Cooperative or Non-Cooperative Transmission in Synchronous DC WSNs: A DTMC-based Approach

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***Abstract*—Cooperative transmission (CT) enables balanced energy consumption among sensor nodes and mitigates the energy hole problem in wireless sensor networks (WSNs). In typical CT enabled medium access control (MAC) protocols, a source node decides to trigger CT or not based on a residual energy comparison between itself and its relay node. In this paper, we propose a receiver initiated CT MAC protocol, in which the receiving node makes the decision on initiating CT or not based on a tradeoff between performing CT and non-CT. In this way, nodes can avoid idle listening and achieve an extended lifetime. A discrete-time Markov chain (DTMC) model is developed to analyze the performance of CT associated with synchronous CT MAC protocols. Using this DTMC model, the performance of the protocol is evaluated with respect to energy consumption, energy efficiency and network lifetime. Numerical results demonstrate the accuracy of the model and the effectiveness of CT, in contrast to non-CT, as it leads to balanced energy consumption and an optimal network lifetime.**

I. INTRODUCTION

Energy hole [1] is a phenomenon caused by uneven energy consumption activities among sensor nodes in a wireless sensor network (WSN). It occurs typically when a relay node (RLN) depletes its battery earlier than the source nodes do since it has more packets to forward. Consequently, the source nodes would be disconnected from the *sink*, resulting in a shorter network lifetime. To mitigate this problem, cooperative transmission (CT) [2] appears as a promising technique. In CT, neighboring nodes collaborate with a sending node to transmit multiple copies of a packet. Then, the distant destination node recovers the packet by combining these copies of the same packet, exploiting both temporal and spatial diversity. CT can be employed in duty cycling (DC) medium access control (MAC) protocols [3] - [4]. In a CT enabled network, a source node may, together with its selected neighbors, transmit a packet directly to a distant node bypassing the relay nodes [3]. Consequently, the energy consumption at the RLN is reduced. Thus the outbreak of the energy hole is postponed.

In the literature many CT MAC protocols employ a sender initiated CT [3] - [4], where a sending node decides whether or when to perform CT based on the residual energy level of the receiving (i.e., the relay) node. However, this procedure requires to exchange several control packets among the RLN, the cooperating nodes and the destination node before making a decision. During the process, nodes participating in the CT waste energy due to idle listening. Furthermore, these protocols are evaluated merely through simulations.

Meanwhile a few analytical models have been developed for evaluating synchronous MAC [5] protocols, including our earlier work [6]. For instance, the energy hole problem was analyzed from a routing perspective in [1]. Indeed, these models were proposed solely for analyzing non-CT operations. To reflect CT operations, a Markov decision process was proposed in [7] with a goal of optimizing the lifetime in a CT network using a combination of routing and MAC mechanisms. However, so far no mathematical models exist to analyze joint CT and non-CT operations in synchronous DC MAC protocols.

In this paper, we propose a receiver initiated (RI) CT, carrier sensing multiple access/collision avoidance (CSMA/CA) based MAC (RICT-MAC) protocol and assess its performance analytically. The proposed discrete-time Markov chain (DTMC) model has two dimensions (2D), one modeling the queue dynamic of a given node, and the other representing the number of active nodes in the same network. Different from existing DTMCs which consider only non-CT operation [5] [6], the developed model includes both the CT and non-CT and it applies to other synchronous CT MAC protocols as well. The solution of this DTMC is used to determine energy consumption, energy efficiency and network lifetime considering both CT and non-CT. The model accuracy is validated through discrete-event simulations. For comparison purposes, we evaluate its performance together with the one obtained by the scheduled cooperative transmission MAC (SCT-MAC) [3] and a non-CT protocol, DW-MAC [8].

The rest of the paper is organized as follows. In Sec. II, we present the network model and the RICT-MAC protocol. Sec. III performs the proposed DTMC model and Sec. IV provides the energy consumption analysis. Numerical results from the discrete-event simulations and DTMC model are demonstrated in Sec. V, before the paper is concluded in Sec. VI.

