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Article

An Efficient Medium Access Control Protocol with Parallel Transmission for Wireless Sensor Networks

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Abstract: In this paper, we present a novel low power medium access control protocol for wireless sensor networks (WSNs). The proposed protocol, EP-MAC (Efficient MAC with Parallel Transmission) achieves high energy efficiency and high packet delivery ratio under different traffic load. EP-MAC protocol is basically based on the Time Division Multiple Access (TDMA) approach. The power of Carrier Sense Multiple Access (CSMA) is used in order to offset the fundamental problems that the stand-alone TDMA method suffers from, *i.e.*, problems such as lack of scalability, adaptability to varying situations, *etc.* The novel idea behind the EP-MAC is that it uses the parallel transmission concept with the TDMA link scheduling. EP-MAC uses the methods for the transmission power adjustment, *i.e.*, uses the minimum level power necessary to reach the intended neighbor within a specified bit error rate [BER] target. This reduces energy consumption, as well as further enhances the scope of parallel transmission of the protocol. The simulation studies support the theoretical results, and validate the efficiency of our proposed EP-MAC protocol.

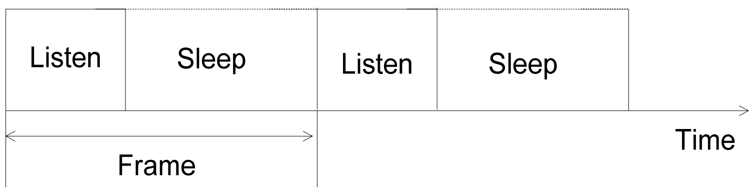
Keywords: medium access control; energy efficiency; parallel transmission; wireless sensor network; carrier sense multiple access

1. Introduction

Wireless sensor networks (WSNs) technology has gained significance due to its potential for supporting a wide range of applications for military operations, industrial, surveillance, target tracking system, health needs, monitoring disaster areas and many other applications.

WSN consists of a large number of very small, low cost sensor nodes that are deployed randomly. The sensor nodes are typically equipped with power-constrained batteries. Unlike other wireless networks, it is generally not practical to charge or replace the battery. Since prolonging the life span of the sensor nodes is extremely vital, energy efficiency becomes the most important aspect of the design of MAC protocol of sensor networks. The idle listening can be considered as the main source of energy wastage for the case of wireless sensor networks [1]. Therefore, in the sensor network, nodes do not wakeup all the time rather they prefer energy preservation by operating in a low duty cycle (sometimes in active mode and sometimes in sleeping mode) as mentioned in Figure 1. With this sleep scheduling technique, nodes can operate in a low duty cycle and thus save energy and extend the network lifetime. But on the other hand this also causes increased communication latency and synchronization overhead as well. Different sleep scheduling schemes have been analyzed in [2] with the proposal of a scheduling methods that can decrease the end to end delay. However, interference free scheduling cannot be ensured with this method. If each communication link can use a separate slot then interference free scheduling can be achieved. In this case the required number of slots will be the same as the number of communication links in the network. But, this method requires much more slots than are actually necessary, and this will definitely augment delay and reduce the channel utilization. On the other hand, in terms of energy preservation, performance of broadcast scheduling is worse than the performance of link scheduling in WSN. We herein offer a new Medium Access Control protocol for WSN, named EP-MAC, which combines the idea of parallel transmission and the link scheduling together where the power of CSMA is used in order to minimize the fundamental problems of using link scheduling alone (pair wise TDMA) with the aim of achieving high energy efficiency as well as high throughput.

Figure 1. Scenario of periodic listen and sleep of a sensor node.



The rest of the paper is organized as follows: Section 2 reviews related works. In Section 3 we elaborate on the design of the Efficient MAC with Parallel Transmission (EP-MAC) protocol. In Section 4 we compare our proposed MAC protocol with other existing protocol and describe the performance in detail. And finally in Section 5 we conclude the paper with mentioning some scope of future works.

