Ph.D Thesis

ENERGY MANAGEMENT IN WIRELESS SENSOR NETWORKS: A CROSSLAYER, CHANNEL ADAPTIVE APPROACH TOWARDS PERFORMANCE OPTIMIZATION

Submitted to

Cochin University of Science and Technology

for the award of the degree of

Doctor of Philosophy

by

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November 2011

ENERGY MANAGEMENT IN WIRELESS SENSOR NETWORKS: A CROSSLAYER, CHANNEL ADAPTIVE APPROACH TOWARDS PERFORMANCE OPTIMIZATION

Ph.D Thesis in the field of *Wireless Sensor Networks*

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CERTIFICATE

This is to certify that the thesis entitled **ENERGY MANAGEMENT IN WIRELESS SENSOR NETWORKS: A CROSSLAYER, CHANNEL ADAPTIVE APPROACH TOWARDS PERFORMANCE OPTIMIZATION** submitted by **Binu G. S.** to the Cochin University of Science and Technology, Kochi for the award of the degree of **Doctor of Philosophy** is a bonafide record of research work carried out by her under my supervision. The contents of this thesis in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma

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DECLARATION

I hereby declare that the work presented in this thesis entitled **"ENERGY MANAGEMENT IN WIRELESS SENSOR NETWORKS: A CROSSLAYER, CHANNEL ADAPTIVE APPROACH TOWARDS PERFORMANCE OPTIMIZATION"** is based on the original research work carried out by me under the supervision of **Dr. K. Poulose Jacob**, Professor, in the Department of Computer Science, Cochin University of Science and Technology. The results presented in this thesis or parts of it have not been presented for the award of any degree.

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ACKNOWLEDGEMENTS

I express my immense gratitude to my research guide **Dr. K. Poulose Jacob**, Professor and Head of the Department, Department of Computer Science, Cochin University of Science and Technology for his exceptional guidance and generous help throughout my PhD work. I am extremely fortunate to work under his inspiring guidance.

I would like to thank all the **Doctoral Committee members** for their worthy remarks towards improving the thesis work. I would also like to thank all the higher authorities for the facilities made available for research at Cochin University of Science and Technology.

I thank the entire library, technical and administrative staff of the department of Computer Science for their co-operation and support.

My special thanks to all the people who have helped, encouraged and supported me directly or indirectly during the period of my research work.

Finally I thank my husband, son and my parents for their love, inspiration, understanding and support.

BINU G S

ABSTRACT

Key Words: Wireless sensor network, Dynamic Power Management, Energy consumption, Fairness, Delivery ratio, Throughput, Delay

The proliferation of wireless sensor networks in a large spectrum of applications had been spurred by the rapid advances in MEMS (micro-electro-mechanical systems) based sensor technology coupled with low power, low cost digital signal processors and radio frequency circuits. A sensor network is composed of thousands of low cost and portable devices bearing large sensing, computing and wireless communication capabilities. This large collection of tiny sensors can form a robust data computing and communication distributed system for automated information gathering and distributed sensing. The main attractive feature is that such a sensor network can be deployed in remote areas. Since the sensor node is battery powered, all the sensor nodes should collaborate together to form a fault tolerant network so as to provide an efficient utilization of precious network resources like wireless channel, memory and battery capacity. The most crucial constraint is the energy consumption which has become the prime challenge for the design of long lived sensor nodes. So efficient energy management needs to be incorporated without ignoring the effects of varying channel quality existing in a wireless sensor network. In this work, a Channel Adaptive Energy Management protocol is developed that can exploit the time varying nature of the wireless links. It also considers the cross layer interaction between the Physical layer, the MAC layer and the Network layer. The power consumption is reduced by turning OFF the interface of the nodes which are not included in the current routing path. The mandatory awakening of all nodes in the routing path, as adopted in all the power saving schemes, is avoided here. The actual energy saving in a wireless environment is realized by deciding the routing path considering the link quality,

the channel quality and the energy resources of each node. This Channel Adaptive MAC algorithm AEMAC implements an efficient packet scheduling and queuing algorithm which also considers the fluctuating channel conditions in wireless sensor networks. Transmission through a bad link is avoided by buffering the packets till the link quality rises above a particular threshold. A wireless sensor network scenario is simulated incorporating the above aspects to explore the performance determining factors in a wireless sensor network like *Energy consumption*, *Throughput*, *Delay*, *Delivery ratio* with respect to varying node densities, Transmission Rates and number of flows. Results indicate that this scheme can achieve a much better performance compared to the traditional protocols which do not adopt channel adaptation, cross layer interaction and intelligent routing. This algorithm could not provide *Fairness* to those nodes having bad link and channel conditions and also may result in buffer overflow at the nodes. To achieve *Fairness*, a Load Prediction algorithm with Adaptive Threshold Adjustment scheme is designed, which implements fair scheduling and queuing in a wireless sensor network by preventing buffer overflow, by the real time monitoring of the queue length and the queue length variations in a particular sampling period. The network is found to achieve better *Fairness* and *Bandwidth*. The overall performance of this scheme is analyzed for a wireless sensor network scenario, with the channel varying property of the wireless channels being taken into account. It is validated that, it has a much superior performance with respect to *Bandwidth*, *Fairness*, *Delay* and *Packet Delivery Ratio*, compared to the existing protocols which use only the power conservation schemes. Finally it is validated with a traffic adapted sleep/listening MAC protocol TASL, in an error prone scenario and its superior performance is ascertained.

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NOMENCLATURE

ACK	Acknowledgement
AH-DPM	Adaptive Hybrid Dynamic Power Management
AODV	Ad hoc On Demand Distance Vector
ARP	Address Resolution Protocol
CA	Collision Avoidance
CBR	Constant Bit Rate
CBQ	Class Based Queuing
CD	Collision Detection
CDMA	Code Division Multiple Access
CSI	Channel State Information
CSMA	Carrier Sense Multiple Access
CTN	Current Transmitting Node
DMAC	Data Gathering MAC
DMD	Distributed Mediation Device
DMS	Dynamic Modulation Scaling
DPM	Dynamic Power Management
DRR	Deficit Round Robin
DSDV	Destination Sequenced Distance Vector
DSR	Dynamic Source Routing
DVS	Dynamic Voltage Scaling
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FTN	Future Transmitting Node
FQ	Fair Queuing
GAF	Geographic Adaptive Fidelity

GPS	Global Positioning System
LL	Link Layer
LMAC	Light weight MAC
MAC	Medium Access Control
MEMS	Micro-electro-mechanical systems
N	Node
NAV	Network Allocation Vector
NIST	National Institute of Science and Technology
NTN	No Transmitting Node
NTP	Network Time Protocol
OGDC	Optimal Geographical Density Control
OS	Operating System
PTM	Pipelined Tone Wakeup
QL	Queue length
QoS	Quality of Service
RED	Random Early Detection
RTS/CTS	Ready To Send / Clear To Send
SFQ	Stochastic Fair Queuing
SMAC	Sensor MAC
STEM	Sparse Topology and Energy Management
TA-DPM	Traffic-Aware DPM
TASL	Traffic Adapted Sleep/ Listening MAC Protocol
Tcl	Tool command language
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
TEEM	Traffic Aware Energy Efficient MAC
TL	Traffic load

UDP	User Datagram Protocol
W	Threshold
SYNC	Synchronising

Subscripts

i	Integer
j	Integer
m/ min	Minimum

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INTRODUCTION

Chapter 1

This chapter expresses the motivation for the research work. It gives an insight into the fundamental aspects of wireless sensor networks, the components and the existing network management architecture. The ranges of applications where sensor networks are widely deployed are highlighted. It also points to the different constraints of wireless sensor networks and emphasizes on the energy efficiency problem which is a matter of prime concern in all wireless sensor networks. The issues at the Medium Access Control layer and the Network layer are discussed. The need for a cross layer optimization approach is suggested for achieving efficient energy management in wireless sensor networks. Along with this, this chapter also presents an overview of the research work, detailed in the thesis.

Sensor networks are dense wireless networks of small, low-cost sensors, which collect and disseminate environmental data. One of the primary benefits of wireless sensor networks is their independence from the wiring costs and constraints. Wireless sensor networks are composed of a set of highly planned deployed sensors, which are very sensitive to the environment and capable of communication with each other through wireless channels. Sensor networks have many small devices equipped with sensors, processing circuits and wireless transceivers. Integration of tiny embedded processors, wireless interfaces and micro sensors based on Micro-Electro-Mechanical-Systems (MEMS) technology led to the emergence of wireless sensor networks. Wireless sensor networks are expected to find rapid deployment in the near future in a variety of applications like sensing information in remote locations, military purposes and so on. They are observed as an important technology development that will experience major deployment in the next few years for a plethora of applications, the main one being national security. They are characterized by their ability to monitor any remote physical environment and the low cost of the node.

1.1 WIRELESS SENSOR NETWORK COMPONENTS

There are four major components in a sensor network: an assembly of localized sensors, an interconnecting network (not always wireless based), a central point of information clustering and a set of computing resources at the central point to handle data correlation, event trending, status querying and data mining. Some of the computing may be done by the network itself. Algorithmic methods for data management play an important role in sensor networks due to the potentially large quantity of data collected. The computation and communication infrastructure associated with sensor networks is specific to the environment and rooted in the device itself.

The generic protocol stack of sensor networks consists of a five layered stack constituting the communication protocols and the management protocols. Layer 1 of the protocol stack forms the physical medium comprising of the communication channel, sensing, actuation and signal processing parts. Layer 2 forms the Link layer which is for channel sharing (Medium Access Control), timing and locality. Layer 3 forms the Network layer which includes adaptive topology management and topological routing. Layer 4 is the Transport layer which includes data dissemination and accumulation, caching and storage. Layer 5 is for in-network applications including application processing, data aggregation, external query processing and external database. The management protocols are for Task management, Mobility management and Power management.

1.2 APPLICATIONS

Wireless sensor networks facilitate the monitoring and controlling of physical environments from remote locations, with enhanced accuracy. They have applications in a variety of fields such as environmental monitoring, military purposes and gathering of sensing information in inhospitable locations. So typical applications include, but are not limited to, data collection, monitoring, surveillance and medical telemetry. They are dense networks for environment sensing and data collection. Sensors are equipped with both data processing and communication capabilities. They measure different parameters from the environment and transform them to electric signals. The prime advantage of sensors is their capability to operate unattended in harsh environments. Wireless sensor networks have a high utility in a variety of industrial, medical, consumer and military applications. They can be classified into three main classes based on the methods of acquiring and propagating sensor data. The first class comprises of processes requiring constant monitoring, where sensor data is acquired from a number of remote points and forwarded to a data collection center on a periodic basis. The second class is event driven, in which one or more crucial variables are to be monitored but transmitted only when a certain threshold is reached. The last case includes applications in which sensor data is captured and stored before transmitting to the base station.

1.3 CONSTRAINTS OF WIRELESS SENSOR NETWORKS

Various resource constraints and design constraints exist in a wireless sensor network.

1.3.1 Resource Constraints

The different resource constraints are as follows.

Power consumption - The constraint in power is due to the limited supply of operating energy.

Communication - The constraints in communication are due to the limited bandwidth of the wireless networks and the noisy channel which results in limited reliability.

Computation - The constraints in computation are due to the limited computation and limited memory resources.

Uncertainty in measured parameters - These constraints are due to node malfunction, collecting/ forwarding incorrect data, desired data getting mingled with noise and node placement.

1.3.2 Design Constraints

The various design constraints are given below.

- Wireless nodes are deployed in a dense manner resulting in communication complexity.
- Wireless nodes should support rapid deployment.
- Wireless nodes are prone to failure.
- Wireless nodes are limited in power, computational capacity and memory.
- Topology of the network changes frequently.
- Wireless nodes do not have global addresses.
- Wireless nodes require special routing and data dissemination mechanisms.
- Wireless nodes require in-network processing.

1.4 REQUIREMENTS OF WIRELESS SENSOR NETWORKS

The critical requirements of all the applications of wireless sensor networks are influenced by the need for a long battery life, small form factor that helps the devices to be embedded in their operating environment, low data rate, low cost and a centralized architecture which insists for the need for a central automation controller. Sensor nodes have various energy and computational constraints because of their inexpensive nature and ad hoc method of deployment.

Energy concerns of wireless sensor networks have inspired several energy efficient protocols, processors, designs and algorithms. Lifetime of sensor nodes depend greatly on the power consumption in each sensor node. Prevalent energy constraint in wireless sensor networks affects the whole network lifetime and leads to the depletion of the whole network. Energy consumption is the most important factor in determining the life of a sensor network because sensor nodes are usually driven by small battery sources and thus have very low energy resources. This makes energy optimization more complicated in sensor networks because it should involve not only the reduction of energy consumption but also the prolonging of the life of the network, as much as possible. Efficient energy management should be incorporated in all levels of system hierarchy. Depending on the application involved, energy dissipation is affected by all the system components. This insists on the need for energy awareness in every level of the system design and operation, so as to maintain the network connectivity and lifetime.

Efficient power management leads to longer lifetime; system lifetime can be much extended by applying energy efficient techniques to all the levels of system design. Much research has been done to have a significant increase in the energy efficiency by taking into consideration the aspects of hardware design, data processing, network protocols, and operating system. The major energy consumers in wireless sensor networks are the sensing unit, the computation unit, and the communication unit.

Energy consumption can be reduced based on the system computation aspects. This can be achieved by adaptively adjusting the supply voltage according to the clock frequency, using different keys of varying length at the Application layer, by the proper design of the operating system for sensors by letting the different components of the node enter various states (idle, sleep, active) and so on.

An approach to decrease the energy consumption is by changing the modulation level as in Dynamic Modulation Scaling (DMS). In Dynamic Modulation Scaling, the modulation level is adaptively changed according to the number of queued packets in the system. Dynamic Modulation Scaling is combined with packet fair queuing algorithm which results in an energy efficient packet scheduling protocol similar to NTP (Network Time Protocol). In distributed networks, time synchronization is needed to have real-time event management and event monitoring. Fluctuation in link quality with time should also be considered while considering the aspects to improve the energy efficiency, by an increase in transmission power or by adding error correction bits to the data.

Sensor node is battery operated and so is energy constrained, affecting the system lifetime. All the aspects like architecture, communication protocols, algorithms, circuits and sensing should be energy efficient. Continuous research is being done to exploit this area by introducing static approaches or by using run time dynamic techniques. The protocols and algorithms used should be tuned for an application. Embedded operating systems and software become a critical requirement of such networks.

A major consumer of energy is the communication circuit. So energy efficient communication strategies should be used. The main routing issues are discussed in section 1.8.

Fairness is a critical issue while accessing a shared wireless channel. Fair scheduling must then be employed in wireless sensor networks to provide proper flow of information. A number of fair scheduling schemes are used, in which some are centralized, and others are distributed.

1.5 MAC PROTOCOLS FOR WIRELESS SENSOR NETWORKS

MAC protocols can be classified from four perspectives such as contention-based, Time Division Multiple Access (TDMA) based, hybrid, and cross layer MAC. The following wide range of MAC protocols which are defined for sensor networks are cited below.

- Sensor-MAC (SMAC) (Ilker Demirkol *et al.*, 2006)

- Wise MAC (Ilker Demirkol *et al.*, 2006)
- SIFT (Ilker Demirkol *et al.*, 2006)
- Timeout-MAC (TMAC) / Dynamic Sensor-MAC (DSMAC) (Ilker Demirkol *et al.*, 2006)
- Traffic-Adaptive MAC Protocol (TRAMA) (Ilker Demirkol *et al.*, 2006)
- IEEE 802.11 **(**Rajesh Yadav *et al.*, 2009)
- Aloha with Preamble Sampling **(**Rajesh Yadav *et al.*, 2009)
- Berkeley Medium Access Control (B-MAC) **(**Rajesh Yadav *et al.*, 2009)
- PAMAS: Power Aware Multi-Access Signaling **(**Rajesh Yadav *et al.*, 2009)
- Optimized MAC **(**Rajesh Yadav *et al.*, 2009)
- Data Gathering MAC (DMAC) **(**Rajesh Yadav *et al.*, 2009)
- Self Organizing Medium Access Control for Sensor Networks (SMACS) **(**Rajesh Yadav *et al.*, 2009)
- Energy Aware TDMA Based MAC **(**Rajesh Yadav *et al.*, 2009)

1.6 MAC LAYER ISSUES IN WIRELESS SENSOR NETWORKS

The various design issues of the MAC protocols suitable for a sensor network environment are (Gowrishankar *et al.*, 2008) as follows.

1. A MAC protocol should avoid collisions from interfering nodes, over-emitting, overhearing, control packet overhead and idle listening

- When a receiver node receives more than one packet at the same time, called “collided packets”, these need to be sent again thereby increasing the energy consumption.
- When a destination node is not ready to receive messages then it is called an over-emitting node
- Overhearing occurs if a node picks up packets that were destined for some other node.
- Sending and receiving of less useful packets result in control overhead.
- Idle listening is an important factor as the nodes often listen to the channel for the possible reception of data which may not have been sent.

2. Scalability, Adaptability and Decentralization are three important criteria in designing a MAC protocol. The sensor network should adapt to the changes in the network size, node density and topology.
3. A MAC protocol should have minimum *Latency* and high *Throughput* when the sensor networks are deployed in critical delay sensitive applications.
4. Since the nodes are deployed randomly, nodes from a highly dense area may face high contention among themselves while reporting events, resulting in a high packet loss. So there should be uniformity in reporting the events, using a MAC protocol.

Although there are various MAC layer protocols proposed for sensor networks, none of them has been accepted as a standard. One of the reasons behind this is the fact that MAC protocols, in general, are application-dependent, which means that there cannot be one standard MAC protocol for sensor networks.

Another reason is the lack of standardization at the lower layers (physical layer) and the (physical) sensor hardware. Some of the issues in the existing MAC protocols are described below.

1. Time Division Multiple Access (TDMA) based protocols have clock drift problems and decreased *Throughput* at low traffic loads due to idle slots. Also it is not easy to change the slot assignment within a decentralized environment for traditional TDMA schemes, since all the nodes must agree on the slot assignments.

2. In Carrier Sense Multiple Access (CSMA) based protocols, additional collision avoidance or collision detection methods should be employed to handle the collision possibilities.

3. Frequency Division Multiple Access (FDMA) based protocols increase the cost of the sensor nodes due to the additional circuitry requirement to dynamically communicate with different radio channels.

4. In Code Division Multiple Access (CDMA) based protocols, high computational requirement is a major obstacle in attaining low energy consumption in sensor networks. Also, there has been limited effort to investigate the source and modulation schemes, the particular signature waveforms, the design of simple receiver models, and the other signal synchronization problems.

5. In SMAC protocol, the duration of a listen period is always fixed and therefore causes unnecessary energy wastage.

6. For solving this problem of static listen-sleep periods as in SMAC protocol, another protocol named TMAC has been proposed. The down-side of TMAC protocol's aggressive power conserving policy is that nodes can go

to sleep rather early, resulting in an increased *Latency* and a lower *Throughput*.

7. DMAC is another protocol that uses adaptive duty cycle. While DMAC outperforms SMAC in terms of *Latency*, *Throughput* and *Energy efficiency*, it remains to be seen if DMAC can support the communication paradigms.

1.7 PERFORMANCE REQUIREMENTS OF MAC PROTOCOLS

The performance requirements of MAC protocols are to minimize *Delay* and maximize *Throughput*, *Robustness, Scalability*, *Stability*, *Fairness* and *Energy efficiency*.

Delay:

Delay refers to the amount of time spent by a packet in the MAC layer before it is transmitted successfully. *Delay* depends not only on the network traffic but also on the design choices of the MAC protocol.

Throughput:

Throughput is defined as the rate at which messages are serviced by the communication system. In wireless environments, it represents the fraction of the channel capacity used for data transmission. The objective of the MAC protocol is to maximize the *Throughput* while minimizing the message *Delay*.

Robustness:

Robustness is a combination of reliability, availability and dependability requirements and it reflects the degree of the protocol insensitivity to errors. Achieving *robustness* in a time varying network like wireless sensor network, depends strongly on the failure models of the links and the communicating nodes.

Scalability:

Scalability refers to the ability of the communication system to meet its performance characteristics regardless of the size of the network and the number of competing nodes.

Stability:

Stability refers to the ability of a communication system to handle the fluctuations of the traffic load over sustained periods of time.

Fairness:

Fairness is achieved if the MAC protocol can allocate the channel capacity evenly among the competing nodes without reducing the network *Throughput*.

Energy efficiency:

Energy efficiency is the major issue in the design of MAC protocols for wireless sensor nodes.

1.8 ROUTING ISSUES IN WIRELESS SENSOR NETWORKS

The different routing issues existing in wireless sensor networks are the network scale and time varying constraints, resource constraints and sensor application data models.

Network scale and time varying constraints:

Routing through a wireless sensor network should adapt to the scalability of the network and the unpredictable time varying characteristics of the network.