II. RICT-MAC: PRINCIPLE AND OPERATION

Consider a cluster of N sensor nodes that send traffic towards a common single *sink*, using one common RLN, as shown in Fig. 1. For analysis convenience, we select arbitrarily

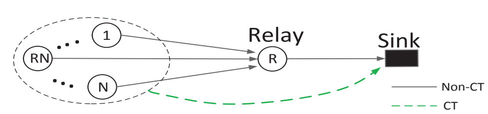

Fig. 1. Illustration of a 2-hop wireless sensor network with both CT and non-CT operations.

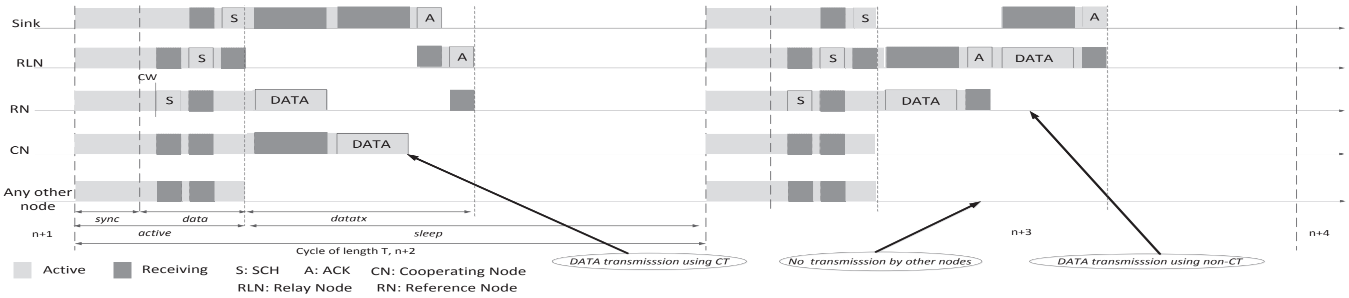

Fig. 2. Illustration of performing CT and non-CT in RICT-MAC.

one of the N nodes, and refer to it as the reference node (RN). Hereafter, *DATA*, *SYNC*, *SCH* and *ACK* denote packets, while t_{DATA}, t_{SYNC}, t_{SCH} and t_{ACK} denote the corresponding packet durations respectively. Meanwhile, we represent the different parts of a cycle as *active*, *sleep*, *sync*, *data* and their corresponding durations as T_{active}, T_{sleep}, T_{sync} and T_{data} respectively.

A. RICT-MAC Protocol Overview

When nodes wake up, they synchronize with one another by exchanging schedule messages during a fixed-length *sync* period, followed by a *data* period used to exchange *SCH* packets. After the *data* period, nodes go to sleep. The time elapsed between a node's wake-up moment and the instant it goes to sleep is regarded as an *active* period. Then, the time interval during which nodes sleep is referred to as a *sleep* period. Furthermore, the time interval defined between two wake-up instants is considered as one *cycle*, i.e., a *cycle* contains successively, a *sync*, a *data* and a *sleep* period.

RICT-MAC uses the *data* period only for reserving medium access for its *DATA* transmission in the subsequent *sleep* period. All active nodes (i.e., those with a non-empty queue) compete in the *data* period to transmit a *SCH* packet. The node that successfully transmits (without collision) a *SCH* packet occupies the medium in the subsequent *sleep* period for *DATA* transmission. If a collision occurs, *DATA* exchange is not possible in the current cycle, and nodes try again in the next cycle by generating new backoff times. In the studied network, we assume that the channel is error-free and transmission failures occur only due to collisions.

Fig. 2 illustrates the operation of RICT-MAC. Assume that the RN is the winner of the contention in the *data* period. After gaining channel access, the RN transmits *SCH* to the RLN, reserving the medium along the subsequent *sleep* period. Then, the RLN forwards this message to the *sink* node to inform it about the follow-up *DATA* transmission. In RICT-MAC, the contention among nodes happens only in the *data* period. That is, no contention occurs during *DATA* exchange. It is worth mentioning that the RICT protocol supports transmitting multiple packets in one cycle similar to DW-MAC [9]. However for presentation clarity, we report hereafter only the model for single packet transmission per cycle.

