

TEC-MAC: Throughput and Energy aware Cooperative MAC Protocol in Wireless Sensor Networks

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Abstract

Cooperative communication is a promising technique which tends to change the traditional transmission scheme in wireless networks. It can improve the performance of the network in wireless environment. This paper proposes a cooperative MAC protocol using active relays in wireless sensor networks called TEC-MAC. This protocol enables remote nodes to send their data by using intermediate nodes as relays (or helpers) to their Access Point (AP). This proposed protocol is performed and evaluated via analytical analysis. Analytical results show that the new protocol significantly improves the network performance in terms of throughput and energy efficiency compared with a Busy Tone based cooperative MAC protocol (BTAC), and IEEE802.11b Medium Access Control (MAC) protocols.

Keywords: Cooperative communication, WSN, Active relays, MAC.

1. Introduction

In the recent years, wireless sensor network (WSN) is considered the most important technology. It is usually low in cost, can be deployed quickly as there is no need for regular deployment, real-time and accurate information can be collected in many events [1]. Such characteristics make WSNs available for use in a large number of applications such as medical, military, and commercial. In medical, wireless sensor technology allows tracking and monitoring doctors and patients inside a hospital. In military, wireless sensor technology can be used in battlefield surveillance application, nuclear, biological, and chemical attack detection. Commercial applications such as interactive museums, managing inventory control and monitoring important areas.

A WSN is consists of a large number of sensor nodes which powered by batteries [2]. The replacement or

recharging of these batteries may be very difficult if not impossible. Therefore, due to these power source limitations of WSN, improving the overall energy consumption for data transmission becomes a major concern in the design and analysis of wireless sensor networks. Another challenge faced by WSNs is the wireless environment itself. Interference and signal loss due to the wireless environment and distance reduce the throughput and data delivery performance of wireless networks. Throughput and data packet delivery delay are another important constraints in wireless sensor networks [3] [4].

Recently, it has been shown that multiple nodes can collaborate with each other by utilizing the broadcast nature of wireless medium and the spatial distribution of sensor nodes. Such a technique is generally termed as cooperative communication [5]. There are many cooperative algorithms and analytical models which have been introduced for physical layer [5][6][7], Medium Access Control (MAC) layer [8][9], or across multiple layers [10]. Cooperative communication is an influential idea improving network reliability and energy efficiency of WSN without including extra infrastructure. There are two types of cooperation: multiple-relay and single-relay cooperative strategies. In multiple-relay strategy, the implementation complexity and the cooperation overhead are relatively higher than that of single-relay strategy. Therefore, the single-relay cooperative strategy is practically much more appropriate for resource-constrained WSNs.

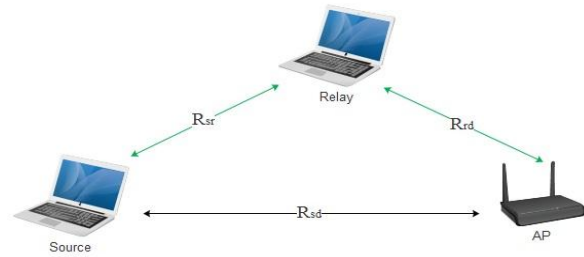
In the traditional direct transmission scheme (i.e., non cooperative transmission) scheme, the process of packet transmission only involves the source and destination node. In single-relay cooperative transmission scheme, one node (called relay or helper) out of a set of potential neighbouring nodes can be selected to aid the communication process. This strategy can significantly reduce the transmission energy required for a successful data transmission [11] [12] [13].

In this paper, a new protocol called a Throughput and energy aware cooperative MAC Protocol in Wireless Sensor Networks (TEC-MAC) is proposed. In TEC-MAC, a node with low data rate which is the source node transmits its own data packets to the AP through a high data-rate node which is the relay node. Then the relay node transmits data packet of source node and its own data packet to the AP. Therefore, the network performance can be highly improved by applying the concept of cooperative communication as explained in section 3.

The rest of paper is arranged as follows. Section 2 presents the system model. Section 3 introduces the proposed TEC-MAC protocol. The analytical model of the proposed TEC-MAC protocol is given in Section 4. Analytical results are presented and discussed in Section 5. Finally, Section 6 presents conclusions.

2. The system model

We consider a wireless sensor network based on IEEE 802.11b standard [14] which provides transmission data rates of 11, 5.5, 2, and 1 Mbps. There is a single physical wireless channel which is available for data transmissions. Assume that sensor nodes are placed randomly in a circle with radius of 100m, while the access point is located at the center of the circle. Data packets are transmitted at different rates, depending on the distance between the AP and the nodes. Let the distances are 50m, 65m, 75m and 100m. Then the nodes in zones III (75m), IV (100m) have the lowest data rates, i.e. 2 Mbps and 1 Mbps, respectively and should use cooperative transmission scheme. While the nodes in zones I (50m), II (65m) have the highest data rates, i.e. 11 Mbps and 5.5 Mbps, respectively and should use direct transmission scheme. The packets arrive in the network according to the Poisson distribution, and the traffic is uniformly distributed across all the nodes in the network. In the traditional direct transmission scheme, the transmission process involves only the source node and the AP. But in the single-relay cooperative transmission scheme as shown in Fig.1 there will be two phases. In the first phase, a source node that has low data-rate in zones III and IV (2 and 1 Mbps) sends its data packets to a high-data rate relay node which forwards these data packets to the AP in the second phase to improve the network performance. Because of the broadcast nature of the channel, the AP will receive the signals transmitted by both the source and the relay node.