2. Related Work

For sensor network, a wide range of MAC protocols have been proposed. Among them S-MAC [1] is one of the pioneering mechanism in the contention based MAC protocol specially targeting sensor networks. The basic idea behind S-MAC is that nodes follow a predefined sleep and listen cycle, where nodes wake and sleep together. In T-MAC [3] the adaptive duty cycle is used to improve the energy efficiency of S-MAC.

TDMA has long been dismissed as an unfeasible solution for wireless *ad hoc* networks for its lack of scalability and adaptability to varying environments. However, it provides a good energy efficient and collision free communication. Recently several techniques [4] have been proposed for TDMA in sensor networks. But these techniques are not successful in dealing with the fundamental problems that stand-alone TDMA method suffers from.

In our previous work [5] we introduced the novel idea of combining broadcast scheduling (broadcast TDMA) and link scheduling (pair wise TDMA) together with CSMA in order to gain energy efficiency as well as efficient use of bandwidth.

In AMAC [6] energy savings is achieved by dynamically changing the schedule of each node depending on the traffic load. B-MAC [7] is the default MAC for Mica2 which adopt LPL (Low power listening) [8] and engineer the clear channel sensing (CCA) technique to improve channel utilization. Z-MAC [9] can dynamically handle CSMA and TDMA together depending on the level of contention in the network. In Z-MAC the knowledge of topology is used to improve MAC performance under high contention situation. The protocol uses DRAND [10], a distributed implementation of RAND [11] in order to assign slots to every node in the network. TH-MAC [12] is a hybrid MAC protocol which uses A-DRAND algorithm for slot assignment. A-DRAND is a modified version of DRAND algorithm for clustered wireless sensor networks. In A-DRAND cluster heads need more slots to relay packets. In [13] a hybrid MAC protocol BAZ-MAC is proposed for *ad hoc* networks. The protocol uses a bandwidth aware slot allotment technique during the set-up phase, slots are assigned to the nodes according to their bandwidth requirements. In WiseMAC [14] a sender can minimize the length of the preamble by exploiting the knowledge of the sampling schedules of its neighbors during communication and thus reducing the preamble transmission overhead.

Our proposed EP-MAC also combines TDMA and CSMA. But EP-MAC is totally dissimilar from Z-MAC and other hybrid MAC protocol. Because, where other hybrid MAC protocol uses the broadcast scheduling the EP-MAC uses the link scheduling technique. Link scheduling technique is chosen because of the fact that its performance is better than broadcast scheduling in WSNs, in terms of energy preservation. Moreover, CSMA is used only to offset the drawbacks of TDMA and EP-MAC suitably vary the transmit power with a goal to reduce energy consumption. In addition, EP-MAC minimizes the message delay by introducing parallel transmission which also addresses the fundamental difficulties of using TDMA protocol.

3. Proposed EP-MAC Protocol Design

We first briefly mention here the terminologies that we have used in our paper. A *Frame* is the periodic interval, which consists of an active or listen period and a sleep period. A *duty cycle* is the active or listen period divided by the entire frame length. The sleep period is further divided into number of data slot. *A data slot* is a time period required to exchange a data packet and ACK between a pair of nodes.

3.1. Virtual Clustering and Synchronization

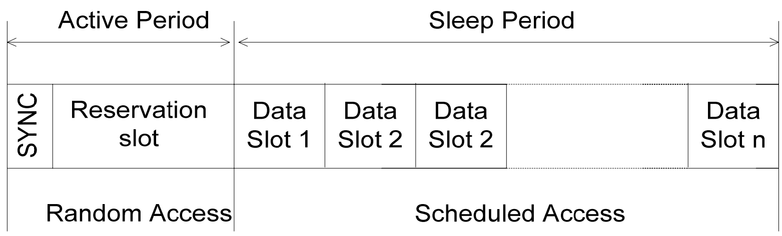
Virtual clustering technique [1] is used for synchronization of frames in the EP-MAC protocol. When a node comes to life, it first listens to broadcasted SYNC message from its neighbors for a predetermined time. During this period if the node hears a schedule message from a neighbor, it configures its schedule as its own. And then the node starts broadcasting this schedule as its own schedule to its neighbors. If the node does not receive a schedule for the predefined period, it chooses a frame schedule and transmits a SYNC packet. When a node has its own schedule but it receives another schedule from another node, if the schedule is different, then the node will adopt both schedules. It is because if the node knows the schedule of a neighbor node which belongs to another virtual cluster, only then the communication is possible between the nodes. During this phase, each node creates the one hop neighbor list of it and with later by using these one hop neighbors list the node constitutes the two hop neighbor list of it. After creations of the neighbor list each node is given an id and within a two hop neighbor this id will be unique.

