ACT-MAC: An Asynchronous Cooperative Transmission MAC Protocol for WSNs

Lakshmikanth Guntupalli[1] , Jian Lin[2], Mary Ann Weitnauer[2] and Frank Y. Li[1]
[1]Dept. of Information and Communication Technology, University of Agder (UiA), N-4898 Grimstad, Norway
[2]School of Electronics and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332–0250, USA
[1]{lakshmikanth.guntupalli, frank.li}@uia.no, [2]{jlin61, maweit}@gatech.edu

Abstract— **Duty cycling (DC) has been proven to be an efficient mechanism to reduce energy consumption in wireless sensor networks (WSNs). On the other hand, cooperative transmission (CT) enables longer range transmission to hop over an *energy-hole* node, resulting in more balanced energy consumption among nodes. In the literature, there exist few CT MAC protocols for DC operated WSNs and these protocols rely on fixed cycle length. In this paper, we propose a novel variable cycle length protocol, namely asynchronous cooperative transmission medium access control (ACT-MAC), which contains both features of reducing the unnecessary idle listening by DC and mitigating the *energy-hole* by making use of CT. The proposed protocol employs a pseudo random sequence (PRS) generator to produce the variable length cycles. Numerical results show the ACT-MAC protocol's superiority over the existing protocols in terms of network longevity and the energy efficiency.**

I. INTRODUCTION

Avoiding unnecessary energy consumption in order to maximize network lifetime is an essential design principle in battery operated wireless sensor networks (WSNs). Duty cycling (DC) saves energy by allowing sensor nodes to turn their radio on and off periodically. Many medium access control (MAC) protocols [1-5] have been proposed to adopt DC to prolong the lifetime of WSNs.

Existing duty cycle MAC protocols proposed for WSNs can be categorized as synchronous and asynchronous protocols. Sensor-MAC (S-MAC) [1], scheduled channel polling MAC (SCP-MAC) [2] and demand-wakeup MAC (DW-MAC) [3] represent synchronous protocols, which typically exchange data during the common active period. A disadvantage of these protocols is that they require precise synchronization, causing more control overhead. A short preamble MAC protocol for duty cycled WSNs (X-MAC) [4] and receiver initiated MAC (RI-MAC) [5] are asynchronous duty cycle MAC protocols in which each node has its own independent duty cycle schedule. In these protocols, a node which has a packet to transmit wakes up and stays awake until it hears from the receiver. This waiting duration may bring significant latency for packet delivery.

On the other hand, the *energy-hole* is a known problem in multi-hop WSNs in which an intermediate node that is carrying heavier traffic has to consume more energy and consequently exhausts earlier [6]. If this node is the only node connecting two parts of a network, then the network partition occurs as a result of an *energy-hole*. Generally, the nodes near the sink are heavily burdened and are prone to the *energy-hole*. To alleviate this problem, cooperative transmission (CT) [7] can be activated [8]. The residual energy activated cooperative transmission (REACT) forwarding protocol proposed in [9] relies on the residual energy information of the nodes to trigger CT. When a parent node has lower residual energy compared with the child node on the route, the child node initiates CT. To perform the CT, the source node collaborates with its neighboring nodes and the collaborators transmit the packet on independent channels toward the destination over a longer distance to reach a two-hop away receiver [7]. As a consequence, the parent node with lower residual energy level is protected. To take advantage of range extension and for *energy-hole* avoidance, a few MAC protocols which combine both DC and CT have been proposed based on REACT. Among those MAC protocols, CDC-MAC [10] and EECDC-MAC [11] employ concurrent CT (CCT), whereas time division CT (TDCT) is used in SCT-MAC [12] and OSC-MAC [13]. However, these protocols rely on a fixed cycle length.

