

# Event-Triggered Sleeping for Synchronous DC MAC in WSNs: Mechanism and DTMC Modeling

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**Abstract**—Overhearing and idle listening are two primary sources for unnecessary energy consumption in wireless sensor networks. Although introducing duty cycling in medium access control (MAC) reduces idle listening, it cannot avoid overhearing in a network with multiple contending nodes. In this paper, we propose an event-triggered sleeping (ETS) mechanism for synchronous duty-cycled (DC) MAC protocols in order to avoid overhearing when a node is not active. This ETS mechanism applies to any synchronous DC MAC protocols and makes them more energy efficient. Furthermore, we develop a two dimensional discrete time Markov chain model to evaluate the performance of the proposed ETS mechanism by integrating it to a popular synchronous DC MAC protocol namely sensor-MAC. Using the developed model, energy consumption, energy efficiency and network lifetime are calculated. Numerical results obtained through both analytical model and discrete-event simulations demonstrate the effectiveness of the ETS mechanism, represented by lower energy consumption, higher energy efficiency and longer lifetime when compared with the conventional control packet triggered sleeping mechanism.

## I. INTRODUCTION

Wireless sensor networks (WSNs) support a wide range of applications including event detection, monitoring, target tracking, etc [1]. The lifetime of a sensor node in such WSNs depends on the capacity of its battery as well as how energy is consumed. Clearly, the battery capacity is fixed and cannot be recharged without energy harvesting. In some applications such as hostile environment monitoring, replacing node batteries might not be feasible or is too costly. Therefore, an energy consumption efficient medium access control (MAC) protocol plays an important role for network lifetime prolongation since the energy consumption activities are determined by MAC. An energy efficient MAC protocol reduces unnecessary energy consumption by avoiding idle listening and/or overhearing experienced by nodes. For instance, idle listening can be minimized by employing a duty-cycled (DC) MAC protocol which allows nodes sleep for a while when no activities are needed in order to conserve energy. On the other hand, wake-up radio has emerged in recent years as an efficient technique for reducing energy consumption in WSNs [2].

For DC enabled WSNs, synchronous MAC has been a popular category for MAC design [3] [4]. With such MAC protocols, nodes are aligned to wake up and sleep periodically according to a predefined schedule. This schedule is exchanged among neighboring nodes when they are awake in the specified duration, regarded as a *sync* period. Data exchange is then

performed in the following *data* period, after which a *sleep* period starts. The whole duration consisting of a successive *sync*, *data* and *sleep* period forms one *cycle*. Synchronization is done in the *sync* period and then nodes compete for medium access and perform data exchange during the *data* period. The duration of the sleep period for each node varies, depending on it wins medium access competition or not. A winning node goes to sleep after completing its transmission, and a node which lost access competition starts to sleep earlier after it receives a control packet indicating that another node has started to transmit. In all synchronous DC MAC protocols including Sensor-MAC (S-MAC) [3], a node initiates a data packet transmission using control packets, but those control packets are named differently in various protocols. The duty cycling principle adopted in the synchronous DC protocols mitigates idle listening, but could not avoid overhearing in the *data* period, as explained in the following sub-section.

## A. Problem Statement

Typically in synchronous DC enabled WSNs, nodes follow the carrier sense multiple access with collision avoidance (CSMA/CA) mechanism for packet transmission during the *data* period. In a network or a network cluster with multiple nodes, all nodes that have packets to transmit contend for channel access in order to send their packets to a single cluster-head or a sink node. However, only one node wins channel access and transmits first a control packet, i.e., the request to send (RTS) packet in CSMA/CA, informing the other neighboring nodes that it is going to transmit. Upon overhearing this control packet, the other nodes go to sleep. This sleeping mechanism is hereafter referred to as control packet triggered (CPT) sleeping mechanism. *In CPT, an inactive node, i.e., a node that does not have any packets to send, still needs to wait until it overhears a control packet before going to sleep.* For example, when no node is active in a network, all nodes need to be awake for the whole duration of the *data* period, leading to high energy consumption.

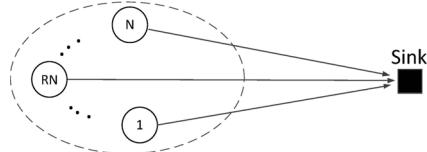


Figure 1: A WSN with multiple contending nodes and a sink.

