Energy Conservation in Mobile Ad Hoc Wireless Networks

Thesis submitted to the Jawaharlal Nehru University
in partial fulfillment of the requirements
for the award of the degree of

DOCTOR OF PHILOSOPHY

By

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August, 2008

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CERTIFICATE

This is to certify that this thesis entitled "**Energy Conservation in Mobile Ad Hoc Wireless Networks**" submitted by **Yaser Mahmood AbdulHamid Hussein**, to the School of Computer and Systems Sciences, Jawaharlal Nehru University, New Delhi, for the award of degree of **DOCTOR OF PHILOSOPHY**, is a bonafide research work carried out by me. This research work has been carried out under the supervision of **Dr. D. K. Lobiyal**.

This research work is original and has not been submitted in part or full to any other University or Institute for the award of any other degree.

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Dedicated T0

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Abstract

Mobile Ad Hoc Networks (MANET) have received significant interest of researchers and industries, and become very popular in last few decades. Most of the research in this area has been initially focused on routing issues due to the frequent route breaks caused by arbitrary change in the network topology. Many routing protocols have been developed and some of them have been considered by the IETF. Despite the progress made in developing the routing protocols, battery-powered devices continue to be the challenge since limited energy results in partitioning of the network. Even advances made in battery technology are not sufficient to ensure the longevity of network life. Hence it is important to use the energy optimally. Therefore, research into energy efficient design of protocols has attracted the attention of researchers in last few years. However, the key challenge of energy efficient design approach is to increase energy efficiency without trading-off other performance characteristics, such as network throughput and end-to-end delay.

A number of power saving schemes and energy efficient protocols have been proposed in the literature by researchers to deal with the problems of energy consumptions in mobile ad hoc networks. Energy efficiency issue in the network spans over each layer of the protocol stack. Therefore, energy efficiency can be achieved by collective collaboration of the physical layer, medium access control layer, network layer, and upper layers. In other words, a cross-layer design is needed to achieve the optimal energy efficiency in an ad hoc network.

Present work focuses on modifying the existing protocols and designing new protocols to reduce the energy consumption over end-to-end paths. In addition to conserve energy, the proposed schemes also satisfy the main objective of any network design i.e. maximizing the network throughput. In this work, firstly, we made the study with experiments to explore the relation between the transmit power levels and interference. This study is extended to show the fundamental impact of the carrier sensing range on the energy efficiency and throughput of the ad hoc networks. From the experimental results, it is

found that there exits an optimum carrier sensing range that reduces the interference effect of the ongoing transmission and increases the network capacity. Therefore, the network can achieve reduction in energy consumption and an improvement in network throughput.

The most popular power control schemes BASIC, PCM and COMPOW have been investigated in this work. Further, we proposed COMPOW based PCM protocols referred to as PCM/COMPOW and IPCM/COMPOW protocols for multi-hop wireless ad hoc networks. IPCM is an improved version of the PCM protocol in which a source node transmits packets with an optimum power level. The power level of the data packets is periodically increased to a suitable level just for enough time rather than to a maximum level as in PCM. Also a modified version of the IPCM protocol (MIPCM) has been proposed in this work. The MIPCM protocol is similar to the IPCM protocol except that the power level of the data packets is periodically increased to a suitable level sufficient to avoid collisions and make spatial reuse. This level is determined with the help of the measured SINR at both the receiver and the transmitter.

We have implemented and simulated the proposed protocols in Glomosim. PCM/ COMPOW and IPCM/COMPOW protocols have been simulated for a network with single flow chain topology and single flow random multi-hop topology. But the MIPCM power control protocol is simulated for a network with single flow chain topology and single-hop random topology. Simulation results show that the proposed protocols have performed better than existing standard IEEE 802.11, BASIC and PCM protocols. We have also conducted experiment for our three proposed protocols under similar simulation environment to evaluate their comparative performance. The experimental results show that MIPCM protocol has performed better than other protocols under study.

Finally, we proposed an energy efficient MAC protocol for the Distributed Coordination Function IEEE 802.11b based ad hoc networks. This protocol also maximizes the overall network throughput in addition to efficient consumption of energy. We call this protocol Traffic Sensing adaptive Rate Power (TSRP) control MAC protocol. The basic idea of TSRP protocol is that in this a sender node selects the most energy efficient rate-power combination to transmit the data packets by sensing the outgoing traffic rather than matching the channel conditions. The design of this protocol has its basis on the remarks obtained from the outcome of theoretical analysis for single-hop model.

We have implemented IEEE 802.11b with the proposed TSRP control protocol using MATLAB based on discrete event modeling approach. The evaluation of the proposed protocol is also conducted using Glomosim. We investigated its performance for different scenarios, various communication distances, different traffic loads and packet size. All the simulation results show that the proposed TSRP protocol can conserve more energy and achieve the same throughput that is obtained by adaptive rate protocol.

Acknowledgements

At the submission of this dissertation work, I take the opportunity to express my deep sense of gratitude and indebtedness to my guide, Dr. D. K. Lobiyal for his invaluable, tireless guidance and constructive criticisms throughout this work. It is only due to his constant motivation and moral support that I was able to pull through many difficult phases of the work and bring it to a successful completion.

My special gratitude is to Prof. Parimala N, Dean of the School and other former deans to provide conducive environment for the research work in the department.

I also take this opportunity to thank and express my deep sense of gratitude to all staff and faculty members of the School of Computer and Systems Sciences.

I am thankful to the team of Glomosim developer at UCLA for making it freely available for academic research.

I would like to thank all the official members and staff of Cultural Attaché, Indian Council for Cultural Relations (ICCR) and Embassy of Yemen in New Delhi- India for providing me the suitable environment to carry out my work and for their great cooperation's. Thank you Dr. Abdulla Ba-Isaa, Munir Hanoom, Salem A.Kasem and others.

I would also like to thank all my friends with whom I made during the past years on my path toward earning my doctoral degree. Thanks for all the great times and encouragement that made this journey much more pleasant and meaningful. Special thanks go Lutfi Khanbary, Khaled Al-Adhal and Ahmed Babiker.

I express my thanks to all my teachers and colleagues, specially my close friends at Faculty of Engineering, University of Aden, Aden-Yemen, who in many ways inspired me to continue my studies.

Above all, my special sincere thanks have to go to my parents, for giving me the best of what parents can give. I would like to extend my thanks to my sisters and brothers for their love and continuous support during all years. Last but not the least, I would like to mention the person for whom the words may not be sufficient to express by gratitude. However not mentioning her will be dishonesty. It is my wife who spared me to fully devote myself to my work at her own cost.

Dated: 31.07.2008 **Yaser Mahmood AbdulHamid Hussein**

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ABBREVIATIONS AND SYMBOLS

Abbreviations

ACK	ACKnowledgment
AODV	Ad-hoc On-Demand Distance Vector routing
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BO	Back-Off
BPSK	Binary Phase Shift Keying
CBR	Constant Bit Rate
CCK	Complementary Code Keying
COMPOW	COMmon POWer
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
CTS	Clear-to-Send
CW	Contention Window
DCF	Distributed Coordination Function
DIFS	DCF Inter-Frame Space
DSR	Dynamic Source Routing
GloMoSim	GLObal MObile SIMulator
GPS	Global Positioning System
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IPCM	Improved Power Control MAC protocol
LAN	Local Area Network
LAR	Location Aided Routing
MAC	Medium Access Control
MANET	Mobile Ad hoc NETwork
MIPCM	Modified Improved Power Control MAC protocol
NAV	Network Allocation Vector

MINPOW	MINimum POWer
OCS	Optimum Carrier Sensing
OSI	Open Systems Interconnection
PARSEC	PARallel Simulation Environment Complex
PCM	Power Control MAC Protocol
PHY	PHYsical
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RBAR	Receiver Based Auto Rate
RTS	Request-to-Send
SIFS	Short Inter-Frame Space
SINR	Signal to Interference Noise Ratio
SIR	Signal to Interference Ratio
SNR	Signal to Noise Ratio
TCP	Transmission Control Protocol
TSRP	Traffic Sensing adaptive Rate Power
WLAN	Wireless Local Area Network

Symbols

α	Path loss exponent
λ_w	Signal wavelength
λ	Inter-arrival time between successive packets
B_t	Unspread signal bandwidth
C	Constant
d	Communication distance between the transmitter and the receiver
$d_{crossover}$	Crossover distance
d_i	Interference node distance
E_t	Exposed terminal
G_r	Receiver antenna gain
G_t	Transmitter antenna gain

h_r	Receiver antenna height
h_t	Transmitter antenna height
H_t	Hidden terminal
L	Data packet size
M	Number of constellation points
N_i	Interference node
P_{common}	Common power
P_i	Interference transmitted signal power
P_l	Path loss
P_{ai}	Avoid interference power level
P_{max}	Maximum power
P_{opt}	Optimal power
P_r	Received signal power
P_{ri}	Interference received signal power
P_{rs}	Radio receiving sensitivity
P_{rth}	Threshold received signal value
PSR	Packet Success Rate
P_t	Transmitted signal power
Q	Q-function
R_{ACK}	ACK packet rate
R_b	Maximum bit rate of the modulation scheme
R_{cs}	Carrier sensing Range
R_{CTS}	CTS packet rate
R_{DATA}	Data packet rate
R_i	Interference Range
R_{ocs}	Optimum Carrier sensing Range
R_{RTS}	RTS packet rate
R_t	Transmission Range
R_{top}	Optimum transmission Range
R_X	Receiver
T	Packet transmit time

T_{ACK}	ACK transmit time
T_{BO}	Back-off time
T_{CTS}	CTS transmit time
T_{DATA}	DATA transmit time
T_{DIFS}	DCF inter-frame space time
T_{RTS}	RTS transmit time
T_{SIFS}	Short inter-frame space time
T_{slot}	Slot time
T_X	Transmitter
W	Channel bandwidth

LIST OF PUBLICATIONS

1. Yaser Mahmood A.Hamid and D. K. Lobiyal, "Effect of Power Control Schemes on the Interference in Ad Hoc Networks", In Proc. of National Conference on Methods and Models in Computing, NCM2C, New Delhi, Dec. 18-19, 2006, pp. 209-214.

2. Yaser Mahmood A.Hamid and D. K. Lobiyal, "Effect of the Carrier Sensing Range on the Performance of the Mobile Ad Hoc Networks", In Proc. of 3rd Innovative Conference on Embedded Systems, Mobile Communication and Computing, $ICEMC^2$, Bangalore, August 11-14, 2008.

3. Yaser Mahmood A.Hamid and D. K. Lobiyal, " IPCM/COMPOW: An Efficient Power Saving Scheme for Multi-Hop Wireless Ad Hoc Networks", In Proc. of International Conference on Wireless Networks, ICWN'08-WORLDCOMP'08, Las Vegas, Nevada, USA, July 14-17, 2008.

4. Yaser Mahmood A.Hamid and D. K. Lobiyal, "An Adaptive Energy Efficient MAC Protocol for Wireless Ad Hoc Networks", In Proc. 4th IEEE International Conference of Wireless Communications, Networking and Mobile Computing, WiCOM'08 , Dalian, China, 12-14 Oct. 2008.

5. Yaser Mahmood A.Hamid and D. K. Lobiyal, "COMPOW Based PCM Protocol for Multi-hop MANET", submitted to an international journal.

6. Yaser Mahmood A.Hamid and D. K. Lobiyal, "Improved Power Control MAC Protocol for Wireless Ad Hoc Networks", submitted to an international journal.

7. Yaser Mahmood A.Hamid and D. K. Lobiyal, "An Adaptive Energy Conserving Protocol for IEEE 802.11b based Ad Hoc Networks", submitted to an international journal.

8. Yaser Mahmood A.Hamid and D. K. Lobiyal, "An Enhanced Carrier Sensing Power Control Protocols for Multi-Hop Wireless Ad Hoc Networks", submitted to an international journal.

CHAPTER 1

Introduction

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
3. Power Management.

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 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 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_{max}, but send DATA/ACK at minimum necessary power P_{min}. The minimum necessary power P_{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_{max} from P_{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 developed 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.

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.

CHAPTER 2

Interference and Carrier Sensing Range

Power control schemes in wireless ad hoc networks use different power levels for RTS-CTS and DATA-ACK. Most of the schemes use maximum transmission power for RTS-CTS and minimum required transmit power for DATA-ACK transmissions in order to save energy. However, different power levels result in asymmetric links between nodes, and more collisions. As a result, instead of saving energy, more energy may be consumed causing degradation of throughput. This chapter presents theoretical analysis and simulation for the effect of power control schemes on interference in wireless ad hoc networks. Further, this chapter also presents analytical and simulation results for the effect of carrier sensing range on both the aggregate throughput and energy conservation. In the beginning of the chapter, medium access control protocols and the limitations of BASIC and PCM power control protocols are described. The rest of the chapter concentrates on analysis, simulation and results obtained from our studies about the effect of power control schemes on the interference and the effect of carrier sensing range on the performance of wireless ad hoc networks.

2.1 Medium Access Control

The Medium Access Control (MAC) protocols are responsible for coordinating the shared access to the channel among active nodes. In addition, these protocols are designed to address the issue of bit errors since the wireless communication channels are inherently prone to errors, and the unique problems such as the hidden-terminal problem and the exposed-terminal problem. The IEEE 802.11 MAC protocol with Distributed Coordination Function (DCF) [22] is used as the MAC layer in these experiments. DCF is the basic access method used by mobiles to share the wireless channel under independent ad hoc configuration. This access scheme is Carrier Sense

Multiple Access/Collision Avoidance (CSMA/CA) with acknowledgments. IEEE 802.11 is designed to use both physical carrier sense and virtual carrier sense mechanisms to reduce the probability of collisions due to hidden terminals. Virtual carrier sense attempts to "sense" the presence of carrier near the intended receiver of a packet before transmitting. If the carrier sense mechanism indicates that the wireless medium is busy, the node defers before transmitting, using a binary exponential back-off. The virtual carrier sense mechanism uses two short packets before the intended data packet to acquire the channel: a Request-to-Send (RTS) and a Clear-to-Send (CTS).

When a sender has a packet to transmit, it senses the channel by detecting the air interface (in the physical layer) and looking up its NAV (Network Allocation Vector). If the channel is busy, the terminal waits until the channel becomes free, in this case it sends a RTS to the destination terminal. On successfully receiving the RTS, the destination replies by sending CTS to the source. The source can begin data transmission after the CTS is received. After the data is received at the destination it sends an ACK to the source, confirming the success of a data reception. This is an ideal case of a four-way handshake. If the source fails to receive CTS or ACK (collision at source or destination), it backs off for a random period of time by doubly increasing its Contention Window (CW) size [69].

2.2 Limitations of BASIC and PCM Schemes

In the Basic Scheme, RTS and CTS frames are always sent at the maximum possible transmit power level and it uses the lowest acceptable power for sending DATA and ACK frames. However, using different power levels cause decrease of the carrier sensing area. When the neighboring terminals cannot decode or sense the packet (because they are outside the decoding and sensing zone), they cannot adjust their NAV's, thus they mistakenly consider that the wireless channel is free and transmit their own packets. This leads to a significant increase in the number of interference nodes that cause collisions at the receiver with the DATA packets and at the transmitter with the ACK packets. This is due to the fact that both DATA and ACK packets are less protected in BASIC scheme than in the 802.11 without power control. These collisions enforce retransmission of the same packets. It therefore, results in higher energy consumption than using IEEE 802.11 without power control. As a result, a solution to the asymmetric link problem is critical and essential to any power control protocol employing high power control frames (i.e., RTS and CTS) for medium reservation and collision avoidance, and reduced power for DATA and ACK frames.

The PCM protocol was proposed in order to overcome the shortcoming of BASIC scheme. In PCM likes BASIC, the RTS and CTS packets are transmitted with a maximum power level whereas the DATA and ACK packets are sent with the minimum power required to communicate between the sender and the receiver. But in order to avoid the potential collision caused by the reduced carrier sensing zone, the PCM periodically increases the power level of the DATA packets to maximum level just for a duration that is long enough for the nodes in the carrier sensing region of the transmitter to lock on it. This protocol achieve a significant energy saving over IEEE 802.11 and BASIC scheme and achieves a throughput comparable to that of IEEE 802.11.

2.3 Effect of the Interference

As mentioned in the beginning of this chapter, the power control schemes use different power levels for RTS-CTS and DATA-ACK which may result in a significant increase in the number of interference nodes that cause collisions at the receiver with the DATA packets and at the transmitter with the ACK packets. These collisions enforce retransmission of the same packets. It therefore, results in higher energy consumption than using IEEE 802.11 without power control. This section presents the effect of power control schemes on interference in wireless ad hoc networks by using interference analysis and simulation results [73].

2.3.1 Interference Analysis

Before the details of interference analysis are discussed, we define some of the basic terms for the clarity of understanding the propagation model.

Transmission range (R_t) of a sender node is the distance within which other nodes can receive and correctly decode the packets received from the sender node. The level of power used in transmission and radio propagation properties (i.e., attenuation) determine the transmission range.

Interference Range (R_i) of a node is the distance from where other nodes can interfere with the reception at this node. The communication pair distance, transmission power levels of both a sender and an interfering node determine the interference range.

Carrier Sensing Range (R_{cs}) of a sender node is the distance within which other nodes can hear the sender's transmission range but cannot decode it. The transmission power level of the sender and the radio sensitivity of the sensing node determine the carrier sensing range.

The node that is inside interference range is called interference node. Since this node cannot detect a packet transmission, therefore it will interfere with the ongoing transmission when it also begins its packet transmission. Whether a collision occurs or not depends on the received power signal and the *SINR* at the receiver.

Propagation Model

As the most of the radio engineers typically use a model that attenuates the power of signal as $1/d^2$ at short distances (free space propagation model) and as $1/d^4$ at longer distances (two-ray ground reflection model), where d is the distance between antennas. The signal propagation model used in our work is a combination of the free space propagation model (for distances less than the reference distance) and the two-ray ground reflection model (for distances greater than the reference distance). The crossover point is called the reference distance. This hybrid model have been used because it accurately models the attenuation of radio waves between antennas close to the ground [60, 5] and it is also available in the GloMoSim simulation package. At near distance, the power received (P_r) is given by

$$P_r = P_t G_t G_r \left(\frac{\lambda_w}{4\pi d} \right)^2 \qquad (2.1)$$

Where P_t is the transmitted power, G_t and G_r are the antenna gain of the transmitter and the receiver, respectively, λ_w is the signal wavelength, and d is the distance between the transmitter and the receiver.