Each node will maintain a table which will record the possibility of the parallel transmission link within the two hop neighbors. The value of the required power for transmission within a particular pair of nodes will also be recorded. Both with transmission power adjustment and without transmission power adjustment will be recorded. Because, using the power adjustment features multiple transmissions can be done in one TDMA data slot. Even though the power adjustment features are not used more than one transmission is possible in some cases.

3.2. Frame Structure

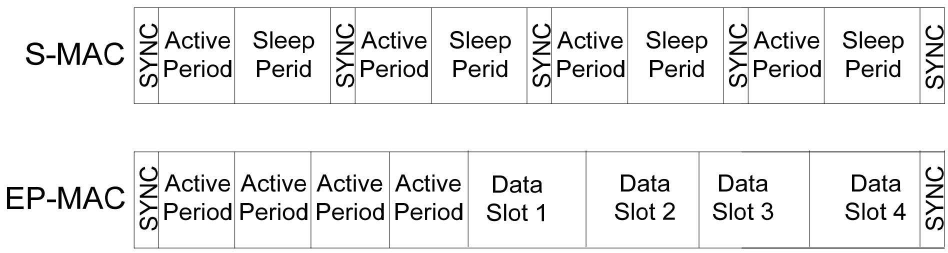
The mechanism of EP-MAC is based on dividing the communication time into variable length frames. The frame structure is shown in Figure 2. Each frame begins with a SYNC period. The purpose of the SYNC packet is to maintain synchronization between the nodes within the same virtual cluster. The next part of the active period of the frame is reservation slot which is used for the data slot reservation. And the last part composed with fixed number of data slots which are used for data and ACK transmission by sensor nodes. The number of data slots in a frame is not fixed. It depends upon the system requirements for a particular application. For example delay bound for the message is not the same for all applications. Moreover, the clock drift and synchronization error are deciding factors for number of data slots in a frame. Within the limit, without violating the synchronization condition, if a frame contains more slots then the nodes will save more energy, because the nodes having no data can sleep longer. On the other hand delay may be increased. So, the duty cycle is chosen very carefully.

Figure 2. Frame structure for the proposed Efficient MAC with Parallel Transmission (EP-MAC) protocol.



In Figure 3, we have shown a sample frame scenario of EP-MAC with comparison to Sensor MAC (S-MAC). We take four data slots in a frame. It is noticeable that to handle the effect of clock drift and to minimize the synchronization error we fix the data slot length a little longer than the required period for sending data and receiving acknowledgement.

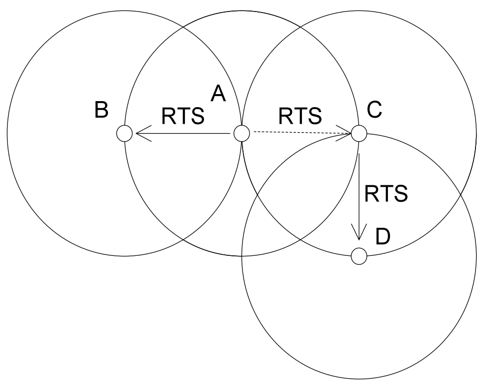
Figure 3. Comparison of Frame structure of EP-MAC with S-MAC.



3.3. Identifying the Maximal Set of Communication Links Supporting Collision Free Transmission Simultaneously

Within two hop neighbors simultaneously more than one transmission is possible without collision. The idea can be explained by the following scenario as explained through Figure 4. We use the similar approach of parallel transmission used in [15]. But we incorporate the concept of transmission power adjustment of sensor nodes in order to find the superset of mutually collision free transmission link which further support more transmission simultaneously. In Figure 4, we take four sensor nodes which are within three hops neighbors and belong to the same virtual cluster to explain the situation. We use the IEEE 802.11 [16] scheme as well.