In this paper, we propose a duty cycling CT MAC protocol with a *variable cycle length*, which is generated by a pseudo random sequence (PRS) generator. The designed protocol is a CT protocol, because it mitigates the *energy-hole* by using CT. This protocol is an asynchronous MAC protocol, since all nodes maintain their own schedules based on a seed. Correspondingly, we refer to this proposed protocol as an asynchronous CT MAC (ACT-MAC) protocol. PRS is not completely random due to its periodic property [14]. Furthermore, regardless of the number of times the seed is used as an input, the generator produces the same sequence. Therefore, when a node knows the seed number of the receiving node, then it can deduce all the wakeup times of its receiver in a computationally efficient way. A novel feature of ACT-MAC is the introduction of the *level number* of the node as its seed; meaning that all the sibling nodes contain the same schedule. Moreover, once it has its *level number*, it automatically knows the *level number* of its parent node. Therefore, a node can know the wakeup slots of the receiving nodes and wake up at the same time, avoiding idle listening, which is a primary energy consumption factor. Furthermore, exchange of any extra control messages is not required to get another node's schedule. In fact, some existing MAC protocols make use of PRS to generate the schedules [14]. However, those are not CT MAC protocols. We evaluate the performance

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of the proposed ACT-MAC using both CCT and TDCT schemes. We further compare it with an energy efficient predictive wakeup MAC protocol (PW-MAC) [14], which is also a PRS based protocol. Moreover, we also compare ACT-MAC with SCT-MAC due to the similar feature of selecting the cooperators from the same collision domain.

The rest of this paper is organized as follows. The network model and protocol design consideration are presented in Sec. II. In Sec. III, we present ACT-MAC design in detail. Energy consumption analysis is presented in Sec. IV. Then the system performance is evaluated and compared with other MAC protocols in Sec. V. Finally the paper is concluded in Sec. VI.

II. NETWORK MODEL AND PROTOCOL DESIGN CONSIDERATIONS

We adopt the same network model from [11] as shown in Fig. 1. The lowest level nodes are C, D etc., with a parent Node B and two-hop away parent Node A. Here, we consider Node A as the sink and assume that it is also duty cycling but powered continuously. When the child nodes transmit packets, the parent node forwards them to the sink node. In such a case, the parent node B consumes more energy and dies earlier than the child nodes do. Then the *energy-hole* occurs and the network is disconnected.

Using CT, Nodes C and D avoid the *energy-hole* by sending the data to Node A directly. How CCT reaches a two-hop away parent node is demonstrated experimentally in [15] using non-coherent processing. Note that CCT can be performed only when at least two cooperating nodes are active in a common interval. In our design, this is possible since all cooperating nodes are chosen from the same level and wake up during the same pseudo random intervals. In order to produce the same schedules with a seed, it is required to install the same PRS generators at all nodes in the network. The *level number* for each node is given by the sink node during the network initialization phase.

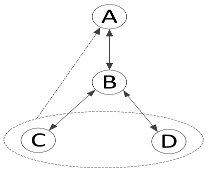

Fig. 1. Network model [11]: A WSN in which C and D may transmit to A directly to diminish *energy-hole* using CT.

III. ACT-MAC DESIGN

The basic principle of ACT-MAC is to generate the *level number* based pseudo random interval wakeup times. Besides, it activates CT for data transmission, if necessary. Similar to the other CT MAC protocols, ACT-MAC utilizes REACT forwarding technique to make the CT or non-CT decision. As in our earlier contribution EECDC-MAC [11], we modify REACT slightly in ACT-MAC. That is, we allow the initiation of CT when the nodes are with equal energy levels to ensure more balanced energy consumption of the receiving node. Therefore, in ACT-MAC, *if the remaining energy of the receiving node E_{rr} is greater than the sending node's remaining energy E_{rs}, then non-CT will be executed otherwise CT is performed.*

During network initialization, the *level number* is distributed by the sink node. We consider that the sink node is at the highest level. The sink assumes its own level as 0 and broadcasts to its child nodes. Then this number will be increased by 1 at each network level. When the child nodes broadcast their levels, the parent node receives it and knows that it has a child. If a node does not hear anything from any child nodes, then it is the lowest level node in the network. Hence in Fig. 1, the *level numbers* of the Nodes A, B are 0 and 1 respectively and the remaining nodes, i.e., C and D, belong to Level 2. After receiving the *level number*, nodes generate wakeup schedules and start duty cycling. How the schedules are produced and the rendezvous for CT is achieved are discussed in the following subsections.

