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Additional Information

Performance Analysis of Synchronous Duty-Cycled MAC Protocols

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***Abstract*—In this letter, we propose an analytical model to evaluate the performance of the S-MAC protocol. The proposed model improves the accuracy of previous models in two aspects. First, it incorporates the dependence among the nodes within a cluster by defining a DTMC that models the number of active nodes, whereas the previous models considered that nodes were mutually independent. Second, it proposes new methods for calculating packet delay and energy consumption. The analytical model is validated through discrete-event based simulations. Numerical results demonstrate that the proposed analytical model and methods yield accurate results under realistic assumptions.**

***Index Terms*—WSNs, duty-cycled MAC protocols, Markov modeling, delay and energy consumption.**

I. Introduction

DUTY cycling (DC) appears as a promising solution to reduce energy consumption in wireless sensor networks (WSNs). In the literature, many medium access control (MAC) protocols have been proposed to adopt DC for achieving energy efficiency. Among them, Sensor-MAC (S-MAC) [1] belongs to the category of synchronous duty-cycled MAC protocols in which all nodes in a cluster are coordinated to follow wake-up and sleep cycles simultaneously. Currently, only few analytical models are available to evaluate the performance of the S-MAC protocol. Among them, an M/G/1 based model was proposed in [2], which requires that packet arrivals follow the Poisson process and that each node has an infinite buffer. Recently, a discrete-time Markov chain (DTMC) model was proposed in [3], supporting a more general packet arrival distribution per cycle and zero packet retransmission.

Our work extends the study presented in [3] in three different aspects. First, a DTMC was proposed in [3] to describe the evolution of the number of packets in the buffer of a node. We refer to it as the *node* DTMC. The solution of their model is based on the assumption that the states of nodes are mutually independent. However, in practice some degree of dependence occurs among nodes. We incorporate this dependence by introducing an additional DTMC, referred to hereafter as the *system* DTMC. It models the number of active nodes in the cluster. As it will be shown later, this new modeling approach substantially improves the model accuracy.

Second, we propose alternative methods to determine two important performance parameters, i.e., delay and energy consumption. The new methods are shown to be more general and accurate than the ones presented in [3].

Third, instead of focusing on zero retransmission, we study scenarios where nodes are allowed to perform infinite retransmissions. S-MAC itself does not specify whether packet retransmission is allowed or not. We consider herein that the operation of S-MAC with zero retransmissions may not be appropriate for certain loss-sensitive applications due to a possibly high number of packet loss. As infinite retransmission is not a feasible mode for node operation, we investigate how many times a packet needs to be retransmitted under various traffic loads in order to achieve zero packet loss. Simulation results show that the vast majority of the packets require only one or two retransmissions, even in a high load scenario. That is, by setting the maximum retransmission counter in the nodes to two, we might achieve close to zero packet loss. This indicates that an infinite retransmission model provides a simpler modeling alternative to the more complex finite retransmission model for systems with negligible packet loss.

II. System Model

Consider a cluster of N nodes consisting of sensors that are one hop away from each other. We focus on this *single-cell cluster* but multiple clusters together may form a larger network. The network employs S-MAC with the CSMA/CA-based RTS/CTS/DATA/ACK handshake, where backoff timers are reset at each cycle initiation. The time is partitioned into cycles, and each cycle is further divided into three parts: synchronization, data transfer and sleep. In S-MAC, a node goes to sleep until the next *data* (*listen*) *period* when: i) it loses the contention (hears a busy medium before its backoff timer expires); ii) it encounters an RTS collision; and iii) after successful transmission (only one packet sent per cycle).

A homogeneous channel traffic generation is assumed, i.e., the fraction of packets sent from one node to any other node is $1/(N-1)$. For simplicity we assume a renewal arrival process, and characterize the number of packets that arrive to a node per cycle by independent and identically distributed random variables. In each cycle, packets arrive following a general distribution irrespective of where the packets were originated, i.e., internally (as a consequence of its own sensing activity) or externally (arriving from another node). Every node has a queue that can store at most Q packets.