After obtaining channel access, two modes are possible for the transmission of a *DATA* packet, as described below.

1) Cooperative Transmission: The RN sends a *SCH* packet to the RLN that includes the residual energy level of the RN, E_{rn}, in addition to the address of the destination node, i.e., the *sink* [8]. The RLN compares E_{rn} with its own energy level, E_f. If $E_f < E_{rn}$, it decides to perform CT by *broadcasting* a reply *SCH* packet containing the ID(s) of the cooperating node(s) (CN(s)). For the network shown in Fig. 1, only one CN is enough to transmit the *DATA* to a two-hop away sink node [3]. This reply message is received by the *sink* node as well. Subsequently, the RN, the *sink* and the CN wake up in the subsequent *sleep* period in order to participate in CT. Note that, to save energy, the RLN does not wake up. To perform CT, the RN first broadcasts the *DATA*, and then it goes to sleep. A copy of the same *DATA* is sent to the *sink* again by the CN in a time division CT manner [3], as shown in Fig. 2. The *sink* combines both copies to decode it properly. Afterwards, the RLN and the RN awake to receive the *ACK* from the *sink*.

In this study we focus on a homogeneous network where all nodes behave in the same way with similar characteristics and have the same initial energy. Then, all nodes have equal probability to be selected as a CN, as we expect an equal energy consumption rate for all source nodes. See Sec. IV.

2) Non-cooperative Transmission: The *DATA* packet is transmitted in a non-CT manner if $E_f \geq E_{rn}$. The RLN replies with a *SCH without any ID* for the CN. Since there is no ID of any collaborator, nodes follow the non-CT mode. Correspondingly, the RN and the RLN proceed with *DATA* exchange, whereas the *sink* delays its wake-up time by $(t_{DATA}+t_{ACK}+2D_p)$ where D_p is the one-way propagation delay. Note that the RN goes to sleep after transmitting the *DATA* packet, while the RLN continues to forward the *DATA* packet to the *sink*, as illustrated Fig. 2.

B. Medium Access in RICT-MAC

Consider that the RN has packets in the queue (is active) and contends with other k, $0 \leq k \leq N-1$ active nodes in a given cycle. All active nodes generate a random backoff time from the set $\{0, W-1\}$ at the beginning of the *data* period. Then the probability that the RN is the only node selecting the smallest backoff time (the winner), and that it transmits a *SCH* successfully (without collision) is given by,

$$P_{s,k} = \sum_{i=0}^{W-1} (1/W)\,(W-1-i)^k \,/W^k \,. \qquad (1)$$

Note that the decision on deploying CT is made later. With a probability $P_{sf,k} = \sum_{i=0}^{W-1} (1/W)(W-i)^k / W^k$, the RN transmits either successfully or with collision. Otherwise, the RN loses the contention with a probability $(1 - P_{sf,k})$, and it defers access until the next cycle.

III. A DTMC Model for RICT-MAC

A state in the 2D DTMC is represented by (i, k), where i is the number of packets in the queue of the RN, $i \le Q$, and k is the number of active nodes other than the RN in the cycle, $k \le K = N - 1$. Assume that packet arrivals follow a Poisson process with rate λ. For cycles of length T, the probability that i (or more) packets arrive to the RN in a cycle is $A_i = (\lambda T)^i \cdot e^{-\lambda T}/i!$ ($A_{\ge i} = 1 - \sum_{j=0}^{i-1} A_j$). Note that the model supports other renewal arrival process as well.

When k nodes compete in a cycle, the probability that any of them transmits a *SCH* packet successfully is $S_k = kP_{s,k-1}$, and the collision probability is $\widehat{S}_k = 1 - S_k$. Furthermore, when a node transmits a *DATA* packet, the probability that its queue becomes empty is

$$P_e = P_s A_0 \pi_1 / P_s (1 - \pi_0) , \tag{2}$$

where P_s is the probability that the RN (or another node) transmits a *SCH* packet successfully in a random cycle, and π_0 and π_1 are the stationary probabilities of finding 0 and 1 packet at the queue of the RN respectively. The probability that it remains non-empty is $\widehat{P}_e = 1 - P_e$. Define also $B_k(l) = \binom{l}{k} \widehat{A}^k A_0^{l-k}$ as the probability that k out of l nodes which have their queues empty receive packets in a cycle, where $\widehat{A} = 1 - A_0$.