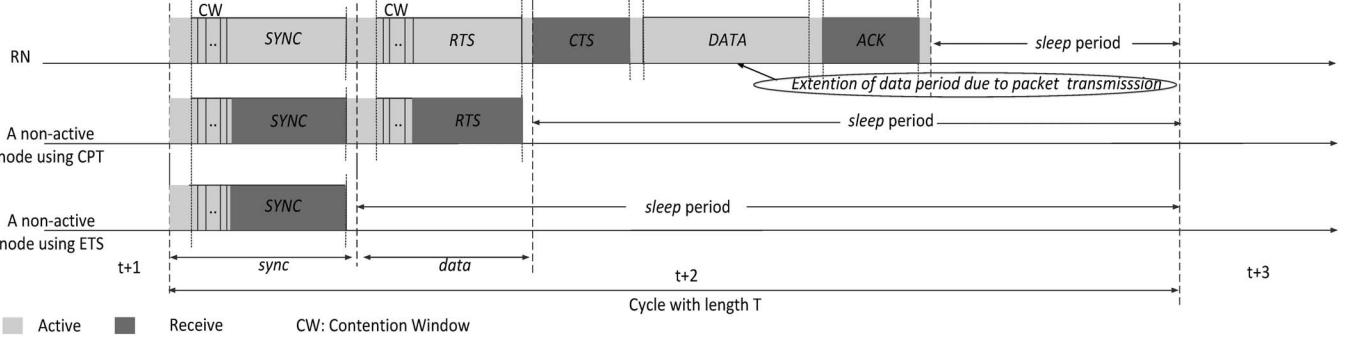


Figure 2: Operation of S-MAC with ETS and CPT. In ETS, an inactive node goes to sleep right after the *sync* period. In CPT, an inactive node which lost channel access contention starts to sleep after the *data* period. The spaces without symbols are inter-frame spaces.

## B. Contributions

In this paper, we propose an event-triggered sleeping (ETS) mechanism to address the overhearing problem occurring in CPT. The main idea of the ETS mechanism is to allow nodes that do not have a packet to send sleep right after the *sync* period without participating in medium access contention. Thus, such a node can sleep longer for the rest of the same cycle, and it consequently saves energy. The ETS mechanism applies to any synchronous DC protocols and suits ideally for WSN scenarios with low traffic rate, for instance in event-triggered monitoring and surveillance applications.

To evaluate the performance of ETS, we develop a two dimensional (2D) discrete time Markov chain (DTMC) model to analyze ETS operating jointly with S-MAC protocol. This 2D DTMC tracks the evolution of both the number of packets in the buffer of a node and the number of active nodes in the cluster. Different from the existing one dimensional DTMCs considering only the number of packets in a queue [5] or obtaining the distribution of active nodes from another additional DTMC [6], the developed 2D DTMC determines the distributions for both the number of packets and the number active nodes. Using the obtained distributions, energy consumption, energy efficiency and the lifetime of a node are calculated. Moreover, the 2D DTMC model results are validated through discrete-event simulations.

The rest of the paper is organized as follows. In Sec. II, we present the network model and the details of ETS along with an overview of S-MAC. Sec. III describes the proposed 2D DTMC model, followed by the energy consumption analysis in Sec. IV. Numerical results are demonstrated in Sec. V, before the paper is concluded in Sec. VI.

## II. SCENARIO AND EVENT-TRIGGERED SLEEPING

This section presents the operation of ETS over S-MAC and the network scenario along with the assumptions.

### A. Sensor Network Scenario

In typical WSN applications, nodes collect data from a sensing field and transmit them to a sink. Within such a scenario, we consider a cluster of  $N$  sensor nodes, each with a queue capacity of  $Q$  packets. Nodes sense activities around them and generate packets according to the Poisson

distribution. The neighboring nodes send their packets towards one common destination, the *sink*, over an error-free channel by competing with each other, as shown in Fig. 1. Nodes containing packets to transmit are regarded as active nodes and the other are inactive ones. For analysis convenience, we select one of the  $N$  nodes arbitrarily and refer to it as the reference node (RN). Hereafter, *DATA*, *SYNC*, *RTS* and *CTS* represent packets and the different parts of a cycle are denoted as *sleep*, *sync*, and *data* respectively.

### B. ETS Operation in S-MAC

Consider that nodes in a WSN may stay as inactive in some cycles and become active in other cycles. ETS lets all inactive nodes sleep immediately after the *sync* period in order to save energy. However, both active and inactive nodes have to wake up in every *sync* period to maintain each other synchronized. Fig. 2 illustrates the operation of S-MAC with a comparison of the ETS and CPT sleeping mechanisms. In ETS, an inactive node does not participate in medium access competition and therefore its sleep period becomes longer, as shown in the figure. In CPT, instead, an inactive node has to wait until an *RTS* packet is received before it goes to sleep. Note however that *only active nodes compete for channel access in both mechanisms*. Assume that the RN is the winner of the contention among  $N$  nodes inside one cluster. After gaining channel access, the RN transmits an *RTS* to the sink. This *RTS* control packet triggers all other active nodes to go to sleep.

For channel access, all *active* nodes generate a random back-off time uniformly from window  $\{0, W - 1\}$  in the beginning of every *data* period. If the smallest backoff time is selected by only one node, then that node wins channel access and reserves the medium for *DATA* transmission in the corresponding *sleep* period. If a node selects a backoff time which is not the smallest one, it loses the competition and waits until the next *data* period to compete again. In case that two or more nodes select the same smallest backoff time, there will be a collision.