A. Access to the Medium

Consider an arbitrarily selected node as the reference node (RN). Active nodes are those with a non-empty queue, i.e., with packets to send. The active nodes generate a random

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backoff time selected from $\{0,\ldots,W-1\}$. When the RN is active, it transmits a packet successfully (without collision) if the other contending nodes selected backoff times greater than the one chosen by the RN. A packet transmitted by the RN will fail (collide) when more than one contending nodes select the same backoff time as the RN, and the backoff time is the smallest among all contending nodes. When the backoff time generated by the RN is not the smallest one among those generated by the other contending nodes, two outcomes are possible: either another node is able to transmit successfully, or other nodes collide while transmitting.

Consider a cycle where the RN is active and denote by k, $0 \leq k \leq N-1$, the number of nodes that are also active in the same cycle in addition to the RN. Let $P_{s,k} = \sum_{i=0}^{W-1} (1/W)\,(W-1-i)^k/W^k$, $P_{sf,k} = \sum_{i=0}^{W-1} (1/W)\,(W-i)^k/W^k$, and $P_{f,k} = (1/W)\sum_{i=0}^{W-1}\left[(W-i)^k-(W-1-i)^k\right]/W^k = 1/W$, be the probabilities that the RN transmits a packet successfully, that it transmits (successfully or with failure), and that it transmits with failure, respectively. $P_{s,k}$ is the probability that the RN selects one backoff value from 0 to $W-1$ and the other k nodes choose a larger value. $P_{sf,k}$ and $P_{f,k}$ can be described in similar terms. Note that $P_{sf,k}-P_{s,k}=1/W=P_{f,k}$ [5].

Conditioned on a successful or unsuccessful packet being transmitted by the RN when contending with other k nodes, the average backoff times are $BT_{s,k} = (1/P_{s,k})\sum_{i=0}^{W-1} i\,(1/W)\,(W-1-i)^k/W^k$, or $BT_{f,k} = \sum_{i=0}^{W-1} i\,(W-i)^k/W^k - \sum_{i=0}^{W-1} i\,(W-1-i)^k/W^k$.

B. Node DTMC

Here we model the evolution of the number of packets in the queue (*state*) of the RN over time by a DTMC. At each *data period*, state transition opportunities occur when: i) the RN is active and it transmits a packet (state can decrease); and ii) a packet is received by the RN (state can increase). Consider the homogeneous case where all the nodes behave as the RN does and also support infinite retransmissions.

Let A_i be the probability that i packets arrive to the RN in a cycle of length T. If packets arrive to a node following a Poisson process with rate λ, then $A_i = (\lambda T)^i \cdot e^{-\lambda T}/i!$ and $\widehat{A}_i = 1-\sum_0^{i-1} A_i$ where $\widehat{A}_i$ denotes the probability that at least i packets arrived during T. Note that our model applies to any other distribution for A_i as well. Let $\boldsymbol{P}=[P_{i,j}]$ be the transition probability matrix of the *node* DTMC, where $P_{i,j}$ is the probability that j packets are found in the queue at cycle $m+1$, conditioned on finding i packets in the queue at cycle m. These transition probabilities are defined by,

$$
\begin{aligned}
&P_{0,i} = A_i\,,\ i \leq Q-1\,, \quad P_{0,Q} = \widehat{A}_Q\,,\\
&P_{i,j} = p_s A_{j-i+1} + (1-p_s)\,A_{j-i}\,,\\
&\qquad i=0\ldots Q-1\,, j=i\ldots Q-1\,,\\
&P_{i,Q} = p_s \widehat{A}_{Q-i+1} + (1-p_s)\,\widehat{A}_{Q-i}\,, \quad i=1\ldots Q\,,\\
&P_{i,i-1} = p_s A_0\,,\ i=1\ldots Q\,, \quad P_{i,j}=0\,,\ j\leq i-2\,.
\end{aligned}
$$

The solution of this DTMC can be obtained by solving the set of linear equations

$$\boldsymbol{\pi} = \boldsymbol{\pi}\boldsymbol{P}\,, \quad \boldsymbol{\pi}\boldsymbol{e}=1\,, \tag{1}$$

where $\boldsymbol{\pi}$ is the stationary distribution vector and $\boldsymbol{e}$ is a column vector of ones. For the *node* DTMC, we adopt the common approximation that the probability of successful transmission, p_s, is independent of the state of the other nodes.