Denote by P_{ct} (P_{nct}) the probability that the RN operates in the CT (non-CT) mode in a random cycle. Clearly, $P_s = P_{ct} + P_{nct}$ holds as CT or non-CT can only occur in cycles where the RN has won the contention. Let us define β, where $0 \le \beta \le 1$, such that, $P_{ct} = \beta P_s$ and $P_{nct} = (1-\beta)P_s$. We refer to this parameter as the *CT coefficient*.

In each cycle, a transition in the DTMC might occur based on packet arrivals and departures at the RN, as well as at the other source nodes, as shown in Tab. I. Denote further by $P_{(i,k),(j,l)}$ the transition probability from State (i, k) to State (j, l). The terms that compose $P_{(i,k),(j,l)}$ is explained as follows. A transition from (i, k) to (j, l) occurs when: i) the RN transmits a packet successfully in the CT mode with probability $P_{s,k}\beta$; ii) the RN transmits a packet successfully in non-CT with probability $P_{s,k}(1 - \beta)$; iii) an active node different from the RN transmits a packet successfully with probability $kP_{s,k}$ and empties its buffer; iv) an active node different from the RN transmits a packet successfully with probability $kP_{s,k}$ and does not empty its buffer; or v) no node is successful with probability $\widehat{S}_{k+1}$. Note that the RN receives $(j - i)$ packets with probability A_{j-i}, except in conditions i) and ii) where it receives $(j - i + 1)$ packets. Also, $(l - k)$ out of $(K - k)$ inactive nodes become active with probability $B_{l-k}(K - k)$, except in condition iii) where $(l - k + 1)$ nodes become active.

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

$$\boldsymbol{\pi P} = \boldsymbol{\pi} , \quad \boldsymbol{\pi e} = \mathbf{1} , \tag{3}$$

where $\boldsymbol{\pi}$ is the stationary distribution, $\boldsymbol{P}$ is the transition probability matrix, whose elements are defined in Tab. I, and $\boldsymbol{e}$ is a column vector of ones. By solving the set of equations (3), $\boldsymbol{\pi}(P_e)$ can be determined for a given P_e. Then, a new $P_e(\boldsymbol{\pi})$ can be obtained from (2) for a given $\boldsymbol{\pi}$, where $\pi_i = \sum_{k=0}^{K} \pi(i, k)$. Denote by P_e the solution of this fixed-point equation, i.e., the value of $P_e(\boldsymbol{\pi})$ at the fixed-point.

A. Calculation of P_{ct} as an Optimal Point

The main goal of RICT-MAC is to balance energy consumption in the network through CT. This means that the lifetime of the RLN, the RN and any other source node would converge to the same value. As shown in Fig. 2, operating in the CT mode continuously wastes the energy of CNs. On the other hand, operating in the non-CT mode would deplete the battery of the RLN earlier. In either case, the network suffers from a limited lifetime, since energy balancing cannot be achieved by running CT or non-CT *alone*.

Therefore, a tradeoff exists between triggering CT and non-CT during network operations. In order to find the optimal probability of deploying CT, we determine the value of β that makes the lifetimes of both the RLN and the RN equal.

IV. Energy Consumption Analysis of RICT-MAC

As explained in Sec. II, each cycle in RICT-MAC contains a *sync*, *data* and *sleep* period. In RICT, one $SYNC$ packet is transmitted every N_{sc} cycles, and one packet might be received per cycle in the remaining $N_{sc} - 1$ cycles as in [5]. So the energy consumed by a node in the *sync* period is $E_{sc} = [(t_{SYNC} \cdot P_{tx} + (T_{sync} - t_{SYNC}) \cdot P_{rx})] \cdot (1/N_{sc}) + (T_{sync} \cdot P_{rx}) \cdot (N_{sc} - 1)/N_{sc}$, where P_{tx} and P_{rx} are the transmission and reception power levels respectively.