On the other hand, the power received (P_r) at far distance is given by

$$P_r = P_t G_t G_r \left(\frac{h_t h_r}{d^2} \right)^2 \qquad (2.2)$$

where h_t and h_r are the antenna heights of the transmitter and the receiver respectively. From Eq.(2.1) and Eq.(2.2), $d_{crossover}$ can be derived, which is considered as the crossing edge from the near to far distances. This distance is given by

$$d_{crossover} = 4\pi \frac{h_t h_r}{\lambda_w} \qquad (2.3)$$

The path loss ($P_{l,}(d_{crossover})$) at the distance $d_{crossover}$ is considered as the reference value in this model. This value is constant (1/C) that depends on the antenna gains, the wavelength, the antenna heights and the crossover distance $d_{crossover}$.

$$P_l(d_{crossover}) = \frac{P_t(d_{crossover})}{P_r(d_{crossover})} = \frac{1}{G_t G_r} \left(\frac{4\pi d_{crossover}}{\lambda_w} \right)^2 = \frac{1}{G_t G_r} \left(\frac{d^2_{crossover}}{h_t h_r} \right)^2 = \frac{1}{C} \qquad (2.4)$$

From Eq.(2.1), Eq.(2.2) and Eq.(2.4), the power received (P_r) at any distance can be rewritten in its general form as given below

$$P_r = P_t C \left(\frac{d_{crossover}}{d} \right)^\alpha \qquad (2.5)$$

Where α is the path loss exponent, α=2 in case of free space propagation model and its value is 4 in case of two-ray propagation model.

Let P_i represents the transmission power of an interfering node at distance d_i from a receiver. Since this interfering node will be at a distance at least equal to the carrier sensing range, therefore it will be considered as a far distance. The receiving power P_{ri} of the signal from the interference node will be calculated as follows:

$$P_{ri} = P_i G_t G_r \left(\frac{h_t h_r}{d_i^2} \right)^2 \tag{2.6}$$

Therefore the Signal to Interference Ratio (*SIR*) value is given by

$$SIR = \frac{P_r}{P_{ri}} = \frac{P_t C}{P_i G_t G_r} * \frac{\left({}^{d_{crossover}}\!/_{d} \right)^{\alpha}}{\left[{}^{h_t h_r}\!/_{d_i^2} \right]^2} \tag{2.7}$$

Since we are interested in the interference signals, other noises are ignored since they are small compared to the interference signal. If $SIR \geq SIR_{th}$, the interference due to hidden nodes can be completely avoided, where SIR_{th} is the threshold value of signal to interference ratio. From the above condition $SIR \geq SIR_{th}$ and equation (2.7), the following equation is obtained:

$$d_i \geq \sqrt[4]{SIR_{th} \frac{P_i G_t G_r}{P_t C}} \left(\frac{d}{d_{crossover}} \right)^{\frac{\alpha}{4}} \sqrt{h_t h_r} \tag{2.8}$$

It is clear from equation (2.8) that any interfering node at a distance $\geq d_i$ from the receiving node will not interfere with receiver node or the transmitter node as this interference node will satisfies the necessary condition given by equation (2.8).

A packet can be successfully received, if and only if $P_r \geq P_{rth}$ and $SIR \geq SIR_{th}$, where P_{rth} is the threshold received signal value. A node is in the carrier sensing range of the transmitter, if and only if it can receive a signal P_r from the transmitting node and satisfying the following equation:

$$P_r = P_t G_t G_r \left(\frac{h_t h_r}{R^2} \right)^2 \geq P_{rs} \tag{2.9}$$

Where P_{rs} is the radio receiving sensitivity of the interference node and R is the distance between the sensing node and the transmitter. This equation is used to determine the range R_{cs} for a given value of P_r=P_{rs}. Therefore, any node other than the receiving node, that is in the carrier sensing range of the transmitting node will defer its transmission, and remain idle until the undergoing transmission is over.

2.3.2 Simulation and Results

To study the effect of power control schemes on the interference using different power levels, IEEE 802.11 using the above equations was modeled in the MATLAB based on discrete event modeling approach. The main objective behind this study is to show the effect of the power control schemes on the performance of ad hoc networks in terms of the interference nodes.

2.3.2.1 Simulation Environment

Plain IEEE 802.11, BASIC and PCM schemes are simulated by considering 100 to1000 nodes randomly distributed in an area of 2000 x 2000 m^2. Two nodes, one is the sender and the other is the destination are randomly selected. The distance between the transmitting and receiving nodes is also randomly distributed. Six discrete power levels 1mW, 5mW, 20mW, 30mW, 50mW and 100mW are used. Further, we have considered the values given in table 2.1 for the various parameters used in the simulation. Each output variable is an average of 2000 simulation runs with distance between transmitting and receiving nodes for each run is random.

Parameter	Value
Antenna gain	1
Antenna height	1.5 m
Signal to interference ratio threshold value	10
Threshold received signal value	-81 dBm
Radio receiving sensitivity	-91 dBm

Table 2.1: Parameter values used to study the effect of power control schemes on the interference.

2.3.2.2 Assumptions

We have made the following assumptions to carry out the experiments and simulation in this study and the other works of this thesis:

- Nodes are in a plane (two dimensional coordinate system).
- The wireless links between two nodes are bi-directional.
- Characteristics of all the nodes in the network such as antenna gain, antenna height, Signal to Interference Ratio threshold, threshold received signal and radio receiving sensitivity are the same.
- All nodes in the network use omni-directional antennas.

2.3.2.3 Experimentation

The experiments carried out in three different phases. In the first phase, plain IEEE 802.11 is simulated using fixed transmission power for all nodes to show the effect of fixed transmission power on the interference range in terms of the number of interference nodes. This experiment is repeated for all the six mentioned power levels. In the second phase, a sender node is selected with certain fixed transmission power selected from the power levels set while all the other nodes use different transmission power. The objective behind this experiment is to show the effect of interference nodes using higher transmission power on the nodes using lesser power level and vice versa. The performance in terms of the interference nodes of the pure IEEE 802.11 using fixed transmission power (5 mW, 20 mW, 100 mW), BASIC and PCM schemes are compared in the third phase.

2.3.2.4 Results and Discussions

This section discusses the results obtained from the simulations carried out for the three mentioned phases. Figure 2.1 shows the effect of different transmission power level on the number of interference nodes. This figure gives the simulation result for pure IEEE 802.11 that uses certain constant transmission powers. It is clearly shown that using lower transmission power produce lesser interference compared to higher transmission powers. This is due to the reason that an increase in transmission power enhances the transmission range as well as the interference range. This increase in interference range increases the probability of the number of the interference nodes to interfere with ongoing transmissions. Therefore, it will be efficient to use lower power for all nodes than the higher power. However, the lower power for each node may result in a disconnected network.

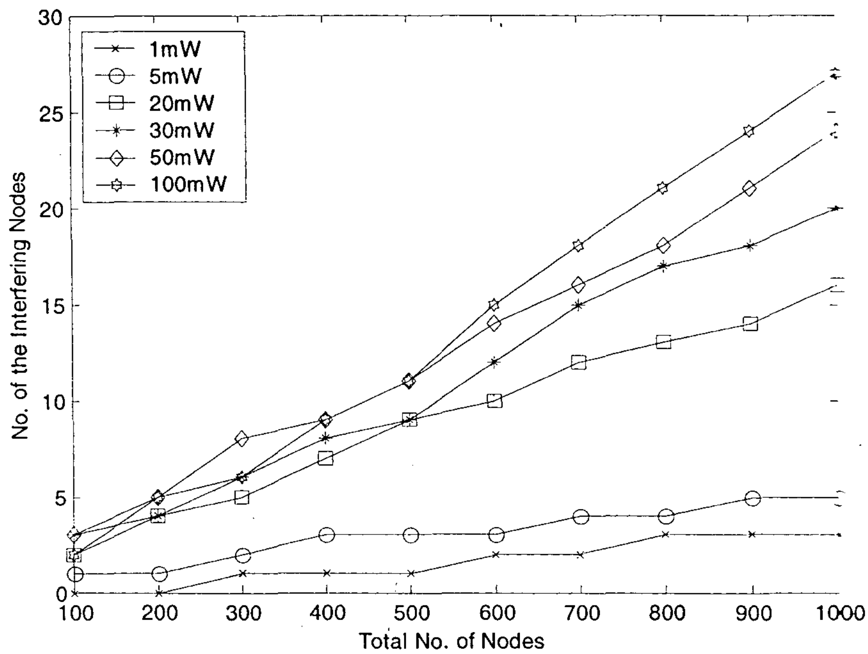

Figure 2.1: Number of interfering nodes for the different transmission power levels in wireless ad hoc networks without power control schemes.

Table 2.2 shows the effect of using different transmission powers in MAC protocol IEEE 802.11. In this case, the number of interference nodes is large when the power level of ongoing transmission is low compared to the power level of interference nodes. Further, it shows that the number of interference nodes increase as the node density increases. As the transmission power of the sender node increases, the number of interference nodes decreases, since the interference effect of other nodes those using lower power is small on ongoing transmission using higher power.

Figure 2.2 compares the pure IEEE 802.11, BASIC and PCM schemes in terms of the number of interference nodes. The number of interference node for PCM power control scheme is comparable with the pure IEEE 802.11 using the maximum transmission power (100 mW) for all nodes because the PCM scheme uses the maximum carrier sensing range as the pure IEEE 802.11. For that reason, the PCM scheme achieves a throughput comparable to the IEEE 802.11 while achieving a significant energy saving over IEEE 802.11 because it uses reduced power level for the DATA and ACK packets compared to the maximum power in the case of pure IEEE 802.11. The Basic IEEE 802.11 scheme has higher interference effect compared to the others due to the reasons mentioned in section 2.2. The pure IEEE 802.11 using 5 mW and 20 mW has a lesser number of interference nodes but it may result in a disconnected networks compared to others.

Node density (10^{-6} nodes/m^2) / Transmitting Power (mW)	25	50	75	100	125	150	175	200	225	250
1	8	17	24	33	39	46	53	61	67	75
5	6	12	17	25	30	34	40	45	50	56
20	3	7	9	13	16	19	22	25	28	31
30	3	5	7	10	12	14	18	20	22	25
50	2	4	5	7	8	10	12	13	15	17
100	1	1	2	2	3	4	5	6	6	8

Table 2.2: Effect of the higher power levels of interfering nodes on the nodes using lower power levels

2.4 Effect of Carrier Sensing Range

The maximum carrier sensing range has been used by the PCM protocol as a way to reduce the energy consumption in wireless ad hoc networks. The objective behind using maximum carrier sensing range is to inform the neighbor nodes about ongoing transmission in order to reduce the interference and increase energy conservation. But, increasing the carrier sensing range to maximum range affects the total throughput of the network, since some nodes in the maximum carrier sensing range can also transmit data successfully to their corresponding receiver without affecting the first ongoing transmission. On the other hand, reducing the carrier sensing range can encourage more concurrent transmissions but at the cost of more collisions. This section presents the effect of carrier sensing range on both the aggregate throughput and energy conservation in wireless ad hoc networks. The analytical and simulation results of this section showed that, there exits an optimum carrier sensing range which can maximize the aggregate throughput and minimizes the total power consumption [75].

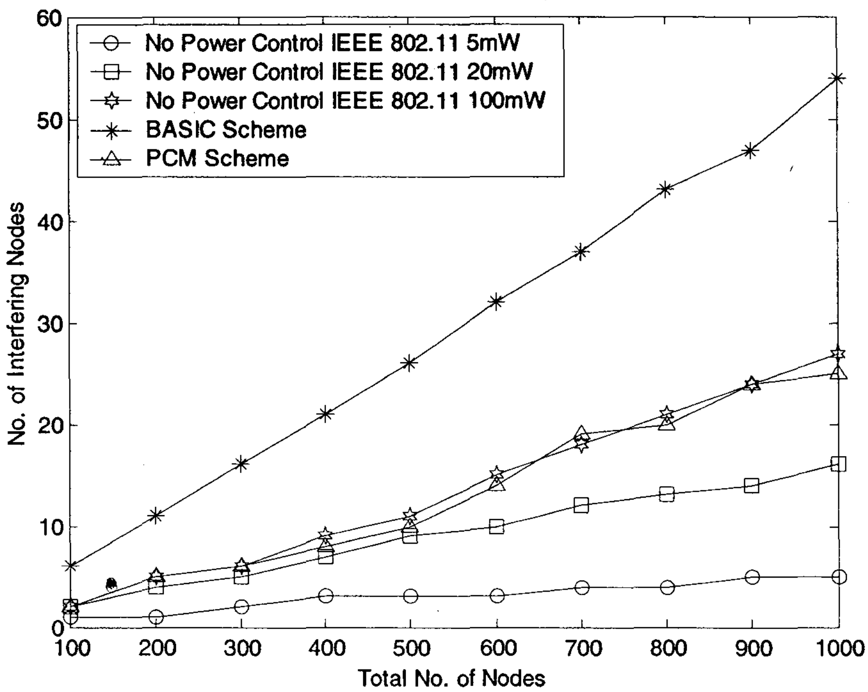

Figure 2.2: Effect of the power control schemes on the interference in wireless ad hoc networks.

2.4.1 Optimal Carrier sensing Range

The hidden terminal problem occurs when another transmitter that is outside the carrier sensing range of ongoing transmission attempt to transmit. If the second transmitter lies within the interference range of the receiver or transmitter of the first communication pair, it results in collision and hence lost of DATA or ACK packets of the first transmission. Conversely, exposed terminal problem occurs when a source lies within the sensing range of the transmitter but outside the interference range of the reference of the receiver or transmitter. Therefore the exposed node will defer its transmission attempt until the first ongoing transmission is over. The hidden node causes loss which degrades the network throughput and increases the energy consumption whereas the exposed node causes loss of spatial reuse which also degrades the network throughput. Therefore, optimal carrier sensing range should balance the trade-off between the spatial frequency reuse and the possibility of packet collisions.

From equation (2.8) it is clear that the interference range of a node varies based on the communication distance between the sender and the receiver and the transmission powers of the sender and interference nodes. On the other hand, it is clear from equation (2.9) that the carrier sensing range depends on transmission power of the sender node and radio receiving sensitivity. A collision occurs due to hidden terminal when a node is in the interference range but outside the carrier sensing range attempt to transmit. Such kind of collision can be avoided if the carrier sensing range is larger than the interference range. Whereas exposed terminal problem occurs when a node is in the carrier sensing range but outside the interference range. Such kind of problem can be avoided if the carrier sensing range is reduced so that the exposed node will be able to initiate a transmission. Therefore the optimum carrier sensing range is that range which will cover the interference range exactly.

The carrier sensing range is at least twice the transmission range and the maximum carrier sensing range covers both transmission ranges of RTS and CTS as shown in figure 2.3. The nearest hidden terminal (H_t) that can be considered as an interference node will be at a distance $\{di=R_{cs}-d\}$.

Therefore the optimum carrier sensing range that can avoid the nearest hidden terminal to initiate a transmission which can cause a collision at the receiver can be written as given below.

$$R_{OCS} = Min\left\{\left(\sqrt[4]{SIR_{th}\frac{P_iG_tG_r}{P_tC}}\left(\frac{d}{d_{crossover}}\right)^{\frac{\alpha}{4}}\sqrt{h_th_r}+d\right), R_{cs}(Max)\right\} \quad (2.10)$$

Therefore the carrier sensing range that can improve the network performance is not always nécessary be the maximum. But it depends on the interference power at the receiver, transmitting power, and the distance between the sender and the receiver.

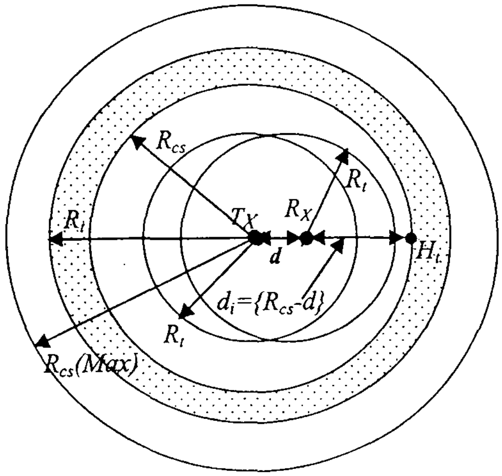

Figure 2.3: Transmission ranges, carrier sensing range, interference range and the nearest hidden terminal that can cause collision at the receiver.

2.4.2 Simulation and Results

MATLAB is used to model all the mechanisms which use CSMA/CA technique based on DCF access method as regulated by IEEE 802.11. This model is used to determine the number of the hidden nodes those can cause collisions with the ongoing transmission and the number of blocked nodes those can be either in the RTS, CTS or carrier sensing range. Glomosim-2.03 is also used in this study to show the effect of carrier sensing range on the aggregate throughput and energy consumption.

2.4.2.1 Simulation Environment

The performance of the mobile ad hoc networks investigated under two different network topologies: chain topology and random topology. The chain topology composed of 31 nodes, 30 flows with equal spacing as used in [28]. The random topology consists of 20, 40, 60, 80 and 100 nodes randomly distributed in an area of 1000 x 1000 m^2. This study considered the transmit power levels and their roughly corresponding transmission ranges as shown in table 2.3 and the maximum carrier sensing range is 550m.The parameters values used are given in table 2.4. Each output variable of the analytical results is an average of 2000 simulation whereas each simulation runs for 20 seconds. All simulation results are an average of 10 simulation runs. The parameter values selected for this study are given in table 2.4.

Transmit Power (mW)	Corresponding Transmission Range (m)
1	40
2	60
3.45	80
4.8	90
7.25	100
10.6	110
15	120
36.6	150
75.8	180
281.8	250

Table 2.3: Transmit power levels used and their corresponding transmission ranges.

Parameter	Value
Channel carrier frequency	2.4 GHz
Antenna height	1 m
Antenna gain	1
Threshold signal to interference ratio threshold value	10
Threshold received signal value	-72 dBm
Radio receiving sensitivity	-86 dBm
Packet size	512 Byte
Bandwidth	2 Mbps
CBR traffic rate	1 Mbps

Table 2.4: Parameter values used to study the effect of carrier sensing range on the performance of the mobile ad hoc networks.

2.4.2.2 Experimentation

The experiments carried out in two different phases for the chain and random topologies respectively. In the first phase, the numbers of the hidden and blocked nodes of IEEE 802.11, BASIC and PCM schemes are determined using an analytical model. In this phase, the analytical model also tries to find an optimum carrier sensing range that has the minimum numbers of the hidden and blocked nodes. In case of the chain topology, a node at the middle of the chain (Node 16) is selected and the number of hidden terminal whose transmission attempts can cause collisions, and blocked nodes those can defer their transmissions when such transmission is active, are determined. Whereas in case of random topology, two nodes, one is the sender and the other is the destination are randomly selected. In the second phase, the performances of IEEE 802.11, BASIC, PCM and the PCM with the optimum carrier sensing range are evaluated in terms of the throughput and energy consumption. . In these evaluations, we considered the energy consumption of all the packets RTS, CTS, DTA and ACK, and we have taken into account the transmitting as well as receiving energy, where as in [28] only transmitting energy is considered. In case of the chain topology, the first node of the chain is considered as the sender node, whereas the last node of the chain considered as the destination node. Whereas in case of random topology, a single-hop traffic pairs are randomly selected with the random distance from 0 to 250 m. For each experiment, we have selected traffic pairs such that there are equal numbers of pairs within the destination ranges of 0-40, 40-60, 60-80, 80-90, 90-100, 100-110, 110-120, 120-150, 150-180 and 180-250 meters. For example, our experiment with a total of 20 traffic pairs, we selected 2 pairs in each distribution range.

