Channel Adaptive MAC Protocol with Traffic-Aware Distributed Power Management in Wireless Sensor Networks-Some Performance Issues

Binu G S[1], Dr. K Poulose Jacob[2]

Department of CSE, Cochin university of Science and technology,
Kochi, India

Summary
In Wireless Sensor Networks (WSN), neglecting the effects of varying channel quality can lead to an unnecessary wastage of precious battery resources and in turn can result in the rapid depletion of sensor energy and the partitioning of the network. Fairness is a critical issue when accessing a shared wireless channel and fair scheduling must be employed to provide the proper flow of information in a WSN. In this paper, we develop **a** channel adaptive MAC protocol with a traffic-aware dynamic power management algorithm for efficient packet scheduling and queuing in a sensor network, with time varying characteristics of the wireless channel also taken into consideration. The proposed protocol calculates a combined weight value based on the channel state and link quality. Then transmission is allowed only for those nodes with weights greater than a minimum quality threshold and nodes attempting to access the wireless medium with a low weight will be allowed to transmit only when their weight becomes high. This results in many poor quality nodes being deprived of transmission for a considerable amount of time. To avoid the buffer overflow and to achieve fairness for the poor quality nodes, we design a Load prediction algorithm. We also design a traffic aware dynamic power management scheme to minimize the energy consumption by continuously turning off the radio interface of all the unnecessary nodes that are not included in the routing path. By Simulation results, we show that our proposed protocol achieves a higher throughput and fairness besides reducing the delay.

Key words:
Wireless sensor network, MAC, Fairness, error rate, energy consumption, throughput.

1. Introduction

1.1 Wireless Sensor Networks (WSN)

Sensor networks are dense wireless networks of small, low-cost sensors, which collect and disseminate environmental data. Wireless sensor networks facilitate monitoring and controlling of physical environments from remote locations with better accuracy. They have applications in a variety of fields such as environmental monitoring, military purposes and gathering sensing information in inhospitable locations. Sensor nodes have various energy and computational constraints because of their inexpensive nature and ad hoc method of deployment [1].

Energy consumption is the most important factor to determine the life of a sensor network because usually sensor nodes are driven by battery and have very low energy resources. This makes energy optimization more complicated in sensor networks because it involved not only reduction of energy consumption but also prolonging the life of the network as much as possible.

Fairness is a critical issue when accessing a shared wireless channel. Fair scheduling must then be employed in WSNs to provide proper flow of information. A number of fair scheduling schemes exist in the literature; where some are centralized, and others are distributed. In general these fair scheduling schemes determine appropriate weights in order to meet QoS criteria. In most schemes weights are assigned and not updated for dynamic network conditions [2].

1.2. MAC Protocols of Wireless Sensor Networks

MAC protocols can be classified from four perspectives such as contention-based, TDMA-based, hybrid, and cross layer MAC [3]. The following are the wide range of MAC protocols which are defined for sensor networks are described briefly by stating the essential behavior of the protocols wherever possible [4].

- Sensor-MAC (S-MAC) [4]
- Wise MAC [4]
- SIFT [4]
- Timeout-MAC (T-MAC) / Dynamic Sensor-MAC (DSMAC) [4]
- Traffic-Adaptive MAC Protocol (TRAMA) [4]

Manuscript received July 5, 2010
Manuscript revised July 20, 2010

- IEEE 802.11 [5]
- Aloha with Preamble Sampling [5]
- Berkeley a Access Control (B-MAC) [5]
- PAMAS: Power Aware Multi-Access Signaling [5]
- Optimized MAC [5]
- Data Gathering MAC (D-MAC) [5]
- Self Organizing Medium Access Control for Sensor Networks (SMACS) [5]
- Energy Aware TDMA Based MAC [5]

2. Related Work

Tijs van Dam et al [6] have described T-MAC, a contention-based Medium Access Control protocol for wireless sensor networks that can be exploited to reduce energy consumption by introducing an active/sleep duty cycle.

Gang Lu et al [7] have proposed Data-gathering MAC (DMAC), an energy efficient and low latency MAC that is designed and optimized for data gathering trees in wireless sensor networks. DMAC solves the interruption problem by giving the active/sleep schedule of a node an offset that depends upon its depth on the tree. They further proposed a data prediction mechanism and the use of more to send (MTS) packets in order to alleviate problems pertaining to channel contention and collisions.

