Duty-Cycle Optimization in Unslotted 802.15.4 Wireless Sensor Networks

Sinem Coleri Ergen, Carlo Fischione, Dimitri Marandin, Alberto Sangiovanni-Vincentelli

***Abstract*—We present a novel approach for minimizing the energy consumption of medium access control (MAC) protocols developed for duty-cycled wireless sensor networks (WSN) for the unslotted IEEE 802.15.4 standard while guaranteeing delay and reliability constraints. The main challenge in this optimization is the random access associated with the existing IEEE 802.15.4 hardware and MAC specification that prevents controlling the exact transmission time of the packets. Data traffic, network topology, MAC, and the key parameters of duty cycles (sleep and wake time) determine the amount of random access, which in turn determines delay, reliability and energy consumption. We formulate and solve an optimization problem where the objective function is the total energy consumption in transmit, receive, listen and sleep states, subject to constraints of delay and reliability of the packet delivery and the decision variables are the sleep and wake time of the receivers. The optimal solution can be easily implemented on existing IEEE 802.15.4 hardware platforms, by storing light look-up tables in the receiver nodes. Numerical results show that the protocol outperforms significantly existing solutions.**

***Index Terms*—Wireless Sensor Networks (WSNs), IEEE 802.14.5, MAC, Duty Cycle, Convex Optimization.**

I. INTRODUCTION

Energy efficiency is essential for applications based on wireless sensor networks (WSNs) where the sensor nodes may not be recharged once their energy is drained. The radio in WSNs consumes a considerable amount of energy and listening to the radio channel consumes as much energy as receiving data. Idle listening should be minimized since it does not contribute to the operation of the network, yet it may require a relatively large amount of energy.

Duty cycling has been proposed as an effective mechanism for reducing idle listening in random access networks. It is based on periodical cycling between a sleep and an awake state. Key parameters determining the duty cycle are the sleep time and wake time. The main advantage of duty cycling is that nodes do not require any additional hardware for low power listening. Even more importantly it does not require complex control mechanisms, as in time division multiple access (TDMA) schemes, for discovering the network topology, keeping the nodes synchronized [1] and running the schedules efficiently [2]. Duty cycling is particularly appealing for dynamic networks where locations of the sensor nodes and data traffic generated at each node are changing over time. However, the intrinsic simplicity of the mechanism has the drawback of smaller energy saving potential as compared to the more complex solutions listed above unless optimization of sleep and wake times is adapted to changing data traffic conditions.

Duty cycling MAC protocols are of two types: synchronous and asynchronous. Synchronized protocols, such as SMAC [3] and TMAC [4], are based on negotiating a schedule among the neighboring nodes to specify when the nodes are awake and asleep. Asynchronous protocols such as the well known B-MAC [5] and X-MAC [6] are based on preamble sampling. In these methods, the receiver wakes up periodically to check whether there is a transmission and the sender, instead of coordinating the neighbors' wake up times, sends a preamble that is long enough to ensure the receiver wakes up during the preamble.

In this paper, we consider the IEEE 802.15.4 communication standard [7] because of its pervasive use in WSNs. Sleep and wake time optimization in preamble sampling for IEEE 802.15.4 was considered in B-MAC [5] and X-MAC [6]. Both B-MAC and X-MAC work on top of IEEE 802.15.4 and do not require any modification of the IEEE standard. Specifically, in X-MAC, an optimization problem is proposed to determine the optimal wake and sleep times, given the packet generation rate. The problem, however, does not take into account the effect of random access, which is a function of the data traffic, MAC parameters and topology, in formulating the energy function. Moreover, in [5], [6] and references therein, no delay or reliability constraint on packet delivery is included. MAC protocols for sensor networks have small latency and high reliability requirements in addition to low energy consumption. Since many applications, e.g. security monitoring, require guaranteed arrival of sensor data to the collection center and others require a certain degree of reliability in delivering sensor data (e.g., control and automation applications), latency minimization must be considered in MAC design.