Resource constraints:

Energy is a key concern in wireless sensor networks. Multi hop packet transmission, scalable routing algorithms and controlling the duty cycle of sensors can reduce the power consumption.

Sensor application data models:

Data model describes the flow of information from the source to the sink. The need to support different data models increases the complexity of the routing design problem.

Cross layer optimization is also an important technique to tackle the energy efficiency problem. Instead of dealing with a single layer, information from a layer can also be incorporated by another layer and thus this can be used to attain energy efficiency effectively.

1.9 MOTIVATION OF THE WORK

Wireless sensor networks have gained rapid worldwide attention in recent years, mainly with the proliferation in Micro-Electro-Mechanical Systems (MEMS) technology which has facilitated the development of small and low cost sensors. But the sensor node lifetime exhibits a strong dependence on its battery life. In most cases, sensor nodes are equipped with limited power sources and replenishment of power may be practically impossible since they are deployed in harsh environments. Power management and power conservation are critical functions for sensor networks and the need to design power aware protocols and algorithms is quite significant. No standard protocols and algorithms exist currently and an integration of many techniques, considered to tackle this problem, is highly essential. It was also found from previous literatures that factors like *Delay*, *Throughput*, *Stability* and *Delivery ratio* affect the performance of a wireless sensor network apart from *Energy efficiency*. Hence any new scheme needs to be evaluated based on these factors.

Sensors consume a large portion of energy and so it is necessary to reduce the energy consumption of sensors. Medium Access Control protocols in wireless sensor networks should not only provide access to the medium but also provide the means to reduce the energy consumption at a node. Dynamic Power Management (DPM) has been found the best option to reduce energy consumption, from previous research. Research has also led to the evolution of various DPM techniques. However in DPM techniques, the nodes in the routing path which are not currently involved in routing remain active leading to energy wastage. This aspect needs to be considered.

In wireless sensor networks, overhead is measured in terms of Bandwidth utilization, power consumption and requirement of nodes. Finding a strategy to balance these needs forms the basis of the routing challenges. Routing protocol overhead increases with an increase in the network size. Design of routing protocols for wireless sensor networks should consider the power and resource limitations of the wireless sensor nodes, the time varying qualities of the wireless channels and the possibility of packet loss and delay. It is also seen in previous literature that, radio communication function is an energy intensive function compared to the energy consumed for sensing or computation. This emphasizes the need to design a communication scheme that conserves energy. One method is to switch OFF the radio transceiver for a period of time which can be effectively accomplished by Dynamic Power Management. The next method is to reduce the distance from the sensing node to the sink which can be well achieved by using multi hop routing.

Previous literature has suggested the need for a cross layer interaction among the layers in a wireless sensor network so as to optimize the overall performance of the network. In this work, a cross layer interaction is made between the MAC layer, the Physical layer and the Network layer. Thus the link layer metrics from the Link layer and channel state information from the Physical layer could be conveyed to the Network layer so as to enable intelligent routing decisions to be made, which in turn can lead to an increase in *Energy efficiency*.

Fairness is also an important attribute to be achieved in a wireless sensor network and it should be guaranteed for all the competing nodes. So while deferring transmission through a poor quality link in an attempt to optimize energy efficiency, the traffic load should also be considered. Sincere efforts need to be made to achieve *Fairness* without compromising *Energy efficiency* and this aspect has not been dealt with adequately in the past. This sparked the development of a new algorithm, referred in this work as AEMAC, which is an energy efficient channel adaptive MAC scheme. It integrates different aspects ie. not only incorporates the cross layer interaction of the channel adaptive MAC layer and Network layer thus making it a Channel Adaptive DPM scheme but also makes it aware of the network traffic load. Thus both *Energy efficiency* and *Fairness* in a wireless sensor network are aimed at, in this work.

1.10 OVERVIEW OF RESEARCH

In this work, *Energy efficiency* is the main factor that is dealt with, along with improving other factors like *Throughput, Delay, Delivery ratio, Fairness* and so on, in the design of a MAC protocol. Energy management problem is the most crucial problem in wireless sensor networks and different techniques have been cited in literature to tackle this problem. This is detailed in chapter 2. The low battery life of a sensor node deployed often in unattended environment adds to the severity of the problem. The lifetime of a sensor network is influenced by the battery resources of each node. The need to have highly efficient power management so as to increase the lifetime of the sensor network is prominent.

Dynamic Power Management is found to be highly recommendable as this involves selectively shutting down the hardware components when not needed. Thus unnecessary energy wastage involved in all nodes, by being active when not needed, is avoided. Dynamic Power Management techniques which involve the reduction in the duty cycle are highly recommendable but should be implemented carefully to provide proper power reduction, during the selection of active nodes. In AEMAC, a traffic aware Dynamic Power Management scheme has been proposed to reduce the power consumption and thus to increase the *Energy efficiency*. This is performed by turning OFF the interface of the unnecessary nodes (nodes not currently involved in routing) that are not included in the routing path. Besides this, only the nodes that are currently involved in transmission are awakened.

Moreover the routing path is decided considering the link and channel quality effects. This is with the intention to provide the actual energy saving in a wireless scenario. Previous research has observed that, by neglecting the effects of varying channel quality, which is very likely to occur in a wireless network, can lead to loss of battery resources. This is due to the fact that unnecessary transmissions from a node transmitting through a bad quality link can lead to energy loss. So in this protocol, the link and channel quality effects are also considered while deciding a good routing path. During situations of bad link and channel quality, transmission through that link is deferred until the quality rises above a threshold.

Fairness could not be achieved in this technique since Fairness could not be provided to the nodes attempting to access the network through a poor quality link. To achieve *Fairness*, a Load Prediction Algorithm with an Adaptive Threshold Adjustment Scheme is proposed in the latter part. Here the minimum quality threshold is adaptively adjusted based on the current incoming traffic load. If the traffic load is found to be increasing, the threshold will be reduced so as to attain *Fairness*. Thus a balance between *Fairness* and *Energy efficiency* could be achieved.

1.11 LAYOUT OF THESIS

The thesis is organized as follows.

Chapter 1 deals with the introduction which provides an exposition of the fundamental aspects of wireless sensor networks, the main components, applications, the prime requirements along with presenting the constraints involved and the issues to be dealt with, which brings forth the motivation for this research. It further emphasizes on the energy efficiency problem in wireless sensor networks and the need to have a cross layer optimization approach to deal with this problem.

Chapter 2 provides the literature survey which briefly surveys about wireless sensor networks, research conducted to achieve power management in sensor networks emphasizing the work done on Dynamic Power Management which is a promising technique in this field.

Chapter 3 gives the details of the Network Simulator NS2 which is used for the validation of the newly designed protocol and also for its comparison with some existing protocols. A real network scenario is depicted using this simulation. Comparison is based on the performance metrics like *Throughput*, *Delay*, *Energy efficiency*, *Fairness* and so on; since it is given in literature that these metrics are most suitable for evaluating the MAC protocols for wireless sensor networks.

Chapter 4 discusses the Channel Adaptive MAC protocol and the Traffic Aware Dynamic Power Management Scheme which was adopted for achieving *Energy efficiency*.

Chapter 5 illustrates the Load Prediction algorithm and the Adaptive Threshold Management Scheme to achieve *Fairness*.

Chapter 6 discusses the validation of the algorithm through simulation results and analysis to prove the superiority of this algorithm with the existing ones.

Chapter 7 depicts the conclusions of this work and gives an insight into the future work that can be conducted.

1.12 SUMMARY

A brief introduction of wireless sensor networks, illustrating the different fundamental aspects and components of wireless sensor networks, the architecture and the various applications of wireless sensor networks was provided. The crucial energy problem which is a cause of concern in the field of wireless sensor networks was also discussed. MAC layer and Routing layer issues in wireless sensor networks were also cited. The need for cross layer optimization approach was suggested. The motivation for the research work along with elaborating the main goal of the research and the layout of the thesis was presented.

2

LITERATURE SURVEY

Chapter 2

This chapter provides an idea, from previous literature about the energy management problem in the field of wireless sensor networks, which needs to be tackled critically. Various topics which can improve the E*nergy efficiency* are discussed. Among this, Power Management is seen as an important technique to handle the energy problem in wireless sensor networks; which if not handled can lead to the depletion of the whole network. Among the various power management techniques, Dynamic Power Management (DPM) is suggested to be superior over the static power management schemes. Various DPM schemes are discussed in this chapter. Duty cycle approach for energy conservation is suggested to be better. In this chapter, Topology control protocols and Power management protocols are discussed. MAC protocols for wireless sensor networks must guarantee efficient access to the communication media while carefully managing the energy allotted to the node. MAC protocols with low duty cycle which enable the handling of energy issues in wireless sensor networks are discussed. The scope of the research work is presented. The need to have a cross layer interaction and also the need to consider the varying channel conditions while handling the energy problem in wireless sensor networks are emphasized.

A sensor network is an infrastructure comprising of sensing, computing and communication elements that gives an administrator the ability to instrument, observe and react to events in a specified environment. The tiny sensor nodes work collaboratively to sense a given environment, perform in-network computation and communicate with a base station when a targeted event occurs. Wireless sensor networks are expected to revolutionize how information is collected and processed from the environment where the networks are embedded. They are characterized by their ability to monitor any remote physical environment, their small sizes and the low cost.

Sensor node is battery operated and so is energy constrained affecting the lifetime of the whole network. Their inexpensive nature and ad hoc method of deployment provides many serious energy and computational constraints (Archana and Vijay Anand, 2004). All the aspects like architecture, communication protocols, algorithms, circuits and sensing should be energy efficient. Continuous research is being done to exploit this area in detail. Several techniques can be applied at design time to reduce the power consumption (static approaches).

Lifetime of sensor nodes depend greatly on the power consumption in each sensor node. Energy constraint in wireless sensor networks affects the whole network lifetime and connectivity. 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 involves not only the reduction in energy consumption but also the prolonging of the life of the network, as much as possible. Efficient energy management should be incorporated in all levels of system hierarchy from hardware to software architecture and from operating system to the communication protocols. All system components critically affect the energy dissipation depending on the application involved (Xiao-Hui Lin and Yu-Kwong Kwok, 2006). So energy awareness must be involved in every level of the system design and operation, to maintain the network connectivity and lifetime (Eugene *et al.*, 2001, Carle and Ryl, 2004, Hong *et al.*, 2001, Raghunathan *et al.*, 2002 and Ye *et al.*, 2002).

Sensor nodes exist in an unattended environment. So highly efficient power management is essential to improve the lifetime (Chuan *et al.*, 2006). System lifetime can be very much extended by applying energy efficient techniques to all levels of system hierarchy (Eugene *et al.*, 2001). Much research has been done to have a significant decrease in energy consumption in various aspects of hardware design, data processing, network protocols, and operating system.

Based on the system computation aspects, the research efforts prove the following results. Supply voltage can be actively and adaptively adjusted, in Dynamic Voltage Scaling (DVS), in conjunction with the clock frequency, in response to the CPU utilization (Sinha and Chandrakasan, 2001). Different keys of varying length can be used at the application layer, by allowing a tradeoff between the expended computation energy and security (Yuang and Qu, 2002). By the proper design of the operating system for sensors, the different components of the node can be made to enter various states (idle, sleep, active), to save energy according to the environmental variations, at the expense of some degree of system performance degradation (Schurgers *et al.*, 2002).

The major energy consumers in wireless sensor networks are the sensing unit, the computation unit and the communication unit. Dynamic Modulation Scaling (DMS), similar to DVS, is proposed by Sinha and Chandrakasan (2001) and Schurgers *et al.*, (2001). According to the number of queued packets in the system, DMS can adaptively change the modulation level, to lower the overall energy consumption, while bounding packet delay at an acceptable level. DMS is combined with packet fair queuing algorithm and this result in an energy efficient packet scheduling protocol similar to NTP (Network Time Protocol). It first organizes the wireless sensor networks to form a hierarchical structure. Along every edge of this tree like structure network, synchronizing algorithm based on a two way message exchange is performed by taking the root node as the reference node. This leads to a simple implementation. Every node must synchronize with the parent node, by pair wise message transmission similar to NTP. Lot of traffic overhead will be incurred (Quing *et al.,* 2005).

The resource availability constraints of the wireless sensor networks impose specific requirements on the protocol design for time synchronization, which is essential for the self configuration feature of the wireless sensor networks. To realize real-time event management and event monitoring in distributed networks, time synchronization is highly essential.

Reliability of data transmission should be reinforced, considering the fluctuation in link quality with respect to time. This can be achieved by increasing the transmission power level or by adding FEC (Forward Error Correction) to the raw data. The first method leads to the rapid depletion of sensor energy and produce interference to wireless transmission at the terminals (Xiao-Hui Lin and Yu-Kwong Kwok, 2006). Using the second method, as the channel quality changes with time, the amount of error protection incorporated should also vary with the instantaneous channel condition, to make sure that Bit Error Rate (BER) rises above the required level. So a more amount of error protection redundancy in the transmitted packet occurs for poorer wireless links and vice versa (Kwok and Lau, 2002). This is due to the reason that more error protection bits are needed in a poor wireless link, in order to provide a reliable transmission.

The following aspects should be considered, while discussing the extra energy dissipation incurred to combat the extra energy consumption.

1. Considering the computation point of view, due to the packet redundancy more energy is expended for encoding and decoding data at the two communication sides. This decreases the battery life.
2. Length of every frame increases on including error protection. So an extra energy is needed for message communication. For the same transmission rate, all the radio circuits have to be ON for a longer duration. More energy is consumed. This makes the design of energy resource management schemes very much challenging (Cianca *et al.,* 2002).

To have scalability and *Energy efficiency* in a sensor network, cluster based hierarchy is preferred as the ideal solution (Zhou *et al.,* 2004) and (Zhao and Govindan, 2003). Data collected by the sensors in close proximity is highly correlated. Communication between each sensor and end user is both energy as well as bandwidth consuming. So the data should be processed locally to get rid of data redundancy. The whole network is divided into different clusters. One sensor node is elected as the cluster head to perform local information filtering, aggregation and data fusion for all the sensors in its cluster. Traffic is routed among cluster heads. Thus the network management gets simplified and also decreases the energy needed for communicating useful data to the end user. Different methods for organization of cluster based networks are discussed by Banbyopadhyay and Coyle (2003), Hac (2003), Shen *et al*., (2000) and Akyildig *et al*., (2002).

2.1 TOPICS DISCUSSED REGARDING *ENERGY EFFICIENCY*

The main issue to be dealt with, in the design of wireless sensor networks is to reduce the energy consumption, so as to prolong the life of the network.

Research efforts in the past which resulted in bringing forth many techniques to tackle this problem, based on various aspects, are discussed below.

2.1.1 Clustering concept

Clustering can localize the route set up inside clusters and reduce the size of the routing table maintained inside a cluster. It can conserve the communication bandwidth, can stabilize the network topology, and can implement the optimized management strategies to enhance the network operation so as to prolong the network lifetime of the sensors (Younis *et al.*, 2003). Cluster heads can effectively schedule the activities in the cluster so that its nodes can switch to low power sleep modes most of the time to reduce energy consumption. Similar packets from multiple nodes may be aggregated. So the number of transmissions gets reduced. Data aggregation combines the data from different sources by using various functions like suppression (for eliminating duplicates), minimum, maximum and average (Krishnamachari *et al.*, 2002). Computation is energy efficient compared to communication. So aggregation can produce good energy savings.

In the self organizing systems, sensor nodes are scattered randomly (Sohrabi *et al.*, 2000, Heinzelman *et al.*, 2002, Younis *et al.*, 2004 and Doina, 2009). In terms of *Energy efficiency* and performance, the cluster head positioning is very crucial. Optimal clustering always leads to an energy efficient network operation. Cluster heads are picked from the deployed sensors in the network of homogeneous sensor nodes (Heinzelman *et al.*, 2002, Lindsey and Raghavendra, 2002). Cluster heads are carefully tasked to avoid the energy from being depleted away unnecessarily. Communication range and proximity to the base station are some important issues to be considered. If the sensor communication ranges do not reach the base station, multi hop routes have to be used. Inter cluster head connectivity is an important factor affecting the clustering schemes (Banerjee and Khuller, 2001 and Banbyopadhyay and Coyle, 2003).

Objective of clustering

(a) Load balancing

Sensors should be evenly distributed among the clusters, where the cluster head performs data processing and intra cluster management duties (Gupta and Younis, 2003). Load balancing is a critical issue in wireless sensor networks where the cluster heads are picked from the currently available sensors (Younis and Fahmy, 2004). For extending the network lifetime, equal sized clusters are important. This prevents the exhaustion of energy of a subset of cluster heads at a high rate and prevents their premature failure.

(b) Fault tolerance

This is to avoid the loss of important data. To recover from cluster head failure re-clustering of the network is needed. But during this process, resource burden occurs on the nodes. Backup cluster heads are also assigned to recover from failure. Neighboring cluster heads can adapt sensors in the failing clusters, if the nodes have sufficient radio range (Gupta and Younis, 2003). Rotating the role of cluster heads among all the nodes in the cluster can be a means of attaining fault tolerance (Heinzelman *et al.*, 2002).

(c) Increased connectivity and reduced delay

In large networks, to decrease the energy needed for communication, inter cluster head connectivity is needed. This becomes a critical requirement unless the cluster heads have long haul communication capability.

(d) Maximum network life

Network lifetime is of major concern especially in bad environments. If cluster heads are richer in resources, the energy for intra cluster communication can be minimized (Younis *et al.,* 2003). Otherwise cluster heads should be placed very close to their sensors (Ilker *et al.,* 2004 and Hou *et al.,* 2005). If cluster heads are regular sensors, lifetime can be increased only by limiting their load. Combined clustering and route setup can be together considered for maximizing the network lifetime (Dasgupta *et al.,* 2003). Adaptive clustering can be used to increase the network life (Khanna *et al.,* 2006 and Moscibroda and Wattenhofer, 2005). Low Energy Adaptive Clustering Hierarchy (LEACH) is proposed by Heinzelman *et al.,* (2002). It forms clusters based on the received signal strength and uses cluster head nodes as the routers to the base station. All data processing is done local to the cluster. Distributed algorithm is used by nodes to make autonomous decisions without using a centralized control. Initially a node decides to be the cluster head and it broadcasts its decision to others. Each non cluster head node now determines its suitable cluster, by choosing the cluster head that can be reached using the least communication energy. Role of being the cluster head can be rotated periodically among the nodes of the cluster, in order to balance the load. Rotation is performed by making each node to choose a random number between 0 and 1. A node becomes the cluster head for the current rotation if this number is less than a Threshold value. The cluster heads are assumed to have sufficient communication range so as to reach the base station directly. Different clustering strategies and clustering algorithms have been discussed by Ameer and Mohamed (2007). The different clustering schemes are classified according to their objectives, the desired cluster properties and the clustering process.

2.1.2 Security aspects in wireless sensor networks

Durability of Distributed sensor networks depends on the *Energy efficiency*. The two important issues for Distributed sensor networks are security for communication and E*nergy efficiency*. Security aspects can be achieved by encryption/decryption processes. Power control mechanisms for sensors to operate at a particular energy and efficient multiple voltage processors are proposed by Eugene *et al.,* (2001). Inserting additional information to the communication channel to guide the selection of proper voltage for encryption/decryption and processing so as to decrease the overall power consumption is also discussed. Several encryption standards on a wide range of processors are experimented and sensor networks are simulated to prove that the lifetime gets extended. Newly developed DVS technique is also proposed here in the design of energy efficient distributed sensor networks. This technique varies the supply voltage and clock frequency based on the computational load to provide the desired performance with minimum energy consumption. A practical DVS system is considered which is capable of switching among different voltage levels. Additional information about the message is incorporated in its message header at the beginning of the message from the message sender sensor. Message header has all information about the different parameters like the message length, type, the expected processing time and so on. This information is utilized by the receiving sensors in the selection of proper voltages for decryption/encryption and processing so as to reduce the energy consumption. The encrypted data received from the other nodes is received by the reception electronics and is passed to the microprocessor. This does data decryption and verification before processing the data. If data is to be sent to the other nodes, it encrypts and then sends; otherwise it halts. Some factors to be noted are that the energy consumption for encryption/decryption is not the same for all public key algorithms. Moreover the computation requirement of the message may not be proportional to the message length. So the message information is stored in the header. A proper selection of the supply voltage can be done to decrease the power consumption. A 60% energy saving has been proved despite the additional overhead of embedding extra information into the header.

2.1.3 Adaptation of Link layer and Physical layer parameters

Energy efficient techniques that adapt the underlying communication parameters ar e presented in the context of wireless sensor networks by Eugene *et al.,* (2001). Adapting the Link layer and the Physical layer parameters like the output transmit power and error control is examined. Due to the remote nature of the sensor networks and the size of each node, nodes may not have access to unlimited energy. So energy efficient algorithms and protocols should be used to prolong the network lifetime. But they should be aware of the user specified quality requirements and data precision. Since these factors depend only on the application, quality should not be compromised while minimizing energy consumption.