Injong Rhee et al [8] have proposed a new hybrid MAC scheme, called *Z-MAC* (Zebra MAC), for sensor networks that combine the strengths of TDMA and CSMA while offsetting their weaknesses. The main feature of Z-MAC is its adaptability to the level of contention in the network – under low contention; it behaves like CSMA, and under high contention, like TDMA. It is also robust to dynamic topology changes and time synchronization failures commonly occurring in sensor networks.

Tao Zheng et al [9] have proposed Pattern-MAC (PMAC) protocol, a novel adaptive MAC protocol for wireless sensor networks that adaptively determines the sleep-wake up schedules for a node based on its own traffic, and the traffic patterns of its neighbors, instead of having fixed sleep-wakeups.

Michael Buettner et al [10] have presented X-MAC, a low power MAC protocol for wireless sensor networks, which employs a shortened preamble approach that retains the advantages of low power listening, namely low power communication, simplicity and a decoupling of transmitter and receiver sleep schedules.

Joseph Polastre et al [11] have proposed B-MAC, a carrier sense media access protocol for wireless sensor networks that provides a flexible interface to obtain ultra low power operation, effective collision avoidance, and high channel utilization. To achieve low power operation, their B-MAC employs an adaptive preamble sampling scheme to reduce duty cycle and minimize idle listening.

Stephan Mank et al [12] have proposed MLMAC; a novel TDMA based MAC protocol that can react on changing radio neighborhoods in mobile networks. MLMAC does not depend on a gateway to start the synchronization; instead, it is fully dynamic.

3. Channel Adaptive MAC Protocol

3.1. Protocol Overview

Packet transmission through a link of high quality consumes less energy than that needed through a “bad” link. Based on this observation, in our proposed scheme, each sensor node should possess the ability to decide the state of its communication unit with respect to the current condition of the wireless link between it and the sink. Every node estimates the channel state and link quality for each contending flow. To represent the channel state and link state at the LLC queue, a flag is initiated. The flag can take three values: Good, Bad or Probe. The proposed protocol calculates a combined weight value based on these flags. Then transmission is allowed only for those nodes with weight greater than a minimum threshold value. Nodes attempting to access the wireless medium with a weight value less than the threshold value will be allowed to transmit again when their weight becomes high.

The energy consumed in an idle mode is less than Active mode, but significantly greater than in the sleep mode. Hence, intelligently switching to sleep mode whenever possible will generally create significant energy savings. We design traffic aware dynamic power management scheme (TA-DPM).The design goal of our proposed dynamic power management scheme is, to minimize energy consumption by continuously turning off the radio interface of unnecessary nodes that are not included in the routing path. For this, we categorize nodes into three types depending upon the state defined by data transmission: Current Transmitting Node (CTN), Future Transmitting Node (FTN), and No Transmitting Node (NTN). A state may dynamically change whenever data traffic is transmitted. Then, only the CTN and FTN nodes are asked to wake up, while other NTN nodes can continuously remain in their sleep modes. This was analyzed in [13], [14] and proved to have very less energy consumption compared with the existing schemes. But fairness was noted to be an important issue to be dealt with, for which the underlying algorithm was designed.

3.2. Adaptive Threshold Adjustment Scheme

To avoid buffer overflow and achieve fairness for the poor quality nodes, we also design a Load prediction algorithm. In the Load prediction algorithm, we adaptively adjust the minimum quality threshold W_m based on the current incoming traffic load TL. For this, the buffer and queue length values of the node are continuously monitored for a specified period. Based on the queue length variations in that period, the traffic load TL can be predicted. Whenever there is a buffer overflow, the threshold is adaptively adjusted, based on the predicted traffic load. i.e., threshold will be reduced or increased if the traffic load is increasing or decreasing, respectively. Thus, we can achieve a balance between energy efficiency and fairness.

The process of buffering packets until the channel threshold constraint is satisfied, is applicable only for nodes with better link quality, since they can always get the most bandwidth shares. As a result of this, the nodes with bad link quality has to wait until its channel quality recovers, leading to starvation. This unfairness problem can cause serious problem for the nodes with link quality less than packet overflow and long queuing delay.

