This chapter introduces the concept of ad hoc network and its applications. A major
section of this chapter covers the concept of energy conservation in mobile ad hoc
networks and the related work that form the basis of this thesis. Further, the scope and
objectives of the work, simulation tools, and the various metrics used for evaluation
of proposed protocols are given. This chapter also includes the accomplishments and
Contribution of the work. Finally, the organization of thesis is described.

1.1 Ad Hoc Network

A Mobile ad hoc network (MANET) is a LAN or a small network of wireless mobile
nodes which communicate with each other in the absence of a fixed infrastructure. In
MANET a node consists of a router, possibly with multiple hosts and wireless
communication device. Thus, each node works as a router and a host. MANET are
formed based on the cooperation among participating nodes and willingness of every
node to forward messages to make sure that messages are delivered from source to
destination in a multi-hop route. Ad hoc networks are useful for applications such as
disaster recovery, automated battlefields, agriculture fields, security and vigilance,
search and rescue, crowd control, conferences, meetings, and lectures where central or
fixed infrastructure is not available [48, 62].

According to IETF [14] a MANET is defined as follows:

A "mobile ad hoc network" (MANET) is an autonomous system of mobile routers (and
associated hosts) connected by wireless links the union of which forms an arbitrary
graph. The routers are free to move randomly and organize themselves arbitrarily;
thus, the network's wireless topology may change rapidly and unpredictably. Such a
network may operate in a standalone fashion, or may be connected to the larger Internet via gateway routers.

One of the major issues and challenges in design, deployment and performance of an ad hoc wireless system is energy saving [62, 12]. In view of the necessity of energy saving, the present thesis focuses on the comparative study and experimentation of various existing energy efficient protocols as well as proposing new protocols that result in conserving more energy.

1.2 Energy Conservation in Ad Hoc Networks

The nodes in ad-hoc networks are battery operated and have limited energy resources. This makes energy efficiency a key concern in ensuring system longevity. Further, studies have shown that the communication subsystems consume a large fraction of total energy and therefore, solutions for energy efficient communication are of great interest. Moreover, under some circumstances, MANET has to be deployed in remote or hostile areas. This makes it impossible to replace or recharge the batteries. Therefore, it is desirable to keep the energy-dissipation level as low as possible to avoid frequent battery replacement. Energy conservation has posed a big challenge due to MANETs’ nature of distributed control, constantly changed network topology and the fact that mobile nodes in MANETs usually are hand-held devices.

In mobile ad hoc networks, energy efficiency is more important than other wireless networks. Due to the absence of an infrastructure, mobile nodes in ad hoc network must act as a router. Since a MANET is a 'cooperative' network, the nodes join in the process of forwarding packets. Therefore, traffic loads on nodes are heavier than in other wireless networks with fixed access points or base stations. A communication-related energy consumption function is needed to design a system to limit unnecessary power consumption. Energy efficiency design issue must consider the trade-offs between different network performance criteria. For example, routing protocols usually try to find a shortest path from a source to a destination. It is likely that some nodes which are on so called 'key positions' will over-serve the network and their
energy will be drained quickly, and thus cause the network to 'break'. To avoid this, the energy-efficient design should balance traffic load among nodes such that low-power nodes can be idle while traffic is routed through other nodes.

1.2.1 Classification

After comprehensive survey and huge study of the previous research works about the energy conservation approaches in mobile ad hoc networks, the energy conservation solutions are generally classified into three categories:

1. Transmission Power Control,
2. Power-Aware Routing, and

1.2.1.1 Transmission Power Control

The transmission power determines the range over which the signal can be coherently received, and is therefore crucial in determining the performance of the network (in terms of throughput and energy consumption). Therefore, the transmit power level determines the transmission range, the quality of the signal received and the interference it creates for the other receivers. Power control has been studied primarily as a way to improve energy efficiency of MAC protocols for wireless ad hoc networks. In addition to power saving, the power control schemes also used to improve the spatial reuse of the wireless channel to increase the network throughput.

