## SIMULATION RESULTS AND ANALYSIS

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This chapter provides an idea of the problem and the causes of Energy consumption in a wireless sensor network and brings forth the idea about the proposed Channel Adaptive MAC protocol. To enable the performance evaluation of this protocol, an overview of the network, performance metrics and performance evaluation of the algorithm are presented. The variation of Energy consumption, Throughput and Delay with respect to the Node density, the variation of Energy consumption, Throughput and Delay with respect to the Transmission rate and the variation of Delivery ratio with respect to the Node density, Transmission rate and Number of flows have been analyzed. The lack of Fairness in Phase 1 work is highlighted and an overview of the Load Prediction algorithm along with the previous scheme is also provided. Variation of Bandwidth and Fairness with respect to Transmission rate and the variation of Bandwidth, Fairness, Delay and Packet delivery ratio with respect to varying Channel error rate conditions are analyzed. Finally the protocol is compared with a Traffic Adaptive Sleep/Listening MAC protocol.
Wireless sensor networks have significantly drawn attention in recent times, in a wide range of applications. It has many characteristics like fast set up, strong survivability and do not need a fixed infrastructure (Xianghui et al., 2010). Energy constraint of sensor nodes is the major problem in wireless sensor networks. It is very critical since energy limitation may consequently lead to the depletion of the whole network. Extensive research is being done in this area to achieve energy management. Power management and power conservation are critical functions in the area of wireless sensor networks in which energy is the prime concern. The need to design power aware protocols and algorithms is quite significant.

In this context, a Channel Adaptive MAC protocol is designed, which uses various techniques to reduce the Energy consumption, Control overhead and Latency, in order to improve the overall system performance. Factors dominating the design of MAC protocols like \textit{Delay}, \textit{Throughput}, \textit{Stability}, \textit{Delivery ratio} and \textit{Energy efficiency} decide the overall performance of a wireless sensor network. The causes for energy consumption in wireless sensor networks were analyzed. They were found to be idle listening in which nodes listen for traffic which is not sent, collision in which many nodes attempt to transmit simultaneously, overhearing in which a node receives packets destined for other nodes, control packet overhead in which more number of control packets get sent compared to the number of data packets sent and frequent switching among different operation modes even if it be for the cause of reducing energy.

A large portion of the energy gets spent during communication. So a good routing path, multi hop routing and good routing algorithms which conserve energy need to be used to reduce the level of energy consumption of the network. Data communication occurs through a wireless channel in a wireless sensor network whose characteristics change with time. This aspect also needs to be dealt with, in
the process of reducing energy consumption so as to prevent un-necessary energy wastage through poor quality links.

Literature also indicates the need to have a cross layer interaction among the layers in a wireless sensor network, as a mechanism to optimize the performance of such a network.

In this work, cross layer interaction between the Physical layer, Data link layer and the Network layer is utilized in the development of this Channel Adaptive MAC protocol. It considers the effects of link quality, channel quality and energy level. Link layer metrics like residual energy, residual bandwidth, and channel quality conditions are conveyed into the Network layer to make intelligent routing decisions, based on this.

The most important design issue of Transport protocols in wireless sensor networks is to avoid packet losses. If packet losses prevail it leads to energy wastage in such networks, in which energy is an important factor which cannot be compromised. Another design issue insists that *Fairness* should be guaranteed to all the sensor nodes in the wireless sensor network. Efforts have been made in this work to achieve *Fairness* without compromising *Energy efficiency*.

A Traffic Aware Dynamic Power Management is proposed to enhance the *Energy efficiency*, by reducing the duty cycle of operation. A Load Prediction algorithm is also designed to prevent the buffer overflow and thus achieve *Fairness*.