A natural solution to this starvation problem is to adjust the minimum weight threshold value W_m adaptively, depending on the current traffic load and queue length of the buffer.

To reduce the buffer overflow and increase the fairness, we design an adaptive threshold adjustment scheme based on load prediction.

Buffer overflow can be prevented by predicting the future traffic load. This can be achieved by constantly measuring the queue length and its variation.

Let $\{t_i, t_{i+1}, t_{i+2}, \cdots\cdots\}$ denotes the sequence of packet arrival times of a node Ni

Let QL_{ti} denote the queue length of the buffer of n_i at time t_i .

Then, QLt_i , QLt_{i+s}, QLt_{i+2s} , ... the sequence of queue lengths at time instants

t_i , t_{i+s} , t_{i+2s},………… ,where s is the sampling interval for incoming packets.

Then the queue length variation V can be calculated as

$Vt_{i+s} = QLt_{i+s} - QLt_i$

$\Delta V = Vt_{i+2s} - Vt_{i+s}$

Where ΔV is the prediction of queue variation at time $t_{i+2s.}$ If ΔV > 0, then the queue length has an increasing tendency; otherwise,

if ΔV < 0, the queue length is likely to decrease.

Based on the queue length variation prediction, we can develop a threshold adjustment scheme. We keep monitoring the incoming traffic, and once the queue length exceeds a value QL_{max}, the threshold adjustment mechanism is started up.

3.3. Load Prediction Algorithm

1. For each packet arrived at time t_{i+s}
   1.1 Find $Vt_{i+s} = QLt_{i+s} - QLt_i$
   1.2 If $QLt_{i+s} > Q_{max}$ Then
      1.2.1 Find $\Delta V = Vt_{i+2s} - Vt_{i+s}$
      1.2.2. If ΔV > 0 Then

1.2.2.1 $W_m = W_m - \delta$, where δ is the scale factor

      1.2.2 Else if ΔV < 0 Then
         1.2.3.1 $W_m = W_m + \delta$
      1.2.3 End if
   1.3 End if
2. End For

4. Performance Evaluation

4.1 Simulation Model and Parameters

We use Network Simulator (NS2) [15] to simulate our proposed protocol. In our simulation, the channel capacity of mobile hosts is set to the same value: 2 Mbps. In our simulation, sensor nodes are deployed in a 1000 meter x 1000 meter region for 15 seconds simulation time. We vary the number of nodes as 25, 50….100. Initially the nodes are placed randomly in the specified area. The base station is assumed to be situated 100 meters away from the above specified area. The initial energy of all the nodes assumed as 4 Joules. All nodes have the same transmission range of 250 meters. The simulated traffic is CBR with UDP source and sink. The number of sources is varied from 1 to 4.

Our simulation settings and parameters are summarized in Table 1.

Table 1: Simulation Settings

No. of Nodes	25, 50, 75 and 100
Area Size	1000 X 1000
Radio Range	250m
Routing Protocol	AODV
Simulation Time	14 sec
Traffic Source	CBR
Packet Size	512
Transmit Power	0.360 W
Receiving Power	0.395 W
Idle Power	0.335 W
Initial Energy	4.0 J
No. of. Flows	1, 2, 3 and 4
Transmission rate	100Kb,200Kb,…..500Kb
Error Rate	0.01,0.02,….0.05

4.2 Performance Metrics

We compare our proposed AEMAC protocol with the SMAC [4] and ZMAC [9] protocols. We mainly evaluate the performance according to the following metrics:

Aggregated Bandwidth: We measure the received bandwidth for all traffic flows

Fairness: For each flow, we measure the fairness index as the ratio of received bandwidth of each flow and total available channel bandwidth.

Average End-to-End Delay: The end-to-end-delay is averaged over all surviving data packets from the sources to the sink.

Packet Delivery Ratio: It is the ratio of the number of packets received successfully and the total number of packets sent

Throughput: It is the number of packets received successfully.

The performance results are presented in the next section.

4.3 Results

4.3.1 Effect of Varying Channel Error Rates

In the initial experiment, we vary the channel error rate as 0.01, 0.02, 0.03, 0.04 and 0.05, keeping the number of nodes as 50, number of flows as 4 and transmission rate as 100Kb.