Consider  $k + 1$  active nodes including the RN in a cycle. When the RN is contending with other  $k$ , where  $0 \leq k \leq N - 1$ , nodes, the probabilities that the RN transmits a packet successfully,  $P_{s,k}$ , transmits a packet (successfully or collided),  $P_{sf,k}$ , and failed (collided),  $P_{f,k}$ ,

Table I: Transition Probabilities of the DTMC Model for S-MAC enabled with ETS

$P_{(0,0),(j,l)} = B_l(K) \cdot A_j ; 0 \leq j \leq Q-1, 0 \leq l \leq K,$	No active nodes. Transitions occur due to new arrivals	$P_{(0,0),(Q,l)} = B_l(K) \cdot A_{\geq Q} ; 0 \leq l \leq K.$
$P_{(0,k),(j,l)} = S_k \cdot P_e \cdot B_{l-k+1}(K-k) \cdot A_j$ $+ S_k \cdot \widehat{P}_e \cdot B_{l-k}(K-k) \cdot A_j ;$ $+ \widehat{S}_k \cdot B_{l-k}(K-k) \cdot A_j ;$ $0 \leq j \leq Q-1, 1 \leq k \leq l \leq K-1,$	RN is an inactive node. Transitions caused by other active nodes	$P_{(0,k),(Q,l)} = S_k \cdot P_e \cdot B_{l-k+1}(K-k) \cdot A_{\geq Q}$ $+ S_k \cdot \widehat{P}_e \cdot B_{l-k}(K-k) \cdot A_{\geq Q} ;$ $+ \widehat{S}_k \cdot B_{l-k}(K-k) \cdot A_{\geq Q} ;$ $1 \leq k \leq l \leq K-1,$
$P_{(0,k),(j,k-1)} = S_k \cdot P_e \cdot B_0(K-k) \cdot A_j ;$ $0 \leq j \leq Q-1, 1 \leq k \leq K,$		$P_{(0,k),(Q,k-1)} = S_k \cdot P_e \cdot B_0(K-k) \cdot A_{\geq Q} ; 1 \leq k \leq K,$
$P_{(0,k),(j,K)} = S_k \cdot \widehat{P}_e \cdot B_{K-k}(K-k) \cdot A_j ;$ $+ \widehat{S}_k \cdot B_{K-k}(K-k) \cdot A_j ;$ $0 \leq j \leq Q-1, 1 \leq k \leq K,$		$P_{(0,k),(Q,K)} = S_k \cdot \widehat{P}_e \cdot B_{K-k}(K-k) \cdot A_{\geq Q} ;$ $+ \widehat{S}_k \cdot B_{K-k}(K-k) \cdot A_{\geq Q} ;$ $1 \leq k \leq K.$
$P_{(i,0),(j,l)} = P_{s,0} \cdot B_l(K) \cdot A_{j-i+1}$ $+ (1 - P_{s,0}) \cdot B_l(K) \cdot A_{j-i} ;$ $1 \leq i \leq j \leq Q-1, 0 \leq l \leq K,$	RN is the only active node	$P_{(i,0),(Q,l)} = P_{s,0} \cdot B_l(K) \cdot A_{\geq Q-i+1}$ $+ (1 - P_{s,0}) \cdot B_l(K) \cdot A_{\geq Q-i} ;$ $1 \leq i \leq Q, 0 \leq l \leq K,$
$P_{(i,k),(j,l)} = P_{s,k} \cdot B_{l-k}(K-k) \cdot A_{j-i+1}$ $+ k P_{s,k} \cdot P_e \cdot B_{l-k+1}(K-k) \cdot A_{j-i}$ $+ k P_{s,k} \cdot \widehat{P}_e \cdot B_{l-k}(K-k) \cdot A_{j-i}$ $+ \widehat{S}_{k+1} \cdot B_{l-k}(K-k) \cdot A_{j-i} ;$ $1 \leq i \leq j \leq Q-1, 1 \leq k \leq l \leq K-1,$	Transitions owing to multiple contending nodes	$P_{(i,k),(Q,l)} = P_{s,k} \cdot B_{l-k}(K-k) \cdot A_{\geq Q-i+1}$ $+ k P_{s,k} \cdot P_e \cdot B_{l-k+1}(K-k) \cdot A_{\geq Q-i}$ $+ k P_{s,k} \cdot \widehat{P}_e \cdot B_{l-k}(K-k) \cdot A_{\geq Q-i}$ $+ \widehat{S}_{k+1} \cdot B_{l-k}(K-k) \cdot A_{\geq Q-i} ;$ $1 \leq i \leq Q, 1 \leq k \leq l \leq K-1,$
$P_{(i,k),(j,K)} = P_{s,k} \cdot B_{K-k}(K-k) \cdot A_{j-i+1}$ $+ k P_{s,k} \cdot \widehat{P}_e \cdot B_{K-k}(K-k) \cdot A_{j-i}$ $+ \widehat{S}_{k+1} \cdot B_{K-k}(K-k) \cdot A_{j-i} ;$ $1 \leq i \leq j \leq Q-1, 1 \leq k \leq K,$		$P_{(i,k),(Q,K)} = P_{s,k} \cdot B_{K-k}(K-k) \cdot A_{\geq Q-i+1}$ $+ k P_{s,k} \cdot \widehat{P}_e \cdot B_{K-k}(K-k) \cdot A_{\geq Q-i}$ $+ \widehat{S}_{k+1} \cdot B_{K-k}(K-k) \cdot A_{\geq Q-i} ;$ $1 \leq i \leq Q, 1 \leq k \leq K,$
$P_{(i,k),(j,k-1)} = k P_{s,k} \cdot P_e \cdot B_0(K-k) \cdot A_{j-i}$ $1 \leq i \leq j \leq Q-1, 1 \leq k \leq K,$		$P_{(i,k),(Q,k-1)} = k P_{s,k} \cdot P_e \cdot B_0(K-k) \cdot A_{\geq Q-i}$ $1 \leq i \leq Q, 1 \leq k \leq K,$
$P_{(i,k),(i-1,l)} = P_{s,k} \cdot B_{l-k}(K-k) \cdot A_0 ;$ $1 \leq i \leq Q, 0 \leq k \leq l \leq K,$	Impossible transitions	$P_{(i,k),(j,l)} = 0 ; 2 \leq i \leq Q, j < i-1, 0 \leq k \leq l \leq K,$ $P_{(i,k),(j,k-1)} = 0 ; 1 \leq i \leq Q, j < i, 1 \leq k \leq K.$
$P_{(i,k),(i-1,l)} = 0 ; 1 \leq i \leq Q, 1 \leq k \leq K, l < k,$ $P_{(i,k),(j,l)} = 0, 0 \leq i \leq j \leq Q, 2 \leq k \leq K, l < k-1,$		