Figure 4. The idea of Parallel transmission using four nodes.



Let us consider that node A wants to send a message to node B. First of all A will send a RTS packet to the sensor node B. But node C will overhear the RTS packet because node C is within the transmission range of node A. By overhearing the RTS the node C concludes that the transmission medium is busy. Now let us consider at the same time node C has a data to send to D. In the conventional method, since node C knows that the transmission medium is busy it will not send any message to initiate any transmission. But we can see from the figure that the communication (RTS) from node C to node D will not affect the previous communication *i.e.*, communication (RTS) from node A to node B. Since collision happens at the receiving end, and node B and node C are not within the same transmission range, transmission of C by no means will interfere with the reception of node B. Similarly if node B sends a RTS to node A, node A will reply with a Clear-To-Send (CTS). This CTS will be overheard by C. But C need not stop its transmission and can send or receive during this time without any collision. By using the transmission power adjustment as described in Section 3.4 of this paper we can maximize the set of communication links which can transmit data simultaneously.

3.4. Reservation of Slot and Data Transmission

At the beginning of each frame the nodes that belong to the same virtual cluster will be synchronized with each other. After synchronization the reservation slot will be used for transmission agreement purpose between nodes. The node that has data to send will contend with other intended sender in a slotted CSMA/CA fashion. And the reservation will be done using the exchange of RTS/CTS technique used in IEEE 802.11 with slight amendment. The amendment is that the CTS message will be accompanied with the data slot number. And that particular couple of nodes who exchange the RTS, CTS successfully will use that data slot. The first couple of nodes who successfully exchange RTS/CTS will get data slot number 1. Data slot number will be sent by the receiver with the CTS. The transmission which involves one node as sender or receiver of the previous successful pair will get priority for the next slot. Priority can be controlled by changing contention window size as described in Section 3.6. Consecutive slot assignment of a node will minimize the on off radio of the node.

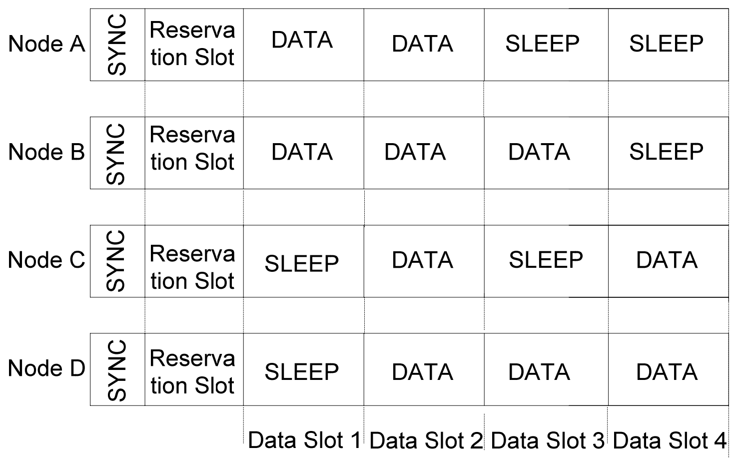
Now the next couple of nodes who successfully transfer RTS/CTS will be given either data slot number 1 or slot number 2 depending on the mutual exclusiveness of the two transmission links. In fact the receiver, *i.e.*, the node sending CTS will decide the slot number by looking at the sets of links created in the way described in Section 3.3 of the paper. In each data slot more than one communication is possible at a time. Which couple of nodes are allowed to communicate simultaneously, it can be found in the neighbors list table. So, the second couple will get the same slot as the previous couple or a new slot depending on the status of the mutually exclusiveness state of the two links in the neighboring list. Thus for the ith couple it can get any slot previously chosen by another couple or a new slot. But if one node is in common with in two transmissions either as sender or receiver in that case the transmissions will never be given the same slot at a time.