Performance requirements of this protocol are to be validated. For this, Network Simulator NS2 is used. This Channel Adaptive MAC algorithm is evaluated with the existing algorithms to prove its performance. The goal is to increase the *Energy efficiency* while achieving a high level of stability and scalability.
6.1 NETWORK OVERVIEW

The protocol design in this work, assumes a large wireless sensor network, having a large number of sensor nodes, with limited storage, communication and processing capabilities. The nodes are configured in an ad hoc, self-organized and self-managed wireless network fashion. To create a realistic depiction of a wireless sensor network scenario, a simulation study is performed using Network Simulator NS2. The simulation network consists of many sensor nodes distributed in a grid pattern of 1000×1000 m\(^2\). Each node is equipped with a radio transceiver capable of transmitting a signal 250 m over a 2 Mbps wireless channel. All nodes have a transmitter power of 0.395 watts, a receiver power of 0.360 watts and an idle power of 0.335 watts. Initial energy for the first set of simulations is taken as 2.7 Joules and for the second setup as 4.0 Joules. All applications run on User Datagram Protocol scheme. The simulated traffic is the Constant Bit Rate type. The sink is assumed to be 250m away from the specific area.

The channel for the simulation is taken as Wireless channel. The radio propagation model is set as the Two Ray Ground propagation model. The network interface is of Wireless Physical type and the Interface queue type is the Drop tail Priority queue. The antenna is an Omni-directional antenna and the routing protocol is AODV.

6.2 PERFORMANCE METRICS

The proposed AEMAC protocol is compared with the SMAC and ZMAC protocols. SMAC and ZMAC protocols aim at energy conservation in wireless sensor networks. SMAC protocol is a static scheme implementing static listen and sleep periods, to bring down the level of energy consumption. ZMAC protocol is a hybrid scheme which uses CSMA mechanism during low contention and TDMA
mechanism during high contention, thus making it possible to adjust to the level of contention in the network. These two protocols which aim at reducing energy consumption are chosen to estimate the performance of the AEMAC protocol. The performance is evaluated according to the following metrics, which are the performance deciding entities of any wireless sensor network.

**Aggregated Bandwidth**: The received bandwidth for all traffic flows is measured.

**Fairness**: For each flow, the fairness index is measured as the ratio of the received bandwidth of each flow and the 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 into the network.

**Throughput**: It is the number of packets received successfully.

**Energy consumption**: It denotes the total energy consumed in the network for a particular flow.

### 6.3 Performance Evaluation of the Algorithm

#### 6.3.1 Phase 1

**6.3.1.1 Effects of Varying Node Density**

The AEMAC scheme is compared with the SMAC and ZMAC schemes, in terms of *Energy consumption, Delay* and *Throughput* with respect to the *Node density*. The number of nodes is increased from 25 to 100.
A) Variation of Energy consumption with Node density

Figure 6.1 presents the Energy consumption graph of AEMAC, SMAC and ZMAC schemes with respect to the number of nodes. Normally when the node density increases, the level of Energy consumption will also increase. This is because, more number of nodes get involved in the route decision process. The store and forward mechanism also adds to the Energy consumption and on increasing the node density, this process involves a large number of nodes. Communication from source to sink also involves many nodes and so the communication energy expended is also high.

<table>
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<th>Parameters</th>
<th>Value</th>
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<td>0.395 watts</td>
</tr>
<tr>
<td>Reception power</td>
<td>0.360 watts</td>
</tr>
<tr>
<td>Initial node energy</td>
<td>2.7 Joules</td>
</tr>
<tr>
<td>Maximum number of packets in Interface queue</td>
<td>500</td>
</tr>
<tr>
<td>Packet size</td>
<td>500 bytes</td>
</tr>
<tr>
<td>Transmission rate (set up 1)</td>
<td>100 Kbps</td>
</tr>
<tr>
<td>Number of nodes (set up 1)</td>
<td>varied from 25 to 100</td>
</tr>
<tr>
<td>Transmission rate (set up 2)</td>
<td>varied from 100 Kbps to 500 Kbps</td>
</tr>
<tr>
<td>Number of nodes (set up 2)</td>
<td>50</td>
</tr>
</tbody>
</table>