are given by  $P_{s,k} = \sum_{i=0}^{W-1} \frac{1}{W} \left( \frac{W-1-i}{W} \right)^k$ ,  $P_{sf,k} = \sum_{i=0}^{W-1} \frac{1}{W} \left( \frac{W-i}{W} \right)^k$ ,  $P_{f,k} = P_{sf,k} - P_{s,k}$  respectively. Correspondingly the average successful backoff time is determined by  $BT_{s,k} = \frac{1}{P_{s,k}} \sum_{i=0}^{W-1} i \cdot \frac{1}{W} \left( \frac{W-1-i}{W} \right)^k$ , while the unsuccessful one becomes  $BT_{f,k} = \sum_{i=0}^{W-1} i \cdot \left[ \left( \frac{W-i}{W} \right)^k - \left( \frac{W-1-i}{W} \right)^k \right]$ .

### III. A 2D DTMC MODEL FOR ETS

A state in the 2D DTMC is represented by  $(i, k)$ , where  $i$  is the number of packets in the queue of the RN,  $i \leq Q$ , and  $k$  is the number of active nodes other than the RN in the network,  $k \leq K = N-1$ . Express the probability of arriving  $i$  packets to a node with an arrival rate of  $\lambda$  in a cycle of length  $T$  as  $A_i = (\lambda T)^i \cdot e^{-\lambda T} / i!$ . Then the probability of arriving  $i$  or more packets is  $A_{\geq i} = 1 - \sum_{j=0}^{i-1} A_j$ . When  $k$  nodes compete in a cycle, the probability of transmitting a packet successfully is  $S_k = k P_{s,k-1}$  and the probability for a collision is  $\widehat{S}_k = 1 - S_k$ . Furthermore, when there is a successful transmission, the probability that a node's queue becomes empty is  $P_e = P_s A_0 \pi_1 / P_s (1 - \pi_0)$  and  $\widehat{P}_e = 1 - P_e$  is the probability that it remains non-empty, where  $P_s$  is the probability of successful transmission,  $\pi_0$  and  $\pi_1$  are the stationary probabilities that the node's queue has '0' and '1' packet, respectively. Consider  $B_k(l) = \binom{l}{k} \widehat{A}^k A_0^{l-k}$  as the probability that  $k$  out of  $l$  nodes

which have their queues empty to receive packets in a cycle, where  $\widehat{A} = 1 - A_0$ . Then,  $P_{(i,k),(j,l)}$  is the transition probability from State  $(i, k)$  to State  $(j, l)$ . The transition probabilities of the proposed 2D DTMC are given in Table I.

