# INTRODUCTION

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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:**

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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 \textit{Energy efficiency}.

\textit{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 \textit{Fairness} without compromising \textit{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 \textit{Energy efficiency} and \textit{Fairness} in a wireless sensor network are aimed at, in this work.

\textbf{1.10 OVERVIEW OF RESEARCH}

In this work, \textit{Energy efficiency} is the main factor that is dealt with, along with improving other factors like \textit{Throughput}, \textit{Delay}, \textit{Delivery ratio}, \textit{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 \textit{Fairness}. Thus a balance between \textit{Fairness} and \textit{Energy efficiency} could be achieved.

\textbf{1.11 LAYOUT OF THESIS}

The thesis is organized as follows.

\textbf{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.

\textbf{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.

\textbf{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 \textit{Throughput}, \textit{Delay}, \textit{Energy efficiency}, \textit{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.

\textbf{Chapter 4} discusses the Channel Adaptive MAC protocol and the Traffic Aware Dynamic Power Management Scheme which was adopted for achieving \textit{Energy efficiency}.  

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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.