Let $M_k(\pi_0)$ be the probability that k nodes, out of the $N-1$ ones other that the RN, are active, where π_0 is the probability that a node is inactive. Assuming a binomial distribution for the number of active nodes [3], $M_k(\pi_0) = \binom{N-1}{k}(1-\pi_0)^k \pi_0^{N-1-k}$. Then,

$$p_s(\pi_0) = \sum_{k=0}^{N-1} M_k(\pi_0)\,P_{s,k}\,, \tag{2}$$

is the (average) probability that the RN transmits a packet successfully, conditioned on the RN being active.

By solving the set of equations in (1), $\pi_0(p_s)$ can be determined for a given p_s. Then, a new $p_s(\pi_0)$ can be obtained from (2) for a given π_0. Denote by p_s the solution of this fixed-point equation, i.e., the value of $p_s(\pi_0)$ at the fixed-point. A different approach for determining p_s is proposed in the next subsection using the *system* DTMC, considering that the binomial distribution assumption may not hold.

Note that the *node* DTMC model applies to zero retransmission as well if p_s is replaced by p_{sf} in (1). As in [3], the probability that the RN transmits a packet (successfully or with failure), p_{sf}, can be obtained by solving a similar fixed-point equation but with $p_{sf}(\pi_0) = \sum_{k=0}^{N-1} M_k(\pi_0)\,P_{sf,k}$.

C. System DTMC for Infinite Retransmissions

The system DTMC models the evolution of the number of active nodes in the cluster. Let $\boldsymbol{P'}=\left[P'_{i,j}\right]$ be the transition probability matrix of the DTMC that models the evolution of *the number of active nodes in the system*, where $P'_{i,j}$ is the probability that j nodes are found active at cycle $m+1$, conditioned on finding i active nodes at cycle m. The transition probabilities of the *system* DTMC are:

$$
\begin{aligned}
&P'_{0j} = B_j(N)\,,\ 0\leq j\leq N\,,\\
&P'_{ij} = \left(\widehat{S}_i + S_i\widehat{E}\right)B_{j-i}(N-i) + S_i E B_{j-i+1}(N-i)\,,\\
&\qquad 1\leq i\leq N-1\,,\ i\leq j\leq N-1\,,\\
&P'_{iN} = \left(\widehat{S}_i + S_i\widehat{E}\right)B_{N-i}(N-i)\,,\ 1\leq i\leq N-1\,,\\
&P'_{NN} = \widehat{S}_N + S_N\widehat{E} = (1-S_N E)\,,\\
&P'_{ij} = 0\,,\ 2\leq i\leq N\,,\ j<i-1\,,\\
&P'_{ij} = S_i E B_0(N-i)\,,\ 1\leq i\leq N-1\,,\ j=i-1\,,\\
&P'_{NN-1} = S_N E\,,
\end{aligned}
$$

where: i) $B_j(n) = \binom{n}{j}\widehat{A}_1^j A_0^{n-j}$ is the probability that j out of n nodes that have their queues empty receive packets in a cycle, ii) $S_k = kP_{s,k-1}$ and $\widehat{S}_k = 1-S_k$ are the probabilities that a packet is successfully transmitted in a cycle when k nodes compete, and its complementary $\widehat{S}_k$ is the probability that packets from two or more nodes collide, and iii) $E = p_s A_0\pi_1/p_s(1-\pi_0)$ and $\widehat{E}=1-E$ are the probabilities that a node's queue becomes empty or remains non-empty when it transmits successfully, respectively. Note that π_0 and π_1 are the stationary probabilities that the queue of a node has '0' and '1' packet, respectively.