For bursty traffic of large message, more than one consecutive data slot can be assigned to a particular link, if sender node of the link asks for more than one data slots during RTS. In that case receiver replies CTS with mentioning id of some consecutive slots. But during huge traffic this consecutive slot allocation to a particular node will be impractical and also it will promote unfairness. So during heavy traffic the ith slot can be given to every frame to that particular couple of node. So that RTS/ CTS exchange will be minimized for that particular couple. When a sensor node successfully exchanges RTS/CTS with another node then they wait for the time to see where one of them can successfully send a RTS or receive a RTS. If so then the node will be given consecutive data slot. If the next successful RTS is directed to other node then the previous couple will go to sleep with an agreement to wake up at the beginning of their designated data slot.

There will be no wastage of the radio/energy due to the multiple on-off. Because the node intended to send multiple data to different nodes usually will do it in the consecutive time slots. The nodes who have failed to reserve any slot during reservation period will go to sleep until the beginning of the next frame. The nodes that successfully reserved slots will perform data transmission during this phase. Since this phase is in fact TDMA, so without any RTS or CTS data will be transmitted between nodes. In this transmission procedure the sensor nodes can save more energy because when a node wakes up it has a guaranteed data slot and thus performs transmission. The protocol ensures throughput maximization and best channel utilization because simultaneous transmission facilities among the neighbors are allowed. Another advantage is the bandwidth reuse.

The slot allocation and transmission technique of the EP-MAC protocol is explained in Figure 5. Consider a simple sensor network consisting of four sensor nodes namely A, B, C, and D and every node runs in the same schedule. Now let us consider that, the communication is possible between node A and D (link AD) and node B and C (link BC) simultaneously without any interference. We further consider a frame which consists of an active period or listen period which is represented by t_L and a sleep period represented by sleep part (t_s). Active period is further divided into two parts. The first part is used for synchronization and the second part is used for making reservation of data slots by sensor nodes. In this part sensor nodes exchange several RTS and CTS for data slot reservation. The next part of the frame is the sleep part, which will be used for data transmission between nodes. The sleep part is subdivided into a few data slots. In this example we take four data slots. The ration of listen and sleep period depends on the duty cycle of the operation of sensor nodes. So, as the SYNC period is fixed, with the change of the duty cycle the span of reservation slot and number of data slot will be changed accordingly.

Figure 5. Timing diagram of sensor nodes working in EP-MAC.



We consider some random transmission between nodes to explain the different scenario of operation of EP-MAC protocol. Let each of the four nodes A, B, C and D have data to send to other nodes. And let the node pair AB exchange RTS and CTS with each other as the first successful pair. The next pair is BC and then sequentially AD, BD and CD. According to our proposed algorithm the data slot 1 will be allocated for the communication between AB. Now the next pair who won the contention is BC. Since B already participated in the data slot 1 so there is no scope of parallel transmission in slot 1 for the BC link. Hence data slot 2 will be allocated for transmission between BC. The third pair is AD. For this pair data slot 1 cannot be allocated because node A is already participating in communication of data slot 1. During the data slot 2 communications will take place between node B and node C. But link BC and link AD are simultaneously collision free transmission free link. So, data slot 2 can be assigned to AD also. For the next pair BD, since B is already participating in the previous two data slot so new data slot 3 is allocated to BD. Again, for the next pair CD though during data slot 1 neither C nor D is participating in the communication but data slot 1 cannot be given to CD. Because link AB and link CD s transmission will interfere with each other. So, data slot 4 will be allocated for transmission of CD.

3.5. Transmission Power Adjustment

The power adjustment features of EP-MAC allow the sensor nodes to suitably vary the transmission power to reduce energy consumption. This concept is based on the power control protocol for wireless ad-hoc network proposed in [17]. During transmission of the RTS and CTS packets EP-MAC protocol use the maximum power P_{max}. If receiver node receives an RTS packet, it sends a CTS packet to the sender node by using maximum power level P_{max}. Now when the source node receives this CTS packet, the source node can calculate the actual required power $P_{desired}$ by using the received power level P_r and transmitted power level P_{max} by using the formula

$$P_{desired} = \frac{P_{max}}{P_r} \times Rx_{thres} \times c$$

where Rx_{thres} is the minimum required signal strength and c is a constant. During the transmission of data packet the source node uses power level $P_{desired}$. In the same way, receiver can determine the actual required power level $P_{desired}$ by using the signal power of received RTS packet. And receiver node use power level $P_{desired}$ for transmitting the ACK packet. This method assumes that the attenuation of the signal is the same in both directions *i.e.*, the direction of both sender and receiver nodes. The noise level at nodes is also assumed to be less than a certain predefined threshold value.