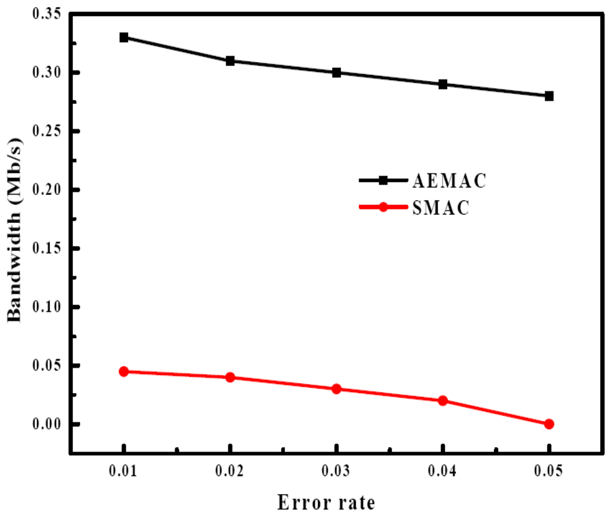

Figure 1: Variation of bandwidth received with respect to error rate

Figure 1 illustrates the aggregated bandwidth for the AEMAC and SMAC protocols. When error rate increases, more losses occur in the network. To prevent losses the schemes implemented use different methods to provide a reliable path to the destination so as to facilitate a reliable data transfer. Normally most power conservation schemes use CSMA to prevent losses. But this scheme alone may not be sufficient in an error prone network where errors can occur in the channel and links and when errors are time varying.

From the Figure 1, it can be seen that AEMAC has received more bandwidth when compared with SMAC. The bandwidth of all the flows slightly decreases, when the error rate is increased. This is because even a network that uses highly efficient schemes may not achieve in keeping up the performance. In SMAC only energy conservation schemes are deployed in addition to the CSMA and RTS/CTS methods for medium access. So the bandwidth received is very low for a low error rate case. For higher error rates, the bandwidth received considerably reduces. As per the proposed algorithm AEMAC, the nodes with high weight values are only allowed to transmit when there is a channel error. As a result the residual bandwidth in each node for a flow will be higher. It could also achieve a bigger portion of the available bandwidth even when the network is in error prone conditions. So the received bandwidth for the proposed protocol is more when compared with SMAC.

Figure 2 shows the fairness index for the AEMAC and SMAC protocols. When error rate increases, the energy conservation networks try to optimally conserve the energy available in the network. This is mainly by implementing a low duty cycle operation by driving nodes to sleep mode. More over such networks use CSMA method of medium access. So most nodes may not be able to transmit as the number of collisions may also increase and they may have to continue in the sleep mode for a long time. Besides this, most algorithms do not consider the varying channel conditions in a wireless sensor network.

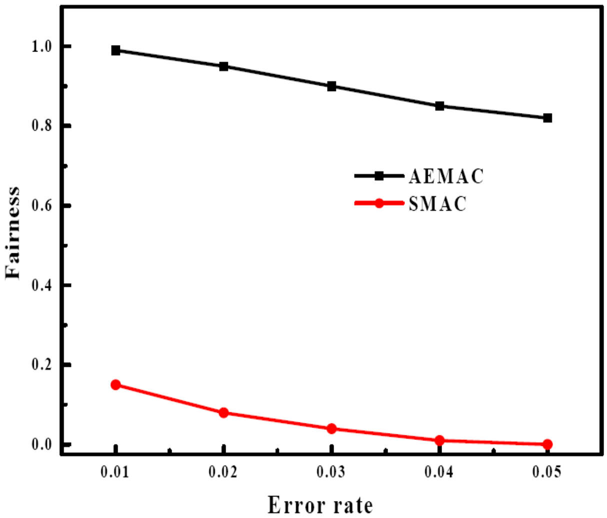

Figure 2: Variation of fairness with respect to error rate

It can be seen that AEMAC achieves more fairness when compared with SMAC. In SMAC only energy conservation schemes are deployed in addition to the CSMA and RTS/CTS methods for medium access. The link failures are never considered in the design of the algorithm. More over many nodes will be driven to the sleep mode as an effort to conserve energy. So many nodes will not get its fair share of the channel resources. Because of the adaptive threshold adjustment scheme, the proposed AEMAC protocol has higher fairness than SMAC, which can be observed from figure 2. When error rate increases, more nodes may end up as poor quality nodes with a lesser weight value. Instead of completely depriving them of their transmission, this protocol invokes the load prediction algorithm and does adaptive threshold adjustment. Thus even in error prone cases, most nodes get the even allocation of channel capacity. But the fairness index decreases with an increase in the error rate even though it is much higher than SMAC.