Reliable data transfer can be obtained by increasing the output power or by adding Forward Error Correction bits (FEC) to the data. Extra processing is required. Energy cost in the communication phase occurs during the transmission of data as well as when framing and error correction is done. The wireless sensor node used could properly scale the energy consumption of different sub components in response to the changes in the environment, the state of the network and the application requirements to maximize the system lifetime and decrease the energy consumption at each node. Thus all the layers of the system can adapt the layer specific parameters. Data collected by a sensor is processed by Strong ARM microprocessor which has low power consumption and high performance. It could be adapted to support Dynamic Voltage Scaling (DVS). Data is transmitted wirelessly, using a radio based on a single chip 2.4 GHz transceiver with an integrated frequency synthesizer, to deliver data to the neighboring nodes. In radio model, power amplifier is ON only during communication. During start up time, no data can be sent/ received by the transceiver. This is because its internal Phase Locked Loop must be locked to the carrier frequency before the data can be demodulated successfully. In this transceiver, power will not vary with the data rate. Start up time has a large impact on average energy/ bit because sensors communicate using short data packets. So transceivers require large initial start up time. When packet size is reduced, energy consumption is dominated by the starting transient and not the active transient. This should be considered while designing energy efficient protocols. Purposes of Link layer discussed here are to specify encoding and the length limit of the packet and for achieving a reliable transmission. Reliability level for a link depends on the application and the user specified constraints.

2.1.4 Time synchronization aspect

Time synchronization plays a key role to meet the real time requirements and to improve the multiplexing efficiency. Performance limitation of time synchronization for wireless sensor networks in terms of synchronization accuracy is discussed by Quing *et al.*, (2005). The sources of synchronization accuracy are identified and the mathematical models to analyze the time synchronization schemes are proposed here. The light weight protocols proposed are capable of suppressing the communication overheads and approaching the performance limit. This is based on the idea that there always exists a synchronization error correlation between nodes receiving the same sequence of time synchronized packets. Theoretical analysis is validated by the simulation results.

Time synchronization is essential in distributed networks to realize real time event management and event monitoring. Redundant information in the events reported at the same time from multiple sensors can be removed to save energy using synchronization clocks. Synchronization clocks can be used to activate the sleeping sensor nodes at the scheduled time and make use of Time Division Multiple Access (TDMA) schemes to improve the overall throughput of wireless sensor networks. In standalone computer applications, precise clock board/ radio clock that receives time reference transmitted from radio stations administered by National Institute of Standards and Technology (NIST) can be used to improve the accuracy of computer time. Global Positioning System (GPS) can be used to synchronize hardware clocks with satellites. Both the above methods are costly. For networked computers, Network Time Protocol (NTP) is used to synchronize computer clocks in a hierarchical way. But its heavy weight implementation cannot be supported by the sensor nodes.

Post factor is a simple method discussed by Elson and Estrin (2001) to synchronize clocks in a local neighborhood of sensor nodes. Nodes are initially unsynchronized. When a stimulus arrives, each node records the receiving time using its local clock. Immediately afterwards, a beacon covering the whole area, broadcasts a synchronizing signal to all the nodes in the neighborhood. With respect to the time reference, receiving nodes correct their stimulus timestamps. Communication range of the beacon is the crucial limit in this algorithm.

RBM derived from Post factor, is proposed by Elson *et al.,* (2002). It keeps the time of the neighboring nodes synchronized. One node periodically broadcasts reference beacons without explicit time stamps, to its neighbors. Receivers use beacon arrival time as reference, to compare their local clocks by exchanging the beacon receiving time. Thus all the nodes know about the clock offset among each other. Large energy is consumed due to the large number of packet transmissions.

Tiny sync and Mini sync (Sichitiu and Veerarittiphan, 2003) are proposed to keep global time in wireless sensor networks by synchronizing any two nodes in the whole network. A pair of nodes use bidirectional time stamped packet transmissions to estimate the clock offset between them thus making two nodes synchronous. To get synchronized, every pair of nodes should perform two way message exchanges. So a large communication overhead is incurred due to the large traffic.

Another time synchronizing protocol to maintain global time is the Time Sync Protocol for Sensor Networks (TPSN) proposed by Ganeriwal *et al.,* (2003). An idea similar to TPSN is suggested by Quing *et al.,* (2005), but the communication overhead is reduced considerably because it requires only some specific adjuster nodes to do the two way message exchange. Here the time synchronizing algorithm requires the client to follow the server. A sequence of reference packets with timestamps are sent by a node to the receiver. The four delays encountered in the message transmission path are process delay, access delay, propagation delay and receive delay. These delays affect the accuracy of the system algorithm. In the LESSAR algorithm, proposed by Quing *et al.,* (2005), a global time is maintained in wireless sensor networks by organizing the whole network system into levels. Level discovery is performed initially when the network is deployed. Sink which collects information from all nodes forms the root and is assigned level 0. It broadcasts level discovery packet to its neighbors. Nodes receiving the packets are assigned level 1 and broadcast the level discovery packet to the other nodes. One node may as a result, receive many packets but it accepts only the one with the lowest level as its ancestor and takes its value +1 as its own level. Thus broadcasting continues. All the sensor nodes are connected in this hierarchical network topology. When a new node enters, it broadcasts the level request packet to enquire the current level values of its neighbors. From the responses obtained, it selects the smallest one + 1 as its level. On node failure, its children notice this, when its timer of observing keep alive message expires. These nodes broadcast level request packet and redo the level discovery process again. In LESSAR, nodes are synchronized level by level. Each node believes that the clocks in its upper level are accurate than its local clock and synchronize with them. It only accepts time sync packets from the upper level and drops all others from the lower levels. So the whole wireless sensor network follows the clock of the sink. This will be synchronized by GPS/NTP. This method has very low resource consumption and computation complexity.

2.1.5 Power management schemes

To deal with the energy management problem, different power management schemes are discussed here. The most important constraint in all wireless sensor networks is the *Energy efficiency* problem since they are equipped with limited power sources. So an efficient power management should be adopted. Research is conducted using static approaches to attain power management by making the nodes which are not currently being utilized to go to low power states but this should be decided earlier, in a fixed time schedule and not at run time.

Dynamic Power Management (DPM) is widely used in wireless sensor networks. During run time, dynamic techniques can further improve the reduction in power consumption by selectively shutting down the hardware components. After designing a system, additional power savings can be obtained by Dynamic Power Management. Protocols and algorithms have to be tuned for an application.

Embedded operating systems and software become a critical requirement of such networks.

Different DPM schemes have been proposed to decrease the power consumption in sensor nodes and battery powered embedded systems (Chuan Lin *et al.,* 2006, Sinha and Chandrakasan, 2001, Chung *et al.,* 1999, A.Z. *et al.,* 2003, IBM and Monta Vista Software, 2002). Sensor node is shut down if no events occur (Benini and Micheli, 1997). Major consumer of energy in a wireless sensor network is the energy communication circuits. So communication should be performed only when needed. DPM should always consider when a node should go to sleep/idle state and how long it should remain there. Sensor nodes communicate using short data packets which have more dominance of startup energy (Akyildig *et al.,* 2002). External events represent the interaction between the sensor node and the environment (Rodrigo *et al.,* 2005). So it must also be considered while reducing the power consumption. Application constraints in different DPM models are described by Chung *et al.* (1999) and A. Z. *et al.,* (2003).

So DPM involves shutting down the sensor node during no event and waking them up when needed. So good energy saving is achieved. But sensors communicate using short data packets. So there is more dominance of startup energy. Therefore DPM should be carefully implemented. Operation in energy saving mode becomes energy efficient only if the time spent in that mode is greater than a decided Threshold. The common DPM policies are the Predictive policy and the Stochastic policy.

Predictive policy:

Predictive policy involves turning OFF the system components if the idle time is greater than or equal to the Timeout Threshold. The assumption is that it may remain idle for a long time. Idle time is predicted by Raghunathan *et al.,*

(2004) using the exponential average method. Operating system based direct management techniques are proposed by Sinha and Chandrakasan (2001).

Stochastic policy:

Stochastic policy is given by Benini *et al., (*1999). System is provided with a service provider, a service requester (both represented by Markov processes), a power manager and a request queue. The power manager represents the device state of operation by issuing proper commands to the service provider.

Energy efficient DPM is proposed by Chuan *et al.,* (2006). It uses a modified sleep state policy combined with Optimal Geographical Density Control (OGDC) (Zhang and Hou, 2004), so as to keep a minimum number of sensor nodes in the active mode. So the network lifetime is prolonged. Power aware sensor model is proposed which describes the power consumption in different levels of node sleep states. There can be many sleep states for a node with many components. Every node has a latency to transition to that state. Every sleep state is characterized by power consumption and *latency* overhead. If a node is in a deeper sleep state, lesser power is consumed and more latency is needed to awaken it. DPM should consider the energy consumption needed for awakening the node back to the active state and how long it remains idle. Saved energy should always be greater than the expended transition energy. Simulation results show that DPM combined with OGDC prolong the network lifetime than with only DPM. The energy and extra time needed to awaken the node are not considered by Sinha and Chandrakasan (2004). In deep sleep state, the sensor cannot detect any event or receive message from the remaining nodes. In clustering protocol, the cluster head should never enter the sleep state. The possible ways to avoid event missing are not considered by Chuan *et al.,* (2006). Another problem with OGDC is that each node should have its positional information.

To realize the actual energy saving in a wireless scenario, the time varying property of the wireless channel is taken into account by Xiao-Hui and Yu-Kwong (2006). This had been neglected in most existing energy saving schemes. Neglecting the effects of varying channel quality, leads to the loss of precious battery resources which in turn leads to the depletion of sensor energy. In effect, at a later instant of time many nodes become dysfunctional which ultimately leads to the partitioning of the network. A Channel Adaptive energy management protocol is proposed here to consider the time varying property of the wireless link. Each node can intelligently access the wireless medium according to the current link quality and the predicted traffic load to produce efficient utilization of energy. Results indicate a 40% increase in energy savings compared to the other protocols without channel adaptation. Quality of a wireless link is a time varying function. So the management of energy resources is crucial to prolong the network lifetime. Energy aware packet scheduling schemes for sensor networks are proposed in a channel fluctuating environment. During the situations of poor channel quality, the packets get buffered until the channel quality recovers to the required Threshold. A network system is proposed in which each sensor can decide the state of the communication equipment (idle/active/sleep) with respect to the current channel condition. A fair scheduling and queuing algorithm is designed, in order to avoid the communication *Latency* and buffer overflow. Thus an optimum balance between the *Energy efficiency* and *Fairness* is attained. CAEM (Channel Adaptive approach to Energy Management) is a cluster based hierarchy in which the nodes are assumed to be static or of low mobility. Adaptive Physical layer design ABICM, proposed by Y. K. Kwok *et al.,* (2002), was adopted in which variable throughput modulator and channel coding are used. When Channel State Information (CSI) is available at the transmitter, it does burst by burst throughput adaptation with respect to the CSI (Cianca *et al.,* 2002), i.e., when CSI indicates a very good quality channel, the transmitter performs high order modulation and appropriate error protection to protect the packet transmission. In CAEM, real time monitoring of the change in the CSI of the wireless link is done for all the sensor nodes. Simplicity of the traffic mode (from sensor to sink) leads to the simplification of the design for MAC layer management. Here sensor nodes are equipped with two radios: a tone radio and a data radio, working at different frequencies. If no data is to be transmitted, both radios are turned OFF. If a sensor has packets to send, it turns ON the tone radio and senses the channel whether it is free or not. If sensed negative, (i.e. receives other than idle tones from the channel head) it keeps monitoring the tone channel. If it senses the data channel to be free, (i.e. receives idle tone pulses), it measures the received tone signal strength and further checks whether it is above the required SNR measurement. If not, it continues monitoring the tone channel; otherwise it backs off for a random period of time. After back off time, the sensor checks whether the channel is free and whether the quality requirement is satisfied. If both are found positive, the sensor turns ON the data radio and transmits the buffered packets. If either of the two cases is not found positive, the sensor returns to the sensing state and again monitors the channel. During collision, the channel head sends collision tone pulses and notifies all the sensor nodes. During data packet transmission, the sensor node should keep its tone radio ON and on receiving collision tone pulses; it stops packet transmission by turning OFF the data radio and returns to the sensing state. In CAEM, CSMA/CD is used to detect collision thus reducing the energy wasted in packet collisions. Simulations prove that the behavior of the wireless channel can influence the energy consumption.

Life of a sensor network is highly influenced by the power consumption at each sensor node. Longer network lifetime results when efficient power management techniques are adopted. Different methods are discussed to design an energy efficient communication process at the hardware and system levels (Perillo and Heinzelman, 2003) and sensor node operating system (Hill *et al.*, 2000). Dynamic Voltage Scaling (DVS) is proposed by Sinha and Chandrakasan (2001) and Calhoun and Chandrakasan (2004). Dynamic Voltage and Frequency scaling is suggested in IBM and Monta Vista Software (2002). Sleep state and Active power management has been dealt by Sinha and Chandrakasan (2001) and Brock and Rajamani (2003). Sentry based power management is proposed by Hui *et al.*, (2003). DPM shuts down components when not used and wakes them up when necessary (Lu *et al.*, 2000).

Sensing coverage is a very important issue in wireless sensor networks. Several centralized and distributed algorithms are proposed for coverage sensing by Ye *et al.*, (2002), Li *et al.*, (2003), Slijepcevic and Potkonjak (2001) and Tian and Georgana (2002). The problem of finding a maximal number of covers in a sensor network is addressed by Slijepcevic and Potkonjak (2001). Different communication models exist in a sensor network. They are direct transmission to base station, multi hop and clustering. In direct transmission, the sensed packets should be transmitted from the sensed node to the base station in a single hop. This single hop transmission is costly and if nodes are far away from the sink, a large amount of transmission energy is required, leading to enhanced energy consumption. In multi hop transmission, transmission occurs over a short communication radius, leading to an energy saving. Data aggregation will lead to enhanced energy saving. Clustering is considered more energy efficient than the other transmission schemes. Communication energy is expensive compared to computation energy. In clustering, the cluster head aggregates and transmits the data to the base station.

2.2 DYNAMIC POWER MANAGEMENT SCHEMES

Dynamic Power Management is widely used in wireless sensor networks to deal with the *Energy efficiency* problem. DPM schemes are classified as follows.

2.2.1 Based on Topology management aspect

Radio is the main energy consumer in a sensor node (Raghunathan *et al.*, 2002, Sohrabi *et al.*, 2000 and Estrin and Govindan, 1999). To reduce the energy, the best way is to turn the radio OFF (Raghunathan *et al.*, 2002). Topology management schemes coordinate which nodes turn the radio OFF and when, so as to maintain traffic forwarding satisfactorily and with minimum energy consumption. When an event occurs, the data should be forwarded to the sink. So the network now transitions to the active transfer state. Separate paging channel is proposed to do this wakeup (Guo *et al.*, 2001). This assumes the listen mode of the paging radio to be of ultra low power. An algorithm that uses low duty cycle radio is proposed by McGlynn and Borbesh (2001). Channel access and node wakeup are integrated together in SMAC (Ye *et al.*, 2002).

A new topology management scheme STEM is proposed by Curt *et al.*, (2002). Energy consumption in the monitoring state is reduced to a bare minimum along with ensuring a sufficient latency for transitioning to the transfer state. STEM offers trading of *energy* for *Latency*. It is found to be more energy efficient than SMAC while assuming a timely transitioning to the transfer state. In the monitoring state, when there is no traffic to forward, only node’s sensors and some preprocessing circuits are ON. This is sleep state. When a possible event is detected, it goes to ON state. On receiving a wakeup message, it turns ON the primary radio which deals with regular data transmission. Multi hop routing is adopted. In the monitoring state, instead of the complete asleep state, it goes to low power listen mode. The initiator node now polls the node and thus wakes up the target node. Now the links between the two nodes are activated. Data gets transferred using the MAC protocol.

2.2.2 Based on the real characteristics of electronic components

Dynamic Power Management for handheld devices which integrates predictive shutdown and non stationary stochastic concepts is proposed by Hung Cheng Shih and Kuochen (2006). Electronic components can have several inactive and active states. The real characteristics of the electronic components are discussed in three situations. Transitioning of states is to save energy. System can transition from a high power consumption state to a low power consumption state if the time in that state is long enough to compensate for the extra energy consumed by the state transition. Time in low power state should be calculated in advance.

Adaptive Hybrid Dynamic Power Management (AH-DPM) is compared with Oracle algorithm (optimal since it is aware of all requests issued), Adaptive Timeout algorithms (Douglis *et al.*, 1995) and Predictive shutdown algorithm (Hac, 2003). The energy consumed in AH-DPM is proved to be very close to the Oracle algorithm. Compared with the classical DPM algorithms, power consumption of AH-DPM is found to be 17.45% less than Adaptive Timeout algorithm (Douglis *et al.,* 1995) and 20.93% less than predictive shutdown algorithm (Hac, 2003). State Transition Matrix in AH-DPM has to be trained. Maximum Likelihood Estimation is used to train the state transition matrix. The time complexity and space complexity are found to be higher.

2.2.3 Operating system directed power management aspect

The success in Dynamic Power Management involves implementing the correct policy for sleep state transitioning. In operating system directed DPM suggested by Sinha and Chandrakasan (2001), a power aware sensor node model describes the power consumption in different levels of sleep states. Nodes in deep sleep state may have minimum power consumption but a higher energy cost to awaken. This model is quite similar to the system power model in APCI (Advanced Configuration and Power Interface) (Banbyopadhyay and Coyle, 2003). Energy efficient DPM in wireless sensor networks is suggested in Curt *et al.*, (2002) where the modified sleep policy developed by Sinha and Chandrakasan (2001) is combined with OGDC (Zhang and Hou, 2004), to keep a minimum number of nodes in active mode.

The state of computation should also be considered when a system turns components ON/OFF to reduce energy. Another issue considered is density control which ensures only a subset of nodes to be in active mode fulfilling coverage and connectivity. The system models and algorithms developed by Sinha and Chandrakasan (2001) are modified, considering the battery status. New energy efficient DPM combined with OGDC is proposed (Zhang and Hou, 2004).

All sleep states of a node may not be useful (Zuquim *et al.*, 2003). The dynamics of sensing coverage versus time is simulated and it is proved that OGDC provides over 95% coverage. DPM with OGDC is found to prolong the network lifetime than that with only DPM. *Latency* is not analyzed and the problem of avoiding event missing in node sleep states has not been addressed here.

2.2.4 Application driven approach

Several DPM approaches have contributed to decreasing the energy consumption but few consider the application constraints. An application driven power management approach is proposed by Rodrigo *et al.*, (2005). The work by *A.Z. et al*., (2003) influenced the development of this work. In this, the state of an embedded program in power state machine formulation is included to adapt the

QoS in communication intensive devices so as to ensure low power consumption in an embedded system. Theory of Hybrid Automata from Henzinger (1996) is adopted for a fire detection scenario. Application driven DPM is compared with Ideal DPM & Naïve model where no DPM is used. In Naive, the total energy spent is constant. Higher the fire probability, higher is the power consumption for Application driven DPM & Ideal DPM models. The similarity in performance proved for Ideal DPM & Application Driven DPM proves the better performance of Application Driven DPM. Multi hop operation is not considered.

2.2.5 Link Quality Aspect

As stated earlier in section 2.1.5, to realize the energy saving in a wireless scenario, the time varying property of wireless channels should be considered because it may lead to the loss of battery resources, if channel conditions are poor. So each sensor node in the network should intelligently access the current link quality and the predicted traffic load, so as to improve the energy utilization. A Channel Adaptive energy management protocol is proposed by Xiao-Hui Lin and Yu-Kwong (2006). Each node in the network can intelligently access the current link quality and predicted traffic load to improve the energy utilization. Cluster based hierarchy is assumed and a fair scheduling and queuing algorithm is designed to avoid buffer overflow and communication L*atency*. An adaptive Physical layer design ABICM proposed by Kwok and Lau (2002) is adopted. CSMA/CD is used to detect collision. Results prove a 40% increase in energy savings, compared to the other protocols.

2.3 DUTY CYCLE APPROACH ON ENERGY CONSERVATION IN WIRELESS SENSOR NETWORKS

The main energy conserving method is to put the radio transceiver in low power mode when communication is not needed. So there is a constant switching between sleep and active states. This is duty cycling. Duty cycle represents the fraction of time the nodes are active.

The sleep/ wake up times should be coordinated since sensor nodes should always process and send the data to the sink. A sleep/ wake up scheduling algorithm should accompany any duty cycling scheme which is a distributed algorithm based on which sensor nodes decide when to transit from active to sleep state.

Duty cycling can be attained by two different approaches. In the 1st set up, a minimum subset of nodes is adaptively selected to remain active so as to maintain connectivity thus resulting in less energy consumption. The other nodes can go to the sleep state. Finding the correct set of nodes is Topology control. It manages to prolong the network life time (Ganeshan *et al.,* 2004, Mainwaring *et al.,* 2002, Warrier *et al.,* 2007). Nodes selected for the above scheme need not maintain their radio ON continuously. So they keep switching between sleep and wake up states forming power management.