Table 6.1: Simulation settings for Phase 1
Initially ZMAC has a higher Energy consumption compared to SMAC and AEMAC schemes for a low node density. When the node density is increased, the Energy consumption increases for all the 3 schemes due to the large number of forwarding packets. When the number of nodes increase, more routing may be involved to have a reliable data transfer. So the total Energy consumption also increases. But AEMAC scheme proves to have a much superior performance than the other 2 schemes since when the node density increases more number of nodes can be brought to the sleep state as the mandatory wake up involved in the other power saving schemes is not involved here. SMAC scheme also has the sleep/listen operations, schedule selection and co-ordination, schedule synchronization, adaptive listening and CSMA and RTS/CTS methods for access control like the AEMAC scheme. ZMAC scheme exhibits the maximum Energy consumption.
B) Variation of Throughput with node density

Figure 6.2 shows the Throughput level of the network with respect to the node density. When the node density increases, Throughput decreases. This may be because on an increase in node density, more nodes are involved in the routing path and more routing decisions are to be taken. So initially the fraction of the channel capacity used for data transmission is less. But when the node density increases, it reaches a state of equilibrium in which, more number of nodes get involved in the routing process, thus enabling more messages to be serviced by the communication system which indicates a lesser decrease in Throughput.

Initially when the number of nodes is less, the Throughput is at a low value for SMAC scheme compared to ZMAC and AEMAC schemes. This is because in SMAC only the active part of the frame is used for communication. Throughput for ZMAC scheme does not exhibit the level of poor performance as in SMAC scheme, for an increase in the number of nodes. As the number of senders increase, the number of senders transmitting during their own slots also increases. So during high contention it maintains a good Throughput compared to SMAC scheme since it behaves like TDMA. AEMAC scheme provides the best performance compared to the SMAC and ZMAC schemes. This is accounted to the fact that, when the number of nodes exceeds beyond 75, AEMAC scheme not only considers the link and channel quality but also the energy and bandwidth available in a node to perform the routing. So only the nodes with maximum residual energy and bandwidth get involved in the routing process.
C) Variation of Delay with node density

Delay decreases on an increase in node density because data needs to spend less time in the MAC layer of a node before getting transmitted successfully. On an increase in node density, more nodes get involved in routing and this result in a quicker delivery of data to the destination by packet delivery through these nodes. But when node density reaches a particular value, an equilibrium state is reached thus providing a constant Delay.

Figure 6.3 presents the Delay level with respect to the node density for the three schemes. The Delay level is much lesser for AEMAC scheme compared to SMAC and ZMAC schemes. Delay is higher for SMAC due to the unwanted delay involved due to the fixed duty cycle involved in the scheme which results in nodes following their schedules strictly. Moreover a message generating event may occur during sleep time and the message will be queued till the start of the next active part. ZMAC scheme exhibits a lesser Delay since the strengths of CSMA and TDMA are merged in this scheme. The Delay encountered by the packets in the
network decreases till the node density increases to 50. This is because of the fact that a better routing and better packet delivery to the destined node can be achieved as the node density increases. But on a further increase in the node density beyond 50, the sensor network reaches a state of equilibrium and so the Delay remains almost constant. Overall, SMAC scheme shows the greatest delay and AEMAC scheme shows the least Delay but when node density is 50, delay of both the schemes AEMAC and ZMAC coincide.

6.3.1.2 Effects of varying Transmission Rate

The Energy consumption, Delay and Throughput are compared for all the 3 schemes AEMAC, SMAC and ZMAC in terms of the Transmission rate. The Transmission rate is varied from 100 Kb/s to 500 Kb/s.