The original contributions of this paper are three: First, we propose a modeling of the energy consumption, reliability and delay of the packets as function of wake and sleep times of preamble sampling protocols for unslotted IEEE 802.15.4 WSNs. Second, we formulate an optimization problem where these protocol parameters are decision variables and data traffic, network topology, delay and successful packet delivery constraints are considered. Finally, because of the computational complexity of the optimization problem that makes it hard to solve on a sensor node with limited computing

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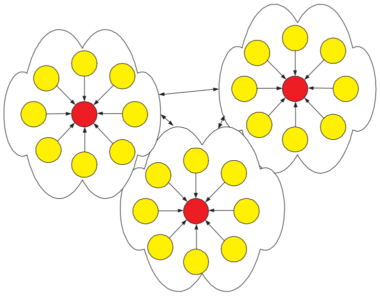

Fig. 1. Clustered network topology. The packets generated by the yellow nodes are transmitted toward the sink node depicted in the middle of each cluster.

capabilities, we formulate a simplified problem where cost function and constraints are approximated using empirical models whose parameters are determined by simulation and stored in a look-up table. To the best of our knowledge, this approach is new.

The rest of the paper is organized as follows: In Section II the system model is presented. In Section III the optimization problem is formulated and the challenges in solving this problem are stated. Section IV presents a simplified approach where the functions involved in the optimization problem are approximated by empirical models whose parameters are determined by simulation. The approach is validated and compared with other methods in Section V.

II. SYSTEM MODEL

We assume that the nodes of the WSN are organized into clusters as shown in Fig. 1. Clustered network topology is supported in large networks that require energy efficiency, since transmitting data through intermediate nodes may consume more than routing directly to the base station [8]. In a clustered topology, nodes organize themselves into clusters with a node which acts as cluster head. All non-cluster head nodes transmit their data directly to the cluster head, while the cluster head receives data from all cluster members and transmits them to a remote base station. Throughout this paper we consider applications where nodes asynchronously generate packets within a period having duration r seconds. Given this source characteristics, the unslotted IEEE 802.15.4 is the best MAC choice [7].

For the network topology and applications we are considering, the asynchronous duty-cycling MAC protocol based on preamble sampling with acknowledgment called X-MAC [6] offers good performance. In preamble sampling protocols, the receiver wakes up periodically for a short time to sample the medium. When a sender has data, it transmits a series of short preamble packets, each containing the ID of the target node, until it either receives an acknowledgement (ACK) packet from the receiver or a maximum sleep time is exceeded. Following the transmission of each preamble packet, the transmitter node waits for timeout. If the receiver is not the target, it returns to sleep immediately. If the receiver is the target, it sends an ACK during the pause between the preamble packets. Upon reception of the ACK, the sender transmits the data packet to the destination. Fig. 2 shows the communication states between a transmitter and a receiver.

Packets in preamble sampling protocols are sent using random access so the time duration between sending the packet to the MAC layer and over the physical link is random. Note that the ACK packets are also sent using random access. The time duration in random access may be much larger than the packet transmission time: In IEEE 802.15.4 [7] radios with default parameter settings, the maximum backoff before packet transmission is 27.4ms whereas the transmission time of a 56 byte packet is 1.79ms at 250kbps. The amount of random access, which depends on the data traffic, network topology and the parameters of the MAC protocol should be included in the energy minimization problem since random access

- determines the time interval between the transmissions of two consecutive preamble packets;
- determines wake time, since the destination node should receive at least one preamble packet during the wake time;
- determines the time-out time for the ACK and data packets;
- is affected by sleep time, since increasing sleep time increases the expected number of preambles.

To illustrate the dependency of the random access on the data traffic, network topology and the parameters of the MAC protocol, we briefly explain the random access mechanism in IEEE 802.15.4 protocol next.

A. IEEE 802.15.4 unslotted CSMA/CA Mechanism

In the unslotted IEEE 802.15.4 carrier sense multiple access with collision avoidance (CSMA/CA) mechanism, each device in the network has two variables: NB and BE. NB is the number of times the CSMA/CA algorithm is required to backoff while attempting the current transmission. NB is initialized to 0 before every new transmission. BE is the backoff exponent, which is related to how many backoff periods a device must wait before it attempts to assess the channel. The algorithm is implemented using units of time called backoff periods. The parameters that affect the random backoff are $BE_{\min}$, $BE_{\max}$ and $NB_{\max}$, which correspond to the minimum and maximum of BE and the maximum of NB respectively.