3.6. Contention Window Size for Priority Fixing

Priority can be set by using different contention window size for sensor nodes. Sensor nodes with a larger number of waiting message in the queue can be set as a high priority and with small number of message can be dealt as a low priority. A node with a high transmission priority, picks a random time uniformly over contention interval [1, CW_{hp}], while nodes with low priority picks a random time uniformly within [1, CW_{lp}]. The average window size observed by a node with high priority would be $(1 + CW_{hp})/2$ and for the node with low priority would be $CW_{own} + (1 + CW_{hp})/2$. The node with high priority will have the smaller contention window. So if the node has a data to send it will take hold of the channel every time. Since sensor nodes works for a common goal so that it is more logical to allocate the transmission channel to the node who has a large number of message waiting in the queue in order to avoid message loss by queuing overflow. For both high priority and low priority transmission nodes, RTS transmission in EP-MAC always stars by waiting and listening for a random time within the contention interval.

4. Results

In this section, we inspect the performance of the proposed EP-MAC protocol. We compare our proposed EP-MAC protocol with three other protocols: S-MAC, T-MAC and Intelligent Hybrid MAC (IH-MAC).

The performance metrics used in the evaluation of EP-MAC protocol are the energy consumption, average delay and average delivery ratio.

We have simulated with Castalia, a simulator for Wireless Sensor Networks and Body Area Networks [18] which is developed on the discrete event simulator OMNET++ [19]. In the simulation setup, we take 100 nodes distributed in a 100 m × 100 m area grid. The nodes considered here are static. The radio range is selected in such a way that all the non-edge nodes have eight neighbors. The sink node is chosen on the bottom left corner of the network grid. We evaluate the performance of our EP-MAC and compare with three other said protocols. We use four data slots in a frame for our proposed EP-MAC. The simulation parameters are given in the Table 1.

Table 1. Parameters for the MAC protocol.

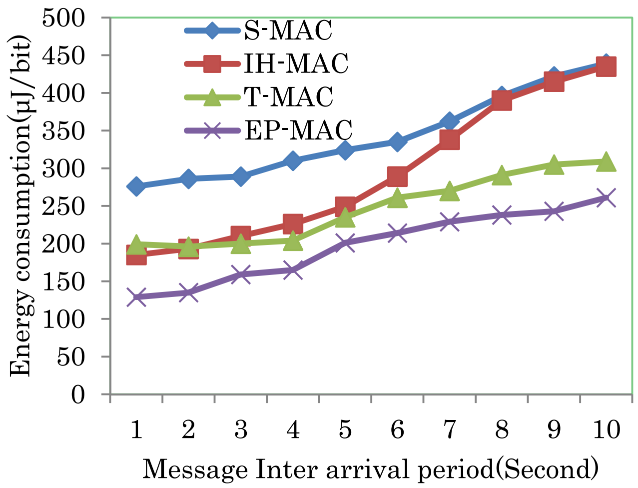
Parameter Name Value
Channel band width 20 kbps
Data packet length 20 bytes
Transmission power 36 mW
Receive power 14.4 mW
Idle power 14.4 mW
Sleep state 15 μW
Frame length 1 s
(for S-MAC,T-MAC,IH-MAC)
Frame length (for EP-MAC) 4 s

Energy efficiency of sensor nodes for EP-MAC, T-MAC, IH-MAC and S-MAC are shown in Figure 6(a). We vary the packet generation interval in order to measure the performance for variable traffic load. We see that the average energy consumption per node of EP-MAC is less than the energy consumption of other three protocols both for low and high traffic load. It is because proposed EP-MAC protocol avoid redundant control signal (RTS/CTS) and work like TDMA as explained in Section 3.4 of this paper.