A. PRS Based Duty Cycling

The PRS can be generated in many ways. However, for comparison purpose, we consider the linear congruential generator (LCG) which is adopted in PW-MAC [14]. Correspondingly, in ACT-MAC, the LCG generates the sequence of cycle lengths according to

$$X_{n+1} = (\alpha . X_n + \beta) \ mod \ M. \tag{1}$$

This generator produces the uniformly distributed pseudo random numbers in the range of [0, $M-1$]. Note that the cycle length generated by (1) varies for each iteration. Here, X_n is the previous cycle length and becomes the seed for generating the current cycle length X_{n+1}. The constants, α, β are the multiplier and increment values respectively, and can be set to any integer number between 0 and $M-1$. Taking X_0 as the initial seed, the combinations of X_0, α, β and M values produce different sequences. ACT-MAC allocates common α, β and M to all nodes, but X_0 is their *level number*.

Using the *level number*, a node is able to predict the wakeup schedules of all other levels in the network. A node is awake during its own slot to receive the DATA from child and follows its parent schedule for transmission. Note that, for a parent node, it does not need to calculate the schedule of its child nodes. Furthermore, the child nodes generate all the higher level node's schedules to wake up for CT. In the considered network, all the Level 2 nodes use Node B's schedule for data transmission. Since 2 is the lowest level, they do not wakeup in their own slots in order to save energy. Moreover, they use Node A's schedule when CT is performed.

B. Asynchronous Cooperative Transmission

ACT-MAC uses a receiver initiated approach for data transmission, which is similar to other asynchronous MAC protocols such as RI-MAC and PW-MAC. An advantage of this beacon based receiver initiated (RI) method is that it reduces the duty cycle at the receiver. A benefit of using the predictive wakeup (PW) mechanism is that it makes a reduction in duty cycle at the sender side. Therefore, combining both RI and PW achieves higher energy efficiency. Thus, in ACT-MAC, when a sender has a packet to transmit, it wakes up at the receiver's wakeup slot and avoids unnecessary

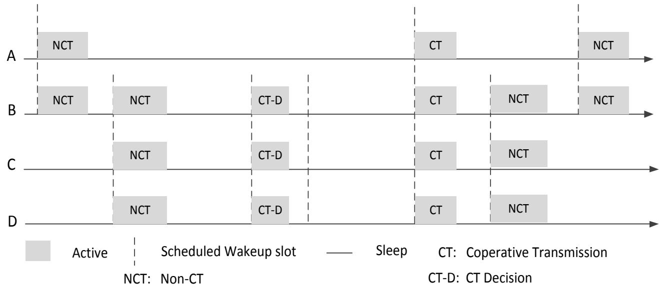

Fig. 2. Duty cycle of receiver and cooperator nodes in ACT-MAC.

idle listening by the sender. Fig. 2 shows the duty cycles of all nodes in the network. In the figure, the slot in which the non-CT transmission occurs is *non-CT* (NCT) slot. A *CT-decision* (CT-D) is a regular *non-CT* slot, but in which the CT decision is made. A slot where the actual CT transmission occurs is referred to as a *CT* slot. The rest of this subsection discusses the operations performed in each of the above mentioned slots.

To initiate transmission, Receiver B from Fig. 1, sends a beacon with its residual energy information (BE). Then the sending nodes, e.g., C and D in the same figure, receive BE and compare the energy value with their own energy levels. After CT or non-CT decision is made, those nodes compete for channel access to transmit the DATA frame. For *non-CT*, DATA is transmitted within the same wakeup slot after the decision is taken. Whereas for CT, the decision is made in the *CT-decision* slot and DATA is transmitted in the *CT* slot. Remember that the *non-CT* slots between *CT-decision* and *CT* slot are not used for data transmission as shown in Fig. 2. Furthermore, ACT-MAC allows only one packet transmission in a *CT* slot. Consequently, it may produce a significant delay. On the other hand, it achieves remarkable energy efficiency. For that reason, our ACT-MAC protocol applies better to delay tolerant sensor applications such as habitat monitoring [12]. To transmit the DATA in *CT*, ACT-MAC adopts either the CCT or the TDCT scheme. To perform CCT, the CT initiator node multicasts DATA to helpers as the first step. Then, both nodes perform the concurrent transmission after a SIFS interval. Whereas in TDCT, the CT initiator node broadcasts the DATA frame first. Then the cooperating node retransmits it again to the two-hop-away parent node. Thus, the main difference between these two schemes is that the CT initiator node transmits the DATA twice in CCT and once in TDCT. To decode the incoming DATA, the two-hop parent node uses Maximum Ratio Combining (MRC) [12]. The MAC procedures for both schemes are described in the following paragraphs as shown in Figures 3-6 in both *CT-decision* and *CT* slots.