The expected number of times random backoff is repeated is a function of the probability of sensing the channel busy, which depends on the channel traffic. Channel traffic depends on data traffic, network topology and duty cycle parameters, i.e. sleep and wake time, since they determine the expected number of preamble packets. This complex interdependence is investigated in the following sections.

III. PROTOCOL ANALYSIS

In this section, we formulate an optimization problem where the objective function is the energy consumption of the network, subject to reliability and delay constraints. The solution of the optimization problem gives the optimal sleep and wake times of the nodes.

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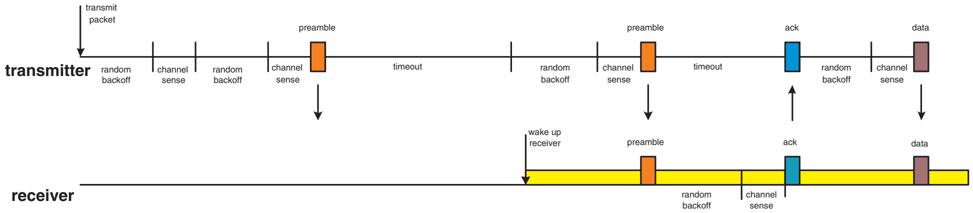

Fig. 2. Communication states between a transmitter and a receiver. A random number of preambles are sent before that one falls in the listening period of the receiver. Afterwards, the receiver sends an ACK. When the transmitter hears the ACK, the data packet is sent.

For each cluster with cluster head n, the optimization problem is:

$$\mathcal{P}_n : \quad \min_{R_s, R_l} \quad \mathbb{E}\left[\sum_{k\in\mathcal{N}_n} E_{tx}^{(k,n)} + E_{rx}^{n} + E_{l}^{n} + E_{s}^{n}\right] \tag{1}$$

$$\text{s.t.} \quad \frac{1}{|\mathcal{N}_n|}\sum_{k\in\mathcal{N}_n} \mathbb{E}\left[R_{(k,n)}\right] \geq R_{\min}\,, \tag{2}$$

$$\frac{1}{|\mathcal{N}_n|}\sum_{k\in\mathcal{N}_n} \mathbb{E}\left[D_{(k,n)}\right] \leq D_{\max}\,. \tag{3}$$

where $E_{tx}^{(k,n)}$ is the transmit energy over link (k,n) and E_{rx}^{n}, E_{l}^{n} and E_{s}^{n} are the receive, listen and sleep energy at node n, respectively; R_s and R_l are the sleep time and wake time respectively; $R(k,n)$ and $D(k,n)$ are the reliability and delay of link (k,n) whereas $R_{\min}$ and $D_{\max}$ are the minimum acceptable reliability and maximum acceptable delay respectively. The symbol $\mathbb{E}$ denotes the statistical expectation over random backoff. The term $\mathcal{N}_n$ denotes the set of nodes communicating with n, whereas $|\mathcal{N}_n|$ is the cardinality of the set. To reduce the computational complexity of the problem, we expressed the constraints with the normalized sum of the delay and reliability, so that the constraints represent an average per link. In Problem $\mathcal{P}_n$, for sake of notation simplicity, we abused notation by neglecting the dependence of R_s and R_l, and $R_{\min}$ and $D_{\max}$ on the cluster-head n .

The exact computation of the analytical expressions in the optimization problem is a difficult task, since the wake time and sleep time of each node affect the delay, reliability and energy, along with the channel traffic. Furthermore, channel traffic, MAC parameters and network topology determine the total backoff, which then determines the number of preambles together with sleep time and wake time of the receiver. The number of preambles in turn affects the total channel traffic in the network. Even if analytical models of the expectations in Problem $\mathcal{P}_n$ were available, the complex relation among the decision variables would require the use of fairly sophisticated optimization tools to solve $\mathcal{P}_n$, which are difficult or impossible to implement on computationally-limited sensor nodes. To overcome these problems, we propose an empirical explicit model, where the cost function and the constraints of Problem $\mathcal{P}_n$ are approximated using Monte Carlo simulations. We will see in the next section that the equations depend on certain regression coefficients, which can be easily derived and stored in a look-up table.