A) Variation of Energy consumption with Transmission rate

Figure 6.4 presents the Energy consumption for the 3 schemes with respect to the Transmission rate. As the node Transmission rate increases, the Energy consumption decreases for all the 3 schemes because a large number of data packets are transmitted per unit of time. So the network nodes will efficiently route these packets to the sink utilizing all their power conservation schemes optimally. Moreover the start up energy overhead decreases on an increase in the transmission rate accounting for the decrease in the energy consumption.
SMAC scheme shows medium Energy consumption because of the static nature of the scheme and the sleep/listen schedule synchronization, CSMA mechanism followed by the RTS/CTS packet exchange and adaptive listening techniques. ZMAC scheme shows the highest Energy consumption for varying transmission rates because nodes tend to wake up longer for transmission due to their large back off window sizes and also because clock synchronization messages are periodically sent. AEMAC scheme exhibits an Energy consumption maintained at a low value compared to the other 2 schemes and as the Transmission rate increases the Energy consumption further decreases to a lesser value. This is due to the highly efficient routing path considered and the avoidance of the mandatory wake up of the neighboring nodes except those of the next hop nodes, at the expiry of the packet duration, as indicated in the RTS/CTS packet. Besides the periodic listen/sleep operations, the schedule selection and coordination, schedule synchronization, adaptive listening, RTS/CTS message exchange after the medium sensing using CSMA are all factors helping to provide low Energy consumption.
Simulation Results and Analysis

Figure 6.4: Variation of Energy consumption with respect to Transmission Rate

B) Variation of Throughput with Transmission rate

Figure 6.5 shows the changes in Throughput for a change in the Transmission rate. As the Transmission rate increases, the Throughput level increases for all the 3 schemes. This is because, when the Transmission rate increases more amounts of data are transmitted per unit of time. So a large amount of data will be serviced by the communication system. Thus the fraction of the channel capacity used for data transmission is increased.

In all the three schemes, as Transmission rate increases, Throughput increases, but better slope is observed for AEMAC and ZMAC schemes. Throughput is initially slightly lower for SMAC scheme compared to the ZMAC scheme because all the factors like periodic listen/sleep operations, the schedule selection and coordination, schedule synchronization, adaptive listening, RTS/CTS message exchange after the medium sensing using CSMA help it to prevent data losses due to collisions and so on. But when more messages get transmitted from the source, it fails to exhibit the previous performance. ZMAC scheme merges the strengths of CSMA and TDMA. In
the beginning, the level of contention in the network is low and so it behaves like ordinary CSMA which is shown by the initial poor performance. Later it manages to achieve a higher performance when the transmission rate is increased since the level of contention in the network increases and it behaves like TDMA. In AEMAC scheme only the nodes having good link quality, channel quality and residual energy are allowed to take part in transmission. Moreover the Traffic aware Dynamic Power Management scheme also helps in categorizing the nodes as active current transmitting nodes, future transmitting nodes and very low power no transmitting nodes. Besides this, the compulsory wake up of neighboring nodes other than the next hop nodes, prevailing in schemes like SMAC is avoided here. Unwanted energy wastages being eliminated in AEMAC scheme, it shows the highest throughput level. So all messages transmitted at a higher rate from the source will be better serviced by the communication system. Consequently the fraction of the channel capacity used for data transmission is much higher in AEMAC scheme compared to the other schemes.

![Graph showing variation of throughput with transmission rate](image)

**Figure 6.5:** Variation of Throughput with respect to Transmission Rate
C) Variation of Delay with Transmission rate

When Transmission rate increases, the Delay incurred for the packets in the network increases. This is because more amounts of data are getting transmitted per second and more data traverses through the nodes. During the initial increase in the Transmission rate, more routing decisions have to be taken to find the best route to the destination with maximum number of hops. Moreover, store and forward mechanism at the nodes will add to the amount of Delay in AEMAC and SMAC schemes. Later when a state of equilibrium is reached, Delay settles to a constant value.

Figure 6.6 shows the changes in Delay for the 3 schemes with respect to the Transmission rate. SMAC scheme exhibits the highest Delay. This is because the latency is increased due to the periodic sleep of each node and the strict schedule followed by the nodes. The static nature of the SMAC scheme also adds to the Delay. Delay is lesser for AEMAC and ZMAC schemes. Superior performance is exhibited by ZMAC scheme because it merges the strengths of TDMA and CSMA schemes according to the level of contention in the network. But the Delay for AEMAC scheme is slightly less compared to the ZMAC scheme initially with an increasing slope till a rate of 300 Kbps but then shows a decreasing slope till 400Kbps. When the rate increases from 400 Kbps, it approximates to the best performance as exhibited by the ZMAC scheme. In AEMAC scheme, listen-sleep mechanisms are used to achieve Energy efficiency. Besides this, increased Delay can also be due to the delay involved in the dynamic best route selection process.
6.3.1.3 Effects on Delivery Ratio

AEMAC scheme is compared with SMAC and ZMAC schemes in terms of packet Delivery ratio for varying transmission rates from 100 to 500 Kbps, node density and number of flows.