Efficient sharing of the communication resources among the sensor nodes is the prime concern in the design of an efficient MAC protocol. Power consumption in MAC protocol in wireless sensor networks is due to collision, overhearing transmission from neighbors, control packet transmission and idle listening (Bahareh and Hooman, 2008). MAC protocols are broadly classified as schedule based and contention based, based on the resource sharing mechanism. Schedule based schemes owing to its ability of power conservation satisfy the requirements of wireless sensor networks. Contention based schemes implement periodic ON and OFF timing of radio using a contention window. This leads to poor performance due to high contention because of high overhead in resolving contention and collision but is simple and has good bandwidth utilization (Ioannis *et al.*, 2008 and Hull *et al.*, 2004). Improved power consumption and higher end to end delay is obtained by implementing low duty cycle schemes (Ioannis *et al.*, 2008 and Edgar and Callaway, 2003).

2.3.1 Topology control protocols

This concept dynamically adapts the network topology based on the application needs (Ya Xu *et al.*, 2003). The number of active nodes is minimized even though all the network operations are allowed. They implement a well connected flat network topology to reduce the number of nodes participating in data delivery. They exploit density to extend the lifetime. These protocols are classified as Geographic information based protocols and Energy conservation protocols with application level information.

(A) Geographic information based protocols

They decide which nodes to turn ON and when, based on the location of sensor nodes.

(1) Geographic Adaptive Fidelity (GAF)

They self configure the redundant nodes into small groups based on their location. A localized distributed algorithm is used to control the node duty cycle. The sensing area is divided into grids (Xu *et al.*, 2001) with all nodes in the same grid equivalent in routing and one node in the grid being in the active state, at a time. A node starts with the discovery state by sending discovery messages among nodes and then enters the active state. Even now it periodically broadcasts discovery messages. If some other node is detected to be involved in routing, it enters the sleep state. After this, it again goes to the connection state. Group leader selection is based on a rank based election algorithm considering the residual energy at the nodes, thus extending the network lifetime.

(2) Cluster based energy conservation

It follows the same principle as GAF. It uses clusters to allow redundant nodes to sleep (Bennett *et al*., 1997).

(3) Geographic Random Forwarding

This makes use of node position and redundancy (Casari *et al.*, 2005 and Zorci and Rao, 2003). A given duty cycle is given to switch between the active and sleep states. An active state starts with listening time so that they can participate in routing, if needed. Nodes become active during data forwarding and broadcasts a packet with the node's and the receiver's location information. Every node has a priority based on its closeness to the destination.

(B) Energy conservation with application level information

More energy can be saved but the need to have a network with application specific characteristics is the limitation.

1. Span (Chen *et al.,* 2002) adaptively elects coordinators of all nodes in the network based on its expected life time. Keeping awake these coordinators, it performs multi hop routing. The other nodes stay in sleep state and periodically check if it needs to wake up and become a coordinator. Coordinator eligibility rule ensures a sufficient number of coordinators. Routing protocols provide neighbor and connecting information.

2. Adaptive Self Configuring Sensor Network Topology (ASCENT), given by Cerpa and Estrin (2002) do not depend on any routing protocol. It measures the local connectivity based on the neighbor threshold. On this basis, they make a decision on which nodes join the routing infrastructure, based on the application requirements.
3. Pico net (Xu *et al.*, 2001 and Rabaey *et al.*, 2002) conserves more energy by designing a system with application specific hardware and protocols.
4. NAPS, (Godfrey and Ratajczak, 2004) are a decentralized topology management protocol based on a periodic sleep/wakeup scheme. Activation to neighbors is advertised using HELLO messages. Then it listens for other HELLO messages from its neighbors. The nodes go to sleep until the next time period when it receives a certain number of messages from the neighbors. Connectivity properties are found to be robust.
5. A similar protocol that deals with time critical monitoring applications is given by Dousse *et al.*, (2004). Information about network density is needed here.
6. To rectify the above stated protocol, Degree Dependent Energy Management Algorithm (DDEMA) is cited by Kong and Yeh (2007), where the work by Dousse *et al.*, (2004) is extended considering only the neighboring information.

Issues involved in Geographic information based protocols

Location information is essential and so sensors should be provided with a Global Positioning System (GPS) unit. But considering the high cost factor and high energy consumption, only a limited number of sensors can be equipped with GPS. Other sensors get location information using different techniques

(Langendoen and Reijers, 2003 and Mao *et al.,* 2007). So connectivity driven methods are preferable. It is shown that energy consumption of topology protocols depend on actual density. There exists the need for an exhaustive research to explore this in detail.

2.3.2 Power management protocols

These are sleep/ wake up protocols and do not depend on topology or connecting aspects.

(A) Independent sleep/ wake up schemes on top of MAC

This is classified as On demand schemes and Scheduled schemes by Armstrong (2005).

(1) On demand schemes

A node should wake up to receive a packet from a neighboring node to reduce energy consumption. In a fire detection scenario (Rodrigo *et al.,* 2005), sensor nodes are in a monitoring state most of the time. Nodes transit to transfer state on receiving an event, thus ensuring reduced energy consumption, in the monitoring state. Two different channels, a data channel for data communication and a wake up channel for waking up nodes are used. Most schemes propose to have two different radios thus reducing the wake up latency but the cost factor is high. Sparse Topology and Energy Management protocol (STEM) is proposed by Schurgers *et al.,* (2002).

Usually topology control protocols are combined with STEM to have a reduction in energy consumption. Combination of STEM-B and GAF is also suggested by Schurgers *et al.,* (2002), to reduce the energy consumption in a sensor network without topology control or power management. Pipelined Tone Wake up (PTW) provides a tradeoff between energy saving and wake up latency (Yang and

Vaidya, 2004). It also uses two channels like STEM, but tone detection is done in the sender unlike STEM. Senders send a wake up tone on detecting an event and receivers wake up periodically. The performance of the PTW scheme is much better in terms of energy consumption and latency than STEM (Yang and Vaidya, 2004). STEM and PTW use an asynchronized sleep/ wake up to enable a duty cycle on wake up radio. In different approaches (Guo *et al.*, 2001, Rabaey *et al.*, 2002, Nosovich and Todd, 2000 and Shih *et al.*, 2002), the low power is continuously in standby mode and on receiving a signal, data radio is woken up. The transmission range of wake up radio is smaller than the data radio but not negligible, in the low power mode. To get rid of these problems, Radio Triggered Power Management scheme is proposed by Gu and Stankovic (2005). Energy in wake up message is used to trigger the activation of the sensor node. The limitation of the scheme is the limitation on the maximum distance from which the wake up message can be sent.

(2) Scheduled scheme

All neighbors should wake up at the same time. Usually all nodes wake up periodically to check for any communication and then return to sleep. The advantage of this scheme is that when a sensor node is awake all nodes will be awake. This facilitates messages to be transmitted to all neighbors (Armstrong, 2005). But synchronization is essential. A detailed research to achieve a good synchronization effect is the prime need.

A fully synchronized pattern is proposed by Keshavarzian *et al.*, (2006). All the nodes in the network wake up at the same time according to a periodic pattern. Such fully synchronized protocols are proposed in SMAC (Ye *et al.*, 2004) and Time out MAC (TMAC) (Dam and Langendoen, 2003). In staggered wake up pattern (Keshavarzian *et al.*, 2006), nodes at different levels wake up at the same time. Staggered wake up pattern is used in DMAC (Lu *et al.*, 2004). In the staggering scheme, the nodes at different levels of the data gathering tree wake up at different times. So during active time only a subset of the nodes is active resulting in a lesser number of collisions. But nodes at the same level wake up at the same time producing small amount of collisions. The fixed active/wake up approach accounts for the limited flexibility. Active period should be less. Adaptive and low latency staggered scheme is proposed by Anastasi *et al.*, (2006).

The length of the active period is set in accordance with the network activity resulting in reduced energy consumption. A new approach derived from on demand TDMA, FPS (Flexible Power Scheduling) is proposed by Hohlt *et al.*, (2004). Slots are arranged to form a periodic cycle. A node keeps its radio ON only if it has something to receive/ transmit. But this scheme also suffers from lack of flexibility.

(B) MAC protocols with low duty cycle

The energy issues in wireless sensor networks can be dealt with considering the MAC protocols. This is usually by having a low duty cycle MAC scheme so as to achieve an efficient power management. Energy conservation is attained by turning OFF radios when not needed thus trading off network delay for energy conservation (Suh and Ko, 2005 and Shah and Khannad, 2005). Most of the existing MAC protocols fall in two categories as TDMA based and Contention based (Li De-liang Peng Fei, 2009).

(1) Schedule based

Schedule based protocols divide time into several time slots using TDMA and channel access is done on a slot by slot basis (Ching *et al.*, 2004, Rhee *et al.*, 2005 and Chen and Khokhar, 2004). Nodes turn ON their radio during their own slots which hence result in low energy consumption. Clustering schemes can also reduce energy consumption since each node need not directly communicate with the sink. This is used in LEACH (Heizelman *et al.*, 2000) and energy aware TDMA based MAC schemes.

Traffic Adaptive Medium Access protocol (TRAMA) proposed by Rajendran *et al.,* (2003) is an energy efficient TDMA based protocol for wireless sensor networks. The time is divided into random access period for slot reservation and scheduled access period for slot access. The two hop neighborhood information from nodes establishes the collision free schedule. A slot is assigned to a node using the election procedure.

Good *Energy efficiency* is achieved in Light weight MAC (LMAC) [Van Hoesel and Havinga (2004)] and it considers the Physical layer properties. The radio state transactions and protocol overhead are reduced. But specifying the fixed time length of the frame prior to deployment is the major drawback. In order to rectify these effects, Adaptive Information centric LMAC is proposed (Chatterjea *et al.*, 2004).

(2) Contention based MAC

MAC protocols used in wireless sensor networks are contention based. They are categorized as synchronous MAC schemes, asynchronous MAC schemes and hybrid MAC schemes.

(i) Synchronous scheme

The most popular synchronous MAC scheme is BMAC (Polastre *et al.*, 2004 and Chaari and Kamoun, 2010). It has a very energy efficient channel access mechanism by implementing a back off scheme, channel estimation, optional ACK and for a low duty cycle an asynchronous sleep/wake up scheme based on periodic listening. Fixed wake up time and no need of synchronization are the features.

SMAC (Edgar and Callaway, 2003, Ye *et al.*, 2004 and Wei Ye *et al.*, 2002) is one of the well known energy efficient protocols for wireless sensor networks. It is a contention based random access protocol with a preset listen/sleep cycle and uses a synchronized sleep mechanism. For the purpose of announcement and synchronization for the subsequent data transmission, synchronizing (SYN) and Ready To Send / Clear To Send (RTS/CTS) control packets are sent during the listen period based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism. Any two nodes exchanging RTS/CTS packets in the listen period require being in the active state and entering the data transmission phase without entering the sleep state. To avoid the energy wastage due to idle listening, all the other nodes enter the sleep state. The duration of a listen period is always fixed in SMAC. This results in redundant energy wastage.

Traffic aware Energy Efficient MAC (TEEM) (Suh and Ko, 2005 and Chaari and Kamoun, 2010) reduces the power consumed in the listening period of SMAC. Listening period is shortened by rearranging the structure of the listening period to save power. But in SMAC and TEEM, all nodes have to wake up to sense the signals during the contention period. DSMAC (Lin *et al.*, 2004) and UMAC (Yang *et al.*, 2005) help to decrease the *Latency* for delay sensitive applications compared to SMAC.

SMAC does not work well when the traffic load fluctuates. FTMAC (Dam and Langendoen, 2003 and Shah and Khannad, 2005) resolves the problem of SMAC by following an aggressive power conserving policy. It is a variation of SMAC with an adaptive length of the active state by a fine time out. Nodes can go to an early sleep state resulting in an augmented *Latency* and a lesser *Throughput.*

Data gathering MAC (DMAC) (Lu *et al.*, 2004) a different protocol using an adaptive duty cycle, gives a low node to sink latency by staggering the wake up times of the nodes in a converge-cast tree. DMAC outperforms SMAC in having a lower *Latency* and higher *Energy efficiency*.

(ii) Asynchronous scheme

Distributed mediation device (DMD) (Edgar and Callaway, 2003) causes neighbor nodes not to have the same schedule as each other. This results in an increase in transmission *Latency* and power consumption. MDMD (Chen and Khokhar, 2004, Shah and Khannad, 2005 and Ching-Wen Chen *et al.*, 2008) rectifies all the problems existing in DMD.

(iii) Hybrid MAC protocols

A new hybrid MAC scheme (ZMAC) (Rhee *et al.*, 2005) is used for sensor networks to merge the strengths of TDMA and CSMA. Its adaptability to the level of contention in the network is the major aspect of ZMAC. Under low contention, it acts like CSMA and under high contention like TDMA. It is robust to the topology changes and time synchronization failures regularly occurring in wireless sensor networks.

Issues

TDMA based protocols deal well with the *Energy efficiency* problem. Nodes turn ON their radio only during their own slots. By having a proper slot assignment algorithm and proper design of protocol parameters, the energy consumption can be reduced. The drawbacks of the TDMA scheme are proposed by Wei Ye *et al.*, (2002). TDMA based protocols perform poorer in low traffic scenarios compared to contention based schemes. So they are not much considered in wireless sensor networks.

Contention based schemes are robust and can adapt to any traffic condition. But the problem is the higher energy consumption involved. Duty cycle schemes help to decrease the energy consumption but extensive research is greatly needed in this field. Hybrid protocols are much complex when node density increases. Considering all these aspects, energy efficient MAC protocols need to be designed to tackle the prevailing energy problem in wireless sensor networks.

2.4 SCOPE OF THE WORK PROPOSED

Energy efficiency is a critical demand in all wireless sensor networks. Considering the rapid deployment of such networks currently and in the near future, this problem ought to be analyzed in different aspects. Since no MAC protocol is accepted till date as a standard, research efforts are to be focused in this direction. Moreover the varying channel conditions in wireless sensor networks are also to be considered while tackling the energy problem in such networks. It is cited in literature that Cross layer interaction can also be used to optimize the performance of such networks (Suh and Ko, 2005), other than dealing with a single layer. Motivated by these aspects, sincere efforts are taken in this work for innovating a new Energy efficient Channel Adaptive MAC algorithm which incorporates the cross layer interaction between the Physical layer, MAC layer and the Network layer. The performance of this algorithm is validated to confirm its superior performance compared to the existing algorithms.

2.5 CLOSURE

In the above mentioned sections, the importance of the *Energy efficiency* problem prevailing in wireless sensor networks is discussed. Various topics like clustering, security aspects, adaptation of Link layer and Physical layer parameters, time synchronization aspects and power management schemes that influence *Energy efficiency* are cited. Amongst these, power management is found to be a promising technique for increasing the *Energy efficiency*. It is depicted in the literature that compared to static power management techniques; higher efficiency is proved for Dynamic Power Management techniques. Innovative efforts are being conducted at national and international level, to exploit this area extensively, by making the nodes not currently needed in the routing path to go to sleep, by turning OFF their radio interfaces; thus reducing the duty cycle. The intelligence of the decision of bringing a large number of nodes to sleep state can significantly reduce the level of power consumption. This decision can be combined with the routing decisions to further improve the performance of wireless sensor networks.

Intensive research efforts are also conducted to explore how MAC protocols can be optimized to attain *Energy efficiency*, by getting rid of the energy wastages occurring due to idle listening, overhearing, collision, control packet overhead and so on. The MAC layer issues are illustrated in Chapter 1. Different MAC protocols possessing significant features, with the motive of improving the performance of wireless sensor networks in terms of better *Energy efficiency*, *Throughput*, *Fairness*, lesser *Delay* and so on; is provided in the literature. But no protocol is yet accepted as a standard. One of the reasons is that MAC protocols are application dependent and so one standard MAC protocol cannot exist for wireless sensor networks which are being deployed for different applications. Another reason is the lack of standardization at lower layers (Physical layer) and the (Physical) sensor hardware.

Besides this, as given in the literature, the efficiency of a wireless sensor network is influenced greatly by the channel and link quality and if these are ignored it may lead to increased energy consumption of the network. In this work, a Channel Adaptive MAC protocol with Traffic Aware DPM algorithm for efficient packet scheduling and queuing in sensor networks is considered which also takes into account the time varying characteristics of the wireless channel.

Transmission is permitted only for those nodes which have a good channel as well as link quality and sufficient energy resources. Moreover to avoid buffer overflow and to attain fairness for the poor quality nodes, a Load Prediction algorithm is designed. Cross layer interaction of the Network layer, the MAC layer and the Physical layer is being exploited to achieve the optimization of the network. The Traffic Aware DPM scheme minimizes the energy consumption by continuously turning OFF the interfaces of the nodes which are not included in the routing path. Along with adopting the usual RTS/CTS scheme of SMAC for increasing the *Energy efficiency*, the next hop node information is also conveyed in the RTS/CTS packets. So only the next hop node comes to the active state by which the unwanted energy consumption involved in SMAC, due to unnecessary mandatory awakening of all nearby nodes is prevented. Simulation using NS2 provides a realistic approach to the scenario under study and so this is used for the evaluation of this algorithm (Network Simulator, http://www.isi.edu/nsnam/ns).

The combined approach of cross layer interaction of MAC, Routing protocols and Physical layer is intended in this work, along with designing an efficient and fair packet scheduling and queuing algorithm which takes into account the time varying nature of the wireless channels, as a technique to improve the energy problem existing in wireless sensor networks.

3

MODELING

Chapter 3

This chapter presents the features of the Network Simulator so as to provide a simulation scenario which offers a realistic view of a wireless sensor network. The network simulator under study is highlighted along with the performance metrics to be evaluated. The various features of the network simulator to form a network topology, like links and nodes, are presented. The packet format, routing protocols and details about queue, delay, timer, Radio propagation model, Energy model and Error models to depict packet loss are also provided. To analyze the output, the details given in the trace file are elaborated and the simulation scenario is depicted.

In this work, a Channel Adaptive Medium Access Control protocol is designed, which uses multiple techniques to reduce the energy consumption, control overhead and latency, so as to improve the overall system performance. It also considers the effects of link quality, channel quality and energy resources of each node. A Traffic Aware Dynamic Power Management is proposed to enhance the energy efficiency, by reducing the duty cycle of operation. A Load Prediction algorithm with an Adaptive Threshold Adjustment scheme is also designed to prevent the buffer overflow and thus to achieve *fairness*. Performance requirements of this protocol are 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* in a wireless sensor network, while achieving a high level of stability and scalability.

3.1 NETWORK OVERVIEW

The protocol design in this work, assumes a big 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. Data generated by the sensors is processed and communicated in a store and forward manner. The applications supported by the network are assumed to swing between long idle periods, during which no events occur, and bursty active periods during which data flows towards the base station, through packet exchange among the peer sensor nodes. The applications are also assumed to tolerate a large latency for an extended network life.

To achieve significant energy savings, this protocol exploits the bursty profile of sensor applications. This is to establish duty cycle operation on nodes in a multi hop network. During the long periods of time when no sensing occurs, the nodes alternate periodically between listening and sleep states. When its radio is turned OFF, each node sets up a wake up timer for a wake up time and sleeps for a certain amount of time. Node becomes active on expiration of the timer. This sleep mechanism reduces the energy consumption. But here nodes do not follow a periodic sleep mechanism. A Traffic Aware Dynamic Power Management scheme is adopted here with the aim to increase the energy efficiency and to decrease the latency, incurring in some existing algorithms. Moreover to increase the energy efficiency further, the link and channel characteristics are also considered. Most existing schemes sacrifice fairness, but here in this work, the Load Prediction algorithm is aimed to prevent this.

3.2 PERFORMANCE EVALUATION

Many performance issues like *Throughput, Delay, Energy consumption, Delivery ratio* and so on, critically influence the performance of wireless sensor networks. So this algorithm is to be validated for these parameters. The algorithm proposed in this work is evaluated and compared with the existing protocols, by simulation using the Network Simulator NS2, wherein the real nature of a wireless sensor environment is created. The reason for selecting NS2 is that, this Network Simulator uses two languages to enable the simulator to do two tasks which are discussed below. NS version2 is a discrete event-driven and object-oriented network simulator. A system programming language is required in detailed simulations of protocols to efficiently manipulate bytes, packet headers and also to implement algorithms that run over large data sets. For such tasks, run time speed is more important compared to turn around time for simulation run, finding bugs and so on, which happens to be less important. Slightly varying parameters or configurations, or quickly exploring a large number of scenarios is involved in detailed network research. For this iteration time is very important. Configuration runs once at the beginning of the simulation, and so run time of this part of the task is less important. Both these requirements are met by Network Simulator NS, with two languages, C++ and object oriented extension of Tool Command Language (OTcl). The code is implemented by C++ while OTcl configures the system. OTcl is an interpreted programming language. C++ is suitable for detailed protocol implementation because it is fast to run but slower to change. OTcl is ideal for simulation configuration since it runs slower but can be changed very quickly and interactively.