IV. SIMULATION BASED EMPIRICAL MODELS

Simple empirical explicit relations of the functions with respect to the decision variables are determined with off-line simulation so that the approximated Problem $\mathcal{P}_n$ can be quickly solved by the nodes. All the numerical values set for the simulations are taken coherently with the IEEE 802.15.4 standard [7] and the Tmote wireless sensors [9]. The simulation environment chosen is ns-2.

The length of preamble, acknowledgement and data packets are 24, 22 and 56 bytes for data payload of 35 bytes, which correspond to 0.77ms, 0.70ms and 1.79ms at 250kbps, respectively. $BE_{\min} = 3$, $BE_{\max} = 5$, and $NB_{\max} = 4$ unless otherwise stated. We simulated up to three clusters with a star topology sending data to their middle nodes. We considered clusters with a number of nodes up to 10, and packet generation periods from 10 s to 300 s. Lower packet generation periods are not useful because they lead to too many collisions, and hence to poor reliability. The simulations takes into account both the no-hidden terminal problem and the hidden-terminal problem.

Implementing Monte Carlo simulations, the average reliability, delay and energy consumption are measured as a function of sleep and wake time. Linear regression is then used to approximate the relationship between these averages, the sleep time, and the wake time. We have chosen linear regression because this allows modeling the relations with convex quadratic functions and yields a closed form solution to the optimization problem. The solution can then be easily implemented on sensors, as we describe in Section IV-D. Obviously, the approximations could be improved using high-order polynomial fittings. However, solving the optimization problem in this case becomes more complex numerically.

A. Reliability Constraint

When $R_l \geq R_{l,\min} = 6\,\text{ms}$, the simulation results show that the reliability constraint in Problem $\mathcal{P}_n$ is well approximated with:

$$\frac{1}{|\mathcal{N}_n|}\sum_{k\in\mathcal{N}_n} \mathbb{E}\left[R_{(k,n)}\right] \approx i_R + r_R\frac{R_s}{R_l}\,, \tag{4}$$

where i_R represents the intercept, r_R denotes the coefficient of R_s/R_l.

In Fig. 3 and 4 we report an example of the simulation results for the reliability measured as function of sleep time and wake time for packet generation periods of 300 s and 30 s respectively, as obtained with 8 nodes. The example is

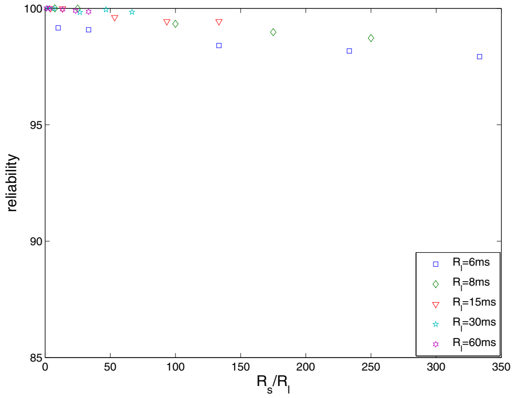

Fig. 3. Reliability as a function of the ratio of sleep time to wake time for data generation period of 300 s (5 minutes).

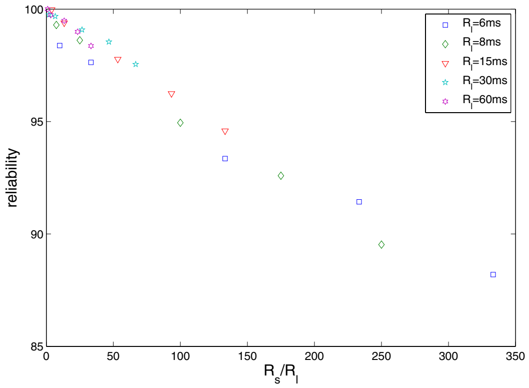

Fig. 4. Reliability as a function of the ratio of sleep time to wake time for data generation period of 30 s.

referred to the case of no-hidden terminal problem. The figures show that as the ratio of sleep time to wake time increases, the expected number of preambles increases, which in turn increases the random backoff and decreases reliability.