A source node can deduce its transmission data rate (Rsd) to the AP by evaluating the channel quality between them. It can also calculate the achievable data rate (Rsr) to each of its neighbouring nodes, i.e. relay nodes, and also the data rate (Rrd) from them to AP by overhearing their transmitted data. Then a periodically list, named (a Relay list) of high data-rate neighbouring (relay) nodes will be maintained by each source node. Each row of this list contains MAC address, Rsr, Rrd, RG. RG stands for the rate gain and is defined as the ratio between the composite data rate of a cooperative transmission to the data-rate of a direct transmission. The relay node that has maximum RG value will be selected by the source node as its optional relay by using the following equation:

$$R_G = \frac{R_{sr} R_{rd}}{R_{sd} (R_{sr} + R_{rd})} \% \quad (1)$$

3. The proposed TEC-MAC protocol

In TEC-MAC protocol, the data transmission modes are divided into two schemes which are the single-relay cooperative transmission scheme and the RTS/CTS direct transmission scheme. In the single-relay cooperative transmission scheme, when a source node finds that a relay node is available, it transmits its data frame to the AP through the relay node. Otherwise, source node uses the direct transmission scheme and transmits its data frame direct to the AP. Fig.2 shows the data transmission during cooperative mode, when the source node has data to send, it waits for a random backoff time and sends a modified ready to send (MRTS) packet to both the AP and selected relay. After receiving the MRTS packet, the AP waits for short inter-frame space time (SIFS) and replies with a modified clear to send (MCTS) packet to both source and relay node to identify that it is ready to receive data from any one of them. Because the relay node is available, it sends a ready to help (RTH) packet to source and AP. The source node transmits its data packet with data rate Rsr to the relay node only. After data packet (DATA-S) is received from the source node after a delay of SIFS slots, then the relay node waits for a delay of SIFS time slots and sends "DATA-S" and its own data packet "DATA-R" to the AP at the data-rate Rrd. Finally, after receiving data packets successfully from both source and relay, the AP replies with

Fig.1 The system Model

cooperative acknowledgement (CAACK) to both source and relay.

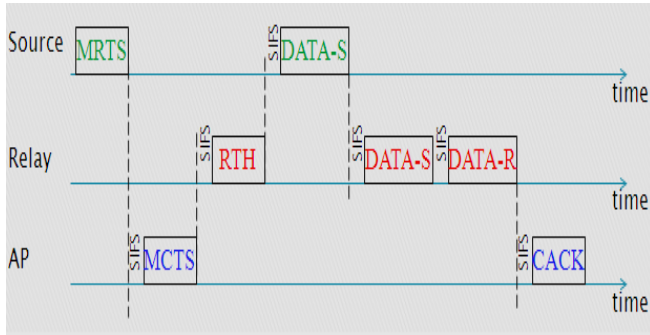


Fig. 2 Cooperative transmission scheme

In case of the relay node is not available, the source node will use the direct transmission scheme as shown in Fig.3. The source node sends a MRTS packet to AP and relay. The AP replies by MCTS packet as usual. If the source node does not receive a RTH packet from relay node after SIFS time, it deduces that the relay node is not active and sends its data directly to the AP. Then, the AP will replay by an ACK, after receiving the data packet from source node.

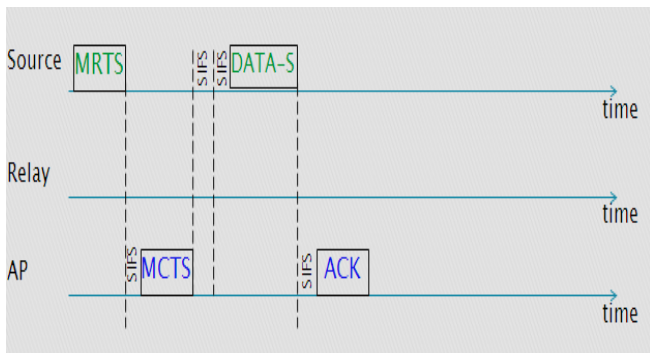


Fig.3 Direct transmission scheme

4. Performance Evaluation

In this section, the overall performance of TEC-MAC protocol will be evaluated. The analytical model is presented here to declare the equations used in analysis of the TEC-MAC protocol.