The use of the maximum power level leads to excessive interference and less opportunity for spatial reuse which increases energy consumption and severely limits the aggregate throughput [20]. Also, higher power level results in a large number of neighboring nodes on an average. Therefore, the cost of maintaining neighboring information increases and it may also increase energy consumption of these neighbors as they get involved in the routing activities.

On the other hand, the use of a small power level at each node can conserve more energy, increase spatial reuse and reduce radio interference. A higher network
capacity can be achieved by transmitting packets to the nearest neighbor in the forward progress direction. The intuition behind this result is that halving the transmission range increases the number of hops by two but decreases the area of the reserved floor to one fourth of its original value, hence allowing for more concurrent transmissions to take place in the same neighborhood. However, this may result in a disconnected network [72]. Therefore, the power levels of nodes define the connectivity structure or the topology of the network. That means the transmission power control can be used as a means of controlling network topology.

The above discussion provides sufficient motivation to dynamically adjust the transmission power for data packets. However, there are many open questions at this point, perhaps the most interesting being whether transmission power control is a network layer or MAC-layer issue. The interaction between the network layer and MAC layer is fundamental to power control in MANETs. On the one hand, the power level determines who can hear the transmission, and hence directly impacts the selection of the next hop. Obviously this is a network layer issue. On the other hand the power level also determines the floor that the node reserves exclusively for its transmission through an access scheme. Obviously this is a MAC-layer issue. Power control has to be introduced from the perspectives of both layers.

A significant energy saving can be provided with the use of the transmission power control with directional antennas. The gains of these antennas are typically much higher than the omni-directional case making them influential in reducing the power required between a transmitter and receiver. Therefore, directional antenna achieves more energy saving by distributing the energy directionally and purposely. Moreover, when dealing with a non-uniform radiation pattern for switched beam antennas, antenna orientation needs to be considered. The positioning of a node’s antenna decides how much power each of its communication links incur. Thus, topology control algorithms need to find power assignments as well as antenna orientation for each node to optimize the power-based cost metric under consideration [67].
The IEEE 802.11 physical layers provide multiple transmission rates by employing different modulation and channel coding schemes. Therefore, many adaptive rate MAC protocols have been mainly proposed to improve the network throughput. Recently, very few MAC protocols have been proposed by combining the transmit power and data rate into one scheme. The purpose behind this cross layers approach is to find an efficient transmission strategy to save more power and maximizing the network throughput.

1.2.1.2 Power Aware Routing

Traditional routing protocols tend to use the shortest path algorithms (minimum hop count) without any consideration of energy consumption. This often results in rapid energy exhaustion for the small subset of nodes in the network that experience heavy traffic load. The purpose of the power aware routing is to find an energy efficient route from the source to the destination. Such kind of routing is generally based on two main objectives. The primary objective is to maximize the time till a node runs out of battery power. The reason behind such objective is to maximize the overall network lifetime. Essentially, the design principle of power-aware routing is to equally balance energy expenditure among mobile nodes to prolong network lifetime, while at the same time conserving overall power consumption as much as possible. In other words, power aware routing protocols try to balance rather than save energy consumption. This requires taking into account the energy resources available at nodes and significantly increases the complexity of selecting optimal routes. The second objective is to minimize the total transmit power consumed by all nodes on the path. Thus, it is likely to have more number of hops than when using a conventional routing protocol with the minimum number of hops.

Different power aware metrics have been proposed to achieve the goals of the above objectives. Singh [61] proposed five power-aware metrics that can be used to classify routing protocols. These metrics are based on battery power level and energy consumption at each node. There are three important factors that one must consider in designing power aware routing protocols. First, balanced energy consumption does
Chapter 1

not necessarily lead to minimized energy consumption, but it keeps certain nodes from being overloaded and thus ensures a longer network lifetime. Second, factors dealing with energy awareness can be implemented at the routing layer with or without help from other layers such as the MAC layer. Third, some routing protocols assume availability of node position information and under this assumption, finding a low power path becomes a conventional optimization problem.