Table I shows on the left the coefficients of (4) for various cases of the backoff exponent and packet generation period as obtained by the simulations for the case of clusters with 8 nodes. In the table, ρ_R^2 is the correlation coefficient between the simulation data and the model (4) whereas p_b and p_c are the busy channel and collision probability respectively (the collision probability is very small so that it can be assumed to be 0 for this scenario). The closer ρ_R^2 to 1, the better the approximation. From the table, ρ_R^2 is very high at 30 s packet generation period. Although ρ_R^2 is only 0.7797 at 300 s packet generation period, the variance of the delivery probability is very low. However, in general a good approximation of (4) in fitting the real data can be observed. Obviously, the approximation could be very accurate if one would use high-degree polynomial fitting. However, this would not allow to solve the optimization problem with a closed form expression, as we will see later. The model (4) holds also for different number of nodes and traffic rates (obviously with different values of the coefficients).

B. Delay Constraint

A good linear relationship between delay and sleep time can be inferred from the Monte Carlo simulations. Using linear regression from the simulation data, the delay constraint of Problem $\mathcal{P}_n$ can be approximated with

$$\frac{1}{|\mathcal{N}_n|}\sum_{k\in\mathcal{N}_n}\mathbb{E}\,D_{(k,n)} \approx i_D + r_{D,s}R_s - r_{D,l}R_l\,. \tag{5}$$

This approximation is valid only when $R_s \geq R_l$ for all the cases considered. However, this is not a limitation, because, to save energy, sensors have to use duty cycles much smaller than 50%, which is perfectly compatible with $R_s \geq R_l$.

In Fig. 5 we have reported one example of the simulations for the average delay for different wake and sleep times for packet generation period of 300 s. It is evident that since the packet transmission time and wake time are very short compared to the sleep time, the delay increases almost linearly with sleep period.

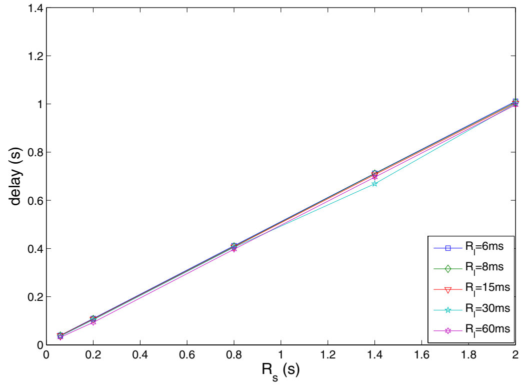

Fig. 5. Average delay for different wake-up and sleep periods for data generation period of 300 s (5 minutes).

In Table I, the values of the linear regression obtained for a few simulations are reported on the right for the case of clusters with 8 nodes. The model (5) holds also for different number of nodes and traffic rates (obviously with different values of the coefficients).

C. Energy

As we did for reliability and delay, it is possible to interpolate the energy values obtained through the simulations as function of the sleep and wake periods. Thus the cost function of Problem $\mathcal{P}_n$ is approximated with

$$E_{\text{tot}} \approx i_E + r_{E,l}R_l^2 + r_{E,s}R_s^2 + g_{E,l}R_l + g_{E,s}R_s\,. \tag{6}$$

In Fig. 6 and Fig. 7 we have reported an example of simulations used to model the energy as a function of R_s and R_l for packet generation periods of 30 s and 300 s respectively, as obtained for clusters with a star topology of 8 nodes. The effect of the tradeoff between the energy consumed when the node is transmitting and receiving a packet is clear only when the data generation period and wake time are small. The

				Reliability			Delay			
$BE_{\min}$	r	p_b	p_c	i_R	r_R	ρ_R^2	i_D	$r_{D,s}$	$r_{D,l}$	ρ_D^2
0	30s	0.01	0.00	98.4218	-0.0449	0.8583	0.0040	0.5027	-0.1444	0.9998
0	300s	0.001	0.00	99.9030	-0.0055	0.7379	0.0077	0.4979	-0.2919	0.9994
3	30s	0.01	0.00	99.6673	-0.0376	0.9728	0.0136	0.5021	-0.3273	0.9999
3	300s	0.001	0.00	99.9533	-0.0062	0.7797	0.0134	0.4997	-0.3283	0.9996

TABLE I
LINEAR REGRESSION COEFFICIENTS FOR THE RELIABILITY (LEFT) AND DELAY (RIGHT).