As shown in Fig. 2, *three SCH* packets are required to transfer a *DATA* packet to the sink in the CT mode. Correspondingly, the duration of the *data* period of a cycle is $T_{data} = (W - 1)T_B + 3t_{SCH} + 2D_p$, where T_B is the duration of a backoff timer *slottime*. Similarly, the duration of the data transmission part in the *sleep* period is $T_{datatx} = 2(t_{DATA} + t_{ACK} + 2D_p)$.

The amounts of energy consumed per cycle by the RN when it transmits successfully (E_{txs}), either in the CT or non-CT mode, and when it acts as a cooperating node (E_{cts}) are given respectively by

$$\begin{aligned} E_{txs} &= t_{SCH} \cdot P_{tx} + (T_{data} - t_{SCH}) \cdot P_{rx} \\ &\quad + t_{DATA} \cdot P_{tx} + (t_{ACK} + 3D_p) \cdot P_{rx} \\ &\quad + (T_{datatx} - t_{DATA} - t_{ACK} - 3D_p) \cdot P_{sl} , \\ E_{cts} &= T_{data} \cdot P_{rx} + t_{DATA} \cdot P_{tx} + (t_{DATA} + D_p) \cdot P_{rx} \\ &\quad + (T_{datatx} - 2t_{DATA} - D_p) \cdot P_{sl} . \end{aligned}$$

Similarly, the amounts of energy consumed per cycle by the RLN in a successful transmission in the CT (E_{ct}) and non-CT (E_{nct}) mode are given respectively by,

Table I: Transition Probabilities of the DTMC Model for RICT-MAC

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

$$
\begin{aligned}
E_{ct} &= t_{SCH} \cdot P_{tx} + (T_{data} - t_{SCH}) \cdot P_{rx} \\
&\quad + t_{ACK} \cdot P_{tx} + (t_{ACK} + 2D_p) \cdot P_{rx} \\
&\quad + (T_{datatx} - 2t_{ACK} - 2D_p) \cdot P_{sl}\,, \\
E_{nct} &= t_{SCH} \cdot P_{tx} + (T_{data} - t_{SCH}) \cdot P_{rx} \\
&\quad + (T_{DATA} + t_{ACK}) \cdot (P_{tx} + P_{rx}) + 2D_p \cdot P_{rx}\,, \\
&\quad + (T_{datatx} - 2t_{DATA} - 2t_{ACK} - 2D_p) \cdot P_{sl}\,,
\end{aligned}
$$

where P_{sl} is the sleep power level. In case that a collision was caused by other nodes but not by the RN, both the RLN and the RN nodes consume the same energy as $E_{txf} = T_{data} \cdot P_{rx} + T_{datatx} \cdot P_{sl}$. If the RN is a participating node in that collision, then it consumes energy as $E'_{txf} = t_{SCH} \cdot P_{tx} + (T_{data} - t_{SCH}) \cdot P_{rx} + T_{datatx} \cdot P_{sl}$. However the energy consumed by the RLN is E_{txf}.

Consider that the number of active nodes in a cycle is $k+1$. As mentioned in Sec. III, the probability that a successful transmission occurs is S_{k+1}, and a failure is $\widehat{S}_k = 1 - S_k$. Then, the average energy consumed per cycle by the RLN for *DATA* exchange is

$$E_{drl,k+1} = S_{k+1}\left[\beta E_{ct} + (1-\beta) E_{nct}\right] + \widehat{S}_k E_{txf}\,. \tag{4}$$