1.2.1.3 Power Management

Transmission power control and power aware routing approaches consider reducing the cost of communication of mobile nodes operated in active periods. It has been observed that in ad hoc networks, energy consumption does not always reflect active communication in the network [37]. Wireless devices suffer from another unique problem of idle listening consumed energy. Ideally, a node that is not sending or receiving data should be in the sleep state. However, a node may have to forward data for other nodes and therefore, by default all nodes are in the listen mode. Listening consumes substantial energy and reducing this overhead is important [57]. Meanwhile, power management aims to intelligently put a device’s wireless interface into an idle or sleep state. The MAC layer is designed to identify certain nodes that are not involved for forwarding the data and to change their state to sleep mode.

1.2.2 Survey

Energy-efficient design for mobile ad hoc networks is a cross-layer topic. It spans almost all layers of the communication protocol stack from physical layer to application layer. Each layer has access to different types of information about the communication in networks, and thus uses different mechanisms for energy conservation. Goldsmith [18] addresses the design challenges of energy-efficient protocols in various layers and places special emphasis on cross-layer design of these protocols. As a result many energy conserving solutions have been proposed from a variety of perspectives. This section presents a comprehensive survey of the previous
works addressing energy saving design within all layers of the wireless network protocol stack.

1.2.2.1 Transmission Power Control

Power control has been studied primarily as a way to improve energy efficiency of MAC protocols for wireless ad hoc networks. In [24, 52, 53] nodes transmit RTS-CTS at maximum power, $P_{\text{max}}$, but send DATA/ACK at minimum necessary power $P_{\text{min}}$. The minimum necessary power $P_{\text{min}}$ varies for traffic pairs with different transmitter-receiver distance, and different interference levels at the receiver side. This scheme is referred to as the BASIC power control scheme. However, the authors of [28, 36] have mentioned that these schemes result in a significant increase in the number of interference nodes that cause collisions at the receiver with DATA packets and at transmitter with ACK packets. It therefore, results in higher energy consumption than using IEEE 802.11 without power control. The adaptive transmission power assignment algorithm in [1] determines the transmission power of the current frame based on the status of the last frame it transmitted to the same destination. The authors in [29] studied the relationship between RTS, CTS, DATA and ACK and then proposed an adaptive power control algorithm that relies on this relationship.

In [28], the authors propose PCM protocol that operates similarly to the basic power control scheme, except that the power level is periodically raised to $P_{\text{max}}$ from $P_{\text{min}}$ for a very short time during the transmission of the DATA packet. PCM achieves a comparable network throughput with IEEE 802.11 and consumes lower energy. Although this scheme provides energy saving compared to the other power control schemes but it does not yield improved spatial reuse as compared to IEEE 802.11.

The transmission power determines the range over which the signal can be coherently received. To control the power, the selection of the “best” transmission range has been investigated extensively in the [43, 33, 46, 32, 54]. The authors of [31] introduce the concept of the power control problem and provide a protocol which suggests that low common transmission power maximizes throughput capacity, extends the battery
life of the nodes. Most of the power control techniques seem to use less energy than the pure IEEE 802.11 but they result in lower throughput due to the interference caused by hidden nodes. The authors in [50, 36] provide solutions for such problems.

In addition to power saving, the power control schemes also used to improve the spatial reuse of the wireless channel to increase the network throughput as in [68, 44, 45]. These schemes introduced interference limited media access control to increase spatial reuse. Concurrent data transmissions are allowed as long as multiple access interference does not corrupt the ongoing neighboring transmissions. However, the design of such schemes require additional channel, that increases the complexity of the system.