3.3 FEATURES OF NETWORK SIMULATOR

Network Simulator uses two languages to do two tasks. Front end is OTcl for simulation configuration and C++ is for detailed protocol implementation. Links that connect nodes in the network are OTcl objects that assemble delay, queuing and loss modules. In the starting phase, a new simulator object is created in Tcl which is then followed by the initialization procedure.

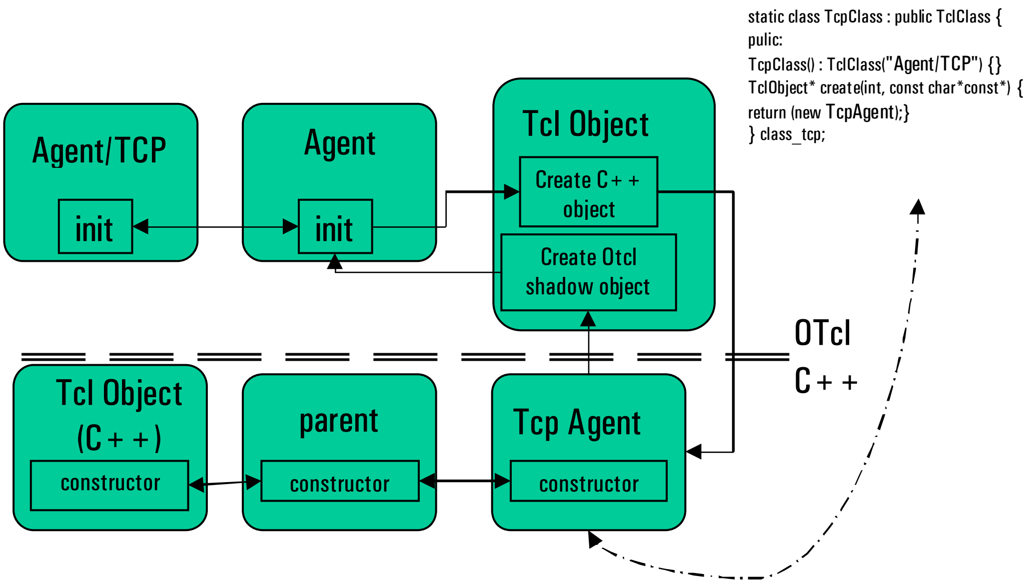


Figure 3.1: OTcl linkage

This procedure includes initializing the packet format, creating a scheduler and creation of a null agent as a discard sink. Field offsets are set up within packets in the packet format initialization, to be used during the entire simulation. The simulation is run by the scheduler in an event driven manner. The scheduler selects the next earliest event, executes it to completion, and returns to execute the next event. Unit of time used by scheduler is seconds. The simulator is single-threaded, and only one event is in execution at any given time. If execution of more than one event is to be scheduled at the same time, their execution is performed on the first scheduled – first dispatched manner. The methods used by the simulator class to set up the simulation falls into three categories as methods for creating and managing the topology (which in turn consists of managing the nodes) and managing the links, methods to perform tracing, and helper functions to deal with the scheduler.

3.3.1 Links

Links are used to connect the nodes and complete the topology of a given wired network. A link between two nodes with the specified bandwidth and delay characteristics is created by the Link class. Figure 3.2 shows the components, of a duplex link, between two nodes, n_0 and n_1. The trace elements are tracked by the following instance variables:

`enqT_` Reference to the element that traces packets entering the queue.

`deqT_` Reference to the element that traces packets leaving the queue.

`drpT_` Reference to the element that traces packets dropped from the queue.

`rcvT_` Reference to the element that traces packets received by the next node.

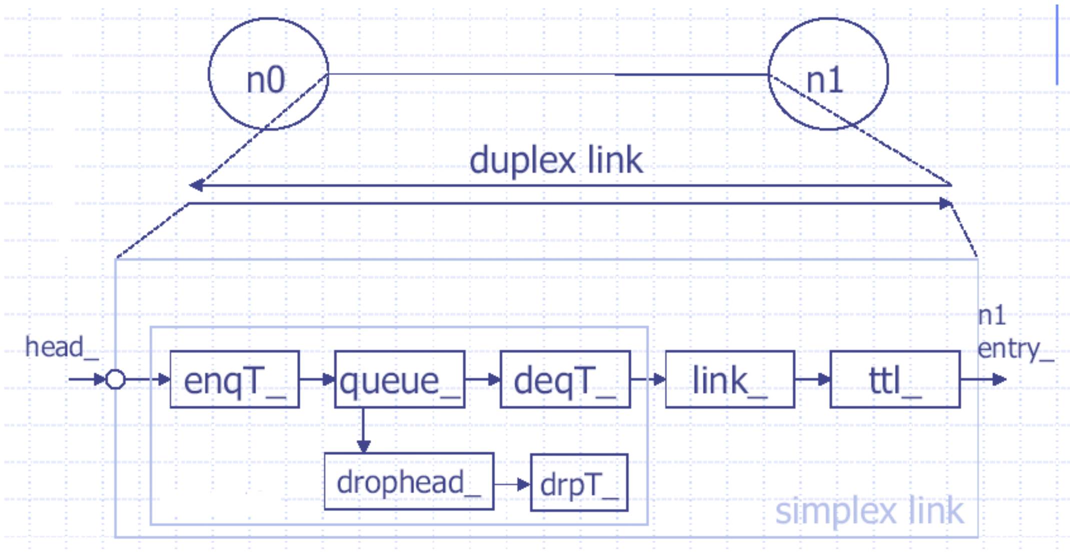


Figure 3.2: Duplex link structure

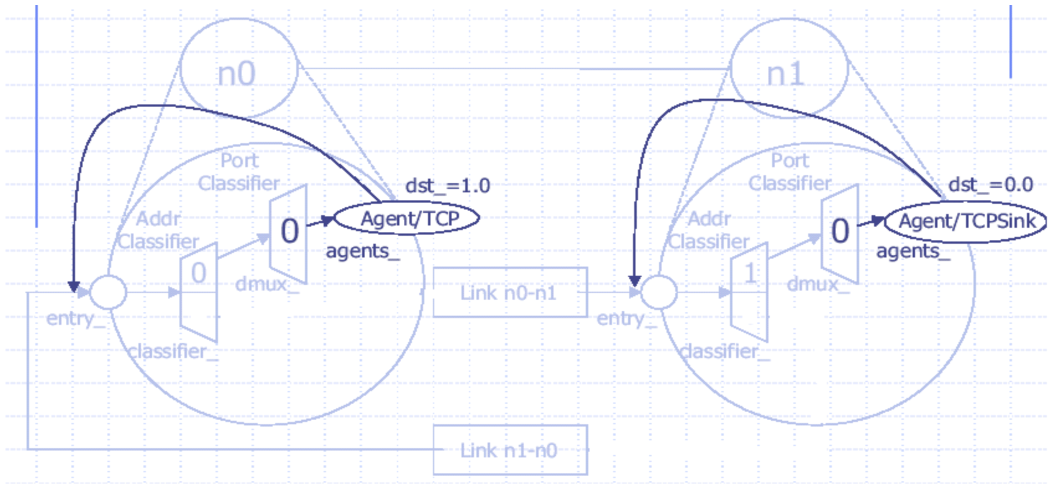


Figure 3.3: Internal structure of nodes

Figure 3.3 shows the internal structure of two nodes n_0 and n_1.

Figure 3.4 shows the packet header format.

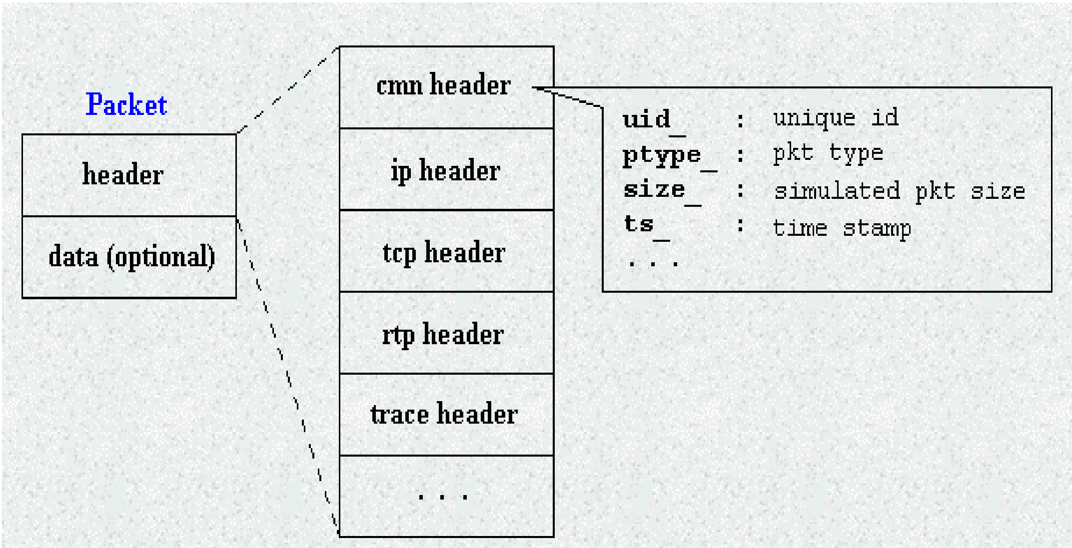


Figure 3.4: Packet header format

3.3.2 Network Nodes

All the network nodes have the following components:

- an address or id_, monotonically increasing across the simulation namespace by 1 (from initial value 0) as nodes are created,
- a list of neighboring nodes,
- a set of agents,
- a node type identifier, and
- a routing module

Node configuration involves defining the different node characteristics before creating them. Node characteristics comprise of the type of addressing structure used in the simulation, defining the network components for mobile nodes, the Link layer type, MAC type, the interface queue type, the interface queue length, the antenna type, the propagation type, the channel type, turning ON or OFF the trace options at Agent/Router/MAC levels, selecting the type of ad hoc routing protocol for wireless nodes or defining their energy model. When a node receives a packet, it examines the fields in the packet, usually its destination address, and during some instances, its source address. Then the values to an outgoing interface object that is the next downstream recipient of this packet is mapped by it.

3.3.3 Routing

Three functional blocks present in every routing implementation in a Network Simulator are as follows.

- *Routing agent* does the routing packet exchange with the neighbors.
- *Route logic* uses the information gathered by routing agents (or the global topology database in the case of static routing) to perform the actual route computation.
- *Classifiers* present in a node do the address and port classification. The computed routing table is used to perform packet forwarding.

3.3.4 Routing Protocol Used

The routing protocol used in simulation is Ad hoc On Demand Distance Vector (AODV). AODV is a combination of both Dynamic Source Routing (DSR) and Destination Sequenced Distance Vector (DSDV) protocols. It not only uses the basic route-discovery and route-maintenance of DSR but also the hop-by-hop routing, sequence numbers and beacons of DSDV. The node in need of a route to a given destination generates a ROUTE REQUEST. The ROUTE REQUEST is now forwarded by the intermediate nodes. During this process, it also creates a reverse route for itself from the destination. When such a request reaches a node with a defined route to the destination, it generates a ROUTE REPLY. This has information about the number of hops required to reach the destination. All the nodes that participate in forwarding this ROUTE REPLY to the source node, creates a forward route to the destination. This state created from each node from source to destination is not the entire route as in the case of source routing but a hop-by-hop state.

3.3.5 Queues

Queues are the locations where packets are held (or dropped). Packet scheduling involves the decision process which is used to choose which packets should be serviced or dropped. The occupancy of a particular queue is regulated using Buffer management. The present queuing techniques available are drop-tail (FIFO) queuing, Random Early Detection (RED) buffer management, Class Based Queuing (CBQ) (including a priority and round-robin scheduler), and variants of Fair Queuing including Fair Queuing (FQ), Stochastic Fair Queuing (SFQ), and Deficit Round-Robin (DRR). Interface queue used in this work is the Drop tail priority queue.

3.3.6 Delay

Delays represent the time needed for a packet to traverse a link. The possibility of a link failure is captured by a special form of this object (“dynamic link”). The amount of time required for a packet to traverse a link is defined as s/b + d where s is the packet size (as given in its IP header), b is the speed of the link in bits/sec, and d is the link delay in seconds.

3.3.7 Agents

Agents denote the endpoints where the network-layer packets are constructed or consumed, and are used in the implementation of protocols at different layers. The class Agent has an implementation partly in OTcl and partly in C++.

3.3.8 Timer

Timers may be implemented either in C++ or OTcl. The functions of a Timer Handler comprise of scheduling a timer, rescheduling a timer, canceling a pending timer or returning a timer status.

3.3.9 Error Models

Packet losses are introduced into a simulation using Error models. The link-level errors or loss is simulated by the Error model, by either marking the packet's error flag or dumping the packet to a drop target. Errors can be generated in simulations, from a simple model such as the packet error rate, or from more complicated statistical and empirical models. The unit of error can be specified in terms of packets, bits, or time-based in order to support a wide variety of models. Corrupted packets are received from Error Model if the drop target exists. Otherwise, Error Model just marks the error flag of the packet's common header, thus allowing the agents to handle the loss.

3.3.10 Output

Output or trace data during a simulation can be collected in different ways. Commonly trace data is stored in a file to be post-processed and analyzed or generally, trace data is displayed directly during the execution of a simulation. Simulator supports two primary and distinct types of monitoring capabilities. The first one is called *trace*. Each individual packet as it arrives, departs, or gets dropped at a link or queue, is recorded by it. Like nodes in the network topology, trace objects are configured into a simulation. The second type of object is called *monitor*. Counts of various quantities such as packet and byte arrivals, departures and so on are recorded by it. A special *common* header is included in each packet to support traces. Each packet includes a unique identifier, a packet type field which is set by agents when they generate packets, a packet size field in bytes, sent time field which is used to determine the transmission time for packets, and an interface label which is used for computing multicast distribution trees. The trace format is divided into the following fields:

Event type This is the first field. It describes the type of event taking place at the node and can be one of the four types:

s send

r receive

d drop

f forward

General tag This is the second field. It starts with "-t" which may stand for time or global setting

-t time

-t * (global setting)

Node property tags The node properties like node-id, the level at which tracing is being done like agent, router or MAC is depicted by this field. The Node property tags start with a leading "-N" and are listed as below:

-Ni: node id

-Nx: node's x-coordinate

-Ny: node's y-coordinate

-Nz: node's z-coordinate

-Ne: node energy level

-Nl: trace level, such as AGT, RTR, MAC

-Nw: reason for the event. The different reasons for dropping a packet are given below:

"END" DROP_END_OF_SIMULATION

"COL" DROP_MAC_COLLISION

"DUP" DROP_MAC_DUPLICATE

"ERR" DROP_MAC_PACKET_ERROR

"RET" DROP_MAC_RETRY_COUNT_EXCEEDED

"STA" DROP_MAC_INVALID_STATE

"BSY" DROP_MAC_BUSY

"NRTE" DROP_RTR_NO_ROUTE i.e. no route is available.

"LOOP" DROP_RTR_ROUTE_LOOP i.e. there is a routing loop

"TTL" DROP_RTR_TTL i.e. TTL has reached zero.

"TOUT" DROP_RTR_QTIMEOUT i.e. packet has expired.

"CBK" DROP_RTR_MAC_CALLBACK

"IFQ" DROP_IFQ_QFULL i.e. no buffer space in IFQ.

"ARP" DROP_IFQ_ARP_FULL i.e. dropped by ARP

"OUT" DROP_OUTSIDE_SUBNET i.e. dropped by base stations on receiving routing updates from nodes outside its domain.

Packet information at IP level The tags for this field begin with a leading "-I" and are listed along with their explanations as follows:

-Is: source address. source port number

-Id: destination address. destination port number

-It: packet type

-Il: packet size

-If: flow id

-Ii: unique id

-Iv: time to live (ttl) value

Next hop info This field provides next hop info and the tag starts with a leading "-H".

-Hs: id for this node

-Hd: id for next hop towards the destination.

Packet info at MAC level MAC layer information is given in this field and starts with a leading "-M" as shown below:

-Ma: duration

-Md: ethernet address of destination

-Ms: ethernet address of source

-Mt: ethernet type

Packet info at "Application level" The type of application like Address Resolution Protocol (ARP), Transmission Control Protocol (TCP), the type of ad hoc routing protocol like DSDV, DSR, AODV etc being traced is given in the packet information at the application level. This field consists of a leading "-P" and list of tags for different applications is detailed below:

-P arp Address Resolution Protocol.

ARP details are given by the following tags:

-Po: ARP Request/Reply

-Pm: source MAC address

-Ps: source address

-Pa: destination MAC address

-Pd: destination address

-P dsr: denotes the ad hoc routing protocol called Dynamic Source Routing. Information on DSR is given by the following tags:

-Pn: number of nodes traversed

-Pq: routing request flag

-Pi: route request sequence number

-Pp: routing reply flag

-Pl: reply length

-Pe: source of source routing->destination of the source routing

-Pw: error report flag

-Pm: number of errors

-Pc: whom to report

-Pb: link error from link a->link b

-P cbr Constant Bit Rate.

Information about the CBR application is given by the following tags:

-Pi: sequence number

-Pf: number of times this packet was forwarded

-Po: optimal number of forwards

-P tcp Information about TCP flow is given by the following subtags:

-Ps: sequence number

-Pa: acknowledgement number

-Pf: number of times this packet was forwarded

-Po: optimal number of forwards

3.3.11 Radio Propagation Models

Radio propagation models are implemented in the Network Simulator. The received signal power of each packet can be predicted using these models. There is a receiving threshold at the physical layer of each wireless node. On receiving a packet, if its signal power is below the receiving threshold, it is marked as error and dropped by the MAC layer. Radio propagation model used here is the Two ray ground radio propagation model.

3.3.12 Energy Model

Energy Model is implemented in the Network Simulator as a node attribute. The level of energy in a mobile host is given in the Energy model. The initial value of the level of energy that the node has at the beginning of the simulation is called `initialEnergy_`. `txPower_` and `rxPower_` denote the energy used by each packet for transmission/reception. `initialEnergy_`,`txPower_` and `rxPower_` are specified in the energy model.

3.3.13 Packet Traversal Details From Layer 3 to Layer 1

Outgoing packets from the Network layer are handed to the Link Layer by the Routing Agent. Link Layer has ARP module which finds the hardware address of the next hop of packets. Packets are then handed to the Interface Queue which has a maximum queue limit that can be maintained at the Queue. Packets are now handed to the MAC layer and then to the Network Interface which stamps the packet with the meta data details like transmission power, wavelength and so on. This is used by the propagation model in the Network Interface to check whether the packet has the minimum power needed to be received or not.

3.4 BASIC STEPS INVOLVED IN NS2

- Create a new simulator object
- Turn on tracing
- Create the Physical layer and the Network layer
- Create the Link and the Queue
- Define the Routing protocol
- Create the Transport connections
- Create the traffic
- Insert errors to simulate an error prone scenario

3.5 SIMULATION SCENARIO

To create a realistic depiction of a wireless sensor network, a simulation study is performed using Network Simulator NS2. 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 over a distance of 250 m on a 2 Mb/s wireless channel. All applications are run on User Datagram Protocol (UDP). The simulated traffic is of Constant Bit Rate (CBR). The sink is assumed to be 250m away from the area. Initial node energy is set as 2.7 Joules for the first set of simulations and 4.0 Joules for the second set of simulations.

The Channel Adaptive MAC protocol with Traffic Aware Dynamic Power Management scheme adopts the periodic sleep/listen operations, schedule selection and coordination, schedule synchronization, adaptive listening and access control mechanisms of the SMAC protocol. The mechanisms existing in this protocol are depicted in detail in the succeeding chapters, Chapter 4 and Chapter 5. This protocol is simulated to validate and confirm its superior performance.

3.6 SUMMARY

This chapter explains the need to have a realistic depiction of a wireless sensor network, so as to evaluate the proposed Channel Adaptive MAC protocol. The different features of the Network Simulator NS2 are presented. Details of the nodes specified in the Network Simulator are discussed so as to create the wireless sensor network topology. Different aspects of the simulator like the Packet format, Routing protocol, Energy model, Radio propagation model, Error model, Timer and so on are detailed; with a view to show that the simulator can provide a realistic network scenario with packet flows, packet losses and so on. The scenario used for simulation in this research work is illustrated in the last section.

4

A CHANNEL ADAPTIVE MAC PROTOCOL WITH TRAFFIC AWARE DYNAMIC POWER MANAGEMENT

Chapter 4

In this chapter, with an aim to have efficient energy management in a wireless sensor network, a Channel Adaptive Medium Access Control protocol with Traffic Aware Dynamic Power Management named as AEMAC in short is proposed for competent packet scheduling and queuing. An overview of the protocol is given which shows the different aspects incorporated for power management as in SMAC like periodic sleep and listen operations, schedule selection and co-ordination, schedule synchronization, access control and exchange of data and message passing. Along with this, a Channel Adaptive MAC protocol is described together with its channel quality estimation, link quality estimation and Traffic Aware Dynamic Power Management. The complete algorithm and the performance parameters to be evaluated are provided in the final section.