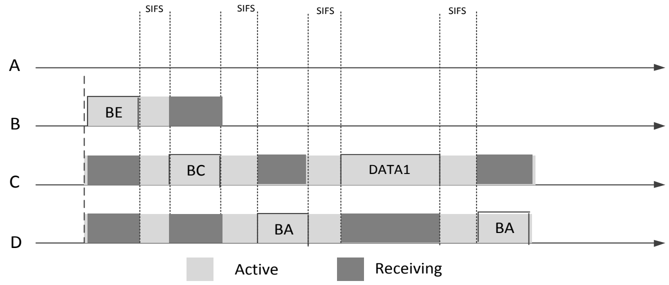

Fig. 3. *CT-D* slot for CCT in ACT-MAC.

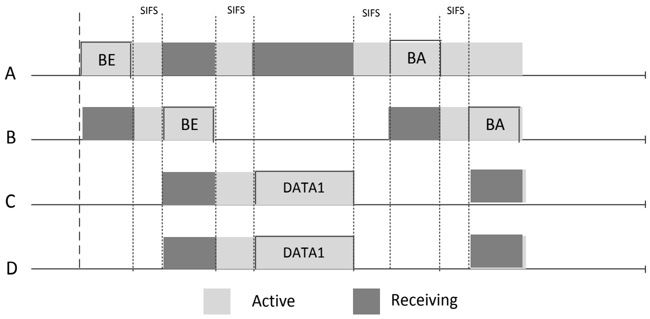

Fig. 4. CCT in ACT-MAC.

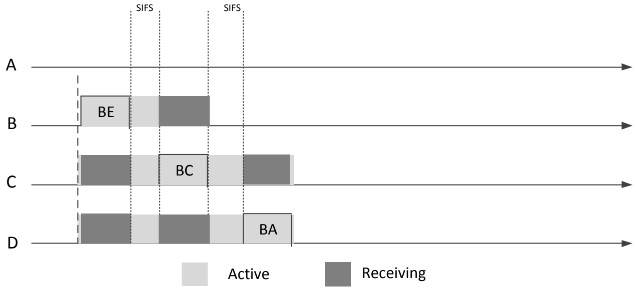

Fig. 5. *CT-D* slot for TDCT in ACT-MAC.

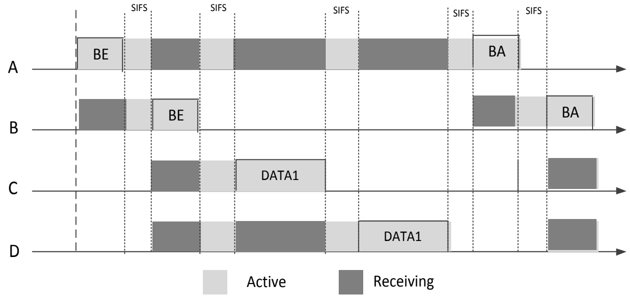

Fig. 6. TDCT in ACT-MAC.

1) CT-decision slot: When the winning node, for example Node C, decides to transmit the DATA using CT, it broadcasts a beacon for cooperation (BC) message. Upon receiving the BC, the cooperator Node D replies with a beacon of acknowledgement (BA) while the receiving node B goes to sleep. Fig. 3 shows the steps performed in *CT-decision* slot for CCT. As shown in the figure, in response to the BA, Node C sends the DATA packet to Node D. After the helping node replies with BA, both nodes go to sleep and wake up again at the *CT* slot. In case of TDCT from Fig. 5, Node C sends BC and Node D replies with BA and both nodes go to sleep.