There are number of protocols that use transmission power control as a means of controlling network topology (e.g., reducing node degree while maintaining a connected network). The size of the reserved floor in these protocols varies in time and among nodes, depending on the network topology. In [55] the authors proposed a distributed position based topology control algorithm that requires the nodes to be equipped with GPS receivers. In [56] a cone-based solution is proposed but this protocol assumes the availability of directional information for which extra hardware is required. Other examples of topology control include [54, 59, 39, 16], which control the node power based on the number of neighbors and end-to-end throughput.

All the above mentioned schemes assume that nodes are equipped with omni-directional antennas. Directional antennas have also been proposed as a means of increasing network capacity [63, 77]. The use of transmission power control in MANETs with directional antennas can provide significant energy saving. [67] presents heuristic algorithms that construct power efficient topologies taking antenna orientation into consideration and demonstrates significant reductions in the power required to keep the network connected. In [34], directional antennas are applied to IEEE 802.11a MAC protocol. RTS, data and ACK packets are sent directionally and a better performance is achieved than current MAC protocols, since it allows simultaneous transmissions that are not allowed by the current MAC protocols. A
power controlled MAC protocol has been proposed for directional antennas in [2]. This protocol overcomes the problems resulted from integration of directional antennas into existing MAC protocols. It uses separate control and data channels to reduce collisions. It allows for dynamic adjustment of the data packet transmission power, such that this power is just enough to overcome interference at the receiver.

Recently, very few MAC protocols are proposed by combining the transmit power and data rate into one scheme. The MAC protocol proposed in [53] computes off line an optimal rate-power combination table for IEEE 802.11a. Then at the run time, a wireless station determines the most energy efficient transmission strategy for each data frame by a simple table lookup. However, this scheme does not take the traffic load and nodes sharing the same transmission medium into consideration. The authors in [47] proposed an adaptive protocol for IEEE 802.11 based wireless LAN's. This protocol uses a higher transmit power while changing to the higher coding rates. The purpose of increasing the power for the higher rates is to improve the network throughput by maintaining same transmission range so that the inference effects remain the same. The MAC layer protocol presented in [42] is basically designed for IEEE 802.11a based ad hoc wireless networks. This scheme generates different transmission rates for the different types of traffic by changing transmission power.

1.2.2.2 Power Aware Routing

Power aware routing has been a very hot research topic over the last several years and addresses the issues associated with energy consumption and conservation. In [26] the authors briefly review landmark papers for each protocol layer and define several metrics for studying power aware routing protocols. MINPOW (MINimum POWer) [33] routing protocol globally optimizes the total energy consumption. It is essentially distributed Bellman–Ford with energy consumption as the metric. The BASIC power control protocol has been used with power aware routing protocols to improve the energy efficiency. For example, power aware routing protocols in [15] [19] select a path that minimizes the aggregate transmit power consumed by all nodes on the path. In [64] Stojmenovic and Lin proposed a localized greedy strategy that focuses directly
on minimizing the energy needed to route a message from its source to the destination. The Location-Aided Power-Aware Routing protocol (LAPAR) [70] is another localized greedy algorithm that uses relay regions.

One drawback associated with the above power aware routing protocols is the overuse of small subset of nodes. The batteries of those nodes may be drained in a short period of time, leading to potential network partition. Several solutions have been proposed to use node energy in a more balanced manner so that traffic routed through nodes that have sufficient remaining energy [65, 66, 41]. These routing protocols use capacity of the batteries as a metric for the choice of routes. In this context, MBCR (Minimum Battery Cost Routing) [66] considers that the remaining capacity of battery reflects lifespan of a node better and chooses the route which maximizes the remaining capacity of the battery. MMBCR (Minimum Maximum Battery Cost Routing) [66] tries to choose a path whose weakest node has the maximum remaining power among the weakest nodes in other possible routes to the same destination. CMMBCR (Conditional Max-Min Battery Cost Routing) [66] proposed to limit the minimal remaining capacity of a set of routes then applies minimum total power route. The CMMBCR considers both the total transmission energy consumption of routes and the remaining power of nodes. This will ensure the choice of a route that the minimal remaining capacity is above a certain limit and hence minimizes the consumption of energy. Chiasserini [10] claims that battery usage and management can also affect the lifetime of a battery. They proposed a Battery Energy Efficient (BEE) protocol based on current discharge and battery capacity.