Figure 3 depicts the average end-to-end delay for the AEMAC and SMAC protocols. When a network is in error, most energy conservation schemes adopt a method which results in careful utilization of the network energy. This is mainly the CSMA and RTS/CTS method of medium access. If a channel is not found idle it invokes the low duty cycle operation in nodes to conserve energy. But most schemes do not take into account the varying channel conditions existing in wireless sensor networks. More over error situations, make finding a reliable route to the sink difficult. For energy conservation, nodes will be brought to the sleep state. So longer distance routes may have to be used. The store and forward mechanism may also add to the delay.

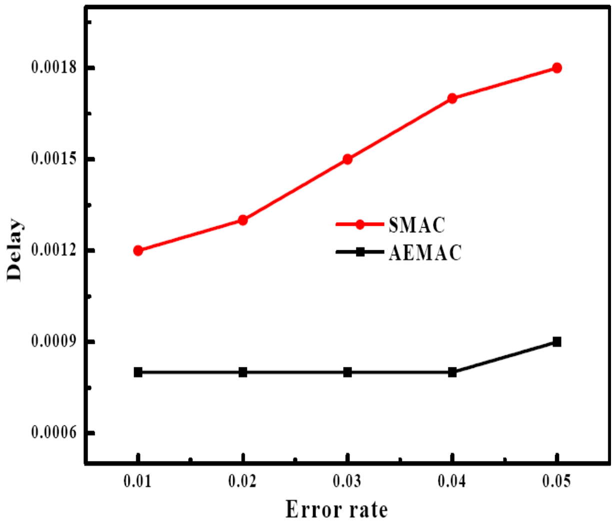

Figure 3: Variation of delay with respect to error rate

We can see that the average end-to-end delay of the proposed AEMAC protocol is less when compared to the SMAC. When the error rate is increased, the end-to-end delay tends to increase for both the schemes. In SMAC the static sleep-listen cycle is followed strictly by the nodes. This produces a higher end to end delay. On higher error rates, finding a reliable route is essential to promote reliable data delivery. This is difficult in SMAC since no schemes are implemented in this to handle this case of high errors in the network. So the ordinary routing protocol in SMAC like AODV may not be able to implement a reliable route. This results in losses and larger end to end delay. In the proposed scheme AEMAC, it considers link quality in addition to the channel quality. When error rate increases, AEMAC permits transmission only to those nodes which have a better link capacity and channel capacity. So the end to end delay encountered by the packets is significantly less when compared to SMAC. In AEMAC, the delay remains almost constant till an error rate of 0.04, proving the superior performance of this protocol. Later it shows a slight increase.

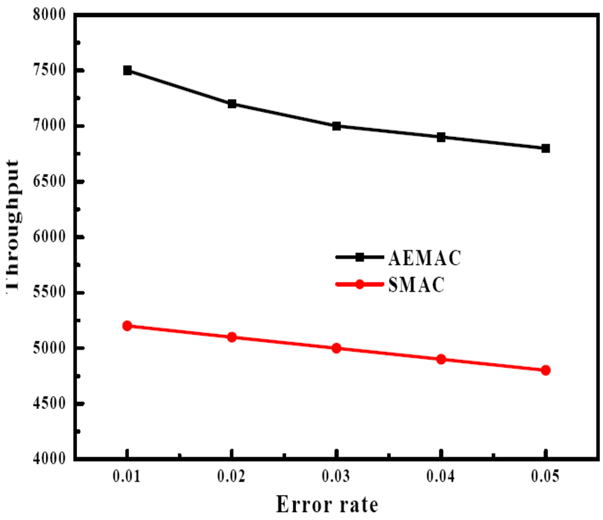

Figure 4: Variation of throughput with respect to error rate

Fig 4 gives the throughput of both the protocols. When error rate increases, the rate at which messages are serviced by the communication system will be adversely affected. In fact, the fraction of the channel capacity used for data transmission reduces. On an increase in error rate, energy conservation protocols aim at minimizing the energy consumption of the network. So the power conservation mechanisms that reduce the duty cycle will be invoked. Thus a large number of nodes are driven to the sleep mode. Finding a reliable route to the sink becomes difficult and so the number of packets received successfully at the sink will be less, in effect reducing the Throughput.