2) CT slot: After this CT agreement, all nodes wake up at Node A's active slot. Similarly, the beacon transmission procedure is followed by Node A as well. In its designated wakeup slot, Node A sends a BE to the sending nodes via Node B. Note that

Nodes C and D delay their wakeup time by the duration of BE to avoid idle listening. Similarly, Node B is allowed to sleep for the duration of (2DATA + 2SIFS) to eliminate the unnecessary energy consumption. However, this node needs to wake up again to forward the BA from Node A to its child node. In case of CCT from Fig. 4, nodes C and D transmit the DATA at the same time. For TDCT, however, Node C broadcasts DATA first as shown in Fig. 6. Then Nodes D sends it again after a SIFS interval.

3) non-CT slot: For non-CT transmission, as shown in Fig. 7, Node C sends its DATA first. Meanwhile, the other node sleeps for the duration of (DATA+ BA + 2SIFS). Then, it wakes up and applies the backoff scheme for its data transmission. In the non-CT phase, a node goes to sleep after the DATA frame is sent in current cycle and wakes up in the next cycle.

C. Prediction Error Correction

To handle the clock-drift during the network operation, we follow the same *on demand prediction error correction mechanism* as mentioned in PW-MAC. In this method, the sender requests an update periodically by setting a flag in the DATA frame. Then the receiver replies with a beacon including update in addition to the acknowledgement. We refer to this beacon as beacon with prediction update (BU). Based on the provided information, the sending node adjusts its wakeup time in order to synchronize with the receiving node active slot. In PW-MAC, this BU contains the seed of receiver (2 bytes), the time difference between sender and receiver (4 bytes), and the last wakeup time of receiver (4 bytes). However, ACT-MAC does not require having the seed in BU, since it is already known.

IV. ENERGY CONSUMPTION ANALYSIS

We analyze the energy performance of ACT-MAC in this section. The analysis is based on the two hop network model described in Sec. II where each node generates packets of fixed size at a variable length pseudo random interval T_{cycle}. In this analysis, we focus on the energy consumed by the radio and the energy spent by the other components such as CPU or sensors is not included in our calculation.

Consider five radio states: transmitting, receiving, listening, idle and sleeping; each drawing the power of P_{tx}, P_{rx}, P_{listen}, P_{idle} and P_{sleep} respectively. The radio transition costs from one state to another state are ignored, since the ON periods for data transfer are assumed to be long enough to render transition costs negligible. The energy consumption of the radio is determined by how much time it spends in the transmitting, receiving, listening, idle and sleeping modes denoted as T_{tx}, T_{rx}, T_{listen}, T_{idle} and T_{sleep} respectively. The time with radio being asleep is simply sleep time and is given by

$$T_{sleep} = T_{cycle} - T_{tx} - T_{rx} - T_{listen} - T_{idle}. \tag{2}$$

In order to compare our results with that of the other earlier protocols, we keep all the terms and the typical values based on the Mica2 radio (Chipcon CC1000 [3]) as listed in Table I. For ACT-MAC, the energy consumption, per node, is the sum of the energy spent in each state:

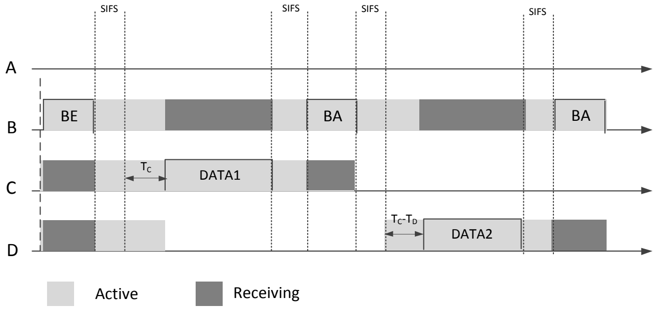

Fig. 7. Non-CT within the same wakeup slot in ACT-MAC.