1.2.2.3 Power Management

Power management can achieve a great saving in mobile ad hoc networks. In the IEEE 802.11 specification, a node can be in one of the two power management modes, Active Mode (AM) or Power Saving Mode (PSM). Jung and Vaidya [27] proposed Dynamic Power Saving Mode (DPSM) based on the idea of using sleep and wake states for nodes in order to conserve power. The transitions from power saving mode to active mode in On-demand power management [57] are triggered by
communication events. On the other hand, the transitions from active mode to power-saving mode are determined by a soft-state timer which is refreshed by the same communication events that trigger a transition to active mode.

In GAF [71], nodes could be in one of the three states, sleeping, discovering or active. At the beginning, a node is in the discovery state and exchanges discovery messages including grid IDs to find other nodes within the same grid. A node becomes a master if it does not hear any discovery messages for a given period of time. If more than one node can become a master, the one with the longest expected lifetime becomes the master and handles the routing process for that grid square. Many others algorithms have been proposed such as span [9] and p-MANET [11] to select certain nodes known as coordinator nodes, while rest of the nodes known as non-coordinator nodes can go to sleep mode.

### 1.3 Scope and Objectives of the work

Most of the work in energy conservation focuses on minimization of energy used by a node for communication and maximizing the lifetime of nodes and the network. However, many other aspects of the energy consumption and conservation still need to be investigated. Some of these are:

- The interference and the hidden terminal problems that cause more transmission due to transmission errors and result in more energy consumption.
- The carrier sensing range and the exposed terminal problems that cause degradation of the network performance and affect the energy consumption.
- The current research in power conservation attempts in saving the energy but results into adversely affecting other performance metric of the network such as throughput and packet delivery ratio.
- Still there is scope for improvement in the existing popular protocols.
- Variable-rate support can be used as the way to conserve more energy.
In the light of the above issues, we proposed to investigate and find out solutions that minimize energy consumption and do not affect the network performance in terms of its throughput. The following objectives were set for the work proposed in the thesis:

- Study and show the effect of the interference on the most popular power control schemes.
- Investigate with experimental study the impact of the carrier sensing range on the network performance.
- Modification of the existing power saving schemes in order to save more energy and maximize the network throughput.
- Combining multiple power saving schemes into one protocol with the goal of saving more power and maximizing the throughput.
- To consider variable-rate support for transmission power control mechanisms and to improve performance of transmission power control mechanism by allowing dynamic adjustment of the information rate.

1.4 Simulation Tools

A number of simulations are performed for evaluating the energy efficiency of the proposed protocols and existing protocols studied in this thesis. The results obtained from these simulations for the existing protocols correspond well with the results presented in earlier studies. We have used GloMoSim [17] simulation tool to implement and carry out the simulations of the proposed protocols. This simulation tool is one of the most popular simulation packages that have been broadly used in mobile ad hoc network studies. The GloMoSim is the simulation software that has been designed for the purpose of scalable wireless network simulations [40]. It was designed using the parallel discrete–event simulation capability provided by PARSEC [4]. PARSEC is a C-based simulation language, developed by the parallel computing laboratory at UCLA, for sequential and parallel execution of discrete event simulation models. GloMoSim Like most of the network systems, models the OSI seven layers network architecture and includes models of different propagation models, Medium Access Control (MAC) protocols, network routing protocols and other upper layers.
At the physical layer, GloMoSim uses a comprehensive radio model that accounts for noise power, signal propagation and reception. Users can develop new protocols or revise the existing protocols using the C language. We have selected GloMoSim as the simulator due to its inclusion of various models, its scalability, less running time and ease of operation.