PHASE 1

In this Channel Adaptive MAC protocol with Traffic Aware DPM (AEMAC), the time varying characteristics of wireless channels are taken into account. A network system has been proposed to execute the fundamental idea in an actual situation wherein each sensor can choose the state of the communication component considering the link condition, channel condition and energy status.

AEMAC protocol is designed to reduce the energy wastages occurring in ordinary wireless sensor networks caused by idle listening, overhearing, control overhead and collisions. The primary goal is to increase the *Energy efficiency* while at the same time achieving some important performance parameters like stability and scalability. This protocol could achieve high *Throughput* and lower *Delay* at the cost of some performance reduction like *Fairness.*

4.1 OVERVIEW OF THE PROTOCOL

A large network comprising of many sensor nodes which have limited storage, communication and processing capabilities is assumed. Configuration of nodes is as in the form of an ad hoc, self-organized and self-managed wireless network. Data generated by sensors is processed and communicated in a store and forward manner. The applications supported by the network are assumed to swing between long idle periods during which there is no event occurrence and bursty active periods in which data flows to the sink through message exchange among peer sensor nodes.

AEMAC uses the bursty profile of sensor applications to inherit high energy savings. Along with schedule selection, co-ordination, synchronization and adaptive listening strategies, it also adopts Traffic Aware Dynamic Power

Management, adaptation to link quality and channel quality conditions and cross layer interaction of the Physical layer, the Data Link layer and the Network layers. These aspects are detailed below.

4.2 PERIODIC SLEEP AND LISTEN OPERATIONS

It was given in Chapter 2 that by establishing a low duty cycle operation for sensor nodes, the energy consumption can be reduced since idle listening gets avoided. In this protocol, all the sensor nodes move into a sleep state during which their radio interfaces are turned OFF. Nodes in sleep state consume very little energy compared to those in listen state.

Based on this scheme, each node sets a wakeup timer and goes to sleep for a particular period of time. When the timer expires, the node wakes up compulsorily and listens into the medium to find if it needs to communicate with any other node. A complete listen-sleep period forms a frame. Duty cycle which characterizes each frame denotes the ratio of the listen interval to the frame length.

Nodes have their freedom to schedule their own listen and sleep intervals. In order to reduce the control overhead needed to achieve communication between the nodes, the schedules should be coordinated.

4.3 SCHEDULE SELECTION AND COORDINATION

The listen and sleep schedules of the neighboring nodes are coordinated. Each node selects a schedule and exchanges it with its neighbors during the synchronization period. A schedule table having the schedule of all its known neighbors is maintained by each node.

In order to select a schedule, a node listens to the channel for a fixed amount of time equal to the synchronization period. If a node does not hear a schedule from another node, on the expiration of the synchronization period, it chooses its own schedule. After performing carrier sensing the node announces its schedule by broadcasting a synchronizing (SYNC) packet. Carrier sensing rules out the possibility of SYNC packet collisions. If a node happens to receive a schedule from a neighbor before announcing its schedule, it accepts the received schedule as its schedule. But the node has to wait till the next synchronization period, in order to announce its schedule to its neighbors. Sometimes a node may receive a different schedule after it chooses and announces its own schedule. This is due to the SYNC packet getting corrupted by collision or channel interference. In this case, it checks whether any other neighboring node is sharing the same schedule as its one. If not so, it discards its own schedule and accepts the new one. But if any other neighboring node is sharing the same schedule as its schedule, the node adopts both the schedules as it is aware that other nodes have adopted its schedule. Hence it has to wake up at the listen intervals of both the adopted schedules.

In some cases, neighboring nodes may fail to know each other due to the loss of a SYNC packet or delay. So nodes should perform neighbor discovery frequently. For this, a node listens periodically for the entire synchronization period. Those nodes that do not have neighbors presently should perform neighbor discovery frequently.

4.4 SCHEDULE SYNCHRONIZATION

Schedule synchronization should be performed periodically by neighboring nodes to prevent long term clock drift. Transmission of SYNC packet is done to update a schedule. The listen interval is divided into two subintervals for a node to receive both data packets and sync packets. Channel access by contending nodes during these intervals is regulated using a multi slotted contention window. The former time subinterval is dedicated for the transmission of SYNC packets. The latter time subinterval is dedicated for the transmission of data packets. In both these time intervals, a time slot is randomly selected by the contending station. Then it performs carrier sensing and transmits its packet only if it finds the channel idle. Thus energy consumption due to unwanted collisions can be reduced. Data transmission uses the Ready To Send/ Clear To Send (RTS/CTS) handshake to achieve a secure exclusive access to the channel during data transmission. Both RTS/CTS packets have different fields which have information regarding the identity of source and destination and the time duration for the whole transmission. So the neighboring nodes can delay their transmissions till this packet transmission ends, thus preventing un-necessary energy wastages due to collisions and idle listening. Moreover the neighboring nodes are made to sleep till the end of the packet transmission, thus preventing energy losses due to over hearing and thus increasing the overall bandwidth utilization.

4.5 ADAPTIVE LISTENING

If all the nodes follow the sleep schedule strictly, it may lead to an increased delay since the packets will get delayed at every hop due to the store and forward mechanism. To improve the latency, adaptive listening is used. During the listen period of a node, if it happens to overhear an RTS/CTS packet exchange between its neighboring nodes, it assumes that it may be the next hop node. So it ignores its wake up schedule and schedules an extra listening period for the time duration as overheard from the RTS/CTS packet till the end of that packet transmission. If the overhearing node receives an RTS it can continue with the transmission. The unnecessary transition between the two power levels is avoided thus improving the energy transmission. If the overhearing node does not receive an RTS, it enters the sleep state till the next scheduled listen interval.

4.6 ACCESS CONTROL AND EXCHANGE OF DATA

To regulate the access to the shared channel, this protocol uses CSMA/CA based procedure, which includes both physical and virtual carrier sensing. It also uses the RTS/CTS handshake to get rid of the hidden and exposed terminal problem. Network Allocation Vector (NAV) is used for virtual carrier sensing. NAV is a variable which has information about the remaining time till the end of the current packet transmission, stored in it. Initially, NAV is set to the packet duration field as indicated in the transmitted packet. On the passage of time, its value is decremented till zero. A node can only initiate a packet transmission if its NAV value reaches zero. Physical carrier sensing is by listening to the channel for some ongoing transmission as in ordinary CSMA. To avoid collisions and starvation, carrier sensing is randomized within a contention window. Only if both the virtual and physical carrier sensing indicate a free channel, a node is allowed to transmit.

To prevent overhearing, nodes are allowed to sleep on hearing an RTS/CTS exchange from the other nodes. Nodes set its NAV to the duration of the packet transmission and sleep till its NAV becomes zero. This leads to significant energy savings.

Packet transmission:

Node first senses the channel. If the channel is busy, it sleeps till the channel becomes free again. On sensing a channel idle, it sends an RTS packet and waits for the CTS packet from the destination node. On getting the CTS packet, it transmits the data packet. Transmission ends on receiving an acknowledgement packet. The communicating nodes will not sleep till the end of the transmission.

4.7 MESSAGE PASSING

A long message is divided into small fragments that a node can process. These fragments are sent in a burst after a single RTS/CTS exchange between the communicating nodes. The medium is reserved for the time needed to transmit an entire message. Each fragment is transmitted, on getting an acknowledgement from the receiving node, for the previous fragment. This process improves the application level performance.

4.8 CHANNEL ADAPTIVE MAC PROTOCOL

Packet transmission through a link of high quality consumes less energy than that through a “bad” link. Based on this observation, in this 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 and its energy status. 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 and the energy status. Then transmission is allowed only for those nodes with a weight value 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 state is less than that in Active state, but significantly greater than in the sleep state. Hence, intelligently switching to sleep state whenever possible will generally create significant energy savings. In this work, a Traffic Aware Dynamic Power Management scheme (TA-DPM) is designed. The design goal of the 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, the nodes are categorized into three types depending upon the state defined by the data transmission as 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 states.

4.9 LINK QUALITY ESTIMATION

The link quality or link metrics such as: *Bandwidth, Delay, Loss rate* are measured by the MAC layer. Link metrics are then introduced to the IP routing protocol. The link metrics are taken into account in order to calculate the path for the new incoming flow by the routing algorithm. Each node computes the Residual bandwidth and Residual energy.

Residual bandwidth R_{bw} is estimated as

$$R_{bw} = C_{bw} - U_{bw} \quad (1)$$

where

C_{bw} - channel bandwidth,

U_{bw} - used or consumed bandwidth,

Similarly the residual energy R_e is estimated as

$$R_e = (C_e - U_e) \quad (2)$$

where,

C_e – Initial energy,

U_e - used or consumed energy,

A radio model defines:

Eelec J/bit - Energy consumption of a transmitter-receiver

Eamp J/bit - Energy consumption of a transmitter amplifier for a signal to noise ratio

Etx - Transmitting energy of a radio beam

The following equation is the factor for sending a *k* (bit) message to a node with a distance of *d* (meters)

$$Z = (Etx / (Eelec + Eamp * k *d*d)) \qquad (3)$$

Now the Link Weight LQ can be calculated as the combined sum of residual bandwidth and residual energy

$$LQ = R_{bw} + Z * R_e \qquad (4)$$

4.10 CHANNEL CONDITION ESTIMATION

Every node estimates the channel conditions for each contending flow. To represent the channel state at the Link Layer (LL) queue, a flag is initiated. The flag can take three values as GOOD, BAD and PROBE

GOOD: A flag is set by the node as GOOD, when it receives from the following flow: (i) a MAC-layer acknowledgment in response to a data frame, (ii) a CTS frame in response to an RTS frame, or (iii) an error-free data frame or RTS.

BAD: The node sets the flag to BAD after a transmission failure. If the collisions or channel errors cause a transmission failure, then the values of the Short Retry Limit (SRL) and the Long Retry Limit (LRL) are selected. If a transmission takes place without receiving an acknowledgement, it is noted by a Long Retry Counter (LRC) and a Short Retry Counter (SRC). By monitoring the values of LRC and SRC, the transmission failure and collisions can be detected.

PROBE: The node switches the flag from BAD to PROBE when a configurable timeout, named as Ptimer, expires. Ptimer starts to run whenever the channel state switches to BAD, and its initial value is doubled when a transition from PROBE to BAD occurs. The duration of Ptimer is reset to its initial value upon a transition from PROBE to GOOD.

Each node $\{N_i, i=1,2\ldots\}$ maintains a queue $\{Q_i, i=1,2\ldots\}$. Each queue has associated with it a weight $\{W_i, i=1,2\ldots.\}$ such that

$$W_i = LQ_i * 1, \quad \text{if flag} = \text{GOOD},$$
$$= LQ_i * -1, \quad \text{if flag} = \text{BAD}.$$

4.11 CROSSLAYER INTERACTION

The link layer metrics like residual bandwidth and residual energy and the channel state information depicted in the Flag is conveyed into the Network layer to make intelligent routing decisions. The residual bandwidth and residual energy information are determined by every wireless sensor network node. Each node estimates a weight value based on its residual bandwidth and residual energy, stores a copy of it and is also broadcast across the network during the Neighbor Discovery process. Each node on receiving the neighbor's packet, checks for the lesser value. The lowest weight value in the network is selected as the minimum weight value. This minimum weight value will be determined at run time during every Neighbor Discovery process, which is performed periodically. So at the end of the Neighbor Discovery process, all nodes become aware of the weight information of its neighbors and the minimum weight value of the network. During the Route Discovery process, the standard Route Request packet of the routing protocol is modified by including the following fields like host address, weight information and timestamp. This is broadcast and any node on receiving this, computes a weight value as the sum of its weight value and the incoming weight value; and this is appended in its Route Request packet and again broadcast. In this way, it reaches the sink node, which gets the total weight value of all nodes in its path. This is sent back to the source in the Route Reply packet. Source selects the route having the highest weight value as its transmission route.

If a node has data to transmit, it checks whether its weight value is greater than the minimum weight value. The nodes with high weights are allowed to transmit. Nodes attempting to access the wireless medium with a low weight value will be allowed to transmit again when their weight becomes high, till then the data is buffered at the node.

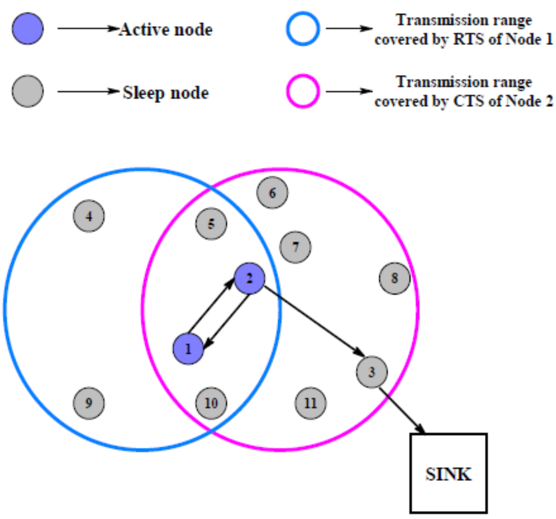
4.12 TRAFFIC AWARE DYNAMIC POWER MANAGEMENT

The nodes are grouped into the following categories:

Current Transmitting Node (CTN): Any node currently participating in the actual data transmission (Like nodes 1 and 2 in Figure 4.1).

Future Transmitting Node (FTN): Any node to be involved in the actual data transmission (Like node 3 in Figure 4.1).

No Transmitting Node (NTN): Any nodes that are not included in a routing path and hence not involved in the actual data transmission at all (Like nodes 4-11 in Figure 4.1).



Node 1 Sends Data to Node 2

Figure 4.1: Classification of node states

The format of RTS/CTS control frames needs to be slightly modified from their original MAC protocol. This modification is for informing a node the fact that its state is changed to CTN or FTN in the corresponding period. The new RTS and CTS packet add only one field to the original packet. The newly added field in RTS is the final destination address, by which the receiver's routing agent can search for the next hop address. The new field of CTS is the next hop node address and it informs which node needs to be CTN to its neighbors.

Referring back to Figure 1, when node 2 receives 1's RTS packet including the final destination address of sink, its routing agent refers to the routing table for getting the next hop node (node 3) and informs back to its own MAC. The MAC agent of node 2 then transmits CTS packet including the information of node 3. After receiving the CTS packet from node 2, node 3 changes its state to CTN and the other neighboring nodes become aware of the fact that they are FTN nodes.

Otherwise, if no such information about FTN is available in node 2's routing agent, it means the routing path is broken or has not yet been established.

4.13 COMPLETE ALGORITHM

The steps involved in the proposed MAC protocol are summarized as:

1. If the category of n_i is NTN, then

1.1 Put n_i into sleep mode

1.2 Terminate

2. Else

2.1 Put n_i into awake mode

3. End if

4. For each node n_i, in awake mode then,

4.1. $R_{bwi} = C_{bwi} - U_{bwi}$

4.2. $R_{ei} = (Ce_i - Ue_i)$

4.3. $LQ = R_{bwi} + Z * R_{ei}$.

Where $Z = (Etx / (Eelec + Eamp * d*d))$

Eelec J/bit - Energy consumption of a transmitter-receiver

Eamp J/bit - Energy consumption of a transmitter amplifier for a signal to noise ratio

Etx - Transmitting energy of a radio beam

4.4. LQ exchanged with neighbors during Neighbor Discovery.

4.5. W_{min} *the minimum threshold value is found based on minimum LQ values of all nodes.*

4.6. Path having highest weight value selected as the routing path.

4.7 Nodes having to transmit, check:

4.7.1. If node n_i receives ACK or CTS or Data from MAC layer, then

Flag = GOOD

4.7.2. Else If node n_i observes collision or transmission errors, then

Flag = BAD

4.7.3. Else

Flag = PROBE

4.7.4 End if

4.8. If Flag = GOOD, then

4.7.1 $W_i = LQ_i * 1$

4.9. Else If Flag = BAD, then

4.8.1 $W_i = LQ_i * -1$

4.10. End if

5. End For

6. If $W_i > W_{min}$, then

6.1 Transmission is allowed

7. Else

7.1 Transmission is rejected.

9. End if.

4.14 PERFORMANCE EVALUATION

Performance of this protocol is evaluated, for different performance metrics like *Energy consumption*, *Delay*, *Delivery ratio* and *Throughput* with respect to number of nodes, number of flows and Transmission Rate in the wireless sensor network, using the Network Simulator NS2. The results are given in Chapter 6.

4.15 SUMMARY

This chapter proposed a Channel Adaptive MAC protocol with Traffic Aware DPM and competent packet scheduling and queuing in a wireless sensor network. The different aspects adopted as in SMAC to have efficient power management like periodic sleep-listen operations, schedule selection, co-ordination, synchronization, access control, data exchange and message passing were elaborated. Moreover the significant and unique aspects of the proposed scheme like Channel Adaptive MAC protocol, channel quality estimation, link quality estimation, cross layer interaction and Traffic Aware DPM were discussed in detail. Finally the complete proposed algorithm and the performance evaluation factors were also detailed.

5

LOAD PREDICTION ALGORITHM WITH ADAPTIVE THRESHOLD MANAGEMENT SCHEME

Chapter 5

In this chapter, the limitation of the previous work is discussed. The proposed scheme had made sincere efforts to optimize *Energy efficiency* but could not achieve fair resource allocation. The poor quality nodes were deprived of transmission until the channel quality rises to the desired level, thus sacrificing *Fairness*. To provide *Fairness* to the poor quality nodes, a Load Prediction Algorithm with an Adaptive Threshold Adjustment scheme is proposed in this chapter. The details of the Load Prediction Algorithm and the performance factors with which this algorithm is evaluated are also discussed.

5.1 WORK DONE IN PHASE 1

It has been explained in Chapter 4 that in this work, an Energy efficient Channel Adaptive Medium Access Control protocol with Traffic Aware Dynamic Power Management (AEMAC) is proposed for competent packet scheduling and queuing in sensor networks. The time varying characteristics of wireless channels, which are neglected in most existing schemes, are also taken into account. A network system has been used to execute the fundamental idea of this protocol, which integrates multiple schemes in an actual situation, wherein each sensor node chooses the state of the communication equipment, considering the link condition, channel condition and energy status. Energy utilization during packet transmission through a poor quality link is more compared to a better quality link. So if energy transmission is allowed through a bad quality link, it will lead to loss of precious battery resources. Communication is allowed only between highly efficient nodes and packet scheduling is done only in the most optimum paths. A node having a low weight value is sent to the sleep state. Thus energy conservation is being achieved. Transmission through an unfavorable path is always prevented. To achieve better energy savings, nodes in the routing path come to the active state only at the onset of data transmission. Otherwise they are in the power saving mode. Thus nodes are classified as Current Transmitting Sensor in a high power level, Future Transmitting Sensor in a lesser power level and No Transmitting Sensor in the lowest power level, depending on the state defined by the data transmission. Dynamic Power Management, considering the channel state is implemented in this protocol. The radio interface of the redundant nodes not involved in routing are turned OFF thus attaining the DPM objective. The transmission of the other nodes having low weight value will be deferred until the weight value turns high. The packets are temporarily buffered until the channel quality rises to the required threshold. Energy is saved by wisely switching to sleep state whenever possible. A traffic aware DPM scheme is thus designed in this section.

5.2 LIMITATIONS OF PHASE 1 WORK

It was stated that, the nodes Ni with $W_i > W_{min}$, where W_{min} is the minimum threshold value, can be selected from the sorted list and allowed to transmit. This was a technique developed to permit transmission only between nodes having sufficient energy reserves, good link quality and good channel quality. Nodes N_j attempting to access the wireless medium with $W_j < W_{min}$, are not allowed to transmit. They will be allowed to transmit again when $W_j > W_{min.}$ This method can achieve its aim of maximizing the *Energy efficiency* since there will be very low power loss as the bad links are not included in the routing path.

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 have to wait until its channel quality recovers, which may lead to starvation. This invokes the idea of tackling the *Fairness* issue which is an important performance parameter in wireless sensor networks. The unfairness problem can cause serious problems like packet overflow and long queuing delay for the nodes with poor link quality.

A Medium Access Control protocol is considered to be fair, if it can allocate the channel resources evenly, especially channel capacity, among all the competing communicating nodes. *Fairness* in wireless sensor networks is desirable to achieve equitable Quality of Service (QoS) and avoid situations where some nodes happen to perform much better than the other nodes. This is based on the assumption that all the nodes in a sensor network have the same demands. The network should be able to support various traffic sources with various traffic generation patterns and a large range of QoS requirements.