The solution of this 2D DTMC is obtained by solving the following linear equations

$$\boldsymbol{\pi} \mathbf{P} = \boldsymbol{\pi}, \quad \boldsymbol{\pi} \mathbf{e} = \mathbf{1}, \quad (1)$$

where  $\boldsymbol{\pi}$  is the stationary distribution,  $\mathbf{P}$  is the transition probability matrix, whose elements are defined in Table I, and  $\mathbf{e}$  is a column vector of ones. By using the stationary probabilities  $\pi_i = \sum_{k=0}^K \pi(i, k)$  obtained from (1), the probability of successful transmission can be calculated as

$$P_s = \frac{1}{G} \sum_{i=1}^Q \sum_{k=0}^K \pi(i, k) \cdot P_{s,k}, \quad (2)$$

where  $G = \sum_{i=1}^Q \sum_{k=0}^K \pi(i, k)$ . By iteratively solving the set of equations (1) and (2),  $P_s$  at a fixed-point can be obtained.

### IV. ENERGY CONSUMPTION ANALYSIS

In this section, we calculate the average energy consumed by the RN in a cycle according to S-MAC when ETS is employed. Hereafter,  $t_{DATA}$ ,  $t_{SYNC}$ ,  $t_{RTS}$  and  $t_{ACK}$  denote the packet transmission duration, and  $T_{sleep}$ ,  $T_{sync}$  and  $T_{data}$  represent the duration of each corresponding period in a cycle.

As described in Sec. II, each cycle contains a *sync*, *data* and *sleep* period. We adopt a synchronization process similar to the one used in [5], in which a node transmits one *SYNC* packet

every  $N_{sc}$  cycles, and receives one packet per cycle in the remaining  $N_{sc} - 1$  cycles. Accordingly, the energy consumed by the RN node in the *sync* period is given by,

$$E_{sc} = \frac{1}{N_{sc}} \cdot [(t_{SYNC} \cdot P_{tx} + (T_{sync} - t_{SYNC}) \cdot P_{rx})] + \frac{N_{sc} - 1}{N_{sc}} \cdot (T_{sync} \cdot P_{rx}), \quad (3)$$

where  $P_{tx}$  and  $P_{rx}$  are the transmission and reception power levels respectively.

The energy consumption for ETS during the *data* period is calculated only when the RN is active. In the following analysis, we assume that  $k + 1$  nodes are active, meaning that the RN is active and it contends with other  $k$  active nodes. The probability that the RN is active among  $k + 1$  active nodes is  $q_{1,k} = (k + 1)/N$ . Then the RN may transmit a *DATA* packet successfully, or failed (due to collision), or just overhears another node's transmission (lost contention). Accordingly, the energy consumption in these three situations is calculated respectively as

$$\begin{aligned} E_{txs,k} &= (t_{RTS} + t_{DATA}) \cdot P_{tx} + (t_{CTS} + t_{ACK}) \cdot P_{rx}, \\ E_{txf} &= t_{RTS} \cdot P_{tx} + t_{CTS} \cdot P_{rx}, \\ E_{oh} &= t_{RTS} \cdot P_{rx}. \end{aligned} \quad (4)$$

Furthermore, if the RN lost the contention, the other nodes might be successful with a probability  $q_{2,k} = q_{1,k}kP_{s,k}$  or unsuccessful with a probability  $q_{3,k} = (1 - q_{1,k}kP_{s,k}) - (1 - q_{1,k})kP_{s,k} - q_{1,k}kP_{sf,k}$ , conditioned on the RN being active. Then, the average energy consumed by the RN during the *data* period of a cycle when it contends with other  $k$  nodes,  $k \geq 1$ , is obtained by

$$\begin{aligned} E_{d,k+1} &= q_{1,k}P_{s,k} [E_{txs,k} + (4D_p + BT_{s,k}) \cdot P_{rx}] \\ &\quad + q_{1,k}P_{f,k} [E_{txf} + (2D_p + BT_{f,k}) \cdot P_{rx}] \\ &\quad + q_{2,k} [E_{oh} + (D_p + BT_{s,k}) \cdot P_{rx}] \\ &\quad + q_{3,k} [E_{oh} + (D_p + BT_{f,k}) \cdot P_{rx}], \end{aligned} \quad (5)$$

where  $D_p$  is the one-way propagation delay. Note that the above terms in  $E_{d,k+1}$  calculation correspond to the RN energy consumption due to: a successfully transmission; a collision; overhearing a successful transmission by the active nodes other than the RN; and overhearing a failed transmission by nodes other than the RN, respectively.  $E_{d,1} = q_{1,0} \cdot [E_{txs,0} + (4D_p + (W - 1)/2) \cdot P_{rx}]$  while  $E_{d,0} = 0$  since an inactive node sleeps in the *data* period. Therefore the average energy consumed by the RN during the the *data* period of a cycle is given by,

$$E_d = \sum_{k=0}^N E_{d,k} \cdot \pi'_k \quad (6)$$

where  $\pi'_k$  is the stationary probability of finding  $k$  active nodes in the network and can be determined by,  $\pi'_k = \sum_{i=1}^Q \pi(i, k-1) + \pi(0, k)$  for  $1 \leq k \leq N - 1$ . Note that  $\pi'_0 = \pi(0, 0)$ , and  $\pi'_N = \sum_{i=1}^Q \pi(i, N-1)$ , respectively.