2.4.2.3 Results and Discussions

This section discusses the results obtained from the study carried out for the two mentioned topologies.

Chain topology

Table 2.5 shows the number of the hidden nodes those can cause collisions with the ongoing transmission for the various distances between the adjacent nodes in case of chain topology. It is clearly shown that the IEE 802.11 and PCM did not have any hidden nodes but that BASIC has a considerable number of hidden nodes. On the other hand, Table 2.6 shows the number of the nodes those can defer their transmission attempts if the node 16 is in the transmission mode for the various distances between the adjacent nodes. It is clearly shown that the IEEE 802.11 and PCM scheme have a large number of blocked nodes compared to the BASIC scheme. The reason behind the above results is that the IEEE 802.11 and PCM reserving the maximum area due to the use of the maximum carrier sensing range which will increase the number of blocked nodes. Whereas the BASIC scheme reserving the lesser area which depends on the transmitting power of the sender. This will increase the number of hidden nodes while the number of blocked nodes reduced compared to IEEE 802.11 and PCM scheme. Then we try to perform the same experiment for PCM scheme under different carrier sensing range to find an optimum carrier sensing (OCS) range. The interference level for this is the same as for PCM scheme with the maximum carrier sensing range. It has less number of the blocked nodes as shown in table 2.5 and table 2.6. When the adjacent nodes are 250 m apart, the numbers of the hidden and blocked nodes of all the schemes are the same.

Distance(m)	802.11	BASIC	PCM	OCS
40	0	8	0	0
60	0	6	0	0
80	0	4	0	0
90	0	4	0	0
100	0	4	0	0
110	0	4	0	0
120	0	2	0	0
150	0	1	0	0
180	0	1	0	0
250	0	0	0	0

Table 2.5: Chain topology: Number of hidden nodes those can cause collisions with ongoing transmission.

Distance(m)	IEEE	BASIC	PCM	OCS
40	25	12	25	21
60	17	8	17	15
80	11	6	11	11
90	11	4	11	9
100	9	4	9	9
110	9	4	9	9
120	7	4	7	7
150	5	3	5	5
180	5	3	5	5
250	3	3	3	3

Table 2.6: Chain topology: Number of blocked nodes those can be either in the RTS, CTS or in carrier sensing range.

Figure 2.4 shows the aggregate throughput obtained from the simulation of the chain topology with 31 nodes and 30 flows. The distance between two adjacent nodes varies and each node generates traffic at the rate of 1 Mbps. The figure shows the comparison of the throughput of IEEE 802.11, BASIC, PCM scheme, and the PCM scheme with OCS. It is clearly shown that, OCS achieves a higher aggregate throughput compared to all other schemes. This is because, it uses a smaller carrier sensing range compared to IEEE 802.11 and PCM schemes, since a larger number of nodes can transmit concurrently. Also this carrier sensing range is larger than the carrier sensing range of the BASIC scheme, and it is sufficient to keep the hidden terminal problem level same as the IEEE 802.11 and PCM schemes. IEEE 802.11 and PCM schemes achieve comparable aggregate throughput as they reserve similar carrier sensing ranges, but the BASIC scheme performs poorly in throughput. Excluding OSC scheme, the aggregate throughput of all others schemes match the results obtained in [28]. As the distance between the adjacent nodes increases, the aggregate throughput of all the schemes increases. The reason is that a large number of nodes can transmit simultaneously as the distance increases.

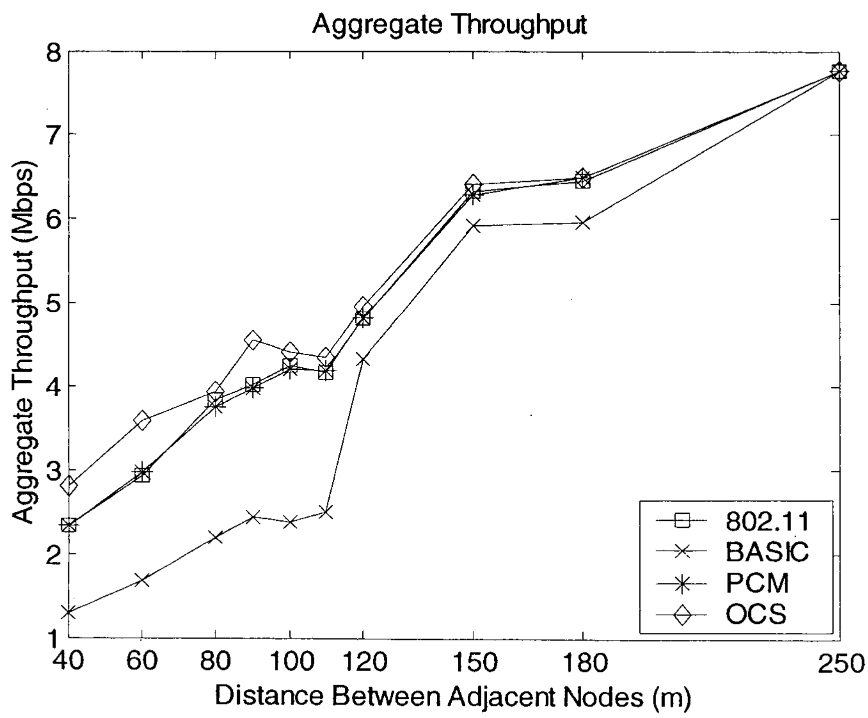

Figure 2.4: Chain topology: Aggregate throughput to study the effect of carrier sensing range on the performance of mobile ad hoc networks.

Figure 2.5 shows the total data delivered per joule (Mbits/Joule) for different schemes. PCM scheme consumes lesser energy compared to 802.11 and BASIC schemes, since it uses lower transmission power for the DATA and ACK packets compared to IEEE 802.11and it has less hidden terminal problem compared to BASIC scheme. As the distance between the adjacent nodes is small (<120 m), the BASIC scheme performs worse than 802.11 scheme due to extra energy consumption resulting from the collisions and retransmissions. At higher distances (≥120 m), the BASIC scheme shows improvement in the total data delivered per joule compared to 802.11 scheme. This is because at 120 m and 150 m, the aggregate throughput of the BASIC scheme jumps due to reduction in number of collisions.

The performance of the OSC scheme is better than all other schemes, since it uses lower transmission power for the DATA AND ACK packets, and lower periodic pulse power. On the other hand, reducing the periodic pulse in OSC scheme is enough to eliminate the hidden node problem. But this reduction in periodic pulse power also reduces the number of deferring nodes, and thus, more data can be delivered per joule. When the adjacent nodes are 250 m apart, the aggregate throughput and the total data delivered per joule for all the schemes are the same. Since all the schemes use the maximum power for all the packets.

Random topology

Table 2.7 shows the number of hidden nodes in case of random topology. It is clearly shown that IEEE 802.11 and PCM have small number of hidden nodes. Whereas the BASIC has a large number of hidden nodes compared to others. On the other hand, table 2.8 shows the number of nodes those can be blocked if a transmission is going in an area of randomly distributed nodes. It is clearly shown that IEEE 802.11 and PCM scheme have a large number of blocked nodes compared to the BASIC scheme. We performed the same experiment for PCM scheme with different carrier sensing range to find an optimum range for any power less than the maximum power, and have the same interference level as PCM scheme with the maximum carrier sensing range but less number of the blocked nodes as shown in table 2.7 and table 2.8.

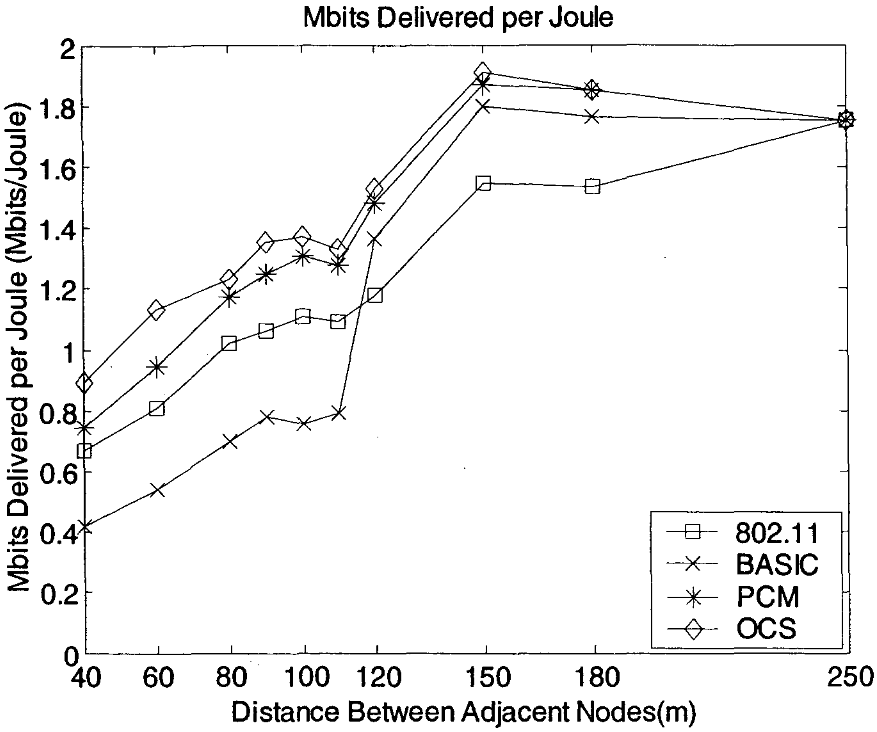

Figure 2.5: Chain topology: Total data delivered per joule to study the effect of carrier sensing range on the performance of mobile ad hoc networks.

Figure 2.6 and figure 2.7 show the performance of various schemes in the random topology. The OCS scheme achieves a better aggregate throughput than the others as shown in Fig. 4. The aggregate throughputs of 802.11 and PCM schemes are quite comparable, where as the BASIC scheme performs poorly.

No. of Nodes	IEEE	BASIC	PCM	OCS
20	2	3	2	2
40	2	5	2	2
60	3	7	3	3
80	4	9	4	4
100	5	12	5	5

Table 2.7: Random topology: Number of hidden nodes those can cause collisions with ongoing transmission.

No. of Nodes	IEEE	BASIC	PCM	OCS
20	16	9	16	14
40	42	19	42	38
60	52	28	52	47
80	68	38	68	60
100	86	44	86	78

Table 2.8: Random topology: Number of blocked nodes those can be either in the RTS, CTS or the carrier sensing range.

The OCS scheme achieves a higher data delivered per joule as shown in figure 2.7. We can also observe a decrease in the data delivered per joule for all the schemes as the number of traffic pairs increases. The reason is that when the number of traffic pairs increases, the number of collisions also increases. This leads to more retransmissions, which reduces the data delivered per joule.

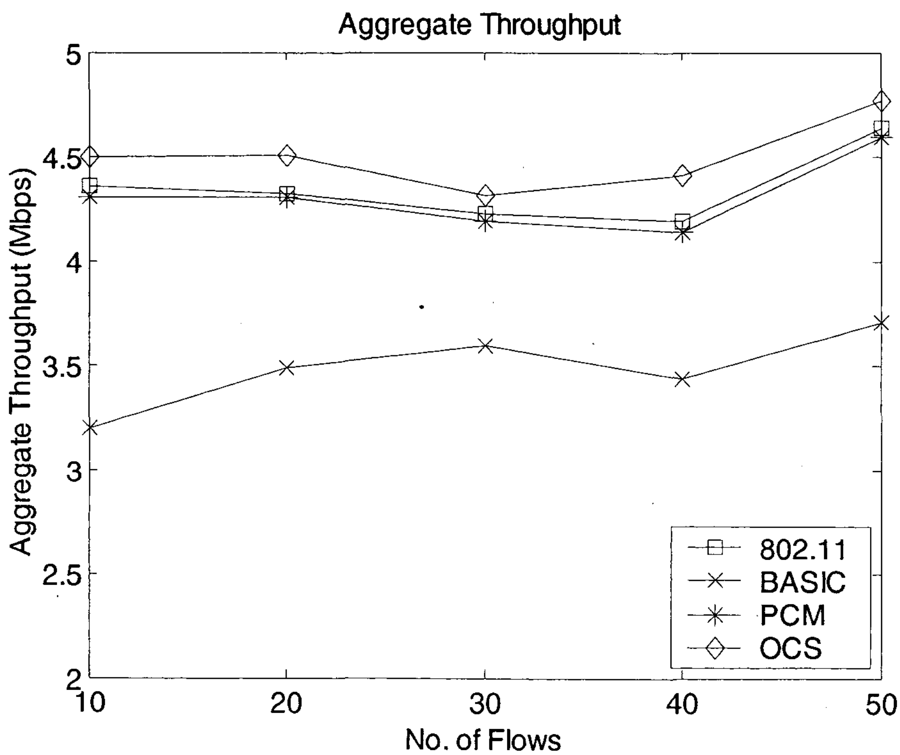

Figure 2.6: Random topology: Aggregate throughput to study the effect of carrier sensing range on the performance of mobile ad hoc networks.

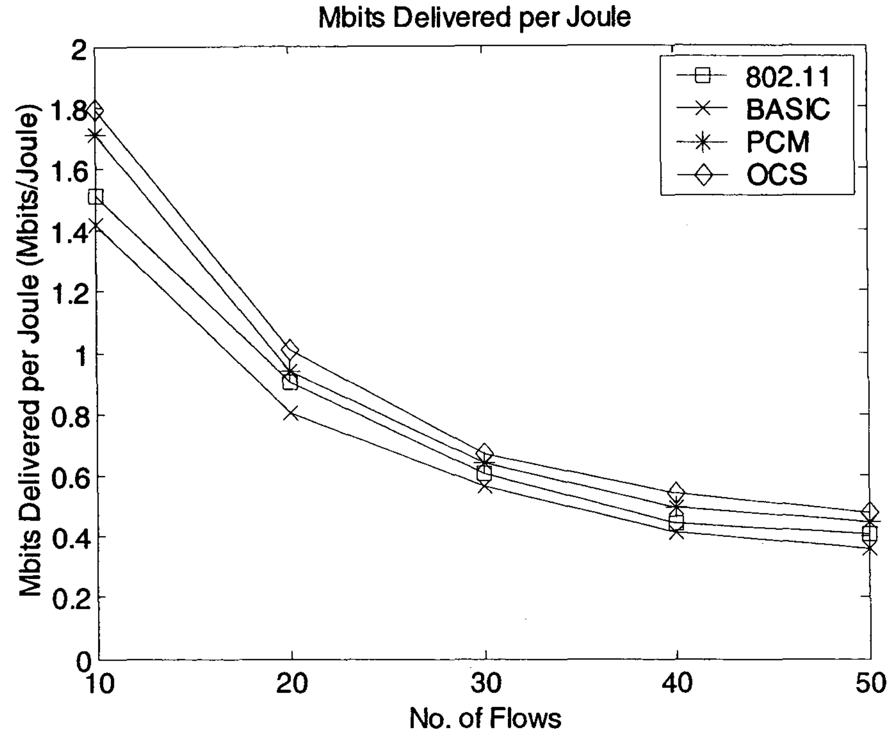

Figure 2.7: Random topology: Total data delivered per joule to study the effect of carrier sensing range on the performance of mobile ad hoc networks.

2.5 Conclusion

In this chapter we have shown the effect of interference from simultaneously transmitting nodes using different power levels and the various power control schemes in wireless ad hoc networks. We show that PCM scheme reduces the interference effect on the ongoing transmissions from other nodes in the network, by increasing its carrier sensing range compared to the BASIC scheme. But this interference effect is comparable to the IEEE 802.11. Therefore, we can say that PCM scheme conserves energy, not only because it uses lesser power for DATA/ACK but also due to the reduced interference.

In this chapter we have also shown the effect of carrier sensing range in terms of hidden and blocked nodes for various energy saving power control schemes in wireless ad hoc networks. Further, we have shown that there exits an optimum carrier sensing range which reduces the number of unnecessary back-off nodes, allows successful concurrency and maintain the same interference level. We have compared the performance of OCS scheme with 802.11, BASIC and PCM power control schemes. We investigated its performance under different network topologies. Our simulation results show that the OCS scheme achieved higher data delivered per joule. This means that the OCS scheme can achieve reduction in the energy consumption. On the other hand, the simulation results also indicate that the OCS scheme also improves the network throughput compared to all other schemes.

CHAPTER 3

COMPOW Based Power Control Protocols

In multi-hop ad hoc networks, the nodes cooperate with each others in forwarding the packets generated by a source to the destination through the network. This means that the throughput is not limited only by the available channel capacity, but also by the forwarding load imposed on intermediate nodes. The total capacity of a network grows with the area it covers. Network coverage can be increased by efficient spatial reuse of the spectrum. However, this effect could seriously limit the network throughput. On the other hand, the multi-hop networks experience more collisions compared to the single hop case as the nodes overlap successively in space. The increase in number of collisions degrades the network throughput and leads to lower data bits delivered per unit of transmit energy. In other way it makes hidden and exposed terminal problems more acute in such networks and the balancing between these two problems is more complex and challenging.

Researchers have proposed many power control schemes for wireless ad hoc networks to reduce the energy consumption for increasing the life- time of the network. However, these schemes may increase energy consumption and degrade the throughput due to the decrease in carrier sensing range or increase in interference range. To show this, we have considered interference effect on the performance of PCM protocol. The carrier sensing range of PCM scheme is always maximum irrespective of the level of the transmission power. However, increasing the carrier sensing range to the maximum reduces the level of spatial reuse. This drawback affects the overall throughput and hence energy consumption especially in case of multi-hop wireless ad hoc networks. Since some nodes of the multi-hop route in the maximum carrier sensing range can also transmit data successfully to its corresponding receiver without affecting the first ongoing transmission. Therefore, using the power control schemes with the conventional ad hoc routing or power aware routing protocols in the case of multi-hop ad hoc networks may degrade its performance badly. The design of an efficient energy conservation scheme in multi-hop wireless ad hoc networks requires considering power control and routing strategies together.