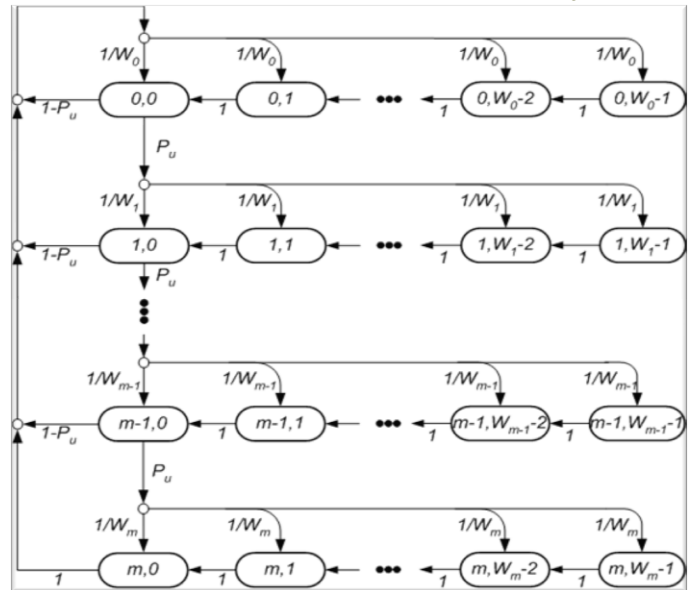


Fig.4 Markov chain model

4.1 The Markov chain model

The Markov chain model in this section is considered as an extension of Bianchi's work in [15]. As known, IEEE 802.11b DCF uses a binary exponential backoff method. At the start of each packet transmission, the backoff time is randomly chosen in the range $(0, CW - 1)$. At the first data transmission attempt $W_0 = CW_{min}$, which is the minimum contention window size. After each retransmission, CW is doubled up to a maximum value, $W_m = CW_{max} = 2^m W_0$, where m is the maximum backoff stage and CW_{max} is the maximum contention window size. Once the CW value reaches to the CW_{max} value, it will remain at that value until it is reset. Therefore, we have:

$$W_i = \begin{cases} 2^i W_0, & \text{if } i \leq m \\ 2^m W_0, & \text{if } i > m \end{cases} \quad (2)$$

where i is the backoff stage, $i \in (0, m)$. Consider $b(t)$ is the stochastic process which represents the backoff time counter for a given node and $s(t)$ is the stochastic process that represents the backoff stage, $(0, \dots, m)$ of the node at time t. So we use the two dimensional process $\{s(t), b(t)\}$ with the discrete-time Markov chain as shown in Fig.4. Let $i \in (0, m)$, $k \in (0, W_i - 1)$ be the stationary distribution of the Markov chain model. Let P_u is the probability that a packet from the nth node is unsuccessfully transmitted. When the backoff time counter reaches zero, the probability τ that a node finds a randomly empty slot time to send its data packet can be expressed as [15]:

$$\tau = \sum_{i=0}^m b_{i,0} = \sum_{i=0}^m P_u^i \cdot b_{0,0} = \frac{1 - P_u^{m+1}}{1 - P_u} \quad (3)$$

Where $b_{0,0}$ can be expressed by [15]:

$$b_{0,0} = \begin{cases} \frac{2(1-P_u)(1-2P_u)}{W_0(1-(2P_u)^{m+1})(1-P_u) + (1-2P_u)(1-P_u^{m+1})} & m \leq m' \\ \frac{2(1-P_u)(1-2P_u)}{W_0(1-(2P_u)^{m+1})(1-P_u) + (1-2P_u)(1-P_u^{m+1}) + 2^m W_0 P_u^{m+1} (1-2P_u)(1-P_u^{m-m'})} & m \geq m' \end{cases} \quad (4)$$

There are two parts of the unsuccessful probability P_u which are collisions between packets P_c and channel induced error P_e . Assumed that P_c and P_e are independent. Therefore P_u can be calculated as [18]:

$$P_u = 1 - (1 - P_c)(1 - P_e). \quad (5)$$

And the collision probability P_c which represents that at least one of the N remaining nodes transmits simultaneously in a given time slot can be represented by [18]:

$$P_{c,i} = 1 - \prod_{j \neq i}^N (1 - \tau_j) \quad (6)$$

4.2 Probability of error for TEC-MAC protocol

The error probability P_e which represents packet corruption due to imperfect channel conditions can be represented under two cases: In direct transmission scheme and cooperative transmission scheme. In direct transmission scheme, the source node sends its data packet directly to the AP with data rate R_{sd} . After sending the RTS packet with no collision, there are four situations for packet transmission to fail which are: RTS, CTS, DATA from source to AP and ACK packets corruption in the consequent transmission. The probability C_1 for RTS corruption given that there is no RTS collision is calculated as follows:

$$C_1 = 1 - (1 - \text{BER}_C)^{8L_{RTS}} \quad (7)$$

where BER_C is the Bit Error Rate at the basic data rate of control packets transmission. L_{RTS} is the RTS packet length in bytes. The probability C_2 that the CTS packet is corrupted but the MRTS packet is transmitted successfully is calculated as follows:

$$C_2 = 1 - (1 - \text{BER}_C)^{8L_{CTS}} \quad (8)$$

where L_{CTS} is the CTS packet length in bytes. As the same, the probability C_3 that the DATA-S packet from the source to the AP is corrupted and both the RTS and CTS are successfully transmitted is calculated as follows:

$$C_3 = 1 - (1 - \text{BER}_{sd})^{8L_s} (1 - \text{BER}_C)^{8L_{PLCP}} \quad (9)$$

where L_s is the data packet length of the source node in bytes. L_{PLCP} is the PLCP header size in bytes. BER_{sd} is bit error rate of the DATA-S from the source node to the AP at the data-rate R_{sd} . The probability C_4 that the

ACK from AP to source node is corrupted and the RTS, CTS and DATA-S are successfully transmitted is calculated as follows:

$$C_4 = 1 - (1 - \text{BER}_C)^{8L_{ACK}} \quad (10)$$

where L_{ACK} is the ACK packet length in bytes. Now, Let $P_{e1,d}$ is the portability of the RTS corruption, $P_{e2,d}$ is the portability of the CTS corruption, $P_{e3,d}$ is the portability of the DATA-S corruption, and $P_{e4,d}$ is the portability of the ACK corruption. These probabilities can be calculated as follows [18]:

$$\begin{aligned} P_{e1,d} &= C_1 \\ P_{e2,d} &= (1 - C_1)C_2 \\ P_{e3,d} &= (1 - C_1)(1 - C_2)C_3 \\ P_{e4,d} &= (1 - C_1)(1 - C_2)(1 - C_3)C_4 \end{aligned} \quad (11)$$