A) Variation of Delivery ratio with Transmission rate

When Transmission rate increases, the amount of packets transmitted from the source per unit of time increases. More number of packets utilizes the network in taking optimum paths to the sink as insisted by the algorithm followed. So the number of packets received at the receiver also increases, indicating a higher Delivery ratio.

As given in Figure 6.7, as Transmission rate increases, Delivery ratio increases for SMAC scheme and it is also at a higher level initially compared to the ZMAC scheme. This is because of the factors like periodic listen/sleep operations, the schedule selection and coordination, schedule synchronization, adaptive

Figure 6.6: Variation of Delay with respect to Transmission Rate
listening, RTS/CTS message exchange after the medium sensing using CSMA which help it to prevent data losses due to collisions and so on. Thus more data can reliably reach the sink. The later decrease for SMAC scheme is due to the static nature of the scheme. Initially when the transmission rate is low, the level of contention in the network is low and ZMAC scheme behaves like CSMA thus showing a poorer performance compared to the SMAC scheme. ZMAC scheme shows an increase in Delivery ratio till Transmission rate rises to 400 Kbps and then shows a slight decrease. This can be because when Transmission rate increases, the level of contention in the network increases and it is forced to behave like TDMA. The Delivery ratio of AEMAC scheme is at a higher level initially when Transmission rate is 100 Kbps and then increases till 300 Kbps and then shows a slight decrease in slope followed by a slight increase. When the Transmission rate is increased, the Traffic Aware DPM and the Channel Adaptive MAC layer help it in finding a reliable path to the destination. This accounts for the increased Delivery ratio of AEMAC scheme compared to the other schemes.

**B) Variation of Delivery ratio with Node density**

Delivery ratio is compared for AEMAC, ZMAC and SMAC schemes for varying number of nodes from 25 to 100. When the number of nodes increases initially, more nodes will be involved in the routing of packets so as to implement a better routing decision. But when the number of nodes increases further, on the energy conservation perspective, all energy conservation algorithms try to bring more number of nodes to sleep state. This accounts for the decrease in the Delivery ratio.
Figure 6.7: Variation of Delivery Ratio with respect to Transmission Rate

Figure 6.8: Variation of Delivery Ratio with respect to Number of nodes

As depicted in Figure 6.8, when the number of nodes increase, Delivery ratio of SMAC is better compared to ZMAC scheme because of the energy conservation policies like the static listen periods involved in the protocol and the
availability of more number of nodes through which data can be transmitted, which results in a better routing scheme. But later on the Delivery ratio decreases because more nodes will be driven to the sleep state so as to conserve energy. In ZMAC scheme, in a low contention level, it behaves like CSMA and shows an inferior performance compared to the static scheme. When the Node density increases, it happens to be in a high contention level and so behaves like TDMA. Overall performance of AEMAC scheme is better. Initially AEMAC scheme shows a better Delivery ratio compared to SMAC and ZMAC schemes. On an increase in the Node density, optimum routing paths involving more nodes will be used. Later when Node density increases further, Delivery ratio decreases since more nodes will be brought to the sleep state so as to improve the Energy efficiency. But the better Delivery ratio proved by AEMAC scheme confirms the superior nature of this scheme.

C) Variation of Delivery ratio with number of flows

The Delivery ratio of AEMAC scheme is compared with SMAC and ZMAC schemes for varying number of flows from 1 to 4. When the number of flows increases, the amount of data transmitted from each source node has to make a reliable route using the given number of nodes. Delivery ratio will be at a high value initially because reliable routes are used by all the three schemes. When the number of flows further increases beyond a particular limit, Delivery ratio increases with a smaller slope, since the number of nodes through which the data flows is limited. So it may be difficult to select a reliable route which leads to less number of packets reaching the receiving end.