The solution of the *system* DTMC can be obtained by solving the set of linear equations in (1) but with $\boldsymbol{P'}$. Let $\{\pi'_n\}$ be the stationary distribution of the *system* DTMC. Furthermore, let α'_k be the fraction of cycles where the RN is active, together with other k nodes, and α_k the probability that k nodes other than the RN are active, conditioned on the RN being active. Then, $\alpha'_k = \binom{N-1}{k}\pi'_{k+1}/\binom{N}{k+1} = (k+1)\,\pi'_{k+1}/N$, $\alpha_k\,(\pi_0) = \alpha'_k/G$, $G = \sum_{k=0}^{N-1}\alpha'_k$, $k = 0, \ldots N-1$.

Finally, $p_s\,(\pi_0)$ can now be obtained as $p_s\,(\pi_0) = \sum_{k=0}^{N-1}\alpha_k\,(\pi_0)\,P_{s,k}$. Clearly, both the *system* and the *node* are one-dimensional DTMCs and they must be solved iteratively to find p_s, the fixed-point equation solution.

III. Delay Analysis

Let D be the average delay that a packet experiences expressed in number of time cycles, i.e., from its arrival until it is transmitted and removed from the buffer. Then, D can be determined by Little's law,

$$D = \frac{N_{av}}{\lambda_a}\,,\; N_{av} = \sum_{n=0}^{Q} n\pi_n\,,\; \lambda_a = \sum_{n=0}^{Q} b_n\pi_n\,, \qquad (3)$$

where $b_0 = \sum_{i=0}^{Q} iA_i + Q\widehat{A}_{Q+1}$ and $b_n = \sum_{i=0}^{Q-n} iA_i + (Q-n+p_s)\,\widehat{A}_{Q-n+1}$, $n > 0$. Note that π_n is the stationary probability of finding n packets in the queue of a node, N_{av} is the average number of packets, λ_a is the average number of packets that entered the queue (*accepted*) per cycle, and that b_n is the mean number of packets *accepted* per cycle at state n. Note also that the last term of b_n is obtained after solving $((Q-n+1)\,p_s + (Q-n)\,(1-p_s))\,\widehat{A}_{Q-n+1}$, where we assume that only one packet can be sent per cycle.

IV. Energy Consumption Analysis

Define the following constants, where P_{tx} and P_{rx} are the transmission and reception power,

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

The average energy consumed by the RN during the data transfer part of a cycle when $k+1$, $k \geq 2$, nodes are contending for the channel, is given by

$$\begin{aligned}
E_{d,k+1} = {} & q_{1,k}P_{s,k}\cdot[E_{txs} + (4D_p + BT_{s,k})\,P_{rx}]\\
& + q_{1,k}P_{f,k}\cdot[E_{txf} + (2D_p + BT_{f,k})\,P_{rx}]\\
& + q_{2,k}P_{s,k}\,\alpha_1\cdot[E_{rxs} + (3D_p + BT_{s,k})\,P_{rx}]\\
& + q_{2,k}P_{s,k}\,\alpha_2\cdot[E_{rxf} + (D_p + BT_{s,k})\,P_{rx}]\\
& + q_{3,k}\cdot[E_{rxf} + (D_p + BT_{f,k})\,P_{rx}]\,.
\end{aligned} \qquad (4)$$

The terms in $E_{d,k+1}$ correspond to the energy consumed by: a packet successfully transmitted, a packet transmitted that collides, a successful packet reception, a successful packet transmitted by nodes other than the RN whose destination is not the RN, and packets transmitted by nodes other than the RN that collide, respectively.