The time duration of these four different scenarios are denoted by $T_{e1,d}$, $T_{e2,d}$, $T_{e3,d}$ and $T_{e4,d}$, respectively. They can be given by:

$$\begin{aligned} T_{e1,d} &= T_{RTS} + T_{CTS} + T_{SIFS} + T_{DIFS} + 2\Delta \\ T_{e2,d} &= T_{RTS} + T_{CTS} + T_{SIFS} + T_{DIFS} + 2\Delta \\ T_{e3,d} &= T_{RTS} + \frac{8L_s}{R_{sd}} + \frac{8L_{PLCP}}{R_c} + T_{CTS} + T_{ACK} + 3T_{SIFS} + T_{DIFS} + 4\Delta \\ T_{e4,d} &= T_{RTS} + \frac{8L_s}{R_{sd}} + \frac{8L_{PLCP}}{R_c} + T_{CTS} + T_{ACK} + 3T_{SIFS} + T_{DIFS} + 4\Delta \end{aligned} \quad (12)$$

Finally, the probability $P_{e,i}^d$ of the transmission error of node i packet that uses direct transmission is calculated as follows [18]:

$$P_{e,i}^d = P_{e1,d} + P_{e2,d} + P_{e3,d} + P_{e4,d} \quad (13)$$

Now, we will derive equations in cooperative transmission scheme:

In this scheme the source node sends its data packet through a helper node to the AP with data rate R_{rd} . After sending the MRTS packet with no collision, there are seven situations for packet transmission to fail which are: MRTS, MCTS, RTH, DATA-S from source to relay, DATA-S from relay to AP, DATA-R from relay to AP, and CACK packets corruption in the consequent transmission. The probability v_1 for MRTS corruption known that there is no MRTS collision is calculated as follows [16]:

$$v_1 = 1 - (1 - \text{BER}_C)^{8L_{MRTS}} \quad (14)$$

L_{MRTS} is the MRTS packet length in bytes. The probability v_2 that the MCTS packet is corrupted, although the MRTS packet is transmitted successfully is calculated as follows:

$$v_2 = 1 - (1 - \text{BER}_C)^{8L_{MCTS}} \quad (15)$$

where L_{MCTS} is the MCTS packet length in bytes. As the same, the probability V_3 that a RTH packet is corrupted and both the RTS and CTS are successfully transmitted is calculated as follows:

$$v_3 = 1 - (1 - BER_C)^{8L_{RTH}} \quad (16)$$

where L_{RTH} is the RTH packet length in bytes. The probability V_4 that a DATA-S from the source to relay is corrupted while MRTS, MCTS and RTH packets are transmitted successfully is expressed as follows:

$$v_4 = 1 - (1 - BER_{sr})^{8L_s} (1 - BER_C)^{8L_{PLCP}} \quad (17)$$

where BER_{sr} is the bit error rate of the data packet which is transmitted from source to relay node at data rate R_{sr} . L_s is the data packet length of the source node in bytes. The probability v_5 that a DATA-S from relay to AP is corrupted while MRTS, MCTS, RTH, and DATA-S (from source to relay) are successfully received is computed as follows:

$$v_5 = 1 - (1 - BER_{rd})^{8L_s} (1 - BER_C)^{8L_{PLCP}} \quad (18)$$

where BER_{rd} is the bit error rate AP of the data packet sent between the relay and the at data-rate R_{rd} . The probability v_6 that a DATA-R is not successfully received while receiving MRTS, MCTS, RTH, DATA-S are received correctly is written as follows:

$$v_6 = 1 - (1 - BER_{rd})^{8L_r} (1 - BER_C)^{8L_{PLCP}} \quad (19)$$

where L_r is the data packet length of the relay node in bytes. Finally, the probability v_7 , that a CACK is corrupted while MRTS, MCTS, RTH, DATA-S (from source to relay), and at least one of both DATA-S (relay-AP) and DATA-R correctly are received successfully, is then expressed as follows:

$$v_7 = 1 - (1 - BER_C)^{8L_{CACK}} \quad (20)$$

where L_{CACK} is the CACK packet length in bytes. Now, Let $P_{e1,C}$ is the probability of the MRTS packet corruption, $P_{e2,C}$ is the portability of the MCTS packet corruption, $P_{e3,C}$ is the portability of the RTH packet corruption, $P_{e4,C}$ is the probability of the DATA-S packet corruption from the source to the relay, and $P_{e5,C}$ is the probability of a DATA-S packet corruption from the relay to the AP, $P_{e6,C}$ is the portability of a DATA-R corruption and $P_{e7,C}$ is the probability of a CACK corruption. These probabilities can be calculated as follows:

$$\begin{aligned} P_{e1,C} &= v_1 \\ P_{e2,C} &= (1 - v_1)v_2 \\ P_{e3,C} &= (1 - v_1)(1 - v_2)v_3 \\ P_{e4,C} &= (1 - v_1)(1 - v_2)(1 - v_3)v_4 \\ P_{e5,C} &= (1 - v_1)(1 - v_2)(1 - v_3)(1 - v_4)v_5 \end{aligned}$$

