty channel.

When $G \geq 1$, exactly one packet is generated for transmission by node(i) in a T_{tp} and almost all the rest of the time is for receiving packets, but due to multiple access environment, a small amount of channel capacity is still used for idle listening. In order to use E_{tot} we have to set some constraints for the equation to be valid with different values of G. The constraints are

$$E_{\text{Rx}} = \begin{cases} 0, & \text{if } G < \dfrac{A_{\text{pkt}}}{R_d T_{\text{tp}}}, \\ \dfrac{(15)}{A_{\text{pkt}}}, & \text{else.} \end{cases} \tag{C.3}$$

Lastly, sleeping is taken into account in E_{tot}. A device stays awake a period of $T_{\text{aw}} = 85$ milliseconds $+ \{0 - (C_{\text{pkt}}/R_d)\}$ ($T_{\text{bwu}} = 85$ milliseconds), where C_{pkt}/R_d is the time needed to communicate one packet, C_{pkt} is the length of the packet on the channel, and T_{bwu} is the base awake time of node(i). When $G < A_{\text{pkt}}/(R_d T_{\text{tp}})$, $T_{\text{aw}} = 85$ milliseconds. When $G \geq 1$, $T_{\text{aw}} = 85 + (C_{\text{pkt}}/R_d)$ milliseconds with high probability. Therefore, we can expect

$$T_{\text{aw}} = T_{\text{bwu}} + G_{\text{mod}} \frac{C_{\text{pkt}}}{R_d}, \tag{C.4}$$

where $G_{\text{mod}} = 1$ when $G > 1$ is the channel capacity limited traffic offered to the channel. Node(i) will sleep for $T_{\text{wup}} - T_{\text{aw}}$ seconds, where T_{wup} is the wake up period defined by sleep groups (SG 00, SG 01, SG 10, and SG 11 of Section 5.2). If a device does not sleep, it belongs to group SG 00, and $T_{\text{wup}} = T_{\text{aw}}$.

If node(i) sleeps, it reduces the number of received packets in a T_{tp} and also that reduces the time T_{tp} itself by reducing MAX(r) of (17), the maximum number of received packets between two consecutive transmissions. The new MAX(r), marked MAX(r_{slp}) can be calculated by the formula

$$\text{MAX}(r_{\text{slp}}) = \left(\left(\frac{T_{\text{aw}}}{T_{\text{wup}}}\right)\left(\frac{S_{\text{Tx}}}{C_d(C_{\text{pkt}} + T_{\text{proc}})} - 1\right)\right) \times \left(1 - \frac{R_{\text{Tx}}}{C_d(C_{\text{pkt}} + T_{\text{proc}})}\right)^{-1}, \tag{C.5}$$

where S_{Tx} is the amount of data the originator transmits data in a packet exchange, T_{proc} is the processing delay measured here in bits, R_{Tx} is the amount of data the recipient transmits data in a packet exchange, and C_d is the duty cycle. T_{tp} can be calculated with MAX(r_{slp}).

In a T_{tp}, there are $m = T_{\text{tp}}/T_{\text{wup}}$ wake-ups and during sleep there are $(G(T_{\text{wup}} - T_{\text{aw}})R_d)/A_{\text{pkt}}$ new arrivals and thus they increase the traffic offered to the channel G_{inc} to be

$$G_{\text{inc}} = G\left(1 + \frac{(T_{\text{wup}} - T_{\text{aw}})^2 R_d}{T_{\text{wup}} A_{\text{pkt}}}\right). \tag{C.6}$$

With the above equations, we can present the total energy consumption E_{tot} with sleep groups E_{WCS} as

$$\begin{aligned} E_{\text{WCS}} = {} & \frac{m T_{\text{aw}} G_{\text{imod}}}{T_{\text{tp}}}\left(\frac{1}{C_{\text{pkt}}} - \frac{1}{R_d T_{\text{tp}}}\right) \\ & \times \left(1 - \frac{A_{\text{pkt}}}{R_d T_{\text{tp}} G_{\text{inc}}}\right) E_{\text{Rx}} + \frac{m(T_{\text{wup}} - T_{\text{aw}})}{A_{\text{pkt}}} M_{\text{Slp}} \\ & + E_{\text{Tx}} + \frac{m T_{\text{aw}}(1 - G_{\text{imod}})}{T_{\text{tp}}} T_{\text{idleRX}} \frac{M_{\text{idleRX}}}{A_{\text{pkt}}}, \end{aligned} \tag{C.7}$$

where $G_{\text{imod}} = G_{\text{inc}}$, when $G_{\text{inc}} \leq 1$, and $G_{\text{imod}} = 1$ otherwise.

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