In this chapter, two power saving schemes mainly based on the COMPOW (COMmon POWer) protocol are introduced. Firstly, we propose a protocol that integrates PCM protocol and COMPOW protocol into one. The goal of the proposed scheme is to save power and maximize throughput in a multi-hop wireless ad hoc networks. Next, with the same goal we have proposed another efficient power saving scheme which is designed by integrating the COMPOW protocol and an Improved Power Control MAC (IPCM) protocol into one protocol. The simulation results show that the proposed power saving schemes achieve high reduction in energy consumption and significant improvement in the throughput compared to other schemes.

3.1 COMPOW Protocol

The COMPOW [46] protocol selects a common minimum transmit power that is required to maintain the network connectivity. Network connectivity is a network layer property, and therefore, power control schemes at the network layer operate along with the routing protocol. The main idea in COMPOW is to maintain multiple parallel routing tables for each power level. Therefore, a separate instance of routing protocol is run using each of the discrete power levels. The smallest power level is chosen which achieves the same level of network connectivity as the highest power level. The COMPOW power control protocol guarantees connectivity of the network, provides power aware routes, reduces MAC contention, and can be used with any proactive routing protocol. It works well if nodes are distributed homogeneously in space, but a single outlying node could cause every node to use a high power level. Therefore, when the spatial distribution of nodes is inhomogeneous, it is obviously not optimal to use a common power level throughout the network. This power control scheme is the only one which has been implemented and tested on a real wireless test-bed [46].

3.2 PCM/COMPOW Power Saving Scheme

We propose a PCM/COMPOW power saving scheme that integrates PCM protocol and COMPOW protocol into one. This new protocol works in two phases. First, it uses COMPOW protocol to select the minimum common power (P_{common}) that can be suitable for providing a link from the source to the destination. In the second phase, PCM uses this selected common power in place of maximum power (P_{max}). We have evaluated the performance of our proposed scheme and compared it with standard IEEE 802.11, BASIC and PCM power control schemes using MINPOW power aware and conventional ad hoc routing protocols. The simulation results show that PCM/COMPOW power saving scheme achieves high reduction in energy consumption and significant improvement in the throughput compared to the other schemes.

3.2.1 PCM/COMPOW Basics

In the PCM/COMPOW scheme, initially, COMPOW algorithm is executed to find the minimum common power that can be suitable to provide a link from the source to the destination. Then, the selected common power is used by the PCM protocol as maximum power. Therefore the RTS-CTS control packets in PCM/COMPOW power saving scheme are transmitted with a power equal to the common power whereas the DATA-ACK packets are transmitted with an optimum power (P_{opt}). Reducing the maximum power level of the control packets RTS-CTS to common power can save more energy and brings down the interference effects of these packets on the DATA-ACK packets. Even the transmission duration of RTS-CTS packets are small compared to DATA-ACK packets but it cannot be ignored since RTS-CTS packets can collide with other packets. Therefore, the effects of control packets on the DATA and ACK packets are reduced more as usually the common power is always lesser than the maximum power.

On the other hand, the power level of DATA packets is periodically raised to P_{common} from P_{opt} for a very short period, during the transmission of DATA packets. Therefore the second benefit of using common power is the significant reduction in carrier sensing range compared to the standard PCM scheme. The standard PCM uses the maximum carrier sensing range which improves the energy efficiency compared to IEEE 802.11 and BASIC schemes but it achieves a network throughput closed to IEEE 802.11. In PCM/COMPOW power saving scheme, the carrier sensing range is a function of the common power that is always lesser than maximum power but P_{common} is usually greater than the optimum level of the DATA packets. Therefore, this carrier sensing range is not the minimum as in case of standard BASIC but it is large enough to avoid the interference effects on various nodes involved in the multi-hop routing. On the other hand, this carrier sensing range is not maximum that creates unnecessary contention between nodes as in the standard PCM scheme. Reducing power level, avoiding collisions, improving spatial reuse and increasing the contentions between the nodes of the multi-hop wireless ad hoc networks, save energy and improve the throughput.

3.2.2 Simulation and Results

In this section, we present the various parameters and inputs considered for simulation, and the results obtained for IEEE 802.11, BASIC, PCM schemes and our scheme PCM/COMPOW through extensive simulation using Glomosim-2.03. We have also simulated the first three schemes using MINPOW as well as conventional ad hoc routing protocols AODV [49], DSR [25] and LAR [35].

3.2.2.1 Simulation Environment

The proposed power saving scheme evaluated using two different network topologies: chain topology and random multi-hop topology. The chain topology composed of 31 nodes, 30 flows with equal spacing whereas the random multi-hop topology consists of 100 nodes randomly distributed in an area of 1000 x 1000 m^2. This study considered the transmit power levels and their corresponding transmission range as given table 2.3. The parameter values given in table 2.4 are used in these simulations. The signal propagation model used in this work is a combination of free space propagation and two-ray ground reflection model whose details are explained in section 2.3.1. Each simulation runs for 20 seconds. All simulation results are an average of 10 simulation runs. The source node in the network generates CBR (Constant Bit Rate) traffic at the rate of 1 Mbps. Packet size is 512 bytes unless otherwise specified (We also performed some simulations varying packet sizes as well).

3.2.2.2 Experimentation

Experiments are carried out for the two mentioned topologies. The performance of IEEE 802.11, BASIC, PCM and PCM/COMPOW are evaluated in terms of the aggregate throughput, effective throughput, total and effective data delivered per joule. In case of the chain topology, the distance between adjacent node pairs is considered uniform. However in the simulations, we vary distance from 40 m to 250 m. The first node of the chain is considered as sender node whereas the last node of the chain is considered as the destination node. In case of random multi-hop topology, two nodes are selected; one is considered as a sender and the other as the destination. These two nodes are located near the opposite corners of the simulation area. In the PCM/COMPOW, a source node finds its route to the destination using COMPOW protocol. Performance of PCM/COMPOW is compared with the standards IEEE 802.11, BASIC and PCM using MINPOW routing protocol and the conventional ad hoc routing protocols AODV, DSR and LAR.

3.2.2.3 Results and Discussions

This section discusses the results obtained from the simulations carried out for the three mentioned topologies.

Chain topology

Figure 3.1 shows the aggregate throughput obtained from the simulation for the chain topology with 31 nodes and 30 flows for the varying distance between two adjacent nodes with a traffic rate of 1 Mbps. The figure shows the comparison of the throughput of IEEE 802.11, BASIC, PCM and the proposed scheme PCM/COMPOW. It clearly shows that the PCM/COMPOW achieves a higher aggregate throughput compared to all other schemes when the adjacent nodes are at distances <150 m. This is because the interference which causes collision with PCM/COMPOW scheme is reduced compared to other schemes. This happens, since the reduction in power levels of the control packets reduces the probability of collisions of control packets with the DATA and ACK packets. The second reason is that PCM/COMPOW uses a smaller carrier sensing range compared to IEEE 802.11 and PCM scheme, therefore, a larger number of nodes can transmit concurrently as this carrier sensing range is sufficient to reduce the exposed terminal problem. The aggregate throughput of IEEE 802.11 and PCM schemes are comparable as they reserve similar carrier sensing range, but the aggregate throughput of BASIC scheme is the worst. Even the carrier sensing range of PCM/COMPOW when the distance between adjacent nodes are 150 m and 180 m is lesser than IEEE 802.11 and PCM scheme but it achieves an aggregate throughput comparable to them. This happened at these distances because the number of blocked nodes with PCM/COMPOW is quite comparable with IEEE 802.11 and PCM scheme.

Figure 3.2 shows the total data delivered per joule (Mbits/Joule) for the different schemes. PCM/COMPOW scheme consumes less energy compared to all other schemes, since it uses common power levels for all the RTS-CTS packets. Common power is lower than the maximum transmission power and lower periodic pulse power compared to standard PCM. All the schemes use maximum power for transmitting packets when the adjacent nodes are 250 m apart. Therefore, the aggregate throughput and the total data delivered per joule for all the schemes are the same.

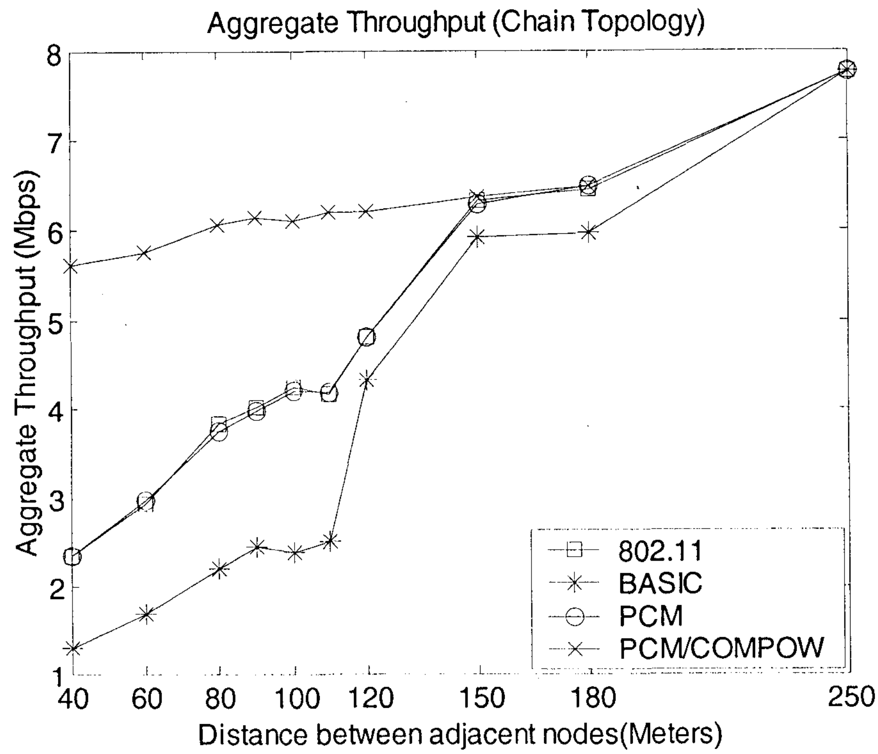

Figure 3.1: Chain topology: Aggregate throughput (PCM/COMPOW).

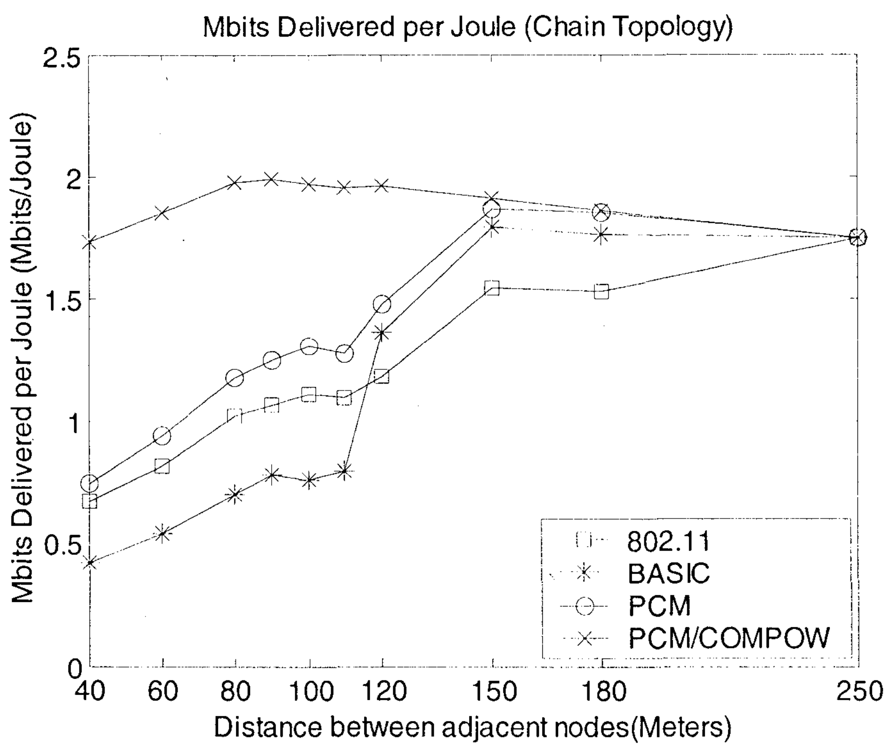

Figure 3.2: Chain topology: Total data delivered per joule (PCM/COMPOW).

To evaluate the performance of the proposed scheme for the chain topology, we have considered only the data delivered to the last node, i.e. node 31. This is due to the reason that only successfully delivered packets are considered for computation of effective throughput. Figure 3.3 shows that the effective throughput of PCM/COMPOW is higher compared to all the other schemes at distances <150 m. The effective throughput of IEEE 802.11 and PCM schemes are comparable but it is higher than BASIC scheme.

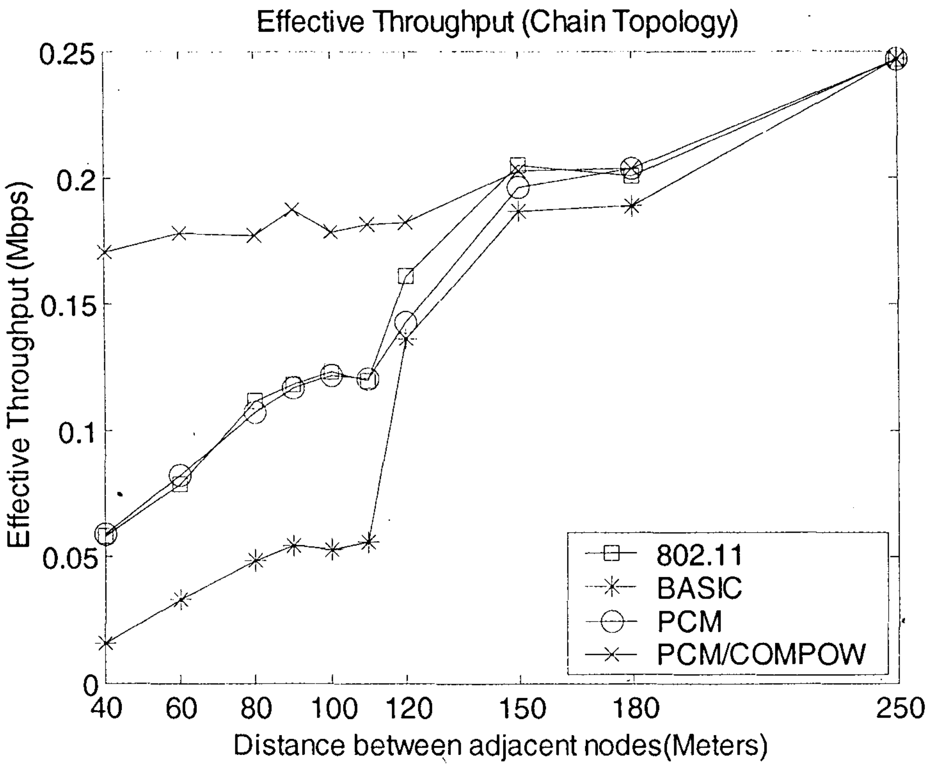

Figure 3.3: Chain topology: Effective throughput (PCM/COMPOW).

The PCM/COMPOW scheme delivers more data per joule to the final destination compared to all the other schemes as shown in figure 3.4. This means that the PCM/COMPOW protocol will conserve a considerable amount of energy while delivering the same amount of data to the destination node than the other schemes.

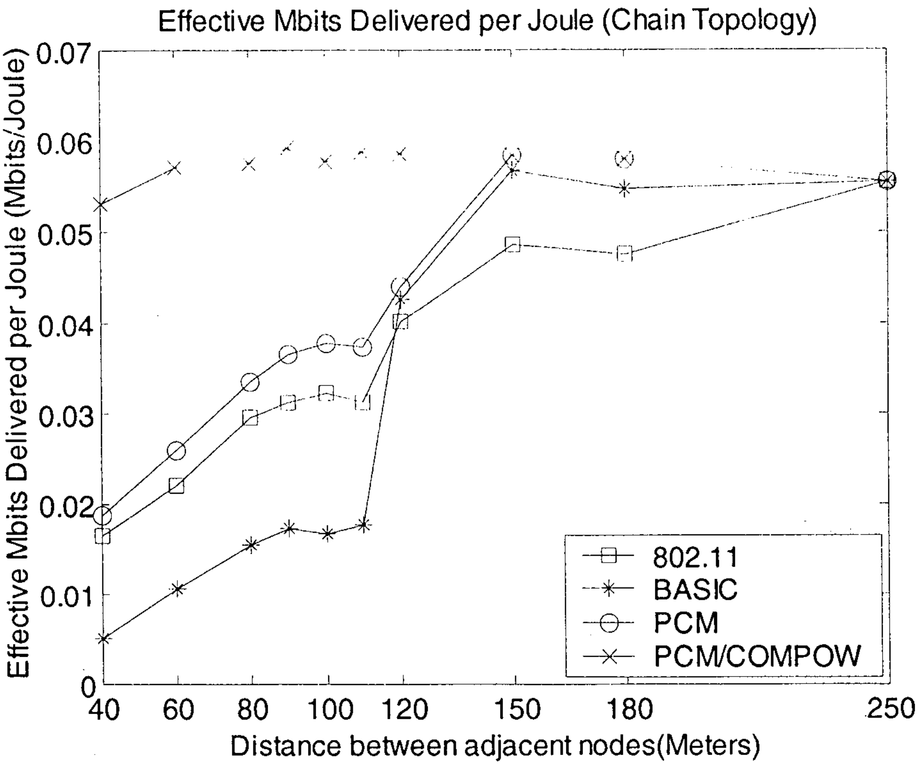

Figure 3.4: Chain topology: Effective data delivered per joule (PCM/COMPOW).

Random multi-hop topology

Figure 3.5 and figure 3.6 show the performance of power control schemes in terms of the aggregate throughput and total data delivered per joule under random multi-hop topology. Results show that the PCM/COMPOW scheme achieves a better aggregate throughput than IEEE 802.11, BASIC and PCM schemes using MINPOW routing protocols as shown in figure 3.5. This is achieved because the carrier sensing range used by the PCM/COMPOW allowed more data delivery over the multi-hop path from source to the destination. The aggregate throughputs of IEEE 802.11 and PCM schemes using MINPOW are quite comparable, whereas the BASIC scheme performs poorly. On the other hand, the better performance of the PCM/COMPOW scheme in terms of the aggregate throughput is also reflected on its energy consumption metric. Figure 3.6 shows that PCM/COMPOW achieves a higher total data delivered per joule compared to others.