Also, the energy consumed per cycle by the RN on average is

$$
\begin{aligned}
E_{drn,k+1} &= q_{1,k} \cdot \left[P_{s,k} E_{txs} + P_{f,k} E'_{txf}\right] \\
&\quad + q_{2,k} P_{s,k} \cdot \left[\beta \alpha_1 E_{cts} + (\beta \alpha_2 + (1-\beta)) E_{txf}\right] \\
&\quad + q_{3,k} E_{txf}\,,
\end{aligned} \tag{5}
$$

where $q_{1,k} = (k+1)/N$ 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 $q_{3,k} = 1 - q_{2,k}P_{s,k} - q_{1,k}P_{sf,k}$ is the probability that nodes other than the RN transmit a packet with failure. Moreover, $\alpha_1 = 1/(N-1)$ is the probability of selecting the RN as a cooperating node when CT is triggered by another node, and $\alpha_2 = 1 - \alpha_1$. Recall that for α_1, we assume a homogeneous network. In (5), the first term describes RN's actions (in CT, non-CT and collision). The second term describes the actions associated to a successful transmission by other nodes different from the RN, where the RN might cooperate in CT. Similarly, the last term represents a collision by the nodes other than the RN. If no node is active, then $E_{drl,0} = E_{drn,0} = T_{data} \cdot P_{rx} + T_{datatx} \cdot P_{sl}$.

In this network, the average energy consumed by the RLN during the *data* period of a cycle is given by,

$$E_{drl} = \sum_{k=0}^{N} E_{drl,k} \cdot \pi'_k \tag{6}$$

where $\pi'_k = \sum_{i=1}^{Q} \pi(i, k-1) + \pi(0, k)$ is the stationary probability of finding k active nodes in a cycle. Correspondingly, the energy consumed while nodes sleep in the *sleep* period of a cycle is given by

$$E_{sl} = (T - T_{sync} - T_{data} - T_{datarx}) \cdot P_{sl}\,, \tag{7}$$

and the average energy consumed by the RLN in a cycle is

$$E_{rl} = E_{sc} + E_{drl} + E_{sl}\,. \tag{8}$$

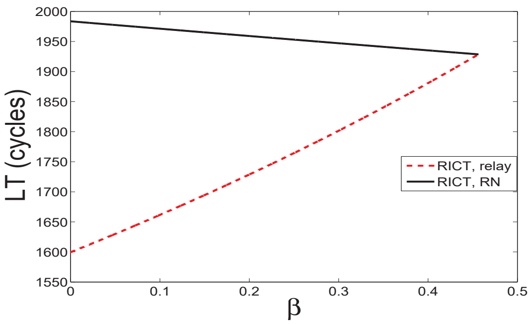

Fig. 3. Optimal CT coefficient β is found to be 0.4565 for $N = 2$.

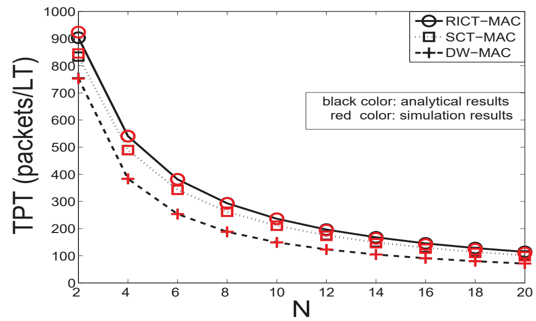

Fig. 4. TPT per cycle for different number of nodes.

The lifetime of the network shown in Fig. 1 depends on the lifetime of the RLN, as the network would be disconnected when RLN's battery is depleted. Accordingly, the network lifetime expressed in cycles is obtained as

$$LT = \left(E_{initial}/E_{rl}\right) \text{ cycles} . \tag{9}$$

Furthermore, the average number of successfully transmitted packets by the RN or any sending node in a cycle can be determined as $\eta = \sum_{i=1}^{Q} \sum_{k=0}^{K} \pi\left(i,k\right) \cdot P_{s,k}$. Accordingly, the mean number of packets forwarded by the RLN during the total network lifetime is given by,

$$TPT = N \cdot \eta \cdot LT . \tag{10}$$

Denote by ξ the energy efficiency of the RLN (network), expressed as the total number of bytes successfully transferred divided by the total amount of consumed energy in the lifetime of the RLN. It is given by

$$\xi = \left(TPT \cdot S/E_{initial}\right) , \tag{11}$$

where S is the size of the *DATA* packet in bytes.