In (4) D_p is the one-way propagation delay, $\alpha_1 = 1/(N-1)$ and $\alpha_2 = (N-2)/(N-1)$. Note that α_1 and α_2 might depend on the routing protocol. Moreover, conditioned on finding $k+1$ nodes active, $q_{1,k} = (k+1)/N$ is the probability that the RN is active, $q_{2,k} = kq_{1,k} + (k+1)\,(1-q_{1,k})$ is the average number of active nodes other than the RN, and $q_{3,k} = q_{1,k}\,[1-(k+1)\,P_{s,k} - P_{f,k}] + (1-q_{1,k})\,[1-(k+1)\,P_{s,k}] = 1-(k+1)\,P_{s,k} - q_{1,k}P_{f,k}$ is the probability that at least one node different from the RN transmits a packet with failure. Note that when the RN is active (with probability $q_{1,k}$) then $1-(k+1)\,P_{s,k} - P_{f,k}$ gives the probability that it does not transmit but the other k nodes collide. However, when the RN is not active (with probability $1-q_{1,k}$) then it is still listening and reacts to the collisions of the other $k+1$ nodes in the same way.

The expressions for $E_{d,1}$ and $E_{d,2}$ can be easily derived from (4), while $E_{d,0} = E_{rxf} + (W+D_p)\,P_{rx}$. Then, the average energy consumed by the RN during the data transfer part of a cycle is given by

$$E_d = \sum_{n=0}^{N} R_n E_{d,n}\,, \qquad (5)$$

where either $R_n = \binom{N}{n}\,(1-\pi_0)^n\,\pi_0^{N-n}$ or $R_n = \alpha_n$. In addition to E_d, a node also consumes energy due to the exchange of signaling messages like SYNC. Also, the energy consumed during the *sleep* part of a cycle is not included, as it is application dependent. Please, refer to [3] for details.

V. Numerical Results

Let $T = T_{SD}/b$ be the duration of a cycle, T_{SD} the duration of the synchronization and data transfer parts, and b the duty cycle fraction. We configure $T_{SD} = 30\cdot10^{-3}$ s. Then, for a given duty cycle fraction b, a different cycle duration T is obtained. To run S-MAC we set: backoff tick $= 1$, $t_{RTS} = 1.8$, $t_{CTS} = 1.8$, $t_{DATA} = 17.16$, $t_{ACK} = 1.8$, and $D_p = 2$, where all values are in units of 10^{-4} s. The *reference configuration* is defined by: $N = 5$, $Q = 10$, $W = 128$, $b = 0.5$, $P_{tx} = 52.2$ mW and $P_{rx} = 59.1$ mW. These values are similar to the ones configured in [3].

Three load conditions are considered for the reference configuration, i.e., low load (LL), medium (ML), and high (HL), which correspond to the arrival rates of $\lambda = \{1.5, 3.0, 4.5\}$ packets per second, respectively. As a reference, the packet loss probabilities induced by these loads due to a buffer overflow are approximately in the order of 10^{-12}, 10^{-6} and 10^{-1} respectively. During overflow episodes, some degree of selective packet discarding must occur at the sensors to give priority to the most important information. Once such imperative information is selected, the sensors rely on a loss-free transfer across the network.

We developed a discrete-event simulation model that mimics the physical behavior of the system. The simulation results are therefore completely independent from those obtained by the analytical model. We evaluate first the impact of configuring the nodes with zero retransmissions as presented in [3], versus with infinite retransmissions as proposed in this study.

In the *zero retransmission mode*, packet loss due to collisions in the channel obtained by simulation for the three load levels are: $\{0.435\%, 1.81\%, 3.92\%\}$, respectively. When

TABLE I
VALUES AND PERCENTUAL RELATIVE ERRORS FOR π_0

	π_0	M2_err	M1_err
LL	0.88	0.03	0.46
ML	0.51	11.76	23.32
HL	0.008	1.40	1.41

TABLE II
VALUES AND PERCENTUAL RELATIVE ERRORS FOR M2

	D_{sim}	D	D^*	$E_{d,sim}$	E_d	E_d^*
LL	1.42	0.92	2.15	5.46	0.20	4.94
ML	4.68	20.23	26.78	3.14	4.63	14.56
HL	17.0	0.42	12.34	1.85	0.006	6.19

the infinite retransmission mode is employed, we noted that more than 99.99% of the packets are transmitted after 1 or 2 retransmissions, even in the worst case (in HL). We also determined by simulation the delay and energy consumption when nodes are configured with a finite number of retransmissions. As expected, we observed that the delay and energy consumption when the maximum number of retransmissions was set to 3 or more remain practically identical, and equal to the values obtained for infinite retransmissions. This confirms that an infinite retransmission model provides a much simpler, yet accurate, alternative to a finite retransmission model for systems with negligible packet loss.