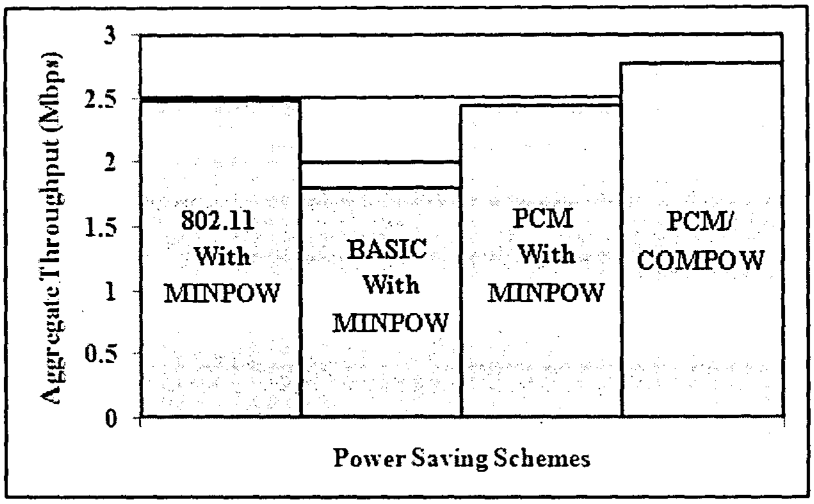

Figure 3.5: Random multi-hop topology: Aggregate throughput (PCM/COMPOW).

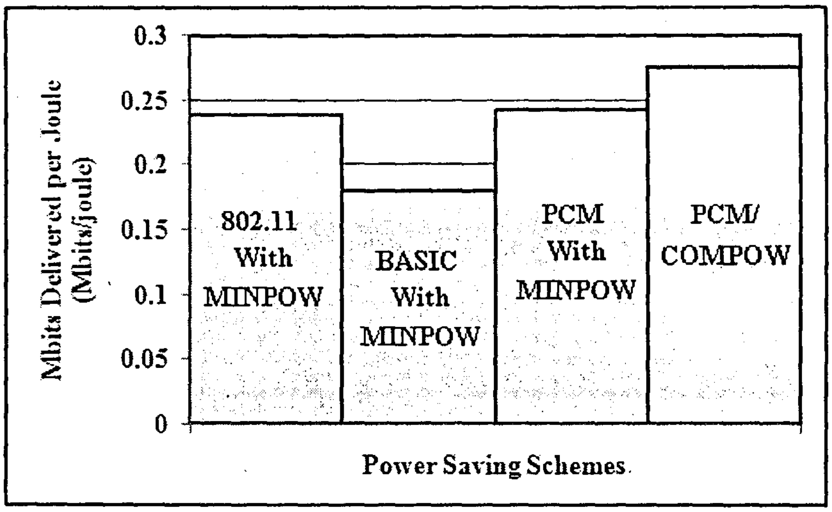

Figure 3.6: Random multi-hop topology: total data delivered per joule (PCM/COMPOW).

Figure 3.7 and figure 3.8 show the performance of all power control schemes and their corresponding routing protocols using random multi-hop topology. In this evaluation also, only the data delivered to the final destination in multi-hop random topology is considered. The effective throughput and effective data delivered per joule of the PCM/COMPOW scheme are high compared to all other schemes as shown in figure 3.7 and figure 3.8 respectively. The performance of the IEEE 802.11, PCM and BASIC scheme using MINPOW routing is much lower compared to the proposed protocol. The reason is that with the MINPOW protocol, the nodes of the multi-hop route use minimum power. This increases the number of hops and therefore, does not provide spatial reuse and the nodes on a path have to share and compete for the channel bandwidth. This affects the effective data compared to the total data. The BASIC scheme in conjunction with the MINPOW routing protocol performs worse than all the others.

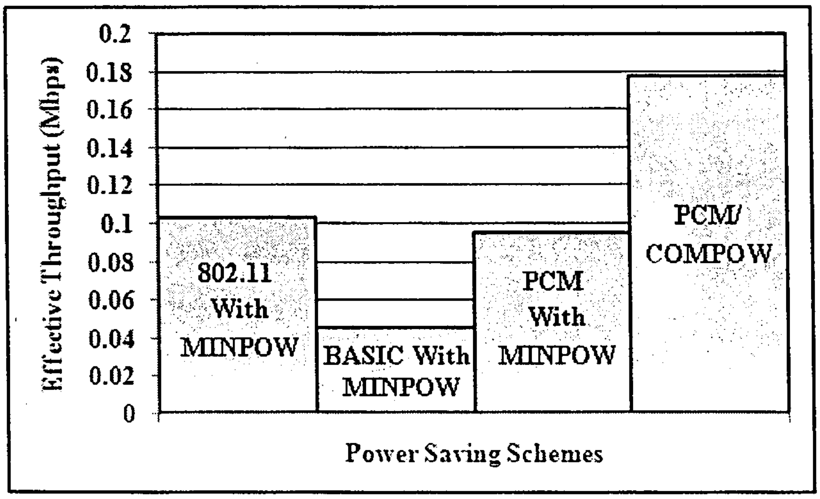

Figure 3.7: Random multi-hop topology: Effective throughput (PCM/COMPOW).

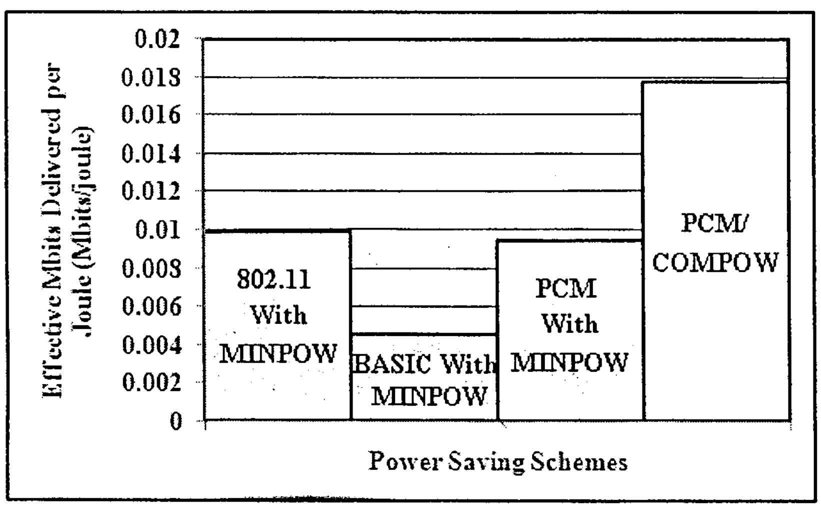

Figure 3.8: Random multi-hop topology: Effective data delivered per joule (PCM/COMPOW).

Figure 3.9 and figure 3.10 show the simulation results for random multi-hop topology with varying data packet size of 64, 128, 256, 512 and 1024 bytes at a traffic rate of 1 Mbps. The results show that the aggregate throughput and total data delivered in PCM/COMPOW scheme are higher than all other schemes with varying packet size. This is due to the reason that the PCM/COMPOW scheme is able to avoid collisions and retransmissions as it allows the spatial reuse. As the packet size increases, the data to the overhead increases for all schemes. This is reflected on all schemes in terms of improvement in aggregate throughput. It is well known that the reason behind the bad performance of the BASIC scheme is the hidden terminal problem, collisions and retransmissions.

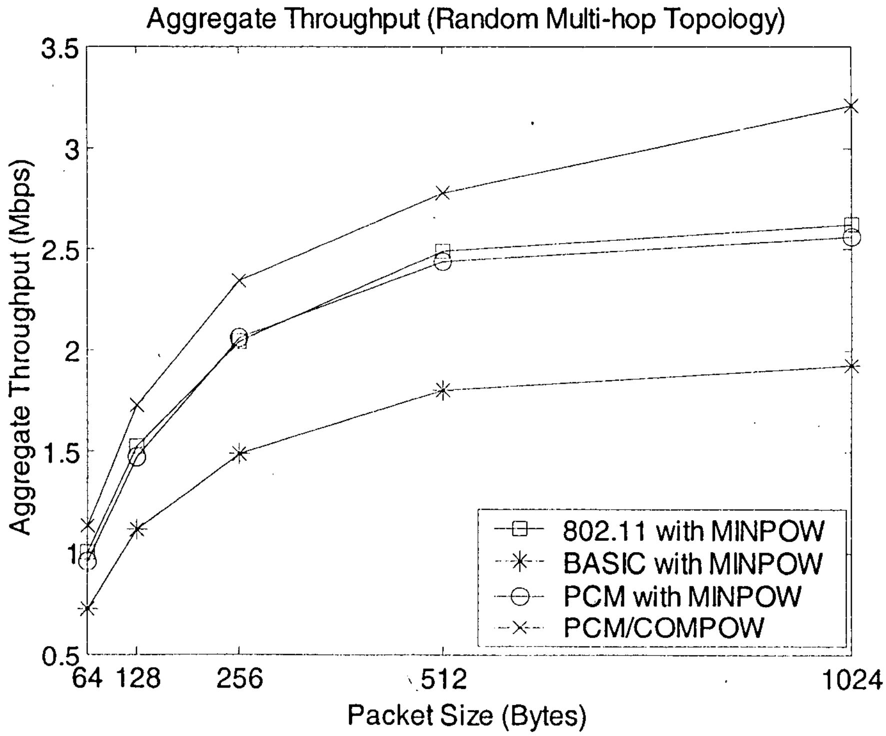

Figure 3.9: Random multi-hop topology: Aggregate throughput with different packet size (PCM/COMPOW).

A number of routing protocols have already been proposed for wireless ad hoc networks. In these conventional protocols, transmission power of each node is kept constant. In this work, we have evaluated the performance of the multi-hop wireless ad hoc network using AODV, DSR and LAR routing protocols in conjunction with the IEEE 802.11, BASIC and PCM scheme. The results show better performance of PCM/COMPOW compared to either IEEE 802.11 or other power control schemes.

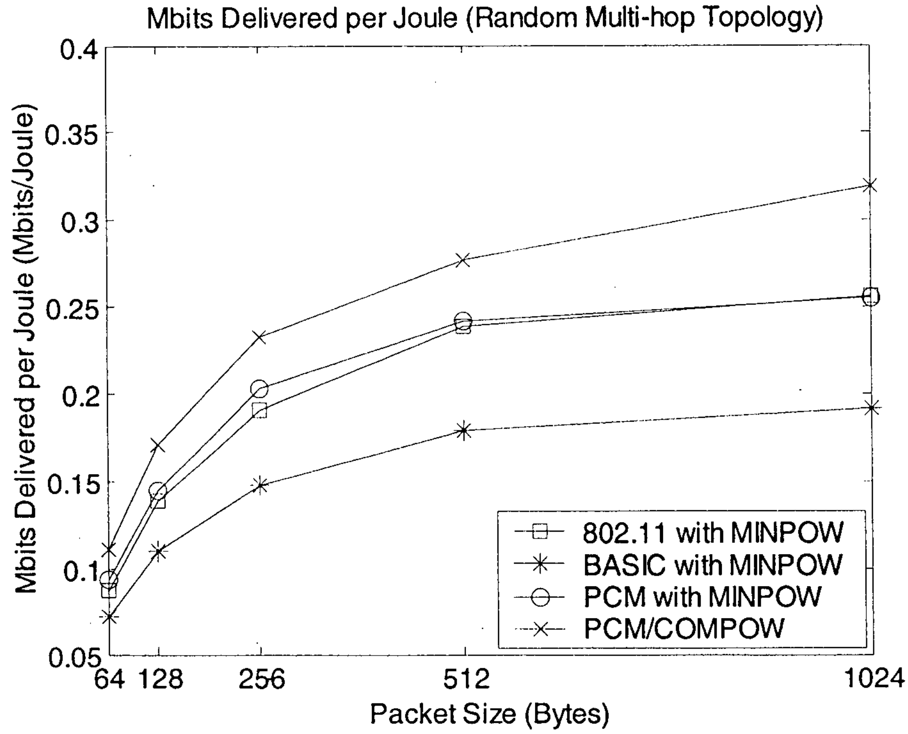

Figure 3.10: Random multi-hop topology: Total data delivered per joule with different packet size (PCM/COMPOW).

Figure 3.11 shows aggregate throughput of the PCM/COMPOW scheme and others power saving schemes under consideration using various routing protocols. From the figure it is clear that the aggregate throughput of PCM/COMPOW scheme is better than others whereas the BASIC scheme using any routing protocol performs badly. The aggregate throughput of all the schemes is also reflected on their total data delivered per joule as shown in figure 3.12. The PCM/COMPOW scheme delivered more total data per joule than others since it uses common power for RTS and CTS packets and minimum transmit power for DATA and ACK packets that reduce collisions and saves more energy. On the other hand, PCM scheme performs better than IEEE 802.11 scheme, since it uses maximum carrier sensing range and lesser transmit power that avoids collisions and saves energy. The BASIC scheme performs the worst among all other schemes.

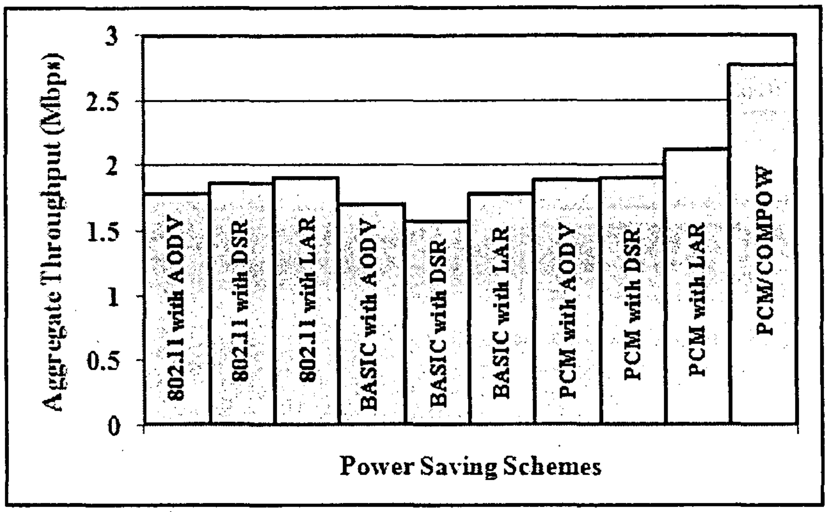

Figure 3.11: Random multi-hop topology: Aggregate throughput using different routing protocols with the power control schemes (PCM/COMPOW).

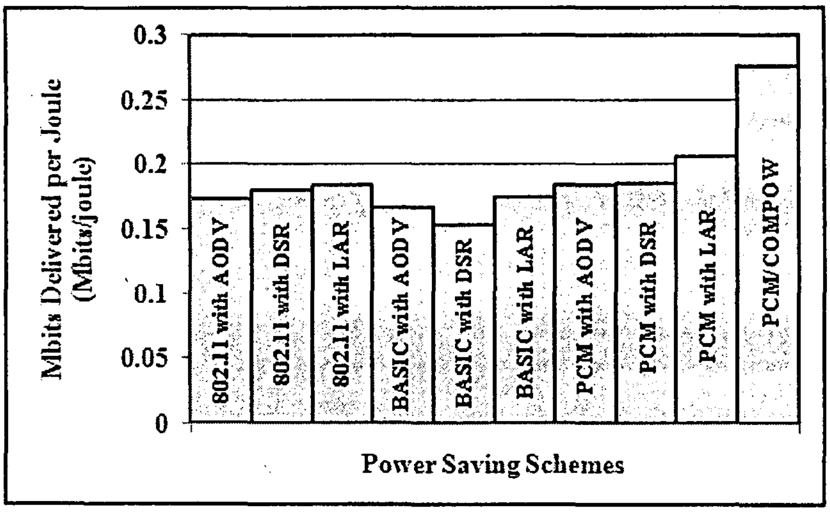

Figure 3.12: Random multi-hop topology: Total data delivered per joule using different routing protocols with the power control schemes (PCM/COMPOW).

3.3 IPCM/COMPOW Power Saving Scheme

We have also proposed another power saving scheme IPCM/COMPOW with the goal of saving more power and maximizing the throughput of a multi-hop wireless ad hoc network [74]. This new power saving scheme can be considered as an improved version of PCM/COMPOW protocol. The IPCM/COMPOW power saving scheme is designed by integrating COMPOW protocol and an Improved Power Control MAC (IPCM) protocol into one protocol. This protocol operates in two phases. Initially, COMPOW protocol is used to select the minimum common power that can be suitable to provide a link from a source to a destination. In the second phase, the level of the selected common power is used by IPCM protocol to find an optimum carrier sensing range that increases network capacity and reduce interference effect on the ongoing transmission. The simulation results show that IPCM/COMPOW protocol can achieve high reduction in energy consumption and also improves the throughput compared to other schemes.

3.3.1 IPCM/COMPOW Basics

The basic functional logic of this protocol has its basis on finding an optimum carrier sensing range so that nodes in the multi-hop routes wish to transmit data packets do not affect the ongoing transmission. Initially, COMPOW algorithm is executed to find the minimum common power that can be suitable for providing a link from a source to a destination. The common power determined is then used as an interference power by the IPCM protocol. Since all the nodes involved in multi-hop route from a source to a destination use a power equal or less than the common power, the interference power cannot be greater than the common power level. This interference power is used by the IPCM protocol to find an optimum carrier sensing range that increase the network capacity and reduce the interference effect on the ongoing transmission.

IPCM protocol transmits all the packets RTS, CTS, DATA and ACK with the optimum power. On the other hand, the power level of the DATA packets is periodically increases for enough time to a suitable level P_{ai} (not to P_{max} as in PCM) sufficient to avoid the collisions. This level P_{ai} is determined based on the value of *SIR* that is calculated using the optimum power, the distance between the sender and receiver, and the interference power (P_i). The common power level determined by the COMPOW algorithm is used as P_i. The carrier sensing range reserved by the pulse power level (P_{ai}) blocks the hidden nodes whose transmissions may affect the ongoing transmission. Whereas the nodes outside the reserved area can initiate a communication with each other, as their effects on the ongoing transmission will be negligible.

PCM protocol transmits the data with maximum periodic pulse power. This means reserving the maximum transmission area for the ongoing transmission, even the distance between the transmitter and receiver is small. The objective behind using maximum periodic pulse power in PCM is to increase the sensing range for informing neighbor nodes about the ongoing transmission in order to reduce the interference and increase energy conservation. But, increasing the carrier sensing range to the maximum affects the total throughput of the network. It is because some of the nodes in the maximum carrier sensing range are stopped from transmitting which otherwise could have transmitted data successfully to their corresponding receiver without affecting the first ongoing transmission.

The required pulse power level (P_{ai}) used in IPCM/COMPOW power saving scheme reduces the energy consumption. It is quite obvious that a lower pulse power will conserve a considerable energy compared to the maximum pulse power as in PCM. Further, the required pulse power also reduces the reservation area that allows concurrent transmissions resulting in improved throughput of the network.