Delivery ratio of SMAC scheme is higher compared to ZMAC scheme due to the static nature of the scheme. Figure 6.9 shows approximately the same slope for SMAC scheme till flow becomes 3, showing that in SMAC scheme reliable
routes exist between the source and the sink. Later it shows a slight decrease in slope because of the static sleep and listen periods and the increase in listen sleep schedule coordination and synchronization needed among the nodes. When the number of flows increases, the \textit{Delivery ratio} increases for ZMAC scheme till number of flows become 3. This may be accounted to the more number of packets arriving at the sink due to the performance of the TDMA scheme, as a result of more number of flows. Thus ZMAC scheme shows a slightly better performance compared to SMAC scheme for increasing number of flows. AEMAC scheme initially shows a higher \textit{Delivery ratio} when the number of flows is low compared to SMAC and ZMAC schemes. This is due to the careful scheduling of traffic through the network due to the AEMAC protocol which also considers the channel state and link state. Whenever the channel condition becomes worse, that node and the corresponding link are not used until its quality improves. So this type of intelligent data flow has resulted in the highest \textit{Delivery ratio} attained by the AEMAC scheme. Even when the number of flows increases, it maintains a higher \textit{Delivery ratio} but the slope of the increase is less. It can be due to the difficulty in finding a favorable path to the destination taking into account the increase in number of flows and more number of nodes driven to sleep state so as to achieve energy conservation. Thus AEMAC scheme exhibits a better \textit{Delivery ratio}. 
6.3.2 Phase 2

To achieve Fairness and thus prevent the nodes from starvation, a Load Prediction algorithm and a Threshold Adjustment scheme is designed. It is detailed in Chapter 5. The validation of the AEMAC algorithm integrating these two schemes is illustrated below. The effects of this algorithm for high channel error conditions are studied in section 6.3.2.2, for various performance metrics. To understand the better performance of the AEMAC scheme compared to a static power conservation scheme, it is compared with the SMAC scheme.

6.3.2.1 Effect of variation of Transmission Rate

In this experiment, the Transmission rate is varied from 100Kbps to 500Kbps, keeping the error rate as 0, the number of flows as 4 and the number of nodes as 50. Both the power conservation protocols AEMAC and SMAC are compared.

![Variation of Delivery Ratio with respect to Number of Flows](image)

**Figure 6.9:** Variation of Delivery Ratio with respect to Number of Flows
SIMULATION SETTINGS

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<th>No. of Nodes</th>
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<td>Radio Range</td>
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<td>Routing Protocol</td>
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<td>Traffic Source</td>
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<td>Transmit Power</td>
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</tr>
<tr>
<td>Receiving Power</td>
<td>0.360 w</td>
</tr>
<tr>
<td>Idle Power</td>
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<tr>
<td>No. of Flows</td>
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<td>Error Rate</td>
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|Table 6.2: Simulation settings for Phase 2|

A) Variation of Aggregated Bandwidth with Transmission Rate

Figure 6.10 gives the variation of aggregated Bandwidth for the AEMAC and SMAC protocols with respect to the Transmission rate. 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. The superior nature of the scheme 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 scheme has received more Bandwidth when compared with SMAC scheme. This proves that, the chances of losses in AEMAC scheme are considerably lower compared to the SMAC scheme. In AEMAC scheme, transmission is permitted only through the most energy efficient routes. These are found on the basis of the residual energy and residual bandwidth of a node. Moreover 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 manner.

**B) Variation of Fairness with Transmission Rate**

Figure 6.11 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 efficient 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. Better energy efficiency results when more nodes are driven to sleep state. 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 data to be transmitted across the network increases. SMAC scheme gives importance for energy efficiency by the listen-sleep operations. Nodes in the sleep state cannot get their share of the resources. But in AEMAC scheme, 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 scheme achieves higher Fairness when compared with SMAC scheme proving the efficiency of the load prediction algorithm and the threshold adjustment scheme.