In Phase 1, fair resource allocation was difficult to achieve while *Energy efficiency* was being optimized; since nodes with poor link and channel quality were always deprived of their transmission. Thus the time varying characteristics of the wireless links which is a major issue in wireless sensor networks makes it difficult to achieve *Fairness*. The resulting starvation problem experienced by a small portion of nodes has to be dealt with.

5.3 ADAPTIVE THRESHOLD ADJUSTMENT SCHEME

To avoid buffer overflow and achieve *Fairness* for the poor quality nodes, a Load prediction algorithm is designed. In the Load prediction algorithm, the minimum quality threshold W_{min} is adjusted 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 tendency for a buffer overflow, the threshold is adaptively adjusted, based on the predicted traffic load. i.e., threshold will be decreased or increased if the traffic load is increasing or decreasing, respectively. Thus, a balance between *Energy efficiency* and *Fairness* can be achieved.

A natural solution to this starvation problem, which happens to be the case of some nodes getting deprived of the available network resources, is to adjust the minimum quality threshold value W_{min} adaptively, depending on the current traffic load and queue length of the buffer.

To reduce the buffer overflow and increase the *Fairness*, an Adaptive Threshold Adjustment scheme, based on Load Prediction, is designed.

Buffer overflow can be prevented by predicting the traffic load. This can be achieved by the real time monitoring of the queue length and its variation for a sampling period.

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

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

Then, QLt_i , $QLt_{i+s,}$ QLt_{i+2s} , ... is the sequence of queue lengths at time instants t_i , t_{i+s} , t_{i+2s},………… ,where s is the sampling interval for the 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 queue variation at time $t_{i+2s.}$

If $\Delta V > 0$, then the queue length has an increasing tendency; otherwise, if $\Delta V < 0$, the queue length is likely to decrease.

Based on the prediction of the queue length variation, a threshold adjustment scheme is developed. The incoming traffic is constantly monitored and once the queue length becomes equal to a value QL_{max}, the threshold adjustment mechanism is started up.

5.4 LOAD PREDICTION ALGORITHM

In the Load Prediction algorithm, the minimum quality threshold W_{min} is adaptively adjusted based on the current incoming traffic load TL. The buffer and queue length values of the node are continuously monitored for a specified period. The traffic load TL is predicted based on the queue length variations in that period. If there is a tendency for a buffer overflow, the threshold is adaptively adjusted, based on the predicted traffic load. i.e., threshold will be reduced if the traffic load is increasing or increased if the traffic load is decreasing. Thus, a balance between *Energy efficiency* and *Fairness* can be achieved.

1. For each packet arrived at time t_{i+2s}
    - 1.1 Find $Vt_{i+2s} = QLt_{i+2s} - QLt_{i+s}$
    - 1.2 If $QLt_{i+2s} = Q_{max}$ then
        - 1.2.1 Find $\Delta V = Vt_{i+s} - Vt_i$
        - 1.2.2 If $\Delta V > 0$ then
            - 1.2.2.1 $W_{min} = W_{min} - \delta$, where δ is the scale factor
        - 1.2.3 else if $\Delta V < 0$ then
            - 1.2.3.1 $W_{min} = W_{min} + \delta$
        - 1.2.4 end if
    - 1.3 end if
2. end for

5.5 PERFORMANCE EVALUATION

Performance of this enhanced protocol is evaluated, for different performance factors like *Bandwidth, Delay, Delivery ratio, Fairness* and *Throughput* with respect to *Error rate* in a wireless sensor network, using the Network Simulator NS2. The aim was to create variable error prone network situations and thus validate and prove the better performance of this protocol, compared to the already existing protocol SMAC. The results are cited in Chapter 6.

5.6 SUMMARY

Chapter 5 provided an overview of the drawbacks of the Channel Adaptive MAC protocol with Traffic Aware DPM. It could not provide *Fairness* to the poor quality nodes leading to node starvation and buffer overflow. To achieve *Fairness*, which is an important performance metric of any MAC protocol, a Load Prediction Algorithm with Adaptive Threshold Adjustment scheme was proposed. In the last section, the details of this algorithm and the performance factors for evaluating its performance were specified.

6

SIMULATION RESULTS AND ANALYSIS

Chapter 6

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 *Delay, Throughput, Stability, Delivery ratio* and *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.

PARAMETERS	VALUE
Transmission power	0.395 watts
Reception power	0.360 watts
Initial node energy	2.7 Joules
Maximum number of packets in Interface queue	500
Packet size	500 bytes
Transmission rate (set up 1)	100 Kbps
Number of nodes (set up 1)	varied from 25 to 100
Transmission rate (set up 2)	varied from 100 Kbps to 500 Kbps
Number of nodes (set up 2)	50

Table 6.1: Simulation settings for Phase 1

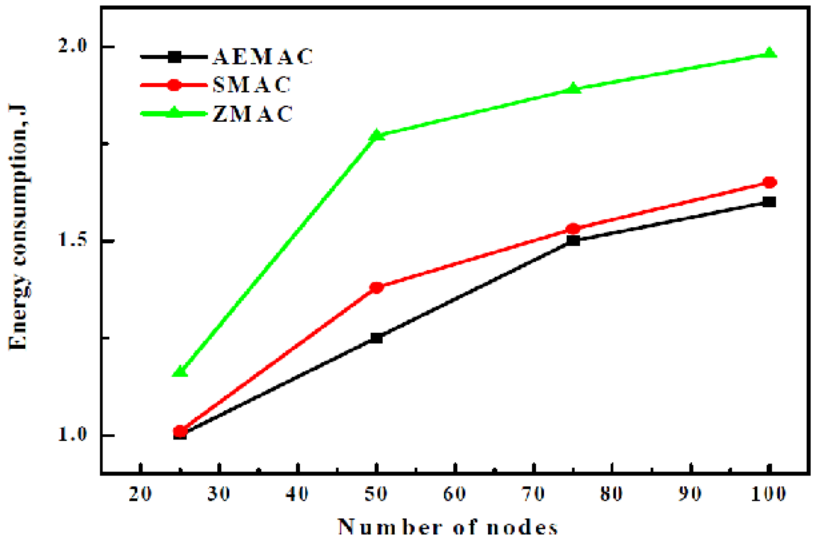


Figure 6.1: Variation of Energy consumption with respect to Number of nodes

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.

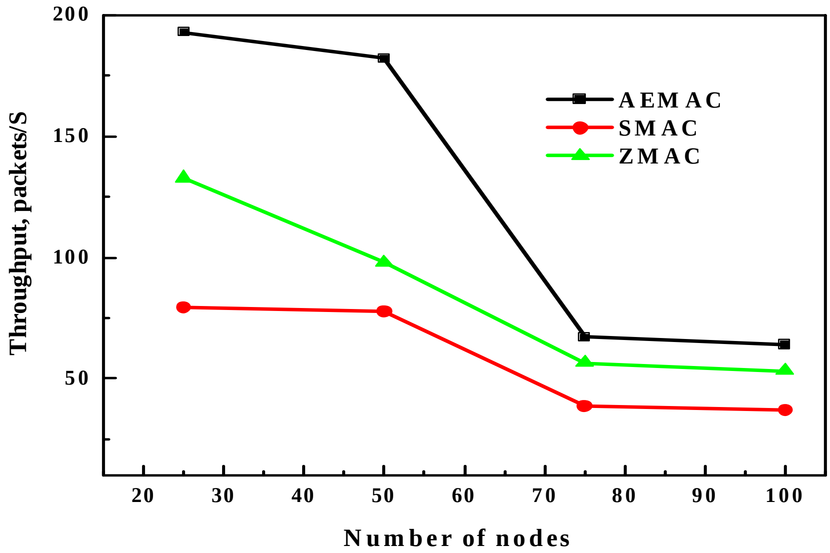


Figure 6.2: Variation of Throughput with respect to Number of nodes

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.

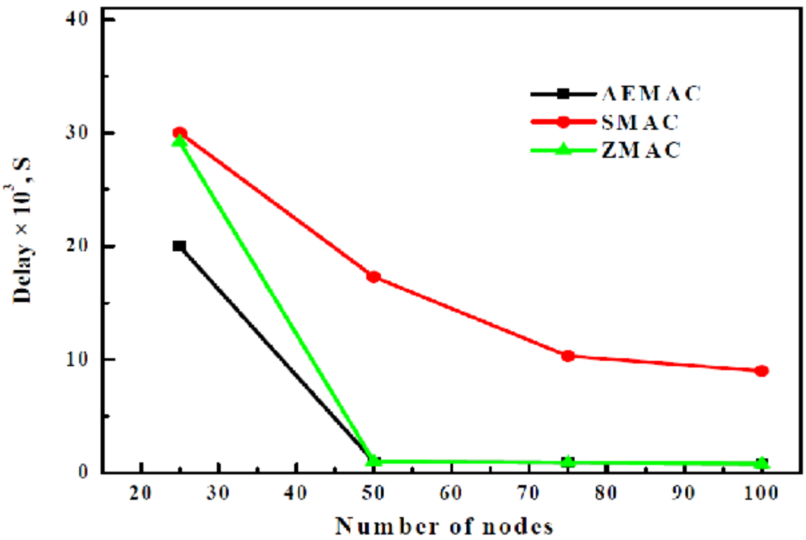


Figure 6.3: Variation of Delay with respect to Number of nodes

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*.

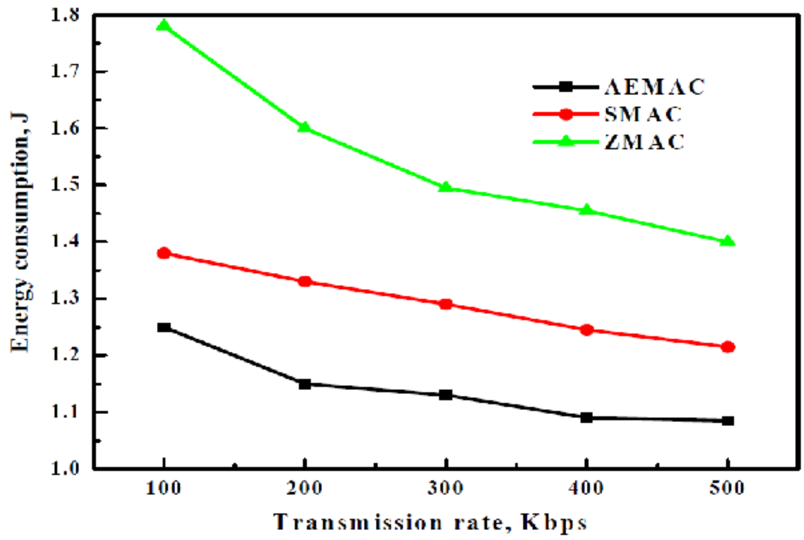


Figure 6.4: Variation of Energy consumption with respect to Transmission Rate

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.

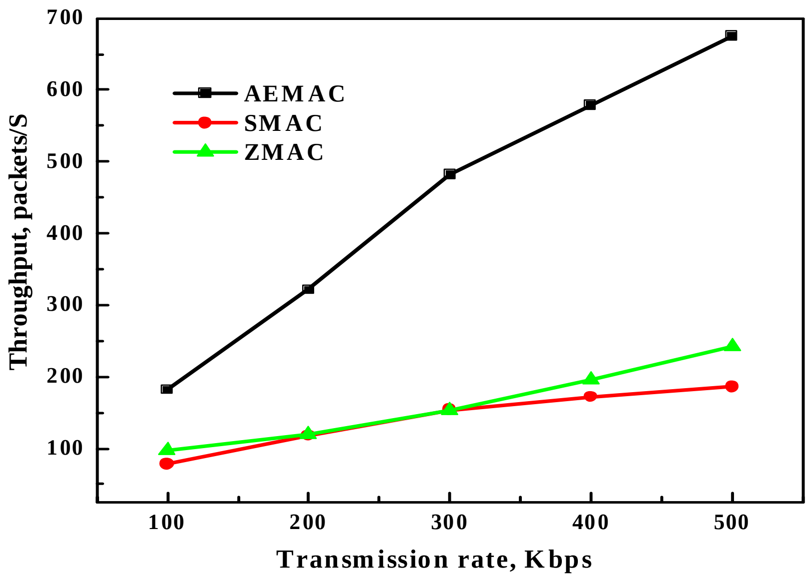


Figure 6.5: Variation of Throughput with respect to Transmission Rate

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.

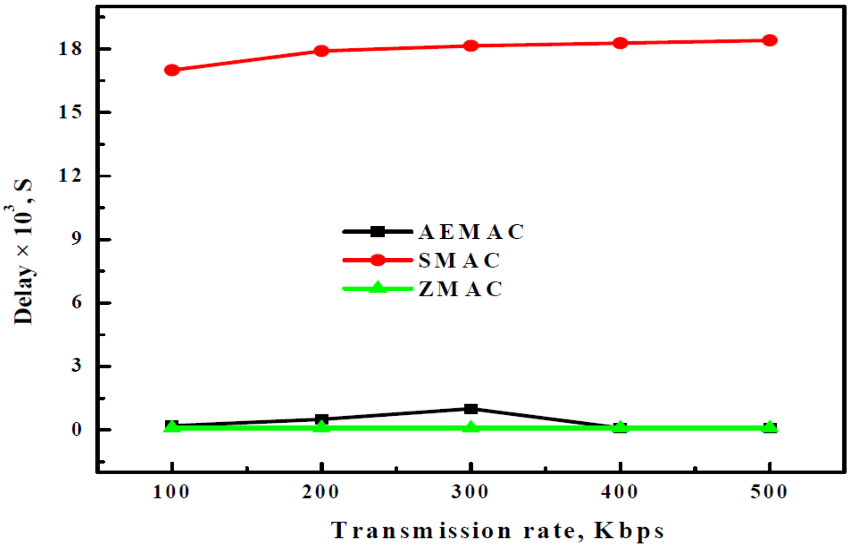


Figure 6.6: Variation of Delay with respect to Transmission Rate

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 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*.

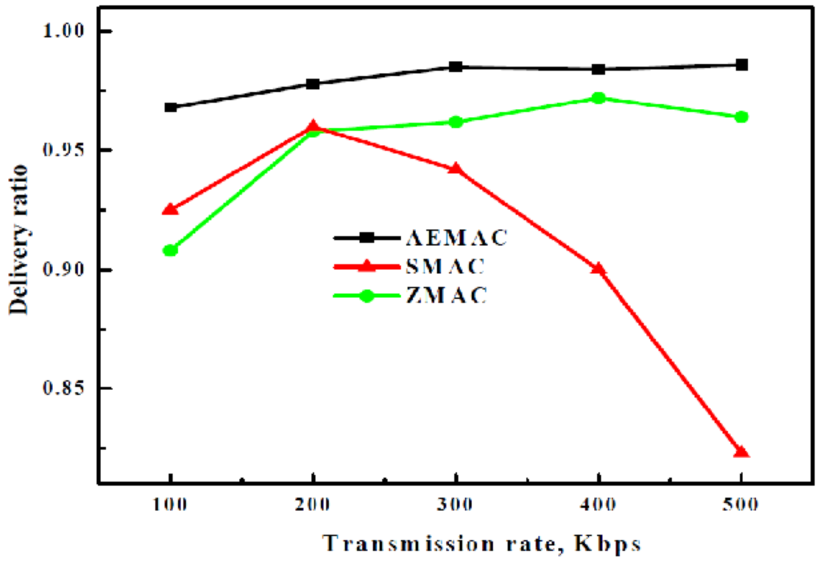


Figure 6.7: Variation of Delivery Ratio with respect to Transmission Rate

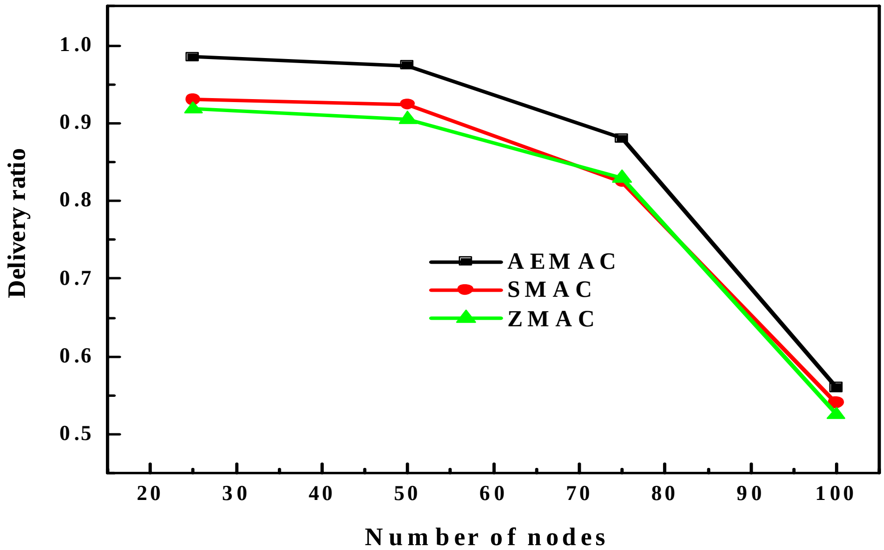


Figure 6.8: Variation of Delivery Ratio with respect to Number of nodes

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 *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 *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 *Delivery ratio* attained by the AEMAC scheme. Even when the number of flows increases, it maintains a higher *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 *Delivery ratio*.

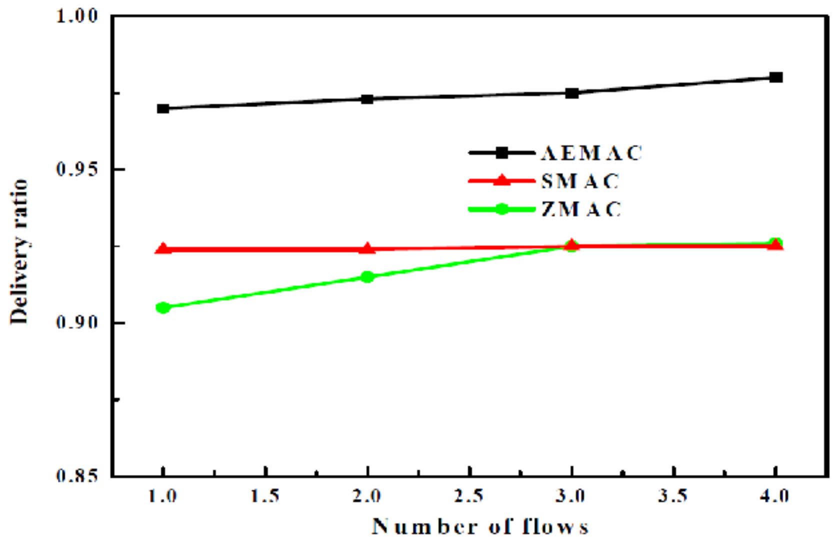


Figure 6.9: Variation of Delivery Ratio with respect to Number of Flows

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.

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	0.395 w
Receiving Power	0.360 w
Idle Power	0.335 w
Initial Energy	4.0 J
No. of. Flows	1, 2, 3 and 4
Rate	100Kb,200Kb,…..500Kb
Error Rate	0.01,0.02,….0.05

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.

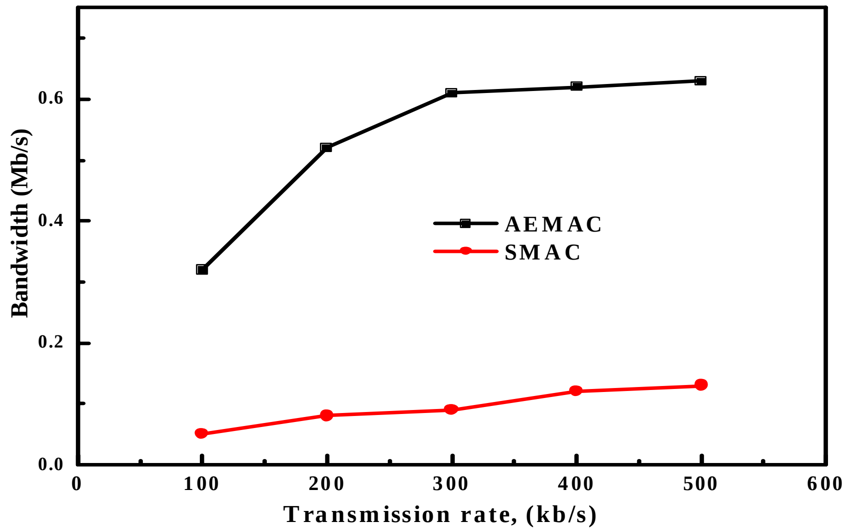


Figure 6.10: Variation of Bandwidth received with respect to Transmission rate

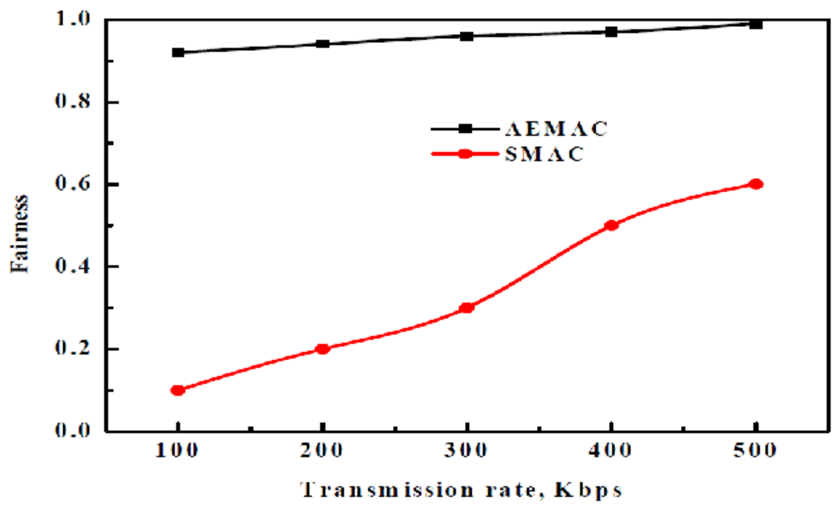


Figure 6.11: Variation of Fairness with respect to Transmission rate

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.