As we can see from the above figure, Throughput decreases for both the schemes on an increase in error rate. The throughput is more in the case of AEMAC than SMAC. In SMAC, on an increase in the error rate, it has only mechanisms like CSMA and RTS/CTS. No policies are considered to tackle the channel errors. But in AEMAC, the link quality and channel quality are also considered besides considering the ways to enhance energy conservation. So the Throughput is initially at a higher level for low error rates. When error rate increases, it restricts permission only to nodes having a better channel and link quality. Thus losses will be considerably less and this is shown by the slight decrease in slope.

Fig 5 presents the packet delivery ratio of both the protocols. The packet delivery ratio gives the ratio between the number of packets sent to that received. It is already explained that, when error rate increases the number of packets successfully reaching the destination is less due to the large number of packet losses. Since the packet drop is less and the throughput is more, AEMAC achieves good delivery ratio, compared with SMAC protocol.

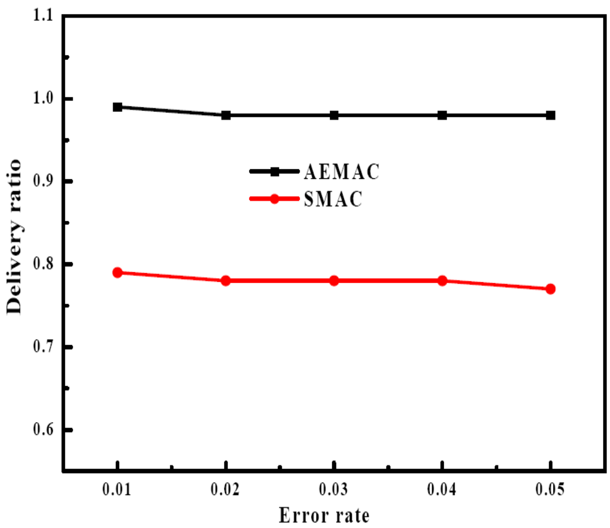

Figure 5: Variation of delivery ratio with respect to error rate

4.3.2. Effect of Varying Transmission Rate

In the forth and final experiment, we vary the transmission rate as 100Kb to 500Kb, keeping the error rate as 0, number of flows as 4 and number of nodes as 50.

Fig 6 gives the aggregated bandwidth for the AEMAC and SMAC protocols. In both the protocols, as transmission rate is increased, bandwidth received increases since large amount of data is transmitted per instant of time. So the schemes try to efficiently transmit the large amount of data to the sink utilizing the strategies in each one. Each node while transmitting utilizes a portion of the bandwidth. According to the superior nature of the scheme involved, lesser bandwidth will be utilized by supporting an efficient transmission. This involves selecting a better energy efficient route so as to minimize the losses occurring in a network. Otherwise the available bandwidth will be utilized only to recover from losses.

It is evident that AEMAC has received more bandwidth when compared with SMAC. This proves that, the chances of losses in AEMAC are considerably lower compared to SMAC. In AEMAC, transmission is permitted only through the most energy efficient routes. These are found on the basis of the residual energy, residual bandwidth of a node. More over it also considers the variable channel conditions prevailing in wireless sensor networks. This strategy helps it in selecting the best routes to the sink. So the available energy will be utilized in an optimum way.