The average energy consumed by the RN during the *sleep* period of a cycle is given by,

$$\begin{aligned} E_{sl,k+1} &= q_{1,k}P_{s,k} \cdot [(T - T_{sync} - T_{d,s,k}) \cdot P_{sl}] \\ &\quad + q_{1,k}P_{f,k} \cdot [(T - T_{sync} - T_{d,f,k}) \cdot P_{sl}] \\ &\quad + q_{2,k}P_{s,k} [(T - T_{sync} - T_{d,os,k}) \cdot P_{sl}] \\ &\quad + q_{3,k} [(T - T_{sync} - T_{d,of,k}) \cdot P_{sl}], \end{aligned} \quad (7)$$

where  $T_{d,s,k} = t_{RTS} + t_{DATA} + t_{CTS} + t_{ACK} + 4D_p + BT_{s,k}$ ,  $T_{d,f,k} = t_{RTS} + t_{CTS} + 2D_p + BT_{f,k}$ ,  $T_{d,os,k} = t_{RTS} + D_p + BT_{s,k}$ , and  $T_{d,of,k} = t_{RTS} + D_p + BT_{f,k}$ . These terms represent the duration of the *data* period corresponding to the terms included in (5).  $E_{sl,1} = q_{1,0} \cdot [(T - T_{sync} - T_{d,s,0}) \cdot P_{sl}]$  and  $E_{sl,0} = [(T - T_{sync}) \cdot P_{sl}]$ , where  $T_{d,s,0} = t_{RTS} + t_{DATA} + t_{CTS} + t_{ACK} + 4D_p + (W - 1)/2$ .

As explained in [5], a node does not go to sleep and would keep awake during the *sleep* period of  $N_{sc}$  consecutive cycles to avoid missing *SYNC* packets from its neighboring nodes. This process happens in one of  $N_{aw}$  sets of cycles. The energy consumed in such an awake cycle,  $E_{aw,k}$ , can be obtained by replacing  $P_{sl}$  with  $P_{rx}$  in (7) since the RN keeps listening to the channel. Then, the average energy consumed during the *sleep* period of a cycle is obtained by

$$E_{s,k} = \frac{E_{sl,k} \cdot N_{sc} \cdot (N_{aw} - 1) + E_{aw,k} \cdot N_{sc}}{N_{sc} \cdot N_{aw}}. \quad (8)$$

Similar to how  $E_d$  is obtained in (6), the average energy consumption during the *sleep* period of a cycle,  $E_s$ , is obtained using the same equation by substituting  $E_{d,k}$  with  $E_{s,k}$  in (6). Finally, the total average energy consumed by the RN in a cycle is obtained by

$$E = E_{sc} + E_d + E_s. \quad (9)$$

Accordingly, the lifetime of the RN can be determined as

$$LT = \frac{E_{initial}}{E} \text{ cycles}. \quad (10)$$

Furthermore, the average number of bytes successfully transmitted per total average energy consumed in a cycle by the RN, or the energy efficiency, denoted by  $\xi$ , is given by

$$\xi = \left( \frac{\eta \cdot S}{E} \right), \quad (11)$$

where  $S$  is size of the transmitted packet in bytes and  $\eta$  is the number of successfully transmitted packets in a cycle and can be determined as  $\eta = \sum_{i=1}^Q \sum_{k=0}^K \pi(i, k) \cdot P_{s,k}$ .

Note that the energy consumption when a non-active node follows CPT as proposed in original S-MAC can be obtained by incorporating the following modifications in (5) and (7).  $q_{2,k} = [kq_{1,k} + (k+1)(1-q_{1,k})] \cdot P_{s,k}$ ,  $q_{3,k} = 1 - q_{2,k} - q_{1,k}P_{sf,k}$ ,  $E_{d,0} = (t_{RTS} + W + D_p) \cdot P_{rx}$  and its corresponding duration.

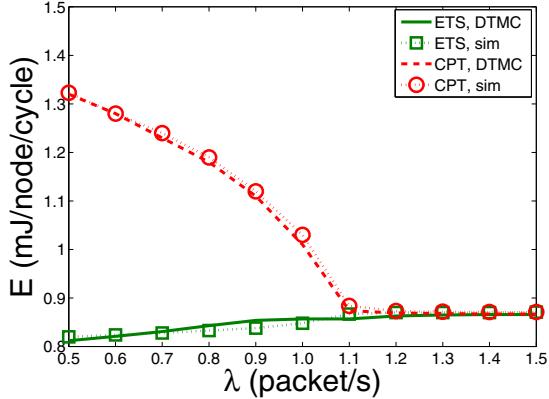


Figure 3: Average energy consumed by the RN per cycle as the packet arrival rate varies, given that  $N = 15$ .