TABLE I. NETWORKING PARAMETERS

Parameter	*Meaning*	*Value*
P_{tx}	Power in transmitting	31.2mW
P_{rx}	Power in receiving	22.2mW
P_{listen}	Power in listening	22.2mW
P_{idle}	Power in idle state	22.2mW
P_{sleep}	Power in sleeping	3μW
T_{cs}	Average carrier sense time	7ms
T_B	Time to Tx/Rx a byte	416μs
T_{sifs}	SIFS time slot	5ms
L_{data}	Data packet length	Varying
L_{be}	Beacon length	10 bytes
$L_{ba/bc}$	Ack/cooperation beacon length	8 bytes
T_{data}	$L_{data}T_B$	Varying
T_{be}	$L_{be}\ T_B$	8.32ms
$T_{ba/bc}$	$L_{ba/bc}\ T_B$	5.82ms
N_c	Number of cooperator nodes	2

$$\begin{aligned} E &= E_{cs} + E_{tx} + E_{rx} + E_{idle} + E_{sleep} \\ &= P_{listen}\, T_{cs} + P_{tx}\, T_{tx} + P_{rx}\, T_{rx} + P_{idle} T_{idle} + P_{sleep}\, T_{sleep}. \end{aligned} \tag{3}$$

Note that the node has to perform carrier sensing before transmitting any packet. Furthermore, an interval of SIFS is maintained between any two consecutive transmissions. This calculation is done for two schemes: CCT and TDCT, since CT in ACT-MAC is performed in one of these schemes. Remember that the receiving node, i.e., the parent node, consumes the same energy in TDCT as it does in CCT during the CT period. However, the energy consumed by a CT initiator node in CCT is higher than it does in TDCT. The energy consumed by a node in each slot can be calculated from the corresponding figures. For example, the energy consumption by the CT initiator, Node C in Fig. 1, in a CT cycle is derived below.

In the *CT-decision* slot, the initiating node, has to receive one BE message and broadcasts the BC. After receiving the cooperating node's reply with the BA, it multicasts the DATA packet as shown Fig. 3. During the *CT* slot shown in Fig. 4, it sends the same data packet again following the CCT in cooperation with cooperators. Of course, it should receive a BE from the sink node via its parent node. After the completion of data transmission, the node receives the ACK message for the sent DATA. Then,

$$T_{tx} = T_{bc} + 2T_{data}, \qquad T_{rx} = 2T_{be} + 3T_{ba}, \qquad T_{idle} = 5T_{sifs},$$

$$T_{sleep} = T_{cycle} - T_{cs} - (T_{bc} + 2T_{data}) - (2T_{be} + 3T_{ba}) - 5T_{sifs}. \tag{4}$$

Substituting (4) into (3), the energy consumed by Node C as a CT intiating node in CT is obtained by,

$$E_{nodect} = P_{listen}T_{cs} + P_{tx}(T_{bc} + 2T_{data}) + P_{rx}(2T_{be} + 3T_{ba}) + P_{idle}(5T_{sifs}) + P_{sleep}(T_{cycle} - T_{cs} - T_{bc} - 2T_{data} - 2T_{be} - 3T_{ba} - 5T_{sifs}). \quad (5)$$

Similarly, the parent node's energy consumption can be obtained from Fig. 3 and Fig. 4. The energy spent by the parent and CT initiating node in TDCT can be calculated from Fig. 5 and Fig. 6. Moreover, the energy consumed by both parent and CT initiating nodes in non-CT can be estimated from Fig. 7.