Let R_{top} be the transmission range of RTS using optimum power. Since RTS and CTS use the same optimum power, the transmission range of CTS will be R_{top} also. Suppose that the periodic pulse power is also the same (i.e optimum), the carrier sensing range is at least twice of the transmission range. If the receiver is just at the edge of the transmission range of the transmitter, carrier sensing range (R_{cs}) covers both transmission ranges of RTS and CTS as shown in figure 3.13. Actually, this case is considered as the worst case. Usually, the periodic pulse power is greater than the optimum used power and/or the receiver is not exactly at the transmission range edge of the transmitter. This means, the ongoing transmission is completely covered by the carrier sensing range.

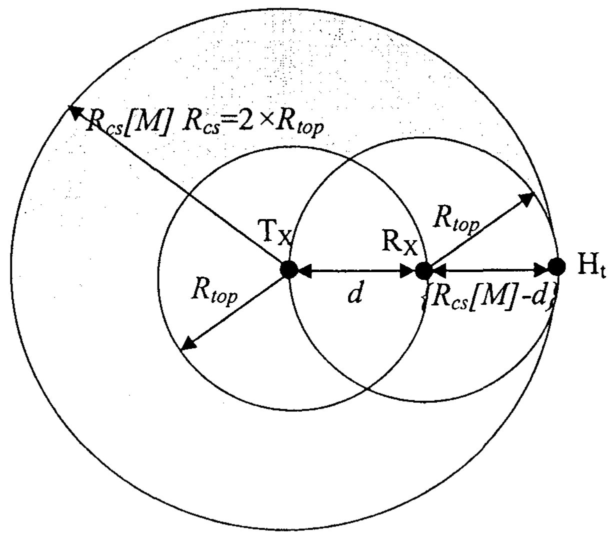

Figure 3.13: The carrier sensing range will cover both RTS and CTS transmission ranges for any used power.

3.3.2 IPCM/COMPOW Algorithm

Before we introduce the IPCM/COMPOW algorithm as given in figure 3.14, it is important to explain the simple diagram shown in figure 3.13. Let $P_t[L]$ be a set of the power levels used for the transmission, where L is an integer varies from 1 to MAX. $P_t[MAX]$ is the maximum power level and MAX is the number of power levels in the set. Let $R_{cs}[L]$ be the set of carrier sensing ranges corresponding to the set of power levels in set $P_t[L]$. Let d be the distance between the transmitter (*Tx*) and receiver (*Rx*). Suppose the transmitter reserves a carrier sensing area $R_{cs}[M]$, where M is an integer variable between 1 and *MAX*. Then the nearest hidden terminal (H_t) that can be considered as an interference node will be at a distance $\{R_{cs}[M]-d\}$ as shown in figure 3.13. This carrier sensing range covers the receiver and $\{R_{cs}[M]-d\}\geq d$ as mentioned earlier.

A. Transmitter :

1. ***Execute*** the ***COMPOW*** algorithm to *find* the smallest common power level which achieves the same level of network connectivity as the maximum power level.

2. ***Let*** $L=1$, p_i =common power level, $P_{ai}=P_t[MAX]$.
3. ***Check*** the node address *and* its stored ***S*** value.
4. ***If S*** is available, ***let*** $L=S$.
5. ***Send*** **RTS** ***with*** Tx. Power $P_t[L]$ and ***include*** the ***L*** value in the **RTS**.
6. ***If*** **RTS** ***timeout*** *and* **CTS** ***not received, increase L, goto*** **5**.
7. ***Receive*** **CTS**, ***observe*** its received power $(P_r.)$, ***store*** node address *and let* $S=L$.
8. ***Determine*** the distance ***d*** between the transmitter and the receiver using the optimal transmit power $P_t[L]$ and the received power $(P_r.)$.
9. ***Let*** $M=L$.
10. ***Determine SIR*** value using the values of $P_t[M]$, d, $d_i=\{R_{cs}[M]-d\}$ and p_i.
11. ***If*** $SIR < SIR_{th}$

    If $P_t[M]== P_t[MAX]$

    goto End

    else

    increase M, goto **10**
12. ***End.***

B. ***Receiver :***

1. ***Receive*** **RTS**.
2. ***Extract*** the ***L*** value from **RTS** packet *and* ***store L*** value.
3. ***Transmit*** **CTS** using the power level $P_t[L]$.
4. ***End.***

Figure 3.14: IPCM/COMPOW power saving scheme algorithm.

3.3.3 Simulation and Results

We evaluated IPCM/COMPOW scheme, IEEE 802.11, BASIC, and PCM schemes using Glomosim-2.03 through extensive simulations. The IEEE 802.11, BASIC and PCM schemes are simulated with MINPOW and using routing protocols AODV, DSR and LAR.

3.3.3.1 Simulation

The parameters values, output metrics, propagation model and the other settings used for evaluating the proposed IPCM/COMPOW and the others schemes are the same as specified in the section 3.2.2.1 and used in the evaluation of the PCM/COMPOW. The detail of the experiments carried out in these simulations is the same as described in the section 3.2.2.2.

3.3.3.2 Results and Discussions

This section discusses the results obtained from the study carried out for the chain and random multi-hop topologies.

Chain topology

The simulation results obtained from the experiments carried out in case of the chain topology show that IPCM/COMPOW achieves a higher aggregate throughput compared to all other schemes as shown in figure 3.15. This is because in IPCM/COMPOW a larger number of nodes can transmit concurrently, since it uses a smaller carrier sensing range compared to IEEE 802.11 and PCM schemes. Also this carrier sensing range is larger than the carrier sensing range of BASIC scheme and it is sufficient to reduce the hidden terminal problem. At the distances of 180 m, the aggregate throughput is comparable with IEEE 802.11 and PCM scheme, since the carrier sensing range determined by the IPCM/COMPOW algorithm at this distance also tends to be the maximum.

This improvement in the aggregate throughput of the IPCM/COMPOW is reflected on the amount of data delivered per joule. Figure 3.16 shows the comparison of the data delivered per joule of IEEE 802.11, BASIC, PCM and the proposed scheme IPCM/COMPOW. It clearly shows that the IPCM/COMPOW scheme consumes lesser amount of energy compared to the others schemes, since it uses lower transmission power for all the packets and lower periodic pulse power. On the other hand, reducing the periodic pulse in IPCM/COMPOW scheme is enough to eliminate the hidden node problem. This reduction in periodic pulse power also reduces the number of deferring nodes, and thus more data can be delivered per joule.

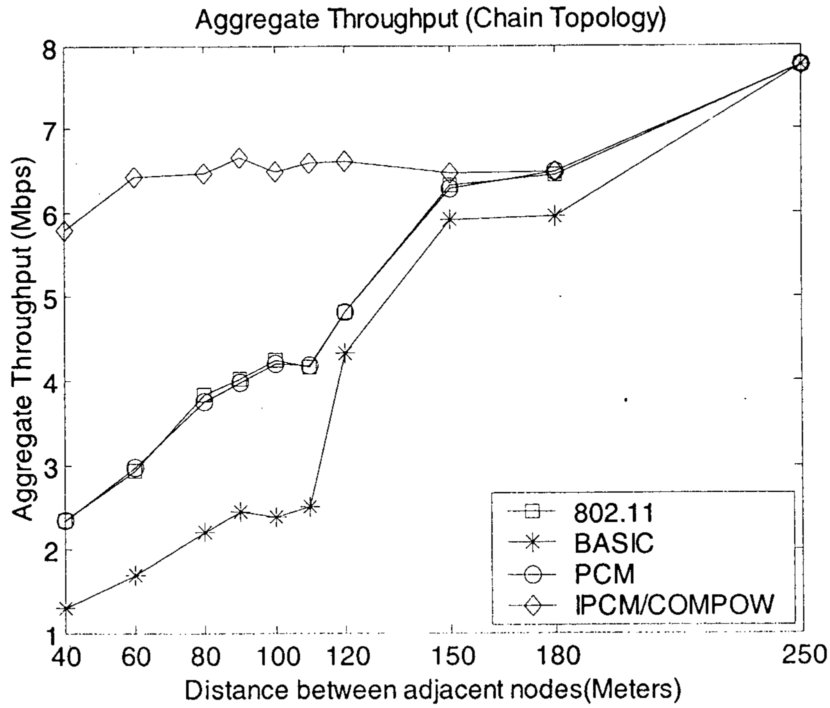

Figure 3.15: Chain topology: Aggregate throughput (IPCM/COMPOW).

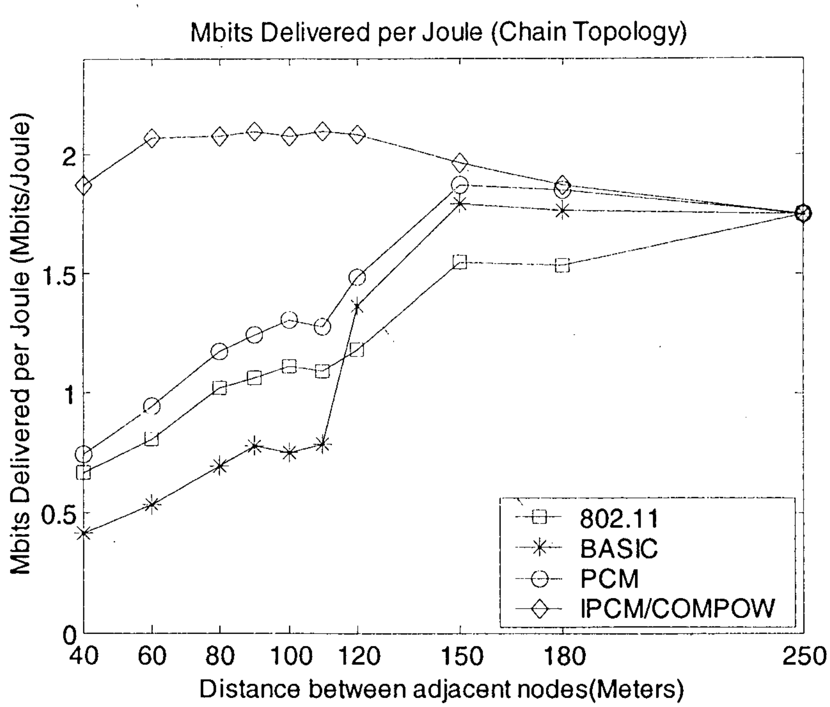

Figure 3.16: Chain topology: Total data delivered per joule (IPCM/COMPOW).

The next simulation results obtained from the chain topology considering only the data delivered to the last node, i.e. 31, since it is the final destination and all the other nodes are just routing nodes for this destination. The effective throughput of the IPCM/COMPOW is much higher compared to all other schemes as shown in figure 3.17. On the other hand, the IPCM/COMPOW scheme delivers more data per joule to the final destination compared to all other schemes as shown in figure 3.18. This means that the IPCM/COMPOW protocol can conserve more energy than others.

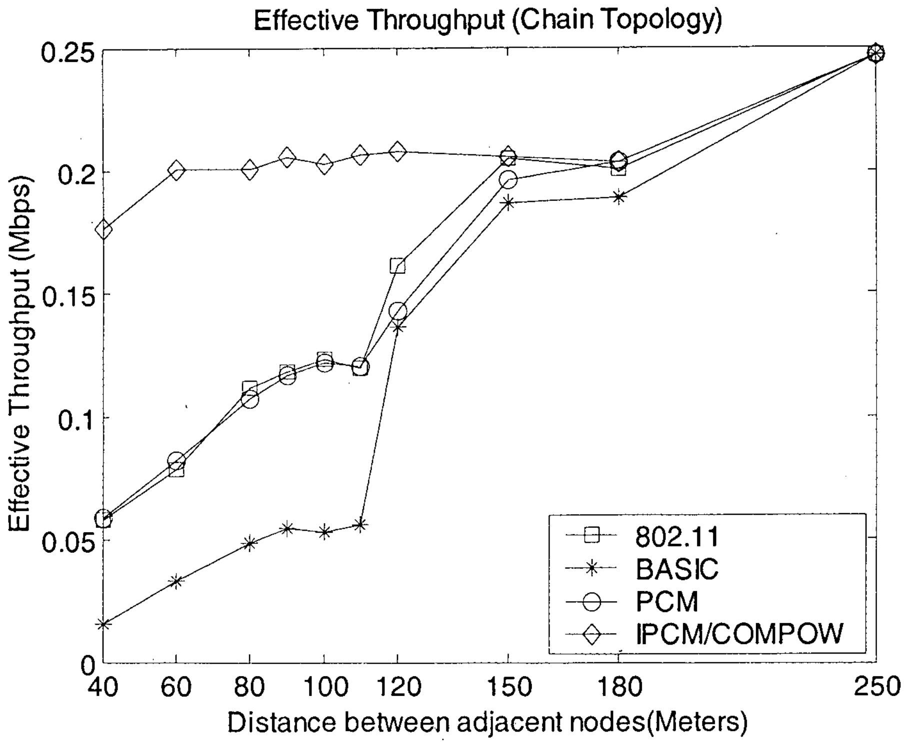

Figure 3.17: Chain topology: Effective throughput (IPCM/COMPOW).

Random multi-hop topology

The simulation results obtained from the experiments carried out for the random multi-hop topology show that the performance of proposed IPCM/COMPOW power saving schemes in terms of the aggregate throughput and total data delivered per joule is better than IEEE 802.11, BASIC and PCM schemes using either MINPOW or the general routing protocols. Figure 3.19 shows that the PCM/COMPOW scheme achieves a much higher aggregate throughput than IEEE 802.11, BASIC and PCM schemes using MINPOW routing protocols, since the carrier sensing range used by IPCM/COMPOW allows more data transmission over the multi-hop path from source to the destination. On the other hand, use of the optimum power levels for all the packets in IPCM/COMPOW scheme reflects on its energy consumption metric. Figure 3.20 shows that IPCM/COMPOW achieves significantly higher total data delivered per joule compared to other schemes.

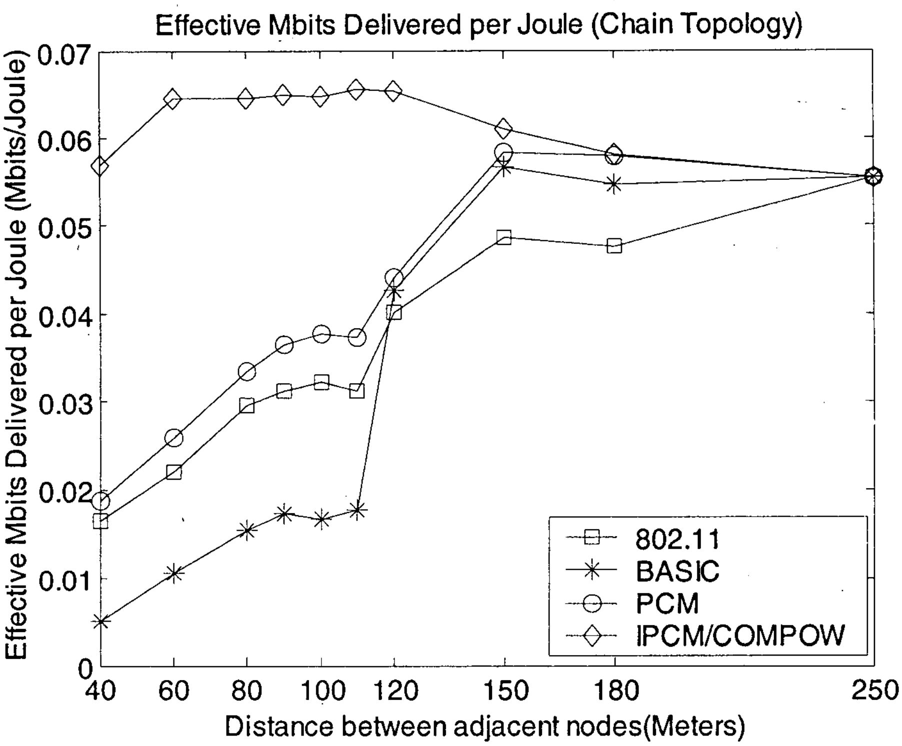

Figure 3.18: Chain topology: Effective data delivered per joule (IPCM/COMPOW).

In the next evaluation of the random multi-hop topology, only the data delivered to the final destination is considered. The effective throughput and effective data delivered per joule of the IPCM/COMPOW scheme are high enough compared to all other schemes as shown in figure 3.21 and figure 3.22 respectively. The reason for this improvement is that firstly, IPCM/COMPOW provides spatial reuse among nodes on a path since it uses smaller carrier sensing range compared to others. The second reason is that IPCM/COMPOW uses minimum power levels for all packets which results in small number of collisions and more power saving.

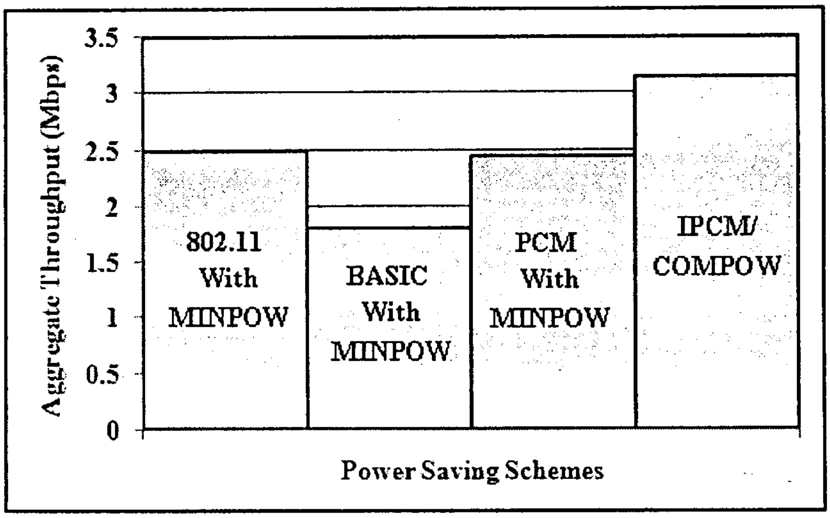

Figure 3.19: Random multi-hop topology: Aggregate throughput (IPCM/COMPOW).

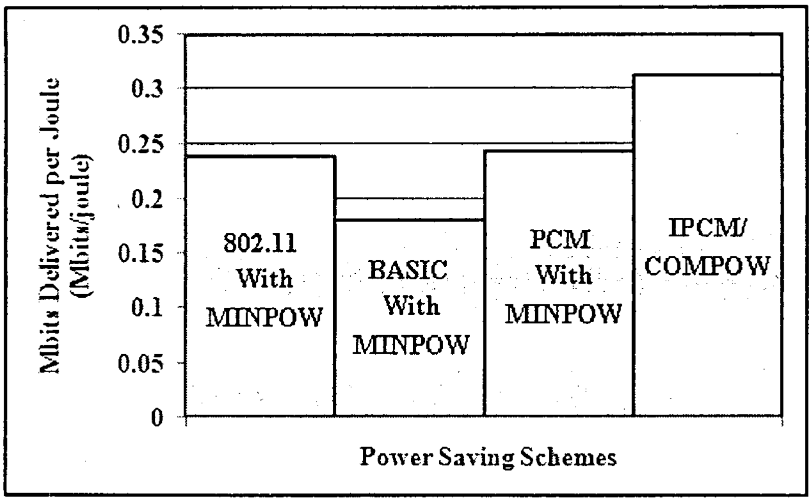

Figure 3.20: Random multi-hop topology: Total data delivered per joule (IPCM/COMPOW).