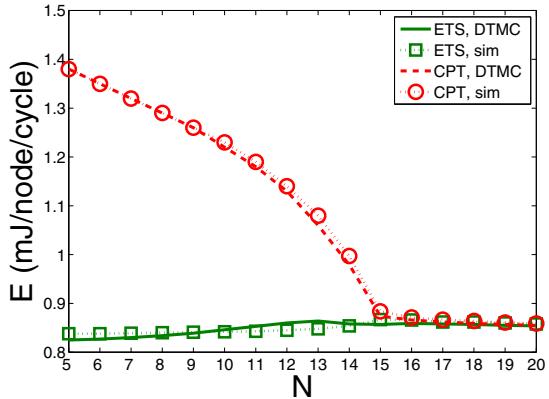


Figure 4: Average energy consumed by the RN per cycle as the number of nodes varies, given that  $\lambda = 1.1$  packet/s.

## V. SIMULATIONS AND NUMERICAL RESULTS

In this section, we evaluate and compare the performance of the ETS and CPT sleeping mechanisms operated on the S-MAC protocol. The considered performance metrics, i.e., average energy consumption, lifetime and energy efficiency of a node are obtained through both the developed DTMC model and discrete-event simulations. The simulation results are reported as the average values over  $5 \cdot 10^6$  cycles.

The network illustrated in Fig. 1 is adopted in our evaluation, configured as: number of nodes  $N \in (5, 6 \dots, 20)$ ; queue length of a node  $Q = 10$  with  $E_{initial} = 1$  J; size of the DATA packet  $S = 50$  bytes; DATA arrival rate  $\lambda \in [0.5, 1.5]$  packet/s; and for the sync period,  $N_{sc} = 10$ ,  $N_{aw} = 40$ . Furthermore, S-MAC is configured with 50% duty cycle. The other MAC parameters are taken from [5]. The transmission, reception and sleep power levels are  $P_{tx} = 52$  mW,  $P_{rx} = 59$  mW and  $P_{sl} = 3 \mu\text{W}$  [7] respectively. The network performance is evaluated by varying the number of nodes  $N$  or packet arrival rate  $\lambda$  while keeping the other parameters fixed at  $\lambda = 1.1$  packet/s or  $N = 15$  respectively.

### A. Energy Consumption and Lifetime

It is obvious that the packet arrival rate will affect the number of cycles in which a node remains active or inactive.

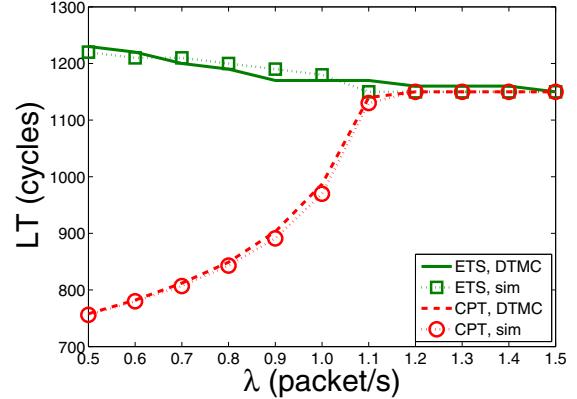


Figure 5: Lifetime of the RN as the packet arrival rate varies, given that  $N = 15$ .

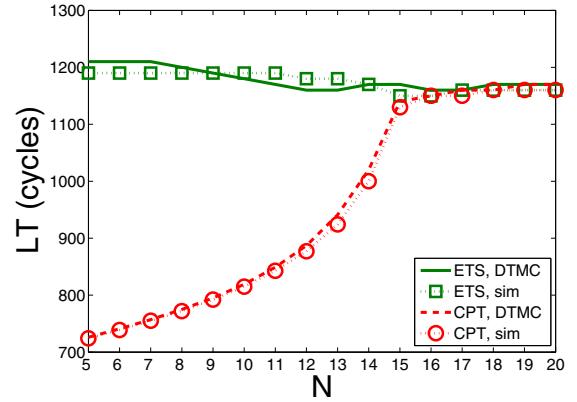


Figure 6: Lifetime of the RN as the number of nodes varies, given that  $\lambda = 1.1$  packet/s.

In Fig. 3, we evaluate both mechanisms with different traffic arrival rates varying from 0.5 to 1.5 packet/s with a granularity interval of 0.1 packet/s. The figure clearly demonstrates the superiority of the ETS mechanism in a network with light traffic. When  $\lambda < 1.1$  packet/s, nodes in the network are inactive during many or even most of the cycles and then can sleep in the *data* period when ETS is employed. Consequently, a node saves a substantial amount of energy. Whereas in CPT, all nodes regardless of whether they have packets in their queue or not have to wake up and keep listening to the channel until an RTS packet is received. Thereby, a node consumes a large amount of energy caused by overhearing. With the increase in packet generation rate, the network will eventually be saturated after  $\lambda \geq 1.1$  packet/s. When saturated, (almost) all nodes in the network become active and contend for channel access in every cycle. Then, energy consumption stabilizes and both mechanisms show the same performance.