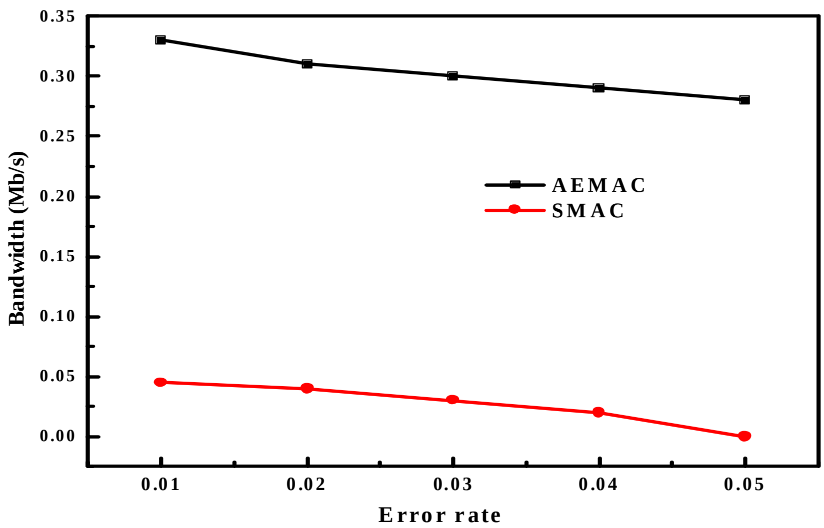


Figure 6.12: Variation of Bandwidth received with respect to Error rate

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.

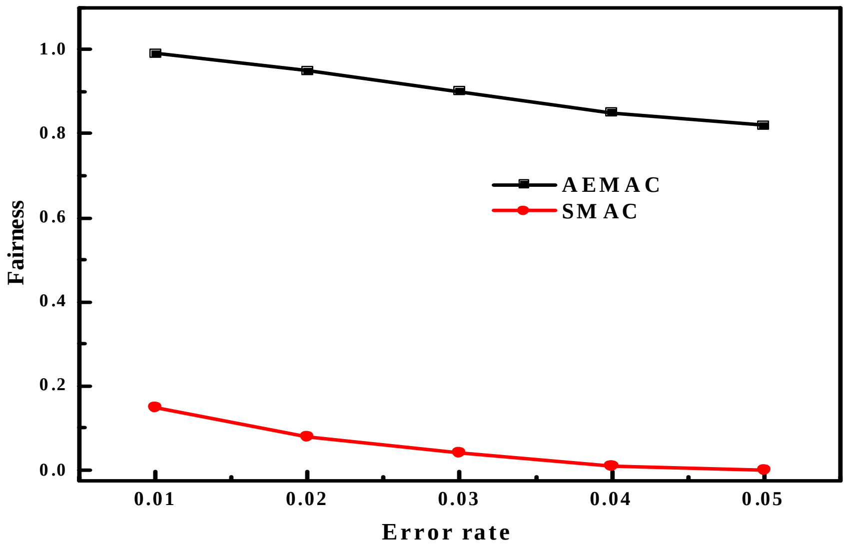


Figure 6.13: Variation of Fairness with respect to Error rate

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.

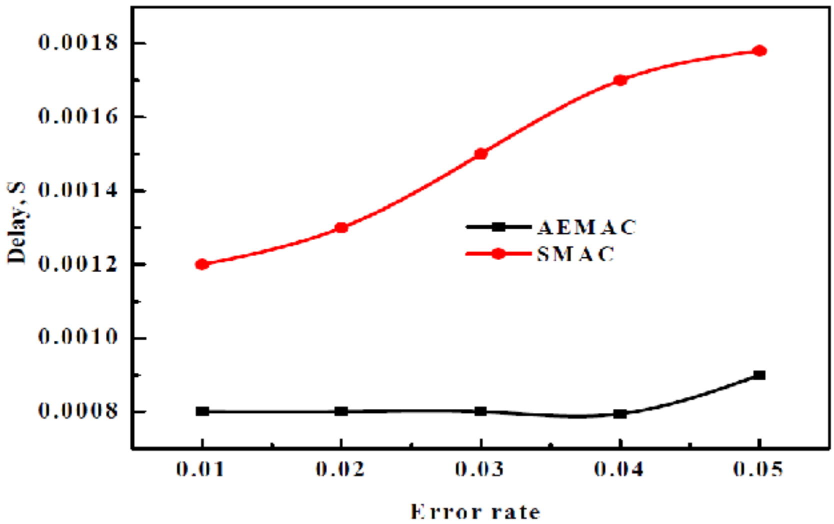


Figure 6.14: Variation of Delay with respect to Error rate

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.

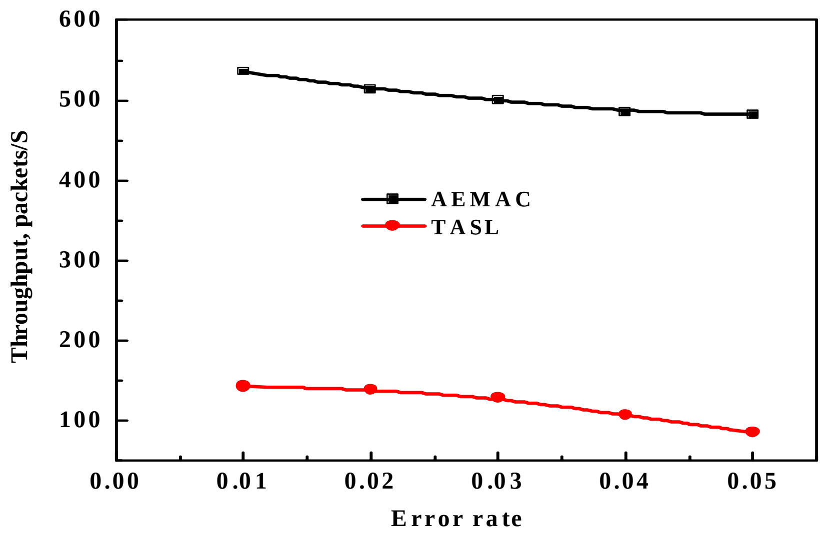


Figure 6.15: Variation of Throughput with respect to Error rate

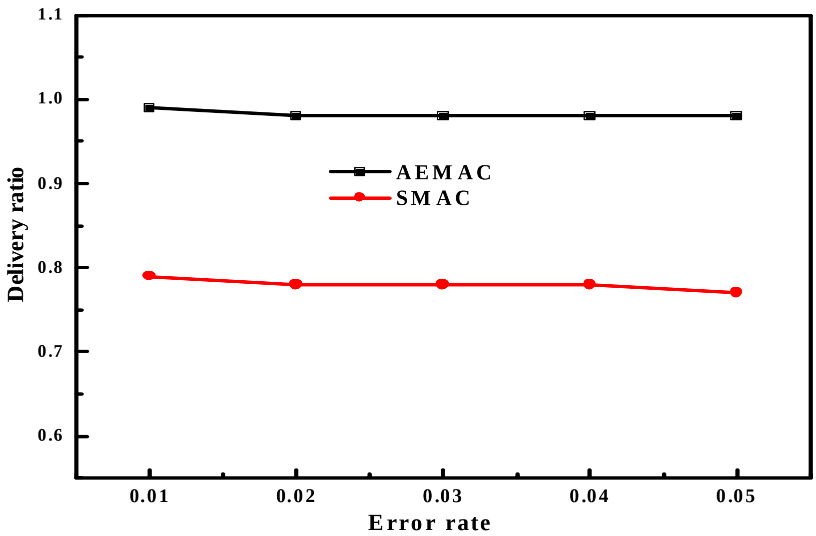


Figure 6.16: Variation of Delivery ratio with respect to Error rate

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

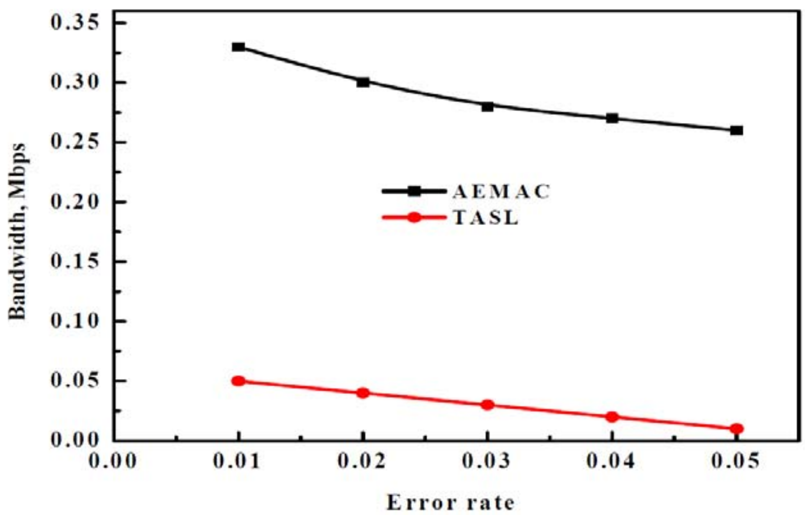


Figure 6.17: Variation of Bandwidth with respect to Error rate

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

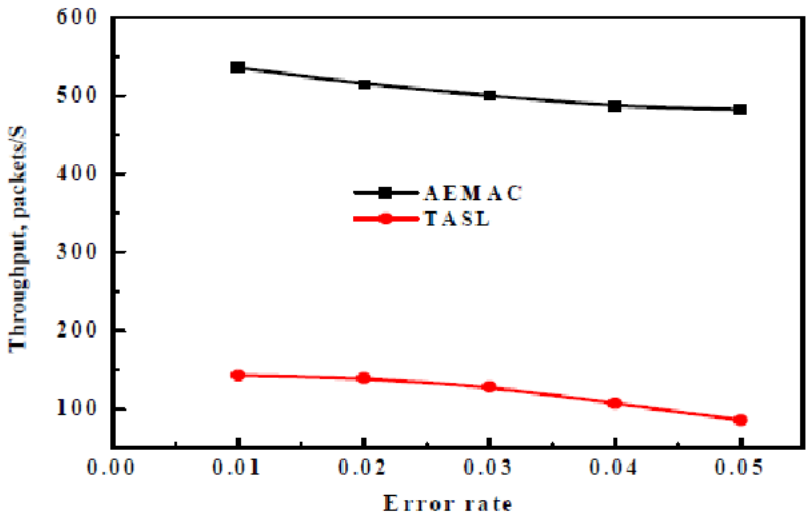


Figure 6.18: Variation of Throughput with respect to Error rate

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

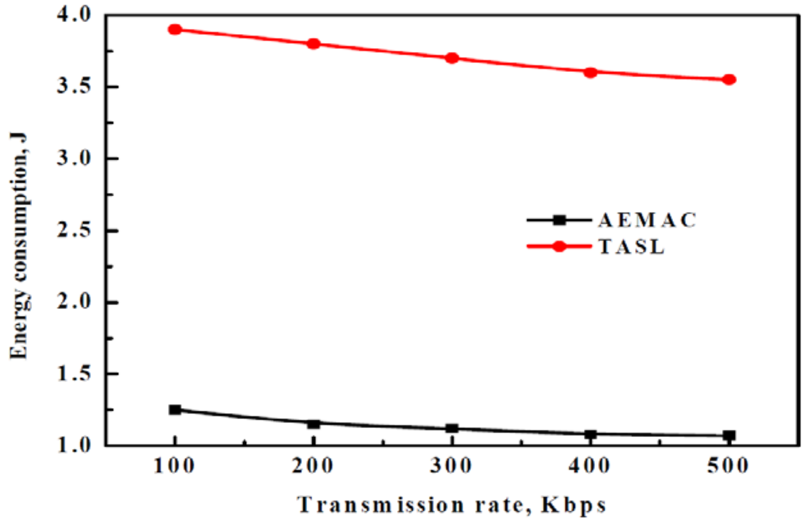


Figure 6.19: Variation of Energy consumption with respect to Transmission rate

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 C*hannel 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.

7

CONCLUSIONS AND SCOPE FOR FUTURE WORK

In this chapter, the performance of the AEMAC scheme, which takes into account the time varying nature of wireless channels in a wireless sensor network and the cross layer interaction between the Physical layer, MAC layer and the Network layer, is discussed. The extensive simulations conducted have demonstrated that the behavior of wireless channels can greatly influence the network *Energy Consumption*. The conclusions observed and the scope for future research work is briefly illustrated below.

Wireless ad hoc networks of battery powered micro sensors are proliferating rapidly and transforming the way information is gathered, processed and communicated. These networks are envisioned to have hundreds of inexpensive sensors with sensing, data processing and communication components. They typically operate in unattended mode, communicate over short distances and use multi hop communication. Many challenges are introduced due to the limited energy, large number of sensors, unfriendly working environment and nature of unpredictable deployment of the sensor network. Energy conservation is found to be the foremost among them since it is often cost prohibitive or infeasible to replenish the energy of the sensors. This energy problem in wireless sensor networks remains one of the major barriers somehow preventing the complete exploitation of this technology. Efficient Energy Management is proved to be the key requirement for the credible design of a wireless sensor network.

The general framework for energy efficient data acquisition is based on a duty cycle approach requiring the sensor to be switched OFF during idle time. Dynamic Power Management is an effective tool in reducing the system power consumption without degrading the performance. The quality of wireless channels or the network topology can change rapidly even in a static network. Routing protocols should quickly detect these dynamics and take measures to maintain robust and efficient routing paths. This needs to be considered in the design of a wireless sensor network. Moreover a cross layer design on power aware communication, considering the time varying nature of wireless channels, is needed to optimize the energy usage. In this work, all the above mentioned ideas are incorporated. Here each sensor node judiciously accesses the wireless medium and communication activity is reduced for those sensor nodes, under poor channel conditions. Hence the time varying nature of wireless channels are taken into account in this work, in the optimization of energy management in a wireless sensor network.

7.1 CONCLUSIONS

- For an increase in the node density, *Energy Consumption* increased for AEMAC, SMAC and ZMAC schemes, due to the increase in routing involved. AEMAC scheme exhibited the lowest *Energy Consumption*, since more nodes are brought to the sleep state, on an increase in the node density. Moreover the mandatory wake up involved in the other power saving schemes, is not used here leading to its better performance compared to the other schemes. ZMAC scheme showed the maximum *Energy Consumption*.
- For an increase in node density, *Throughput* decreased for AEMAC, SMAC and ZMAC schemes. This may be due to the more routing decisions involved on an increase in node density resulting in less fraction of the channel capacity being used for data transmission. The improved methodology of the AEMAC scheme led to its increased *Throughput*.
- On an increase in node density, *Delay* decreases for all the three schemes AEMAC, SMAC and ZMAC. This is due to the large number of nodes getting involved in routing, which results in quicker data delivery to the sink through these nodes. Later *Delay* settles to a steady value in all the three schemes. AEMAC scheme exhibited the lowest *Delay* and SMAC scheme showed the largest *Delay*.
- An increase in *Transmission Rate* provided a decrease in *Energy Consumption* for all the three schemes AEMAC, SMAC and ZMAC; since all the schemes use their power conservation methods effectively in

transmitting the large number of data packets transmitted per unit of time. Moreover the start up energy overhead also decreases on an increase in the *Transmission Rate*. AEMAC scheme showed the lowest *Energy Consumption* and ZMAC scheme showed the highest *Energy Consumption*. So an increase in *Transmission Rate* can be opted as a good method to decrease the *Energy Consumption* in a wireless sensor network.

- On an increase in the *Transmission Rate*, *Throughput* increases for AEMAC, SMAC and ZMAC schemes because the large amount of data which is transmitted gets serviced by the communication system. AEMAC scheme provided a very large *Throughput* compared to the other two schemes. Thus an increase in the Transmission Rate can be an effective method to increase the *Throughput* in a wireless sensor network.
- An increase in *Transmission Rate* initially provided a slight increase in *Delay* for SMAC and AEMAC schemes. AEMAC scheme provided the minimum *Delay* along with ZMAC scheme and SMAC scheme provided the maximum *Delay*. So static schemes prove to provide higher *Delay* in a wireless sensor network. Also the increase in *Transmission Rate* has very little effect on the *Delay* encountered by the data packets in a wireless sensor network.
- An increase in the *Transmission Rate* provided a better *Delivery Ratio* for AEMAC and ZMAC schemes. The *Delivery Ratio* of SMAC scheme which was initially higher than ZMAC scheme for a lower *Transmission Rate*, stooped to a low value on an increase in the *Transmission Rate*. Thus in a wireless sensor network, the better performance of the static schemes in terms of *Delivery Ratio* gets degraded on an increase in the *Transmission Rate*. Also the increase in the *Transmission Rate* can provide a better

Delivery Ratio in a wireless sensor network which uses effective route selection policies.

- As the node density increases, the *Delivery Ratio* decreases for all the three schemes AEMAC, ZMAC and SMAC. AEMAC scheme exhibits the highest *Delivery Ratio* compared to the other schemes.
- As the number of flows increases, *Delivery Ratio* increases slightly for AEMAC and ZMAC schemes. AEMAC scheme shows the maximum *Delivery Ratio* and ZMAC scheme provides the minimum *Delivery Ratio*.
- For an increase in the *Transmission Rate*, AEMAC scheme could receive a much higher *Bandwidth* compared to the SMAC scheme. In wireless sensor networks, increase in the *Transmission Rate* can be opted for increasing the Bandwidth in the network.
- On an increase in the *Transmission Rate*, *Fairness* increases considerably for the AEMAC scheme compared to the SMAC scheme. So to achieve better *Fairness* in a wireless sensor network, the increase in *Transmission Rate* can be selected as an optimum method.
- The *Bandwidth* decreases in a wireless sensor network having a higher *Error Rate*. But the decrease is lesser in a network which adopts channel adaptive schemes thus proving the better performance of the AEMAC scheme compared to the SMAC scheme.
- *Fairness* decreases in a wireless sensor network having a higher *Error Rate* and the SMAC scheme shows a very low *Fairness* compared to the AEMAC scheme. In a wireless sensor network with varying channel conditions, it is difficult to achieve Fairness. The Load Prediction algorithm

and the Threshold adjustment scheme of AEMAC scheme accounts for the increased *Fairness*, even in a network with a higher error rate.

- In a wireless sensor network, on an increase in the *Error Rate*, the *Delay* increases considerably for SMAC scheme compared to the AEMAC scheme. If proper channel adaptive schemes are used in a wireless sensor network, the *Delay* encountered by the data packets can be considerably reduced, which is proved in the superior performance exhibited by the AEMAC scheme.
- On an increase in the *Error Rate* in a wireless sensor network, the *Throughput* decreases. The AEMAC scheme provides a much higher *Throughput* compared to the SMAC scheme proving that channel adaptive protocols can be used effectively in a wireless sensor network, with varying channel conditions.
- On an increase in the *Error rate*, the *Delivery Ratio* decreases initially and then remains almost constant for both AEMAC and SMAC schemes. AEMAC scheme shows a better *Delivery Ratio* compared to the SMAC scheme at high error rates, proving that the channel adaptive techniques adopted in the AEMAC scheme can provide a better performance in a wireless sensor network, with varying channel quality.

7.2 SCOPE FOR FUTURE WORK

This work had implemented an Energy efficient Channel Adaptive MAC protocol in a wireless sensor network with static nodes. This scheme had provided improvement gains in *Energy efficiency, Throughput, Delay, Bandwidth and Delivery Ratio*. But the superior nature of this scheme depends on many environmental factors, such as operation scenarios, specific data types etc. Thus more research work needs to be done in future to find the respective application scenarios for this scheme with all the related factors taken into consideration. This technique needs to be implemented in a wireless sensor network with mobile nodes, since mobility was not taken into account in this work. The effects of very large node densities need to be investigated. Multi hop routing was adopted in this work. The feasibility of using the clustering technique and data aggregation needs to be tested in the same wireless sensor network. In this work, energy problem was not tackled at the Transport layer. Means to devise this scheme from the Transport level view point needs to be explored.

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