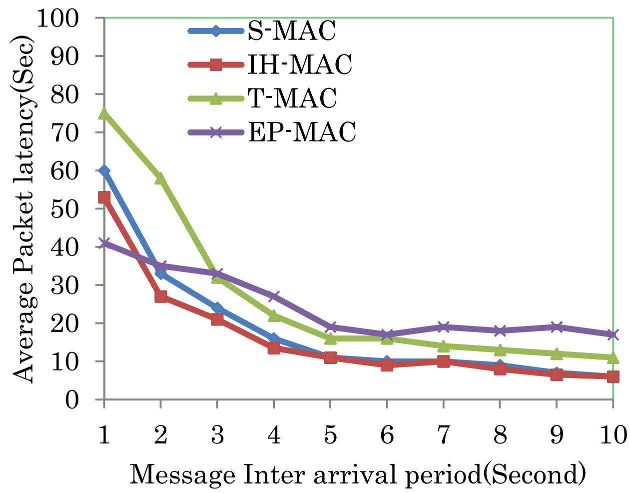
Figure 6(b) shows the average packet delay for proposed EP-MAC and other three protocols. As the packet inter arrival time increases and reaches to a certain level the average packet delay of EP-MAC become steady. But the delay in EP-MAC is a little bit higher than the delay of the other three protocols because it trades off latency for energy savings. But the delay performance of EP-MAC is better than the pure TDMA because of using the concept of parallel transmission which is explained in Section 3.3 of this paper.

Figure 6(c) shows the average packet delivery ratio for our proposed EP-MAC protocol and the other three protocols. EP-MAC clearly outperforms the T-MAC, S-MAC and IH-MAC in terms of packet delivery ratio for different traffic load. This is due to using the concept of TDMA and parallel transmission together in the EP-MAC protocol.

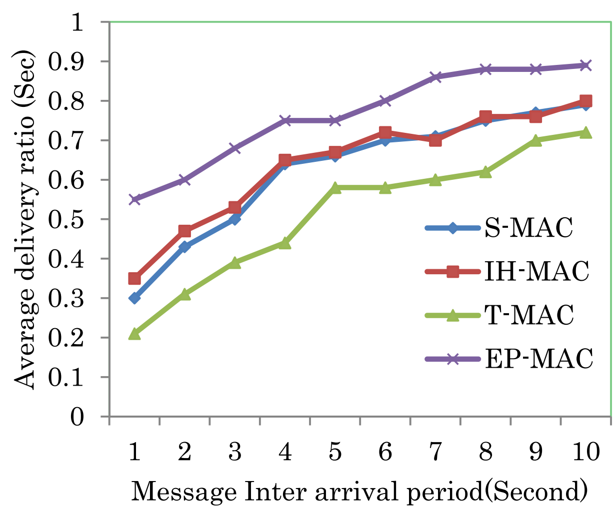
Figure 6. (**a**) Average energy consumption per bit under different traffic load; (**b**) Average Packet Latency under different traffic load; (**c**) Average Packet delivery ratio under different traffic load.



(**a**)



(**b**)



(**c**)

5. Conclusions and Future Work

This paper presents EP-MAC; a novel energy efficient medium access control protocol for wireless sensor networks. The EP-MAC protocol is basically based on the TDMA approach. However, EP-MAC uses the strength of the contention based scheme to offset the drawback of the schedule based approach in medium access control of Wireless Sensor networks to achieve a significant amount of energy savings. In addition, EP-MAC uses the concept of parallel transmission for minimizing the latency and maximizing energy savings. The transmission power adjustment feature of EP-MAC is very promising which further enhances the scope of parallel transmission and contributes to increase the sensor nodes lifetime.

Since all the features of EP-MAC are yet to be implemented, as a future work; we expect more detailed results concerning energy efficiency, throughput and the fairness issue of our proposed EP-MAC protocol. Further, we plan to implement our proposed EP-MAC protocol on hardware mote.

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