$$\begin{aligned} P_{e6,C} &= (1 - v_1)(1 - v_2)(1 - v_3)(1 - v_4)v_6 \\ P_{e7,C} &= (1 - v_1)(1 - v_2)(1 - v_3)(1 - v_4)(1 - v_5v_6)v_7 \end{aligned} \quad (21)$$

where $(1 - v_5v_6)$ denotes the probability that at least one of the DATA-S (relay-AP) and DATA-R packets are received successfully by the AP. The time duration of these seven different scenarios are denoted by $T_{e1,C}$, $T_{e2,C}$, $T_{e3,C}$, $T_{e4,C}$, $T_{e5,C}$, $T_{e6,C}$, and $T_{e7,C}$ respectively. They can be calculated by:

$$\begin{aligned} T_{e1,C} &= T_{MRTS} + T_{MCTS} + T_{SIFS} + T_{DIFS} + 2\Delta \\ T_{e2,C} &= T_{MRTS} + T_{MCTS} + T_{SIFS} + T_{DIFS} + 2\Delta \\ T_{e3,C} &= T_{MRTS} + T_{MCTS} + T_{RTH} + 2T_{SIFS} + T_{DIFS} + 3\Delta \\ T_{e4,C} &= T_{MRTS} + T_{MCTS} + T_{RTH} + \frac{8L_s}{R_{sr}} + T_{PLCP} + 4T_{SIFS} \\ &\quad + T_{DIFS} + 4\Delta \\ T_{e5,C} &= T_{MRTS} + T_{MCTS} + T_{RTH} + \frac{8L_s}{R_{sr}} + \frac{8(L_s+L_r)}{R_{rd}} + \\ &\quad 3T_{PLCP} + T_{CACK} + 6T_{SIFS} + T_{DIFS} + 7\Delta \\ T_{e6,C} &= T_{MRTS} + T_{MCTS} + T_{RTH} + \frac{8L_s}{R_{sr}} + \frac{8(L_s+L_r)}{R_{rd}} + \\ &\quad 3T_{PLCP} + T_{CACK} + 6T_{SIFS} + T_{DIFS} + 7\Delta \\ T_{e7,C} &= T_{MRTS} + T_{MCTS} + T_{RTH} + \frac{8L_s}{R_{sr}} + \frac{8(L_s+L_r)}{R_{rd}} + \\ &\quad 3T_{PLCP} + T_{CACK} + 6T_{SIFS} + T_{DIFS} + 7\Delta \end{aligned} \quad (22)$$

Finally, the probability $P_{e,i}^C$ of transmission error of node i packet that uses cooperative transmission is calculated as follows:

$$P_{e,i}^C = P_{e1,C} + P_{e2,C} + P_{e3,C} + P_{e4,C} + P_{e5,C} + P_{e6,C} + P_{e7,C} \quad (23)$$

4.3 Saturated throughput analysis

Now, we will drive an expression for the saturated throughput of TEC-MAC protocol taking into account transmission errors. We can define the saturated throughput η as a ratio of successfully transmitted payload size to the slot time between two consecutive transmissions.

A slot time can be idle or sensed busy due to collision, successful transmission, and erroneous transmission due to imperfect channel conditions. Let $i = 1, 2, \dots, N$ and N is the network size. According to this definition, the throughput η is expressed as follows [18]:

$$\eta = \frac{8L \sum_{i=1}^N P_{s,i} (1 - P_{e,i})}{E[T_I] + E[T_S] + E[T_C] + E[T_E]} \quad (24)$$

where $E[T_I]$ is the average idle slot duration, $E[T_C]$ is the average collision slot duration, $E[T_S]$ is the average

successful transmission slot duration, and $E[TE]$ is the average slot duration due to erroneous transmission.

Let the probability P_{tr} represents that there is at least one transmission in the chosen slot time. Each node access the channel with probability τ_i ,

where $i = 1, 2, \dots, N$ and N is the network size. Then

P_{tr} can be calculated as follows [18]:

$$P_{tr} = 1 - \prod_{i=1}^N (1 - \tau_i) \quad (25)$$

Consider σ is the slot time duration. Then, the average idle slot duration can be calculated as follows [18]:

$$E[T_I] = (1 - P_{tr})\sigma \quad (26)$$

Let the probability P_s represents that only the n th station is successfully transmitting over the channel is given by [18]:

$$P_s = \tau_i \prod_{j=1, j \neq i}^N (1 - \tau_j) \quad (27)$$

Then, the average slot duration of a successful transmission, which depends on the transmission technique (cooperative or direct) of the n th station, can be calculated as follows [18]:

$$E[T_S] = \sum_{i=1}^N P_{s,i} (1 - P_{e,i}) T_{s,i} \quad (28)$$

In the case of direct transmission scheme, the successful time T_s^d can be calculated as:

$$T_s^d = T_{RTS} + T_{CTS} + \frac{8L_s}{R_{sd}} + T_{PLCP} + T_{ACK} + 3T_{SIFS} + T_{DIFS} + 4\Delta \quad (29)$$

In the case of cooperative transmission scheme, the successful time T_s^c can be calculated as:

$$T_s^c = T_{MRTS} + T_{MCTS} + T_{RTH} + \frac{8L_s}{R_{sr}} + \frac{8(L_s + L_r)}{R_{rd}} + 3T_{PLCP} + T_{CACK} + 6T_{SIFS} + T_{DIFS} + 7\Delta \quad (30)$$

Note that there are two forms of cooperative transmission successful time the first when the source station at zone III and the second when the source station at zone IV due to the different data rate in each case.