![Figure 6.10: Variation of Bandwidth received with respect to Transmission rate](image)

![Figure 6.11: Variation of Fairness with respect to Transmission rate](image)
6.3.2.2 Effect of variation of Channel Error Rate

In the initial experiment, the Channel error rates are varied 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 rate as 100Kbps. Error rate is increased to show the time varying characteristics of a wireless channel. Normally, when the Channel error rate is increased, the received Bandwidth, Throughput, Fairness and Delivery ratio of all the flows will tend to decrease.

A) Variation of Bandwidth with Error Rate

Figure 6.12 gives the aggregated Bandwidth for the AEMAC and SMAC protocols. When Error rate increases, more losses occur in the network. To reduce the effect of 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.

![Figure 6.12: Variation of Bandwidth received with respect to Error rate](image_url)
From the figure, it can be seen that AEMAC scheme has received more Bandwidth when compared with SMAC scheme. 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, when the Error rate in the network increases. In SMAC scheme, 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 the SMAC scheme.

B) Variation of Fairness with Error Rate

Figure 6.13 gives 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 the nodes to sleep state. Moreover 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 state for a long time. Besides this, most existing algorithms do not consider the varying channel conditions in a wireless sensor network.

From the figure, it can be seen that AEMAC scheme achieves more Fairness when compared with SMAC scheme. In SMAC scheme, 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. Moreover many nodes will be driven to the sleep state 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 could provide higher Fairness than SMAC scheme, which can be observed from Figure 6.13. 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 the SMAC scheme.

![Graph](image)

**Figure 6.13:** Variation of Fairness with respect to Error rate
C) Variation of Delay with Error Rate

Figure 6.14 gives 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. Moreover 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.

From the figure, it is seen that the average end-to-end Delay of the proposed AEMAC protocol is less when compared to the SMAC scheme. When the Error rate is increased, the end-to-end Delay tends to increase for both the schemes. In SMAC scheme, 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 scheme, since no additional schemes are implemented in this, to handle this case of high rate of errors in the network. So the ordinary routing protocol in SMAC scheme 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 and energy level at a node. When Error rate increases, AEMAC scheme permits transmission only to those nodes which have a better link capacity, energy level and channel capacity. So the end to end Delay encountered by the packets is significantly less when compared to the SMAC scheme. In AEMAC scheme, 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 in slope.

![Graph of Delay vs Error Rate]

**Figure 6.14:** Variation of Delay with respect to Error rate

**D) Variation of Throughput with Error Rate**

Figure 6.15 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 state. 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 seen from the figure, Throughput decreases for both the schemes on an increase in Error rate. The Throughput is more in the case of AEMAC scheme than SMAC scheme. In SMAC scheme, on an increase in the Error rate, it has only
mechanisms like CSMA and RTS/CTS to support reliable transmission. But in AEMAC scheme, the link quality energy level 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 many transmissions by providing permission only to nodes having a better channel and link quality and energy level. Thus losses will be made considerably less and this is shown by the slight decrease in slope.

E) Variation of Packet Delivery Ratio with Error Rate

Figure 6.16 presents the packet Delivery ratio of both the protocols. The packet Delivery ratio gives the ratio of the number of packets received to those sent. 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 scheme achieves good Delivery ratio, compared with SMAC protocol.

![Figure 6.15: Variation of Throughput with respect to Error rate](image-url)
Simulation Results and Analysis

Figure 6.16: Variation of Delivery ratio with respect to Error rate

6.4 VALIDATION WITH A TRAFFIC ADAPTED SLEEP/LISTENING MAC PROTOCOL

The Channel Adaptive MAC protocol scheme is compared with a Traffic Adapted MAC protocol for wireless sensor networks, TASL, in error prone wireless scenarios. TASL scheme dynamically adjusts the duty listening time based on the traffic load to ensure that data can obtain channel access and reach the sink. It aims to solve the un-proportionate problem between the bandwidth required in practice and the bandwidth provided by the sensor nodes. Each node at the end of the data transmission, checks whether the listening time is left or not. If the listening time has elapsed, it increases the listening time in the next duty cycle or vice versa. This process repeats till the bandwidth meets the required bandwidth (Yuang Yang et al., 2006).
Energy consumption is a major significant factor to be dealt with in a sensor network. So AEMAC scheme and TASL performance with respect to Energy consumption is also verified.