The simulation results for random multi-hop topology with varying data packet sizes of 64, 128, 256, 512 and 1024 bytes at a traffic rate of 1 Mbps are shown in figure 3.23 and figure 3.24. The results show that the performance of IPCM/COMPOW scheme is better than all other schemes with varying packet size. As shown in the figures, the throughput and the total data delivered per joule of IPCM/COMPOW is higher compared to others. It is because IPCM/COMPOW scheme is able to avoid the collisions and retransmissions and allows the spatial reuse.

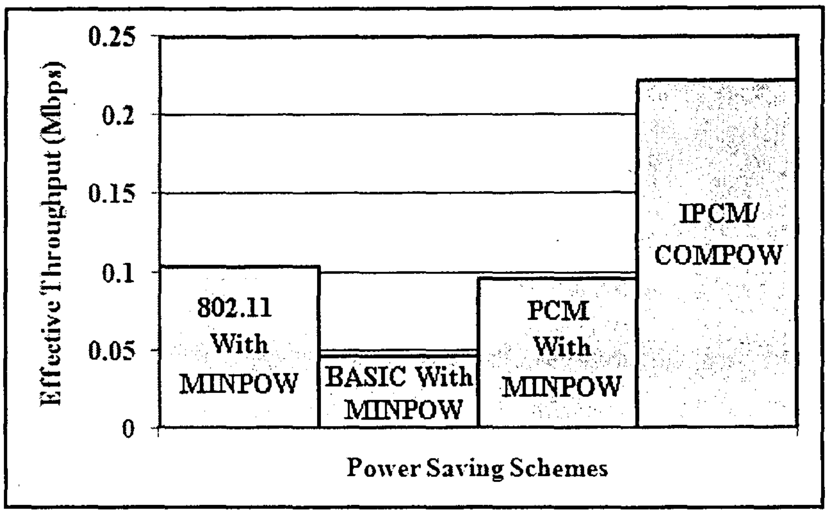

Figure 3.21: Random multi-hop topology: Effective throughput (IPCM/COMPOW).

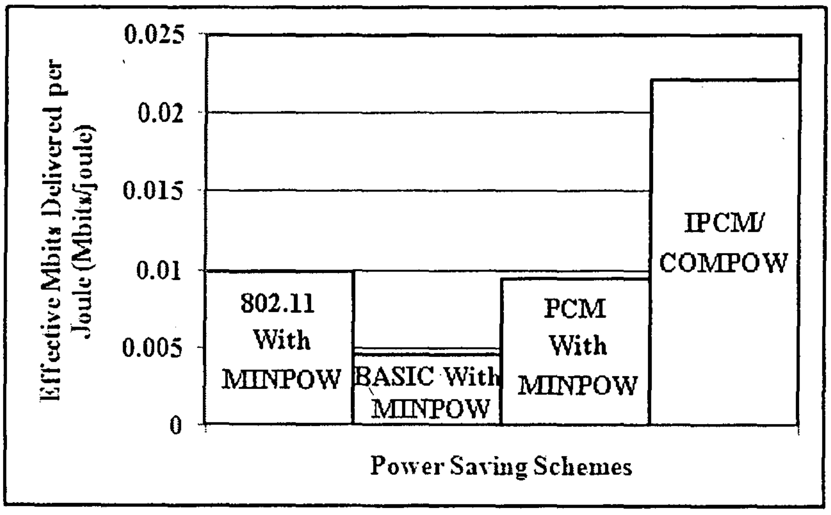

Figure 3.22: Random multi-hop topology: Effective data delivered per joule (IPCM/COMPOW).

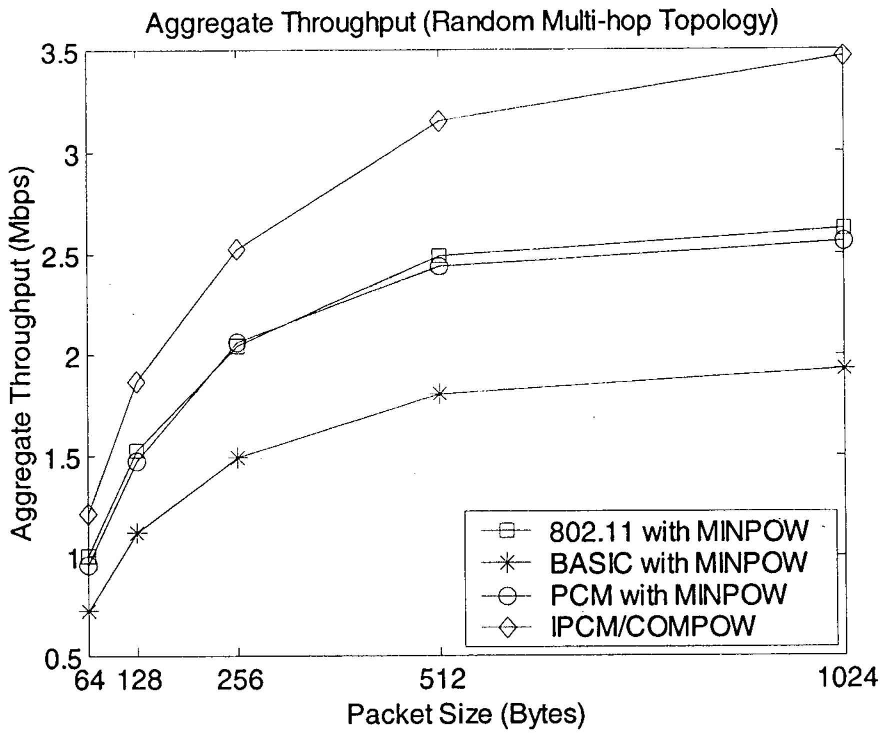

Figure 3.23: Random multi-hop topology: Aggregate throughput with different packet size (IPCM/COMPOW).

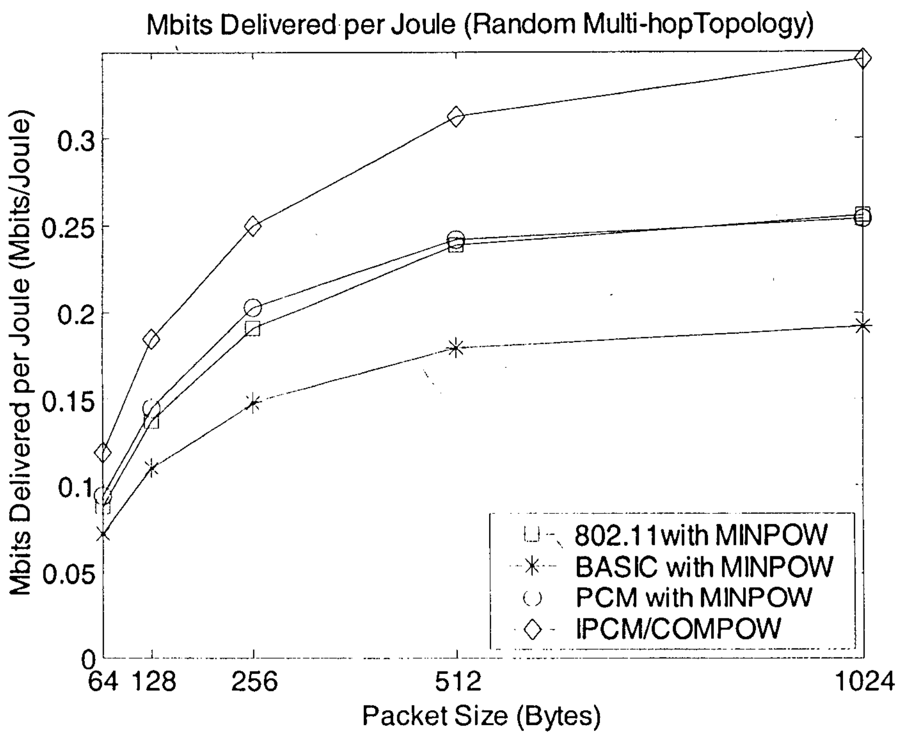

Figure 3.24: Random multi-hop topology: Total data delivered per joule with different packet size (IPCM/COMPOW).

The performance of the multi-hop wireless ad hoc network using IPCM/COMPOW power saving scheme is also compared with the conventional routing (AODV, DSR and LAR) in conjunction with the IEEE 802.11, BASIC and PCM scheme. The results show that IPCM/COMPOW performs better compared to the conventional ad hoc routing with power control schemes. Figure 3.25 shows the aggregate throughput of the IPCM/COMPOW scheme and the other power saving schemes under consideration using various conventional ad hoc routing protocols. It is clear that the IPCM/COMPOW scheme is able to improve the aggregate throughput compared to the others. On the other hand, the IPCM/COMPOW scheme also delivered more total data per joule than others as shown in figure 3.26, since it uses lower transmit power for all packets. The reasons behind the performances of IEEE 802.11, PCM and BASIC schemes are already described in the section 2.3.2.3.

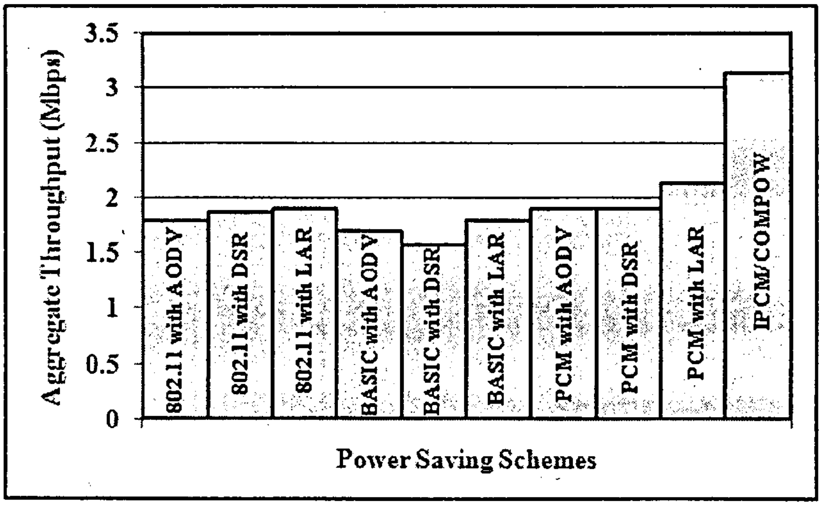

Figure 3.25: Random multi-hop topology: Aggregate throughput using different routing protocols with the power control schemes (IPCM/COMPOW).

The results shown by PCM/COMPOW and IPCM/COMPOW protocols are encouraging. These protocols can be useful for dense multi-hop wireless ad hoc networks where interference and energy consumption in general are more due to collisions. Therefore these protocols may also help in enhancing the life time of a network since they reduces the energy consumption.

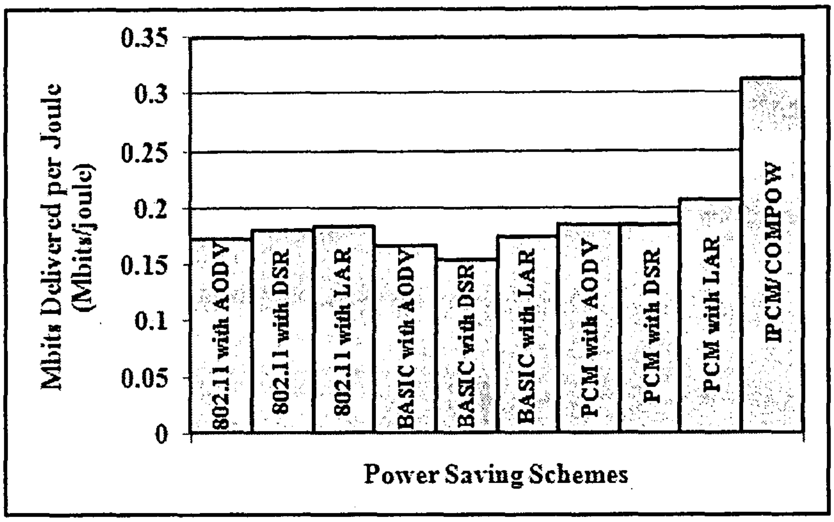

Figure 3.26: Random multi-hop topology: Total data delivered per joule using different routing protocols with the power control schemes (IPCM/COMPOW).

3.4 Conclusion

In this chapter, we have proposed two new power saving schemes for multi-hop wireless ad hoc networks based on the COMPOW protocol. These new power saving schemes are known as PCM/COMPOW and IPCM/COMPOW power saving schemes. We have compared the performance of these schemes with IEEE 802.11, BASIC and PCM power control schemes. Their performances are investigated under different network topologies, different packet size and various ad hoc routing protocols. The simulation results show that these schemes achieve higher total data delivered per joule. This means that the proposed schemes can achieve a high reduction in energy consumption. On the other hand, the simulation results also indicate that these schemes significantly improve the network throughput compared to other schemes. PCM/COMPOW and IPCM/COMPOW protocols are able to meet their goals as they are mainly designed for multi-hop wireless ad hoc networks to avoid the interference, save energy and improve the throughput.

CHAPTER 4

Modified Improved Power Control MAC Protocol

Several MAC layer power control protocols for wireless Ad Hoc networks have been proposed in the literature. These protocols allow transmit power control on per packet basis to reduce power consumption and/or increase the network throughput. Most of these power control schemes use maximum transmission power for RTS-CTS and minimum required transmit power for DATA-ACK transmission in order to save energy. In the previous chapter we introduced two power saving schemes based on the COMPOW protocol, mainly designed for multi-hop wireless ad hoc networks. This chapter presents the design details and evaluation of the proposed power control MAC protocol which we call Modified Improved Power Control MAC (MIPCM) protocol. The goal of this proposed protocol is to improve the throughput and yield energy saving for wireless ad hoc networks. MIPCM protocol is a modified version of IPCM. The simulation results show that MIPCM protocol scheme achieves high reduction in energy consumption and improves the throughput compared to other schemes. This chapter also presents a comparative study between PCM/COMPOW, IPCM/COMPOW protocols described in chapter three and MIPCM protocol explained in this chapter. We compare these three protocols under the same simulation environment and experiments.

4.1 Modified Improved Power Control MAC Protocol

MIPCM protocol sends all the packets RTS, CTS, DATA and ACK with optimal transmit power which saves energy, makes spatial reuse of the wireless channels and achieves the maximum throughput. On the other hand, the power of the data packets is periodically raised to a suitable level (P_{ai}) to avoid the interference but not to the maximum so that it does not create unnecessary contention between nodes. The power level of P_{ai} depends on finding the optimum carrier sensing range that increase the network capacity and reduce the interference effect of the ongoing transmission. Our simulation results show that MIPCM protocol scheme can achieve high reduction in energy consumption and also improves the throughput compared to other schemes.

4.1.1 MIPCM Protocol Basics

The proposed MIPCM protocol transmits all the packets RTS, CTS, DATA and ACK with optimal transmit power but the power level of DATA packets is periodically increased, for enough time to a suitable level (P_{ai}) that is sufficient to avoid the collisions. MIPCM protocol can be considered as an improved version of PCM protocol. The PCM scheme uses maximum carrier sensing range which may affects the total throughput of the network, since some nodes in the maximum carrier sensing range can also transmit data successfully to its corresponding receiver without affecting the ongoing transmission. For example, suppose there are two transmitters and each one is willing to send data to its corresponding receiver. Therefore, each transmitter works as an interference node for the other. If the *SINR* (Signal to Interference Noise Ratio) of the first transmission $\geq SINR_{th}$ (Threshold Signal to Interference Noise Ratio) and the *SINR* of the second transmission $\geq SINR_{th}$, both the transmissions can take place simultaneously instead of one transmission. Therefore, the overall network throughput will increase. The essential design goal of MIPCM protocol is to choose an optimal carrier sensing range that can increase the channel utilization while maintaining a certain *SINR* value suitable to avoid hidden terminal and exposed terminal problems. The hidden terminal problem occurs when other transmitters that are outside the carrier sensing range, but lie within the interference range of receiver of ongoing transmission, attempt to transmit. It results in a packet loss or collisions. Conversely, exposed terminal problem occurs when a node lies within the carrier sensing range of an ongoing transmission and future transmission attempts will not collide with the ongoing transmission. But this exposed terminal defers from accessing the channel even it can transmit at the same time as the sender, without causing a collision to occur.

In the proposed protocol, all packets RTS, CTS, DATA and ACK are transmitted with the optimum power. Using optimum power levels for all packets, firstly, reduces the energy consumption. This is because lower power level for RTS and CTS packets conserves a considerable energy compared to the maximum power level as in the BASIC and PCM schemes. Secondly, the optimum power levels reduce the interference effect on other nodes, which results in lower number of collisions. This also improves the energy efficiency of the network. On the other hand, MIPCM protocol increases the power level of DATA packets periodically to a suitable pulse power level (P_{ai}). Using the required pulse power level, firstly, reduces the energy consumption since lower pulse power conserves considerable energy compared to the maximum pulse power as in PCM. Secondly, the required pulse power reduces the reservation area, which results in concurrent transmission at the same time. This improves the throughput of the network. The required pulse power level which results in an optimum carrier sensing range is determined by using the observed *SINR* values at the receiver and the transmitter.

In [28], the authors show that the number of interference nodes get reduced in the chain topology with 30 flows using PCM scheme compared to the BASIC scheme. In IPCM protocol, since all the packets are transmitted using the optimum powers and with the help of the interference analysis, we find that optimum carrier sensing range, which is lower than the maximum is sufficient to avoid the collisions. This means, other concurrent transmissions can also take place. For example, in a chain topology of 31 nodes with 30 flows and the distance between adjacent node pairs is 40 m, the carrier sensing range of 134 m is enough to avoid interference compared to 550 m as in case of PCM.

4.1.2 MIPCM Protocol Description

Before we introduce the MIPCM protocol algorithm shown in figure 4.2, it is important to explain the simple interference model shown in figure 4.1. The optimal carrier sensing range that can cooperatively solve the hidden and exposed terminal problems is obtained using the worst interference case as illustrated in figure 4.1. Let d be the distance that separates two communicating nodes pair. Let R_{OPT} be the transmission range for RTS packets using the optimum power. Since RTS and CTS use the same optimum power, the transmission range for CTS will be R_{OPT} also. Suppose that the periodic pulse power is also the same (i.e optimum), the carrier sensing range will be at least twice of the transmission range [30]. Therefore, the carrier sensing range (R_{cs_MIN}) will cover both transmission range of RTS and CTS as shown in figure 4.1. According to IEEE 802.11DCF, any node in the carrier sensing range defers its transmission request. This node maintains a NAV (Network Allocation vector), which indicates the remaining time of the ongoing transmission session. The time period in the NAV is long enough for a source node to receive an ACK frame. The duration of an ongoing transmission in NAV is initially longer than that of an ACK transmission. When a transmitter receives an ACK frame, a node in the carrier sensing range goes to a back-off period and sense the medium again after expiry of back-off period. If the transmitter that received the ACK has more data to transmit, the node in the back-off mode will notice the medium busy and maintains another NAV period.