Let us now evaluate the *node* DTMC model in isolation versus the hybrid *node* and *system* DTMC model. Denote by model M1 the model that employs the *node* DTMC alone using the binomial distribution to find p_s, as proposed in [3]. The model that combines the *node* DTMC together with the *system* DTMC to find p_s, as proposed in this letter, is referred to as M2. In both models nodes have retransmissions enabled. Based on the reference configuration and the above mentioned three load levels, we compare the accuracy of these two models using the relative error $|x-y|/y$ as a measure, where x is the value obtained by the corresponding analytical model and y is the value obtained by simulation.

Table I presents the absolute values (π_0) and percentual relative errors (M2_err and M1_err) obtained for π_0. Clearly, the relative error achieved by M1 is much larger, particularly at ML. This is likely due to the fact that the independence assumption of the state of the nodes in the network does not hold. Using M2, the relative error for π_0 is substantially reduced, especially at LL and ML. Note that at the limit of the LL and HL regimes, the distribution of active nodes would be: i) $\pi'_0 \cong 1$ and $\pi'_i \cong 0, i \geq 1$; ii) $\pi'_N \cong 1$ and $\pi'_i \cong 0, i \leq N-1$, respectively. Then, in these regimes, when a node accesses the channel it always finds the same number of contenders. However, in the ML scenario finding a good distribution of active nodes is crucial to determine p_s, and therefore to solve the node DTMC accurately.

Next, we compare the average packet delay for the reference configuration but with $Q = 5$, in order to highlight the differences with the delay model proposed in [3]. Columns D_{sim} and $E_{d,sim}$ in Tab. II show absolute values obtained from simulation for delay in cycles (units of 60 ms) and energy consumption in units of 10^{-4} J. Columns D, D^*, E_d and E_d^* show relative errors when $\{\pi_n\}$ is obtained by M2. Column D shows the relative errors obtained using Little's law, as proposed in Sec. III. Column D^* shows the relative errors obtained when expression (15) in [3] is adopted. As observed, the errors in D^* are larger than those in D. This is likely due to the fact that expression (15) in [3] is implicitly based on the application of the arrivals see time averages (ASTA) property. However, ASTA does not hold in this system [4].

Furthermore, using also M2 and the reference configuration, we analyze the energy consumed by the RN during the data transfer part of a cycle. Column E_d in Tab. II lists the relative errors obtained by expression (5) proposed in Sec. IV. Column E_d^* shows the relative errors obtained by the energy model in [3]. As observed, the errors in E_d^* are substantially larger than those in E_d for all traffic load levels. This discrepancy is likely due to two facts. First, expression (4) above and expression (37) in [3] have different terms. Second, expressions for $BT_{s,k}$ and $BT_{f,k}$ derived in this letter are different from those in [3].

To further improve the accuracy, we combine both *system* and *node* DTMCs to define a two dimensional DTMC. A state in the new DTMC is represented by (i, m), where i is the number of packets in the queue of the RN, and m is the number of active nodes in the system. With this new model, the relative errors obtained at ML for π_0, delay and energy consumption are 3.20%, 6.05% and 1.85%, respectively. The relative errors obtained under LL and HL are also lower than the ones displayed in Tab. II. Details for this integrated model can be found in [5].

VI. CONCLUSIONS

We developed an analytical model for S-MAC operating in an infinite retransmission scenario, which involves the interaction of two one-dimensional DTMCs that model the evolution of the number of packets in the queue and the number of active nodes in a cluster, respectively. The proposed model is verified by extensive discrete-event based simulations under various traffic load conditions, which show accurate results. We also proposed alternative methods to determine delay and energy consumption, which are more general and accurate than those proposed previously.

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