We have also used MATLAB [7, 8], a quite powerful tool to study the effects of the interference and carrier sensing range. This tool is also used for the numerical computations of theoretical analysis of a single-hop model which is considered as the base of the proposed TSRP control protocol. MATLAB is software for numerical calculations often used to model such kind of studies. We use MATLAB because it can internally handles large data in a way that programming complexity is significantly reduced.

1.5 Evaluation Metrics

In this thesis, the metric data delivered per Joule (Mbits delivered per joule) is used to evaluate the performance of various protocols in terms of energy consumption in the network. This is calculated as the total data delivered by all flows divided by the total amount of energy consumption over all flows. This measures the energy efficiency of delivering data within a network. Apart from achieving good energy conservation in the network, a good network protocol should be able to deliver the data packet reliably and quickly. Aggregate throughput of overall flows in the network has been used to evaluate the general performance of a network protocol. These two metrics are suggested by Eun-Sun Jung and Nitin H. Vaidya [28] for evaluating the performance of the power control MAC protocol proposed by them.

In addition to these two metrics, the following evaluation metrics for measuring the performance of the proposed protocols have also been used:

- Effective throughput, in this metric only the data packets delivered to final destination nodes are considered. Whereas the data packets delivered to the intermediate nodes are not considered.
Effective data delivered per joule is a measure of the total data delivered to the destination nodes divided by the total energy consumption over all the flows. In this metric, we considered only the data delivered to the destination node.

Packet delivery ratio is the ratio between the number of packets received by the TCP sink at the final destinations and the number of packets originated by the application layer sources. It is a measure of efficiency of the protocol.

1.6 Accomplishments and Contributions

Our accomplishments that are an outcome of the present work are elaborated in the successive chapters of this thesis. However, a brief summary of the accomplishment is given below:

- The effect of the interference on the standard IEEE 802.11, BASIC and PCM schemes have been studied extensively with experiments.
- The effect of the carrier sensing range on both the energy conservation and aggregate throughput has been explored with experiments.
- Proposed and evaluated the COMPOW based PCM protocol known as PCM/COMPOW for multi-hop MANET by integrating the COMPOW and PCM protocols into one.
- Proposed and evaluated the IPCM/COMPOW, an efficient power saving scheme for multi-hop MANET by integrating an improved version of PCM (IPCM) protocol and COMPOW protocols into one.
- Proposed and evaluated a Modified version of IPCM (MIPCM) protocol for wireless ad hoc.
- Evaluated and compared the proposed PCM/COMPOW, IPCM/COMPW and MIPCM protocols under similar simulation environment.
- Proposed and evaluated an energy efficient MAC protocol for the DCF IEEE 802.11b based ad hoc networks. The design of this proposed protocol is based on the outcomes remarks obtained from the theoretical analysis for a simple single-hop model.
Chapter 1

1.7 Organization of Thesis

This thesis is organized into six chapters. Next chapter presents a brief overview of medium access control IEEE 802.11 and the limitations of the BASIC and PCM power control schemes. It also discusses the effect of interference on the existing power control schemes and the effect of maximum and optimum carrier sensing range on the performance. Chapter 3 begins with a brief review of COMPOW protocol then elucidates the implementation and evaluation of the proposed PCM/COMPOW and IPCM/COMPW protocols. Chapter 4 discusses the modified improved power control MAC (MIPCM) protocol and its performance evaluation. It also discusses the experimental results for the comparative evaluation of the power saving protocols proposed in chapters 3 and 4. Chapter 5 describes the design steps, implementation and evaluation of the Traffic Sensing adaptive Rate Power (TSRP) control MAC protocol. It also includes theoretical analysis of a single-hop model which is considered as the base of TSRP protocol. Finally, chapter 6 concludes the work presented in the thesis giving its findings, contribution and possible future extensions.