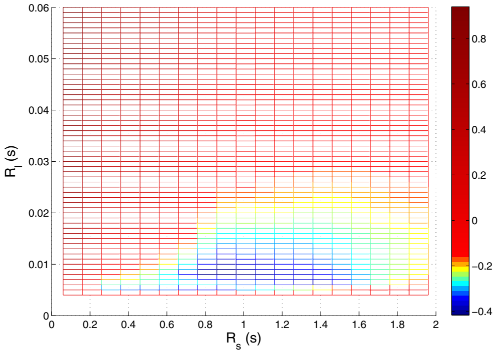

Fig. 6. Average energy as a function of R_s and R_l for 30 s packet generation period (the values of the energy are reported in log units).

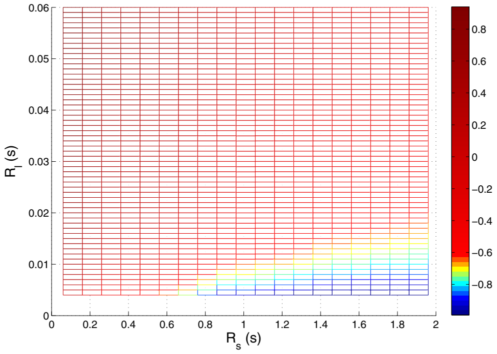

Fig. 7. Average energy as a function of R_s and R_l for 300s packet generation period (the values of the energy are reported in log units).

optimal sleep time decreases whereas the optimal wake time increases as the packet generation rate increases.

For the cases studied in Fig. 6 and Fig. 7, the value of the correlation coefficient between the simulation data and the model (6), which is denoted with ρ_E^2, is 0.9390 and 0.9867 for packet generation periods of 30 s and 300 s respectively, confirming the usability of regression equation for the energy. We observed that the correlation coefficient for the model (6) has the same behavior for different number of nodes and packet generation rates (obviously with different values of the regression coefficients).

D. Optimal Solution

The models of the energy, reliability and delay constraints given by Equations (6), (4) and (5) respectively can be put together to approximate Problem $\mathcal{P}_n$ as

$$\begin{aligned} \tilde{\mathcal{P}}_n : \min_{R_s, R_l} \quad & i_E + r_{E,l} R_l^2 + r_{E,s} R_s^2 + g_{E,l} R_l + g_{E,s} R_s \quad (7) \\ \text{s.t.} \quad & i_R + r_R \frac{R_s}{R_l} \geq R_{\min} , \\ & i_D + r_{D,s} R_s - r_{D,l} R_l \leq D_{\max} , \\ & R_s \geq R_l , \\ & R_l \geq R_{l,\max} . \end{aligned}$$

Problem $\tilde{\mathcal{P}}_n$ is a convex optimization problem, because the objective function is convex, and the constraints can be easily rearranged in the standard linear from. The optimal solution can then be obtained in a closed-form by the Lagrange duality theory and the KKT conditions [10]. After some algebra, the optimal solution is given by

$$R_l^{\text{opt}} = \frac{\lambda_1 (i_R - R_{\min}) + \lambda_2 r_{D,l} - g_{E,l}}{2 r_{E,l}} , \qquad (8)$$

$$R_s^{\text{opt}} = \frac{\lambda_1 r_R - \lambda_2 r_{D,s} - g_{E,s}}{2 r_{E,s}} , \qquad (9)$$

where

$$\lambda_1 = \frac{a_{12}^2 b_2 + a_{22} a_{11} b_2 - a_{22} a_{12} b_1 - a_{11} a_{22} b_2}{a_{12} (a_{12}^2 + a_{22} a_{11})} ,$$

$$\lambda_2 = \frac{a_{21} b_1 + a_{11} b_2}{a_{12}^2 + a_{22} a_{11}} ,$$

and

$$a_{11} = \frac{(R_{\min} - i_R)^2}{2 r_{E,l}} + \frac{r_R^2}{2 r_{E,s}} ,$$

$$a_{12} = \frac{(R_{\min} - i_R) r_{D,l}}{2 r_{E,l}} + \frac{r_R r_{D,s}}{2 r_{E,s}} ,$$

$$a_{22} = \frac{r_{D,l}^2}{2 r_{E,l}} + \frac{r_{D,s}^2}{2 r_{E,s}} .$$

E. Implementation

Using Monte Carlo simulations, a look-up table for the coefficients of Equations (4), (5) and (6) is filled out for representative values of collision and busy channel probabilities, and packet generation rates. The optimization is then performed at the cluster head by just finding the corresponding entry to these values and computing R_l^{opt} in Equation (8) and R_s^{opt} in Equation (9). The entries for the packet generation rates are assumed known whereas the collision and busy channel probabilities are periodically estimated from each non-cluster head node. The collision probability is estimated based on the receipt of acknowledgement to the data packet whereas busy channel probability is determined at the MAC layer.