Now, the average slot duration of collision transmission can be calculated by:

$$E[T_C] = P_c^d T_C^d + P_c^c T_C^c \quad (31)$$

where, P_c^d and P_c^c is collision probability in direct transmission and in cooperative transmission respectively. T_C^d and T_C^c are collision time in direct and cooperative transmission, respectively.

The average duration of the slot due to erroneous transmissions is evaluated as [18]:

$$E[T_E] = \sum_{i=1}^N P_{s,i} T_{e,i} \quad (32)$$

And,

$$T_{e,i} = \sum_{i=1}^N P_{e,i}^d T_{e,i,d} + \sum_{i=1}^N P_{e,i}^c T_{e,i,c} \quad (33)$$

4.4 Energy efficiency analysis:

In this section, we will derive an expression for the energy efficiency of WSN. The energy efficiency of WSN, indicated by ϵ , can be defined as the ratio of the successfully transmitted data bits to the total energy consumed. Its unit is bits/joule. The overall energy consumed by the node i in the network can be divided into five parts: the energy consumption during the backoff period $E_B^{(i)}$, the energy consumption during the collision period $E_C^{(i)}$, the energy consumption during the overhearing transmissions $E_O^{(i)}$, the energy consumption when there are transmission errors $E_E^{(i)}$ and the energy consumption during the successful transmission $E_S^{(i)}$. It is assumed that a node consumes a transmitting power P_{TX} , a receiving power P_{RX} and P_{IX} for sensing or being idle, respectively. Each node saves its power by using sleep mode where there is neither transmission nor reception. During data transmission, only nodes involve in data transmission will be active and other nodes will be in sleep mode to save the overall network energy consumption. So, the energy efficiency of WSN can be calculated as follows:

$$\epsilon = \frac{8L \sum_{i=1}^N P_{s,i} (1 - P_{e,i})}{\sum_{i=1}^N (E_B^{(i)} + E_C^{(i)} + E_O^{(i)} + E_E^{(i)} + E_S^{(i)})} \quad (34)$$

The calculation of the energy consumption during a backoff period $E_B^{(i)}$, the energy consumption during the collision period $E_C^{(i)}$ and the energy consumption during the overhearing transmissions $E_O^{(i)}$ is explained in [16]. Now, the energy consumption during a successful transmission $E_S^{(i)}$ of the intended node i can be calculated as follows:

$$E_S^{(i)} = E_S^d + E_S^c \quad (35)$$

where E_S^d is a successful direct transmission and can be computed as follows:

$$E_S^d = P_{TX} \left(T_{RTS} + \frac{8L_s}{R_{sd}} + T_{PLCP} \right) + P_{RX} T_{CTS} + P_{IX} (T_{ACK} + 3T_{SIFS} + T_{DIFS} + 4\Delta) \quad (36)$$

where E_S^c is a successful cooperative transmission and can be computed as follows:

$$E_S^c = P_{TX} \left(T_{MRTS} + \frac{8L_s}{R_{sd}} + T_{PLCP} \right) + P_{RX} (T_{MCTS} + T_{RTH} + \frac{8(L_s + L_r)}{R_{rd}} + 2T_{PLCP}) + P_{IX} (T_{CACK} + 6T_{SIFS} + T_{DIFS} + 7\Delta) \quad (37)$$

For cooperative transmission scheme, let E_1, E_2, \dots, E_7 be the energy consumption of observed node during durations T_1, T_2, \dots, T_7 , respectively. Also, for direct

transmission scheme, let E_1, E_2, \dots, E_4 be the energy consumption of observed node during durations T_1, T_2, \dots, T_4 , respectively which can be calculated the same concept as in [16], therefore the energy consumption during the erroneous transmissions $E_E^{(i)}$ is given by:

$$E_E^{(i)} = \sum_{i=1}^4 \bar{N}_i^d E_i^d + \sum_{i=1}^7 \bar{N}_i^c E_i^c \quad (38)$$

Where \bar{N}_i^d and \bar{N}_i^c are the average number of retries due to corruption of control and data packet in direct and cooperative transmission schemes respectively. They are given by:

$$\bar{N}_i^d = E[N_r] \frac{(1-P_{c,i})P_{ej}^d}{P_{u,i}}, \quad j=1, 2, 3, 4. \quad (39)$$

$$\bar{N}_i^c = E[N_r] \frac{(1-P_{c,i})P_{ej}^c}{P_{u,i}}, \quad j=1, 2, \dots, 7. \quad (40)$$

Where $E[N_r]$ is the average number of retries that the intended node will do before it successfully transmits a packet and presented in [16].

5. Analytical Results

In this section, we will validate the performance of our protocol based on MATLAB program to become deeper understanding of the protocol behavior in wireless sensor networks. The results of our protocol are compared with BTAC [17] [18] and IEEE 802.11b [14] [15] MAC protocols in terms of throughput and energy efficiency. The parameters used in analysis are set to values which are summarized in Table 1.