6.4.1 Effect of variation of Channel Error Rate

AEMAC scheme and TASL scheme are validated in an error prone scenario for Error rates from 0.01 to 0.05, to estimate its performance. Variation in Bandwidth and Throughput are compared. More losses are incurred in the network when Error rate increases. AEMAC scheme implements different methods to provide reliable data transmission even in channel fluctuating conditions.

A) Variation of Bandwidth with Error Rate

![Variation of Bandwidth with respect to Error rate](image)

**Figure 6.17:** Variation of Bandwidth with respect to Error rate

When Error rate increases, the Bandwidth received by the nodes in the network decreases even if efficient schemes are incorporated to deal with the errors. The scheme which can successfully provide reliable data transmission, in
spite of the channel errors in the network, will exhibit the superior performance. As seen in Figure 6.17, the Bandwidth received is higher for the AEMAC scheme.

**B) Variation of Throughput with Error Rate**

![Graph showing variation of throughput with error rate](image)

**Figure 6.18:** Variation of Throughput with respect to Error rate

The rate of service of messages by the communication system gets adversely affected on an increase in the Error rate. On an increase in the Error rate, most power saving schemes drive most of the nodes to the sleep state. Now discovering energy efficient reliable paths to the destination becomes difficult leading to a degraded Throughput. Throughput level is much higher for AEMAC scheme proving its superior performance, as depicted in Figure 6.18.

**6.4.2 Effect of variation of Transmission Rate**

When Transmission rate increases, the overall energy consumed in the network decreases. The network nodes which succeed in finding energy efficient
routing paths to the destination by making intelligent routing decisions will consume lesser energy.

A) Variation of Energy consumption with Transmission Rate

![Variation of Energy consumption with Transmission Rate](image)

**Figure 6.19:** Variation of Energy consumption with respect to Transmission rate

Figure 6.19 shows the variation in Energy consumption with Transmission Rate. Energy consumption decreases for both the schemes AEMAC and TASL, on an increase in the Transmission Rate. Overall Energy consumption of AEMAC scheme is much lesser compared to the TASL scheme, proving its success in finding energy efficient paths and routing the packets effectively and reliably to the destination.

### 6.5 CLOSURE REMARKS

In this chapter, the validation of the Channel Adaptive MAC protocol scheme carried out is reported in section 6.3.1; the Load Prediction scheme and the Threshold Adjustment scheme integrated with the AEMAC scheme as validated, is given in section 6.3.2. Performance evaluation was conducted for various
performance metrics which critically affect the performance of any MAC protocol in a wireless sensor network. In section 6.3.1, the variation of Energy consumption, Throughput and Delay with respect to the Node density, variation of Energy consumption, Throughput and Delay with respect to the Transmission rate and the variation of Delivery ratio with respect to Node density, Transmission rate and Number of flows were analyzed. In section 6.3.2, the variation of Bandwidth and Fairness with respect to Transmission rate was analyzed. In the latter part 6.3.2.2, the variation of Bandwidth, Fairness, Delay and Packet delivery ratio with respect to varying Channel error rate conditions were analyzed. In section 6.4, AEMAC scheme is further validated by comparing with a Traffic Adapted MAC scheme TASL, to find the variation in Bandwidth and Throughput for different channel error conditions and the variation in Energy consumption for different Transmission rates.

Simulation results prove that, the proposed scheme AEMAC exhibits a much superior performance compared to the existing schemes SMAC and ZMAC, in terms of all the performance metrics used for evaluation. AEMAC scheme gives a lower Energy consumption and Delay and a higher Throughput, Bandwidth, Delivery ratio and Fairness, with respect to number of nodes, number of flows and Transmission rate. Compared to the other schemes, much better performance was exhibited by AEMAC scheme even in error prone networks.