Traffic congestion in a network can be caused by either injecting higher traffic loads to all nodes or increasing the node population. Configuring  $\lambda$  to 1.1 packet/s which is the saturation point, we examine the performance of ETS by increasing the network size from 5 to 20 at a granularity level of 1. Clearly, fewer number of nodes with a constant  $\lambda$  generate lighter traffic in the network. Furthermore, due to less

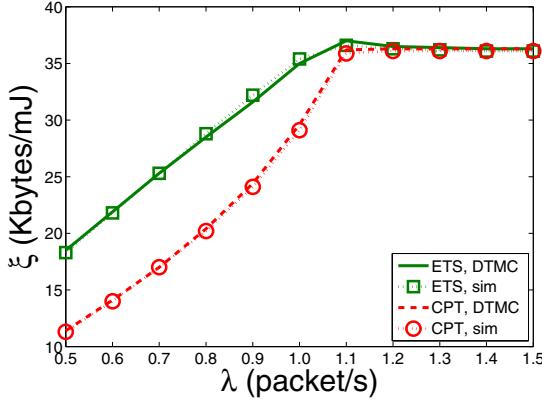


Figure 7: Energy efficiency of the RN as the packet arrival rate varies, given that  $N = 15$ .

competition, the probability of obtaining channel access for a node is higher. Then, a node can transmit packets successfully with a higher probability, meaning it is less likely that node will continue to be active in the next cycle. Therefore, with a lower node population, nodes following ETS consume lower energy. The same level of energy consumption is maintained for both mechanisms after the network is congested, as shown in Fig. 4. Again, a CPT node consumes higher energy because of its dependence on receiving an RTS packet to enter into the *sleep* period. The competition increases when more nodes join the network. Then, a node stays active in many cycles and consecutively the level of energy consumed by a node using CPT decreases until the saturation point. After  $N = 15$ , nodes stay active in all cycles and the energy consumption level remains stable for both ETS and CPT.

Correspondingly, the obtained node lifetimes with the same configurations are presented in Fig. 5 and Fig. 6 respectively. Obviously, lower energy consumption leads to longer node lifetime. As observed, ETS achieves approximately 65% longer lifetime at  $N = 5$  in Fig. 6 and at  $\lambda = 0.5$  packet/s in Fig. 5, in comparison with its CPT counterpart. Consequently the network lifetime which is very much relevant to node lifetime is also extended.

### B. Energy Efficiency

As defined, the energy efficiency of a node,  $\xi$ , depends on the average number of bytes transmitted successfully by that node as well as the total average energy consumption,  $E$ , in a cycle. With both configurations, we observe that  $\xi$  behaves similarly for ETS and CPT once the network is saturated.

Within the non-saturation regions, however, ETS achieves much higher energy efficiency than CPT does. As shown in Fig. 7 with a fixed network size and variable packet arrivals,  $\xi$  increases monotonically in both mechanisms, but ETS achieves approximately 65% higher efficiency. This is because that the number of packets successfully transmitted by both mechanisms is at a constant level while much lower energy consumption per cycle is achieved in ETS. Similarly, in the constant arrival rate and variable network size case, ETS maintains a high level of stability in  $\xi$  as illustrated in Fig. 8,

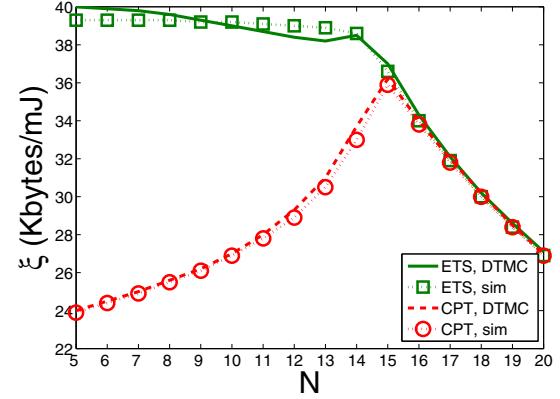


Figure 8: Energy efficiency of the RN as the number of nodes varies, given that  $\lambda = 1.1$  packet/s.

since the consumed energy per cycle,  $E$ , is low and almost stable for ETS (shown in Fig. 4). When there are more nodes in the network after  $N = 15$ ,  $\xi$  decays drastically in both ETS and CPT owing to the decrement of number of successfully transmitted packets by a node per cycle.

## VI. CONCLUSIONS

In this paper, we proposed an event-triggered sleeping mechanism to mitigate energy consumption caused by overhearing in prevailing control packet triggered sleeping mechanisms for synchronous duty cycle MAC protocols. Furthermore, a two dimensional DTMC model is developed to evaluate both the ETS and CPT mechanisms operated on S-MAC and closed-form expressions for calculating energy consumption, lifetime and energy efficiency are derived. The obtained analytical and discrete-event simulation results match precisely for both mechanisms. It is demonstrated that the proposed ETS mechanism achieves about 65% longer lifetime and 65% higher energy efficiency under light traffic conditions when compared with the legacy CPT mechanism and both mechanisms achieve the same performance when the network is saturated.

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