The size of the node's memory taken by the look-up table is quite small: Considering that there are 9 coefficients in the optimization problem in Equation (7) and each coefficient is allocated 2 bytes in the memory, the size of the look up table is just around 5 Kbyte for 3 different packet generation rates, 3 different collision probabilities and 3 different busy channel probabilities, and up to 10 transmitter nodes.

V. NUMERICAL RESULTS

In this section, we present a performance analysis of the protocol solution presented in this paper and its comparison with X-MAC [6] only since X-MAC outperforms B-MAC. Recall that X-MAC does not take into account random backoff, reliability and delay constraints. Therefore, for the sake of comparison of the protocol proposed in this paper and X-MAC, we pose $D_{\max} = \infty$ and $R_{\min} = 0$, which implies neglecting the delay and reliability requirements, i.e., the energy is minimized without constraints, as done in X-MAC.

The energy consumption corresponding to the optimal protocol parameters within region $\{R_s \leq 2\,\mathrm{s}, R_l \geq 6\,\mathrm{ms}, R_s \geq R_l\}$ of Fig. 6 and Fig. 7 as obtained by the protocol proposed in this paper is shown in Fig. 8. The figure also shows the energy consumption achieved by X-MAC. Our protocol outperforms X-MAC in all the scenarios considered. Specifically, when the packet generation period is high (300 s) the difference is small, but as the packet generation period decreases the improvement is substantial. The main reason for this difference is that the nodes consume much less energy in packet transmission compared to the model in [6]. X-MAC is based on the assumption that the transmitter sends preamble packets back to back until the receiver wakes up while actually there is random backoff before packet transmissions during which the transmitter puts its radio in sleep mode. Since the transmit energy dominates the receive energy much earlier according to the model in [6], the optimal wake time becomes considerably higher compared to the actual optimal wake time.

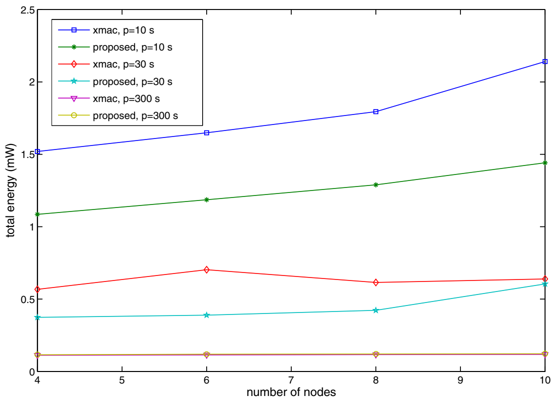

Fig. 8. Comparison of energy consumption as obtained by the proposed protocol and X-MAC.

VI. CONCLUSIONS

We presented a novel optimization method for the determination of the duty-cycle parameters of preamble sampling protocols for the IEEE unslotted 802.15.4 WSNs. This approach represents a major advancement with respect to the B-MAC and X-MAC protocols. The optimization problem is formulated using models of the complex relationship among duty cycle parameters, the MAC parameters of unslotted IEEE 802.15.4 standard, energy consumption, reliability and delay in the packet delivery. The protocol resulting from the optimization minimizes the energy consumption while guaranteeing delay and reliability requirements. We approximated the optimization problem by deriving empirical explicit models for cost function and constraints as function of sleep and wake time. This simplification allows to solve in closed form the optimization problem, hence making it possible to compute the optimal solution at sensor nodes online. The solution of the optimization problem achieved significant energy savings, at the cost of storing look-up tables in the receiver nodes. The tables contain coefficients that are adapted to the traffic load and channel condition.

A challenging task of our activity will be devoted to finding exact theoretical models to characterize the energy consumption, the reliability and delay constraints without resorting to simulations.

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