V. PERFORMANCE EVALUATION

To demonstrate the efficacy of the proposed protocol, the results for ACT-MAC are compared with PW-MAC and SCT-MAC. The results presented in this section are evaluated using MATLAB based on the analysis in Sec. IV. We use the same LCG to evaluate the performance of PW-MAC. The generated cycle lengths are in between 1 and 9 seconds. The values of α, β are cofigured as 1 and 2 respectively. However, according to the design of PW-MAC, a BU has to contain all the values α, β, M and X_0 of the receiver node, and as mentioned in [14], 10 bytes is required in addition to the base beacon size of 6 bytes [5]. Hence, the BU size in PW-MAC is 16 bytes. In ACT-MAC, we add 4 bytes to include the residual energy information in a BE. Thus, the BE size in the proposed protocol is 10 bytes, while the BU size is 18 bytes as explained in Sec. II. However, the BA size is same in both protocols and is 8 bytes [5]. In order to compare our protocol with others, SCT-MAC is evaluated using the mean of the produced pseudo random sequence and the other information required is taken from [12]. The SH packet in SCT-MAC works similar to the beacon in our protocol. However, the size is 14 bytes since it contains a number of CT and non-CT reservations in the current cycle. Moreover, we have neglected the energy consumption in the initialization phase for all studied protocols.

A. *Comparing with Asynchronous MAC Protocol*

Fig. 8 illustrates the lifetimes of Nodes B, C and D in Fig. 1 for the two studied asynchronous protocols. The first observation is that the lifetime of the parent node is shorter when compared with its child nodes in PW-MAC and both child nodes have the same lifetime. This is obvious since the PW-MAC's parent node is heavily loaded in serving both of its children as a non-CT protocol, and the child nodes share the same load. ACT-MAC exhibits the advantage of CT clearly in the nodal lifetime. The energy is balanced among the parent and initiating nodes and they exhaust at the same time. In this paper, we adopt the network lifetime definition as the lifetime of the first exhausted node. Accordingly, from the network lifetime point of view, ACT with CCT scheme has achieved 151.55% longer network lifetile when compared with the PW-MAC protocol.

B. *Comparing CT Schemes*

To analyze the energy balancing nature further, ACT-MAC, is evaluated using the TDCT scheme also. Fig. 8 shows the lifetime comparison of both CCT and TDCT schemes for ACT-MAC. In this figure, CCT exhibits the superiority in terms of balancing the node energy consumption in comparison with the TDCT scheme. Remember that, protecting the energy constraint node by CT is achieved at the cost of consuming more energy of the other nodes. This fact is confirmed when TDCT is used. In TDCT, the cooperator node spends energy in transmitting the packet again to the sink node after receiving it from the CT initiating node. Whereas the CT source node transmits the packet only once. So, it consumes lower energy than the helping node. This energy difference creates the imbalance in the nodal lifetime when CT is used more often. Since in CCT the energy expenses are shared among the CT source and cooperating nodes almost equally, CCT achieves more balanced energy consumption. Nonetheless, TDCT has achieved 9% longer network lifetime.

C. *Comparing with the SCT MAC Protocol*

We further compare ACT-MAC with the SCT-MAC protocol. In order to compare them fairly, we use TDCT in

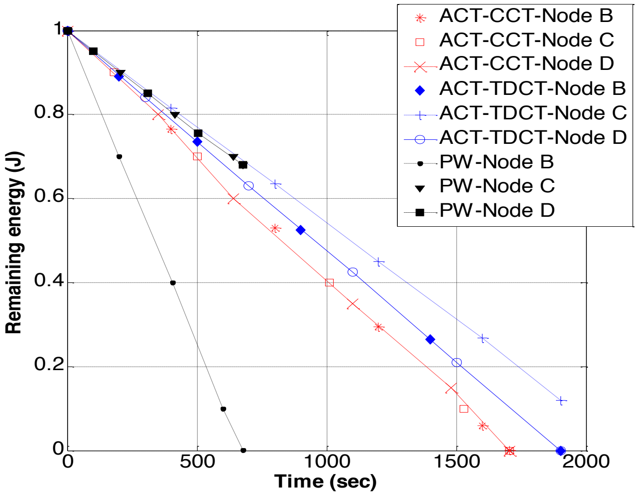

Fig. 8. Lifetime comparison of ACT-MAC and PW-MAC protocols.