Table 1: Parameters values

Parameter	Value	Parameter	Value	Parameter	Value
MAC header	28 bytes	Slot time	9 μ sec	RTH	38 bytes
PHY header	24 bytes	SIFS	16 μ sec	CACK	38.25 bytes
RTS	44 bytes	DIFS	50 μ sec	PLCP rate	1Mbps
CTS	38 bytes	MRTS	50 bytes	CWmin	15
ACK	38 bytes	MCTS	38.25 bytes	CWmax	1023

The TEC-MAC protocol is performed and evaluated for nodes with different data-rates. We study our protocol under two conditions which are:

- (a) Under ideal channel conditions:

Fig.5 shows that the saturated throughput of TEC-MAC, BTAC and IEEE 802.11b with respect to the number of sensor nodes under ideal channel conditions. As shown in this Figure., the throughput of IEEE 802.11b decreases as the number of nodes increases. The reason is due to the increasing of collision probability. However, In TEC-MAC and BTAC, the throughput

increases in an exponential form as the network size increases. The reason is due to the increasing of the number of relay nodes that can be used by low data rate nodes. As shown in Fig., the TEC-MAC protocol performs significantly better than that of the other two transmission protocols.

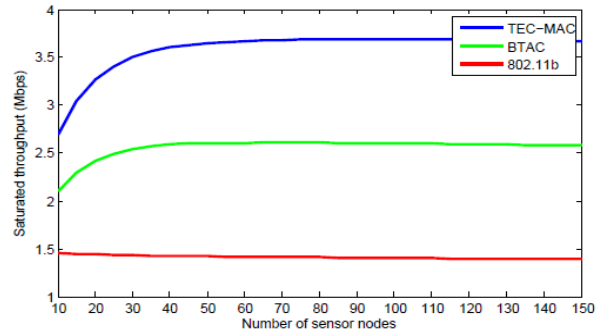


Fig.5 Saturated throughput versus number of nodes with ideal channel conditions, $L=1500$ bytes

Fig.6 shows the saturated throughput of TEC-MAC, BTAC and IEEE 802.11b is traced with the packet length under ideal channel conditions. The packet size is varied from 400 to 2000 due to standard IEEE 802.11b values. This Figure shows that the throughput of all three protocols increases as the packet size increases. These result because when the packet length increases, the overhead is reduced. However, the TEC-MAC protocol performs significantly better than that of the other two transmission protocols.

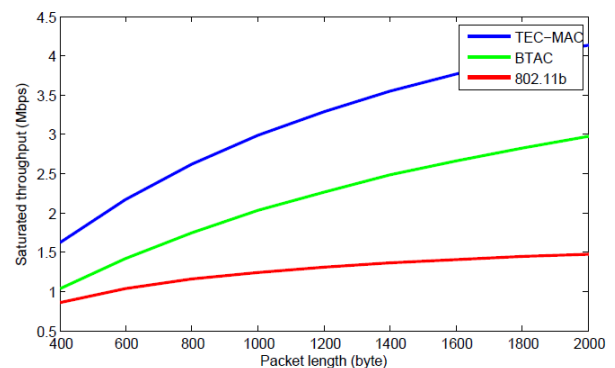


Fig.6 Saturated throughput versus packet length with ideal channel conditions.

The energy efficiency of TEC-MAC, BTAC and IEEE 802.11b is traced with the number of sensor nodes under ideal channel conditions in Fig.7. It can be seen that the energy efficiency of three protocols exponentially decreases as the number of nodes increases due to

collisions. Therefore, the nodes consume more energy to retransmit collided packets and to sense the medium. As shown, energy efficiency of nodes using TEC-MAC can achieve more energy saving than those using BTAC and IEEE 802.11b.

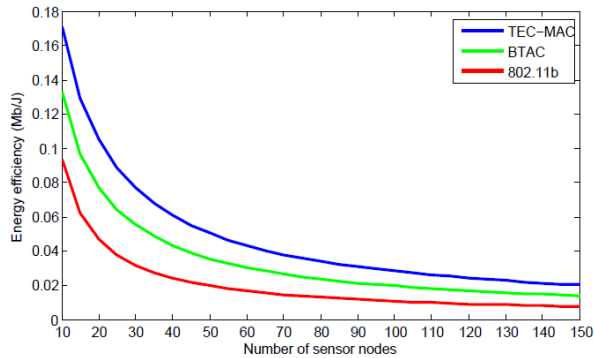


Fig.7 Energy efficiency versus number of nodes with ideal channel conditions

In Fig.8, as shown it describes the relation between the energy efficiency of TEC-MAC, BTAC and IEEE packet length increases the energy efficiency also increases. The reason returns to as the packet length increases, the overhead reduces. Therefore, less energy is consumed, and the energy efficiency then increases. As shown in Fig.8, energy efficiency of nodes using TEC-MAC can achieve more energy saving than those using BTAC and IEEE 802.11b.