In the same way, the lifetime of the RN can be obtained using the corresponding energy terms calculated from (5) and substituting them into (6)-(9) instead of the RLN related terms. Moreover, the calculations for SCT-MAC can be determined by replacing T_{data} with $(W-1)T_B + 5t_{SCH} + 4D_p$, as SCT needs 4 *SCH*s for channel reservation and 1 *beacon* for disseminating the residual energy information [3]. Likewise, the metrics for DW-MAC are obtained by keeping $P_{ct} = 0$ and $\alpha_1 = 0$.

V. Simulations and Numerical Results

In this section, we validate the proposed analytical model by comparing numerical results obtained from it with the ones obtained from simulations. The RICT-MAC and the other two studied protocols are simulated in a custom C based discrete-event simulator, SMPL. The behavior of each node in the simulated network is decided by the applied protocol and is therefore independent of the DTMC model. In our simulations, all nodes generate packets following a given distribution and compete among themselves for channel access according to the adopted protocol in every cycle. The results presented in this section are averaged over $5 \cdot 10^6$ cycles, each of 3.2 seconds.

Three protocols are studied in the network illustrated in Fig. 1 with nodes containing a queue length of $Q = 10$. The *DATA* packet size is configured to be of 100 bytes. Packets arrive at a rate of $\lambda = 1.5$ packet/s, and a node transmits a *SYNC* packet every $N_{sc} = 10$ cycles. Furthermore, we employ a 5% duty cycle while the other MAC parameters are taken from [8]. The transmission, reception and sleep power levels are $P_{tx} = 31.2$ mW, $P_{rx} = 22.2$ mW and $P_{sl} = 3$ μW [10] respectively. The performance metrics are determined by varying the number of nodes N from 2 to 20 at a granularity level 2. All nodes have the same initial energy $E_{initial} = 1$ J.

A. Optimal CT Operation

In order to determine the performance metrics, an optimal P_{ct} needs to be determined first, using the procedure presented in Sec. III. To do so, we calculate the lifetimes of both the RLN and the RN nodes by varying β at a granularity level of 1×10^{-5}. Then, we identify the β with which the lifetimes of both nodes coincide (both deplete their battery at almost the same time). That is, the optimal β is the point where the difference between E_{rl} and E_{rn} is smaller than 1×10^{-5} J. For a given network size N, we determine the optimal β, P_{ct} , P_{nct} , and the other performance metrics for the CT MAC protocols. In Fig. 3, this approach is applied to the aforementioned scenario with $N = 2$, and the optimal values were found to be $\beta = 0.4565$, and correspondingly $P_{ct} = 0.4565 \times P_s$. Note that this procedure does not apply to DW-MAC since it is a non-CT protocol, i.e., $\beta = 0$. With a difference network size, another optimal value should be identified.

As observed in Figs. 4 to 7, the analytical results precisely match with the simulation results up to $N = 12$. This is because that the CT balanced the energy perfectly among the nodes in the network with few nodes and the modeling approach identified the exact β. Clearly, identifying the optimal β is a good approximation for networks of small size.

Recall that the triggering of CT depends on the residual energy levels of the RLN and the source nodes. It is clear that CT is employed in the next cycle only when the winner of the current non-CT cycle obtains channel access again, and this probability, P_{ct}, decreases when N becomes larger. Then, in reality, the RLN consumes slightly higher energy on average when compared with source nodes including the RN. Consequently, the RLN will have slightly shorter lifetime than the RN does as obtained through simulations. On the other hand, the analytical model is based on a determined β which represents the energy balancing point that provides

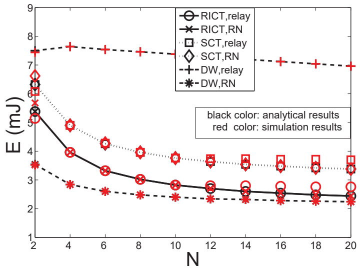

Fig. 5. E for different number of nodes.