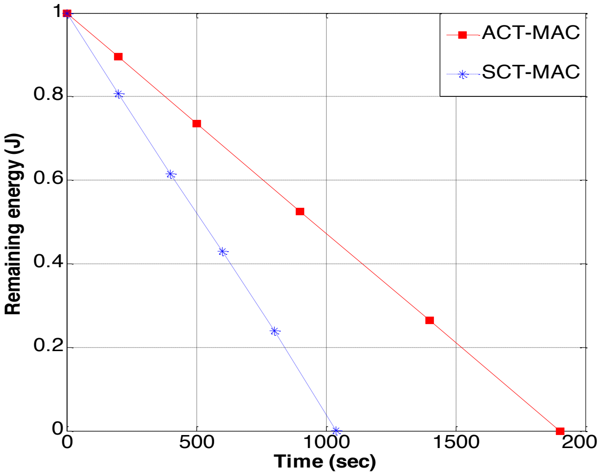

Fig. 9. Lifetime comparison of ACT-MAC (with TDCT) and SCT-MAC.

ACT-MAC here, since SCT-MAC is also based on TDCT. Fig. 9 represents the lifetime of parent nodes of the ACT and SCT-MAC protocols, which is the network lifetime of TDCT. Again, ACT-MAC achieves 81.714% longer lifetime over SCT-MAC. This shorter lifetime for the SCT protocol is due to the synchronization overhead.

D. *Comparing CT Schemes*

In this study, we define energy efficiency as the number of successfully delivered information bits per consumed joule of energy. The number of bits delivered during the network lifetime by these three protocols per unit joule energy with different packet sizes is shown in Fig.10. The packet size is varied from 50 bytes to 250 bytes considering the maximum packet size supported by CC1000 radios [3]. Clearly the energy efficiency is increased with larger packet size for all these three protocols. Furthermore, more bits are transmitted by ACT-MAC per unit joule of energy due to longer lifetime. The percentage increase in ACT-MAC's energy efficiency with DATA packet size is illustrated in Table II. When the packet size is 100 bytes, ACT-MAC has 21.66% and 51.18% higher energy efficiency compared with SCT-MAC and PW-MAC respectively.

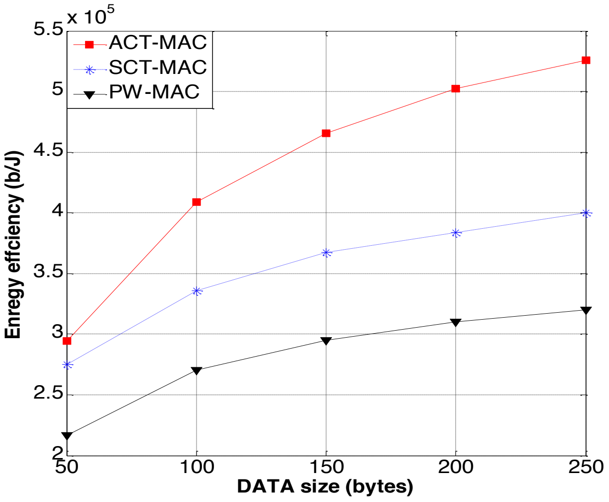

Fig. 10. Energy efficincy comparison of the ACT-MAC, SCT-MAC and PW-MAC protocols.

TABLE II. PERCENTAGE INCREASE IN ACT-MAC'S ENERGY EFFICIENCY WHEN COMPARED TO SCT-MAC AND PW-MAC PROTOCOLS

L_{data} *(bytes)*	50	100	150	200	250
SCT-MAC	6.97	21.66	26.79	30.38	31.50
PW-MAC	35.79	51.18	57.72	61.85	64.37

VI. CONCLUSIONS

In this paper, we have presented ACT-MAC, an asynchronous cooperative transmission (CT) MAC protocol for duty cycling (DC) WSNs. The proposed protocol employs a pseudo random generator to schedule the wakeup slots of all nodes based on their *level numbers*. This feature makes the proposed protocol asynchronous. Using the *level number* as the initial seed, this protocol integrates CT with asynchronous DC. The results demonstrate that the energy consumption levels of sensor nodes are evenly distributed in the network by using ACT-MAC. Furthermore, due to the absence of synchronization overhead, ACT-MAC could achieve longer lifetime. Consequently, higher energy efficiency is achieved when compared with the synchronous SCT-MAC protocol. Finally, since the scheduling is based on a *level number*, ACT-MAC is expected to apply to large scale WSNs.

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