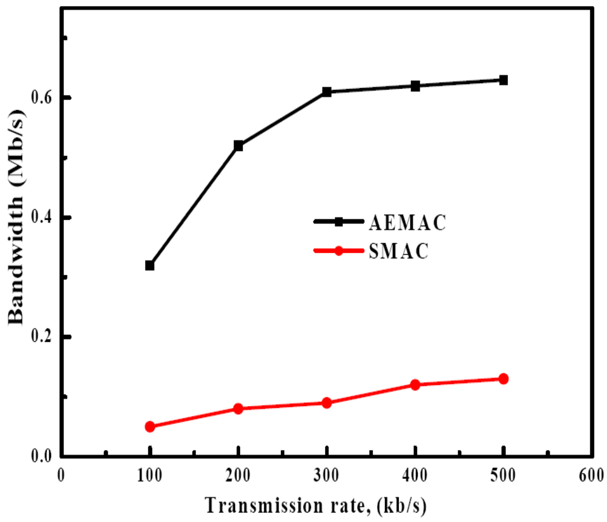

Figure 6: Variation of bandwidth received with respect to transmission rate

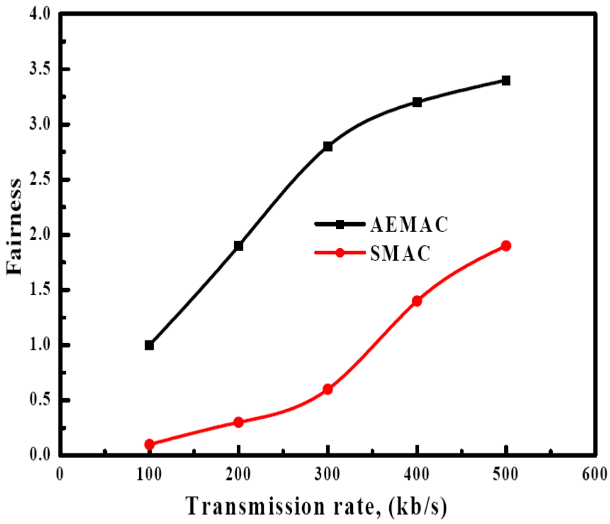

Figure 7: Variation of fairness with respect to transmission rate

Fig 7 illustrates the fairness index for the AEMAC and SMAC protocols. As the transmission rate is increased, more packets are liberated into the network. Energy conservation algorithms emphasize on energy efficiency strategies. They aim at providing energy efficient routes to the destination. Most algorithms use power conservation mechanisms to reduce the duty cycle of operation by forcing some nodes to sleep. When more nodes are driven to sleep mode, better energy efficiency results. But many nodes will be deprived of the equal share of the channel resources. Achieving fairness among competing nodes is desirable to achieve equitable QoS and to prevent starvation of nodes.

As transmission rate is increased, the amount of resources available to the nodes also increases. SMAC gives importance for energy efficiency by listen-sleep operations and so on. Nodes in the sleep mode cannot get its share of the resources. But in AEMAC, in addition to the energy conservation strategies adopted, an effort is made to improve the fairness by the Load prediction scheme. So the nodes which should have been deprived of transmission due to poor link state get a share of the resources. From the figure, it can be seen that AEMAC achieves higher fairness when compared with SMAC proving the efficiency of the load prediction algorithm and the threshold adjustment scheme..

5. Conclusions

We have developed **a** channel adaptive MAC protocol with a traffic-aware dynamic power management algorithm for efficient packets scheduling and queuing in a sensor network, with time varying characteristic of wireless channel taken into consideration. The proposed protocol calculates a combined weight value based on the channel state and link quality. Then transmission is allowed only for those nodes with weights greater than a minimum quality threshold and nodes attempting to access the wireless medium with a low weight will be allowed to transmit again when their weight becomes high. To avoid buffer overflow and achieve fairness for the poor quality nodes, in this paper, we have designed a Load prediction algorithm in which the minimum quality threshold is adaptively adjusted based on the current incoming traffic load. By Simulation results, we have shown that our proposed protocol achieves higher throughput, bandwidth, delivery ratio and fairness while reducing the delay.

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Binu G S is a research scholar in Department of Computer Science, Cochin University of Science and Technology. She is a graduate in Electronics and Communication Engineering and a post graduate in Computer Science Engineering. She has many research papers in National and International conferences. She has more than 10 years of academic and research experience. Her research area of interest is in wireless sensor networks.

Dr K Poulose Jacob, Professor of Computer Science at Cochin University of Science and Technology since 1994, is currently Director of School of Computer Science studies. A National merit scholar all through, he was Dean of the Faculty of Engg. He has more than 75 research publications to his credit. He has served as a member of the standing committee of the UGC on Computer Education and Development. He is the zonal coordinator of the DOEACC society under the Ministry of Information Technology, Govt. of India. He serves as a member of the AICTE expert panel for accreditation and approval. He is on the editorial board of 2 International Journals in Computer Science. He is a member of the ACM and Life Member of the Computer Society of India. His research interests are in Information System Engg, Intelligent architectures and Networks.