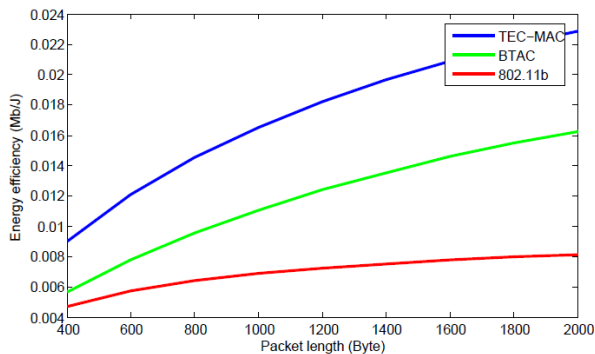


Fig.8 Energy efficiency versus packet length with ideal channel conditions

(b) Under dynamic channel conditions:

Fig.9 and Fig.10 shows the saturated throughput of TEC-MAC, BTAC and IEEE 802.11b versus the number of nodes and the packet length respectively when the BER=1*10⁻⁵. As known, the throughput comes down when the channel becomes imperfect. As shown in two Figures, the throughput of TEC-MAC can achieve better than BTAC and IEEE 802.11b under imperfect channel conditions. As a result, the saturated throughput of TEC-MAC protocol outperforms that of BTAC and IEEE 802.11b under all channel conditions.

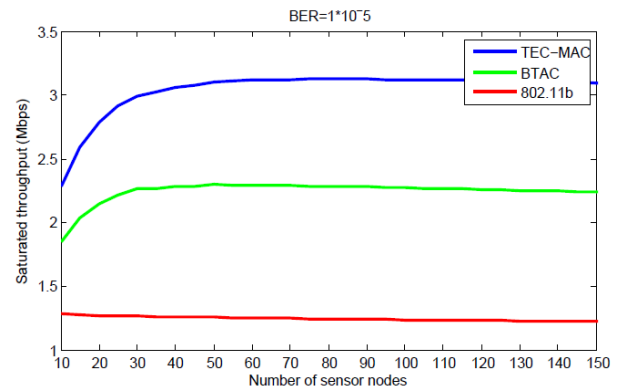


Fig.9 Saturated throughput versus number of nodes with BER= 1*10⁻⁵

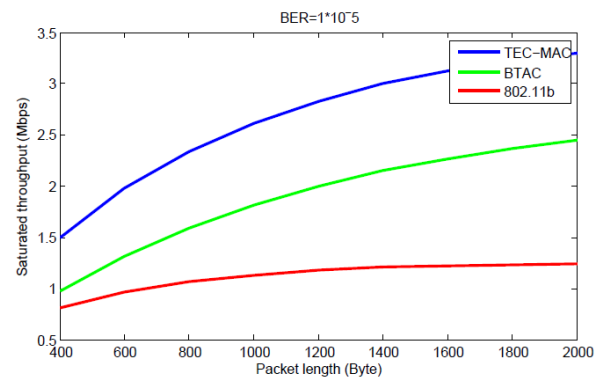


Fig.10 Saturated throughput versus packet length with BER= 1*10⁻⁵

Fig.11 and Fig.12 show that the energy efficiency of TEC-MAC, BTAC and IEEE 802.11b versus the number of nodes and the packet length respectively when the BER=1*10⁻⁵. As shown in two Figures, the energy efficiency of networks using TEC-MAC can achieve more energy efficiency than those using BTAC and IEEE 802.11b under dynamic channel conditions.

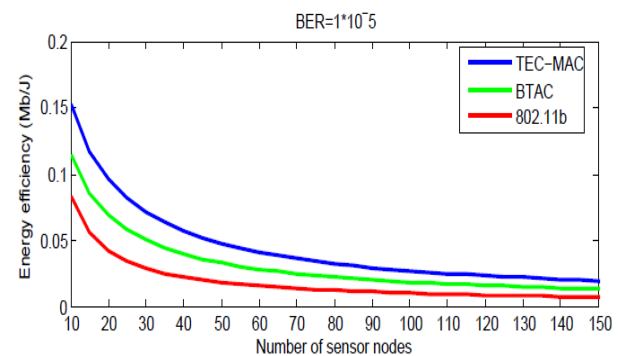


Fig.11 Energy efficiency versus number of nodes with BER= 1*10⁻⁵

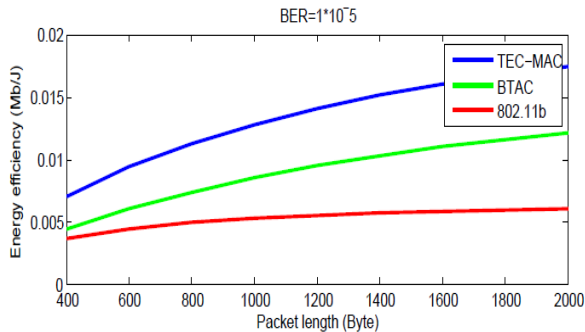


Fig.12 Energy efficiency versus packet length with BER= 1*10⁻⁵

6. Conclusions

In this paper, we propose a new Medium Access Control protocol, named Throughput and energy aware cooperative MAC Protocol (TEC-MAC) in Wireless Sensor Networks. In TEC-MAC, to improve the overall transmission rate, the low data-rate nodes use the best relay node for data transmission to AP. TEC-MAC enables a relay node to send its own data packet without the handshake procedure for accessing the channel. Therefore, TEC-MAC first provides a novel transmission scheme for the relay node and it can achieve both cooperative diversity gain and multiplexing gain. A new analytical approach is developed to determine the performance of TEC-MAC under ideal and imperfect wireless channel conditions. Analytical results show that TEC-MAC protocol improves significantly the overall system throughput and energy efficiency under different channel conditions, compared with BTAC cooperative MAC protocol and IEEE802.11b.

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