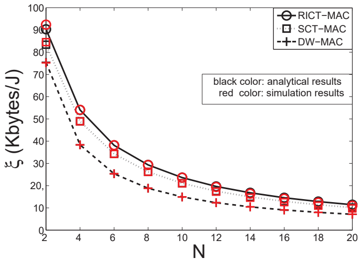

Fig. 6. ξ for different number of nodes.

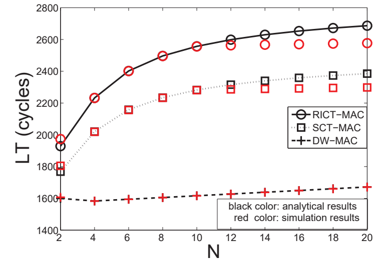

Fig. 7. LT for different number of nodes.

nodes with an equal lifetime and this procedure does not rely on the residual energy level information. Clearly, the analytical approach based on an optimal β leads to the same lifetime (energy consumption) for both the RLN and the RN whereas the simulations give a slightly shorter lifetime (higher energy consumption) to the RLN. Therefore, in Figs. 5 and 7, the discrepancy increases beyond $N = 12$. Anyhow, the deviation beyond $N = 12$ is still below 4% for both CT MAC protocols.

B. *Performance Comparison of Three Protocols*

Figs. 4 to 7 depict the total number of packets transmitted during the lifetime, the average energy consumed per cycle by the nodes, the energy efficiency, and the network lifetime, as the number of nodes in the network varies for all three studied protocols. It is obvious that the probability of getting a successful access is higher when fewer contentions occur (a smaller N). Consequently more packets are transmitted, as shown in Fig. 4. Accordingly, highest energy consumed by nodes per cycle is attained at $N = 2$ as depicted in Fig. 5. Moreover, highest energy efficiency is obtained at $N = 2$ as shown in Fig. 6, since ξ depends on TPT and $E_{initial}$ as defined in (11). The same trend applies to all three protocols.

More collisions occur when the network size grows. Recall that in case of a collision, no *DATA* transmission occurs. Consequently, with a larger N, lower energy is consumed per node (Fig. 5), and the energy efficiency decreases (Fig. 6), as TPT is reduced (Fig. 4). Beyond $N = 12$, the network is saturated. Then, all nodes have packets in their queues (are active) in almost all cycles. This leads to the stabilization of the network conditions. Consequently, very little performance variation is observed beyond $N = 12$.

The impact of operating CT is clearly visible in Fig. 5, where the energy consumed by the RLN and the RN is almost equal for both RICT and SCT protocols. However, RICT achieves lower energy consumption (Fig. 5) and higher energy efficiency. The reason behind this is a shorter *data* period, due to the fact that CT is initiated by the RLN.

In DW-MAC, the RLN consumes much higher energy than in the other two protocols, as a result of the continuous operation in the non-CT mode. As observed in Fig. 5, the energy consumed by the RN is lower than the one in CT protocols. However, the network lifetime is decided by the lifetime of the RLN. Therefore, the network lifetime in DW-MAC is much shorter, as plotted in Fig. 7. Observe that the shape of the network lifetime curve is approximately the inverse of the energy consumption curve, as shown in Fig. 7. For example, RICT achieves 12.04% and 58.2% longer lifetimes at $N = 10$ than in SCT-MAC and DW-MAC respectively.

VI. Conclusions

In this paper, we proposed a receiver initiated cooperative transmission MAC protocol, RICT-MAC, for synchronous duty-cycled WSNs. We developed a DTMC model to evaluate the performance of cooperative and non-cooperative transmissions in such a network. A method to calculate the optimal probability to initiate CT in a cycle, based on the CT coefficient β, was proposed. Using the developed model, the proposed receiver initiated cooperative transmission MAC protocol was evaluated. The energy consumption by the nodes, the lifetime of the network, the total number of packets transmitted successfully and the energy efficiency were calculated. It was validated that the analytical results precisely matched with those obtained from simulations. Moreover, initiating CT by the relaying node in RICT-MAC prolongs network lifetime, when compared with the sender initiated SCT-MAC protocol and non-CT protocols like DW-MAC.

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