On the other hand, any node outside of this minimum carrier sensing range will be either silent or part of another ongoing communication pair. If any of these outside nodes is in transmitting mode and it is in the interference range then the ongoing transmission will interfere with it. Usually, the interference range is larger than the transmission range, and it is a function of distance between the sender and receiver. DATA packets and ACKs can be successfully received if the $SINR$ at both the transmitter and receiver are greater or equal to $SINR_{th}$. This kind of transmission attempt results in more number of concurrent transmissions and improves the aggregate network throughput. Therefore, an increasing carrier sensing range to the maximum (R_{cs_MAX}) causes exposed nodes to defer their transmission attempts until the ongoing transmission is over. An optimal carrier sensing range (R_{cs_OPT}) should balance the trade-off between the amount of spatial frequency reuse and the possibility of packet collisions.

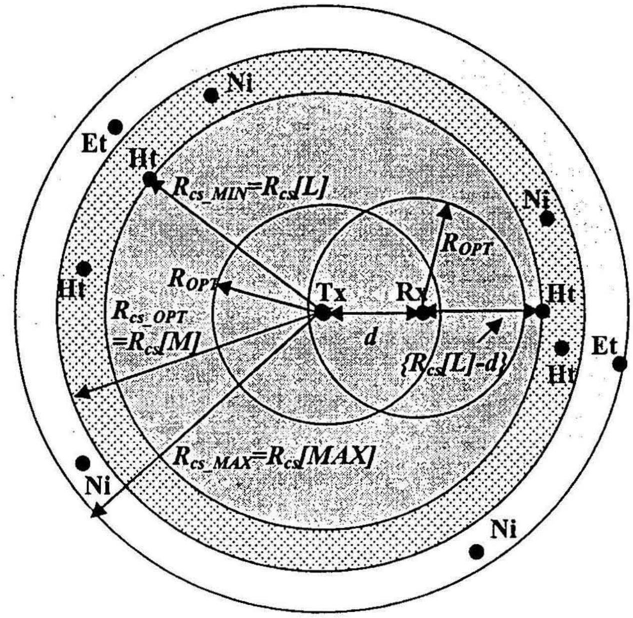

Figure 4.1: The interference model.

Let $SINR_{RX}(t)$ be the current signal to interference noise ratio at the receiver obtained with an optimum power and the minimum carrier sensing range $d_{SC}(L)$.

$$SINR_{RX}(t) = \frac{P_{r,RX}(t)}{P_N(t) + P_{ri,RX}(t, d_{CS}(L))} \tag{4.1}$$

Where $P_{r,RX}(t)$ is the power received which depends on the transmitting power and the environment of the communication link, $P_N(t)$ is a noise power and $P_{ri,RX}(t,d_{SC}(L))$ is the interference power signal from the neighboring nodes outside the carrier sensing range $d_{SC}(L)$.

Suppose that there are n interference nodes at distance d_i from the receiver where $i=1..n$. Under worst case, assume that all the interference nodes are at the edge of the carrier sensing range, i.e. $d_i=\{d_{CS}(L)-d\}$, then the interference power can be expressed as shown below.

$$P_{ri,RX}(t, d_{CS}(L)) = \frac{\sum_{i=1}^{n} h_i(t)}{(d_i)^4} \le \frac{\sum_{i=1}^{n} h_i(t)}{(d_{CS}(L) - d)^4} \tag{4.2}$$

Where $h_i(t)$ depends on the interference power and the communication environment of i^{th} node. If the carrier sensing range is increased from $d_{SC}(L)$ to $d_{SC}(M)$ under the similar communication environment, the transmit power and noise power, the $SINR_{RX}$ with the carrier sensing range $d_{SC}(M)$ will be as given below

$$SINR_{RX}(M) = \frac{P_{r,RX}(t)}{P_N(t) + P_{ri,RX}(t, d_{CS}(M))} \tag{4.3}$$

Where $P_{ri,RX}(t,d_{SC}(M))$ is the interference power signal from the neighboring nodes with carrier sensing range $d_{SC}(M)$. This increase in the carrier sensing range reduces interference range by $(d_{SC}(M)-d_{SC}(L))$ which may reduce the number of interference nodes from n to m where $m \le n$. Also the most near interference node will be at the distance $(d_{SC}(M)-d)$ which is greater than $(d_{SC}(L)-d)$. Under such situation, the interference power is expressed as given below

$$P_{ri,RX}(t, d_{CS}(M)) = \frac{\sum_{i=1}^{m} h_i(t)}{(d_i)^4} \le \frac{\sum_{i=1}^{n} h_i(t)}{(d_{CS}(M) - d)^4} \le \frac{\sum_{i=1}^{n} h_i(t)}{(d_{CS}(L) - d)^4} \tag{4.4}$$

The noise power is ignored since it is small compared to the interference signal. The above two equations (4.1) and (4.3) can be rewritten in the following form:

$$SINR_{RX}(M) = SINR_{RX}(t) * \frac{P_{ri,RX}(t, d_{CS}(L))}{P_{ri,RX}(t, d_{CS}(M))} \tag{4.5}$$

From Eq.(4.2), Eq.(4.4) and Eq.(4.5) and using the worst case interference analysis, the $SINR_{RX}$ at the receiver with the carrier sensing range $d_{SC}(M)$ can be expressed using the following equation

$$SINR_{RX}(M) = SINR_{RX}(t) * \frac{(d_{CS}(M) - d)^4}{(d_{CS}(L) - d)^4} \tag{4.6}$$

If the receiver is at the edge of the transmission range of the transmitter, since the minimum carrier sensing range $d_{SC}(L)$ is at least twice of the transmission range then $d_{SC}(L) \approx 2d$. Therefore $SINR_{RX}$ can be approximated using the following equation:

$$SINR_{RX}(M) = SINR_{RX}(t) * \left(\frac{2 * d_{CS}(M)}{d_{CS}(L)} - 1 \right)^4 \quad (4.7)$$

Actually, this case is considered as the worst case. Usually, the distance between the transmitter and receiver is always less than the transmission range. The above analysis concerns the transmission of DATA packet from a sender to a receiver. The same analysis can be applied to the transmission of ACK from a receiver to a sender.

$$SINR_{TX}(t) = \frac{P_{r,TX}(t)}{P_N(t) + P_{ri,TX}(t, d_{CS}(L))} \quad (4.8)$$

Where $SINR_{TX}(t)$ is the current signal to interference noise ratio, $P_{r,TX}(t)$ is the power received, $P_N(t)$ is noise power and $P_{ri,TX}(t,d_{SC}(L))$ is the interference power at the transmitter side. The interference power with k interference nodes can be written as shown below.

$$P_{ri,TX}(t, d_{CS}(L)) = \frac{\sum_i^k h_i(t)}{(d_i)^4} \leq \frac{\sum_i^k h_i(t)}{(d_{CS}(L))^4} \quad (4.9)$$

The increase of the carrier sensing range from $d_{SC}(L)$ to $d_{SC}(M)$ changes the $SINR_{TX}$ value to:

$$SINR_{TX}(M) = \frac{P_{r,TX}(t)}{P_N(t) + P_{ri,TX}(t, d_{CS}(M))} \quad (4.10)$$

This reduces the number of interference nodes from k to l where $l \leq k$ and increases the worst case interference distance from $d_{SC}(L)$ to $d_{SC}(M)$. The interference power at the transmitter can be

$$P_{ri,TX}(t, d_{CS}(M)) = \frac{\sum_{i=1}^{l} h_i(t)}{(d_i)^4} \leq \frac{\sum_{i=1}^{k} h_i(t)}{(d_{CS}(M))^4} \leq \frac{\sum_{i=1}^{k} h_i(t)}{(d_{CS}(L))^4} \quad (4.11)$$

The noise power is ignored since it is small compared to the interference signal. The above two Equations (4.8) and (4.10) can be rewritten in the following form:

$$SINR_{TX}(M) = SINR_{TX}(t) * \frac{P_{ri,TX}(t, d_{CS}(L))}{P_{ri,TX}(t, d_{CS}(M))} \quad (4.12)$$

From Eq.(4.9), Eq.(4.11) and Eq.(4.12) and using the worst case interference analysis, $SINR_{TX}$ at the transmitter with the carrier sensing range $d_{SC}(M)$ can be expressed in the form of following equation

$$SINR_{TX}(M) = SINR_{TX}(t) * \frac{(d_{CS}(M))^4}{(d_{CS}(L))^4} \tag{4.13}$$

4.1.3 MIPCM Protocol Algorithm

Let $P_t[L]$ be a set of power levels used for transmission, where L is an integer that varies from 1 to MAX. $P_t[MAX]$ is the maximum power level and MAX is the number of power levels in the set. Let $R_{cs}[L]$ be the set of carrier sensing range corresponding to the power level set $P_t[L]$.

The proposed MIPCM protocol works in the following steps:

1) Transmitter sends an RTS packet with the optimum transmit power level that is attached to the transmitted RTS as shown in algorithm.

2) Receiver decodes the RTS packet, finds the power level value, observes the $SINR_{RX}$ value and attaches the $SINR_{RX}$ value to the CTS packet. Then transmits CTS using the same optimum power.

3) Transmitter observes the $SINR_{TX}$ value, extracts the $SINR_{RX}$ value from the CTS packet and sends the DATA with the optimum power, and periodically increases the power level of the DATA packets to P_{ai} to avoid interference. The P_{ai} value is selected based on the ratio of the channel capacity and the carrier sensing range.

4) The receiver sends ACK using the optimum power level.

The Shannon capacity [6] is used as the achievable channel rate,

$$Channel\ \ Capacity = W \log_2(1 + SINR) \tag{4.14}$$

Where W is the channel bandwidth.

Since, we are interested in the maximum aggregate throughput of the busy network. A network is assumed busy in which each station is always waiting, continuously backing off and it initiates a transmission whenever it is allowed. The busy network situation always occurs, when nodes are ready to transmit data but they are present either in the transmission range or in the carrier sensing range of some other ongoing transmission. The aggregate throughput is directly proportional to the channel capacity and the total number of concurrent transmission that can take place.

By increasing the carrier sensing range, the *SINR* value is increased. Therefore, channel capacity is increased. But this increase in channel rate enhances the reservation area. Therefore, reduces the number of concurrent transmissions, and results in reduction of network throughput. The protocol tries to find the suitable carrier sensing range that makes a balance between the channel rate and the reservation area with an acceptable *SINR* value.

A. Transmitter :

1. **Let** $L=1$, *Max_Capacity_Area_Ratio=0*, $P_{ai}=P_t[MAX]$.
2. ***Check*** the node address and its stored S value.
3. **If** S is available, ***let*** $L=S$.
4. ***Send*** **RTS** with Tx. Power $P_t[L]$ and include the L value in the **RTS**.
5. ***If*** **RTS** ***timeout*** and **CTS** ***not received***, ***increase L and goto*** **4**.
6. ***Receive*** **CTS**, ***observe*** its $SINR_{TX}$, ***extract*** the $SINR_{RX}$ value from **CTS** packet, and ***store*** node address, ***let*** $S=L$.
7. ***Let*** $M=L$.
8. ***If*** $SINR_{TX} < SINR_{RX}$

   $SINR[M]= SINR_{TX}$

   else

   $SINR[M]= SINR_{RX}$
8. ***If*** $M>L$

   If $SINR_{TX} < SINR_{RX}$

Determine SINR[M] value according to Eq.(4.13)

else

Determine SINR[M] value according to Eq.(4.7)

10. ***Determine*** the ***Capacity_Area_Ratio*** according to the following Equation

$$Capacity\_Area\_Ratio = \frac{W \log_2(1 + SINR[M])}{2\pi * (R_{CS}[M])^2}$$

11. ***If Capacity_Area_Ratio > MAX_Capacity_Area_Ratio***

MAX_Capacity_Area_Ratio = Capacity_Area_Ratio

and $P_{ai} = P_t[M]$.

12. ***If*** $P_t[M] < P_t[MAX]$

Increase M, goto 8.

13. ***End.***

B. Receiver :

1. ***Receive*** RTS.
2. ***Observe*** its ***SINR*** value, **extract** and **store** the ***L*** value.
3. ***Insert*** the ***SINR*** value in the **CTS** packet.
4. ***Transmit*** **CTS** using the power level $P_t[L]$.
5. ***End.***

Figure 4.2: MIPCM protocol algorithm.

4.1.4 Simulation and Results

In this section we evaluate the performance of the proposed MIPCM with the standard IEEE 802.11 and other existing power control schemes BASIC and PCM. Before presenting the results, we explain the simulation environment as well as the experimentation details to carry out the tests. To simulate the new protocol and compare its performance with the others Glomosim-2.03 simulator has been used.

4.1.4.1 Simulation Environment

In this simulation two different network topologies have been considered. The chain topology composed of 31 nodes, 30 flows with equal spacing and the random topology consists of 100 nodes randomly distributed in an area of 1000 x 1000 m^2. The signal propagation model used in this work is a combination of the free space propagation and the two-ray ground reflection model whose details are explained in section 2.3.1. The transmit power levels and the value of parameters used in these simulations are given in table 2.3 and table 2.4. Each simulation runs for 20 seconds. Each data point in the results represents an average of ten simulation runs with the same traffic. The source node in the network generates CBR traffic at the rate of 1 Mbps unless specified since we performed some simulations with 2 Mbps traffic rate or varying traffic loads. The packet size is 512 bytes unless specified as we performed some simulations with varying packet size.

4.1.4.2 Experimentation

The experiments are carried out for two mentioned topologies. The performance of IEEE 802.11, BASIC, PCM and MIPCM power saving schemes are evaluated in terms of the aggregate throughput, effective throughput, total and effective data delivered per joule. In case of chain topology, the distance between adjacent node pairs is uniform. In the simulations, the distance is varied from 40 m to 250 m. The first node of the chain is considered as the sender node whereas the last node of the chain considered as the destination node. In case of random topology, single-hop traffic pairs are randomly selected with the random distance is from 0 to 250 m. For each experiment, we have selected traffic pairs such that there are equal numbers of pairs within the destination ranges of 0-40, 40-60, 60-80, 80-90, 90-100, 100-110, 110-120, 120-150, 150-180 and 180-250 meters. For example, the experiment with a total of 20 traffic pairs, we selected 2 pairs in each destination range. In these evaluations, we have considered energy consumption of all the packets RTS, CTS, DTA and ACK and we have also taken into account the transmitting as well as receiving energy.

4.1.4.3 Results and Discussions

This section discusses the results obtained from the simulations carried out for both the topologies.

Chain topology

Figure 4.3 shows the aggregate throughput for all schemes obtained from the simulation for the chain topology with a traffic rate of 1 Mbps. The figure shows the comparison of throughput of IEEE 802.11, BASIC, PCM and the proposed MIPCM schemes. IEEE 802.11 and PCM schemes achieve comparable aggregate throughput as both reserve maximum carrier sensing ranges, but the BASIC scheme performs poorly. As the distance between the adjacent nodes increases, the aggregate throughput of IEEE 802.11, BASIC and PCM schemes increase. The reason is a large number of nodes can transmit simultaneously and the collision between nodes reduces as the distance increases. The MIPCM protocol achieves a much higher aggregate throughput compared to all other schemes at all distances. It is clearly shown that in general the aggregate throughput of the MIPCM remains stable around 6.8 Mbps when the distance between the adjacent nodes is (≥60 m) and (≤180 m). This is because the MIPCM protocol uses an optimum carrier sensing range which tries to balance between the number of hidden and exposed nodes. Therefore, this optimum carrier sensing range enhanced the spatial reuse and reduced the collisions which resulted in a maximum aggregate throughput compared to other schemes.

Figure 4.4 shows the total data delivered per joule (Mbits/Joule) for different schemes under study. The performance of MIPCM scheme is much better than all other schemes, since it uses optimum transmission power for all the packets, and lower periodic pulse power. The reduction in power levels of all packets brings down the collisions between the nodes. On the other hand, reducing the periodic pulse in MIPCM scheme reduces the number of deferring nodes and therefore, delivers more data per joule. When the adjacent nodes are 250 m apart, the aggregate throughput and the total data delivered per joule for all the schemes are the same. Since all the schemes use the maximum power for all the packets.

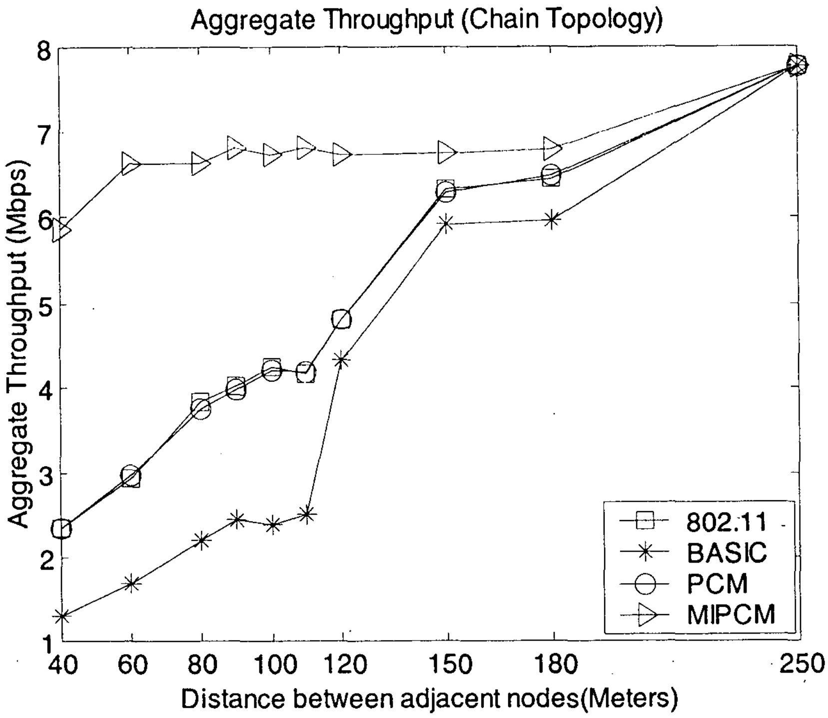

Figure 4.3: Chain topology: Aggregate throughput at a traffic rate of 1 Mbps (MIPCM).

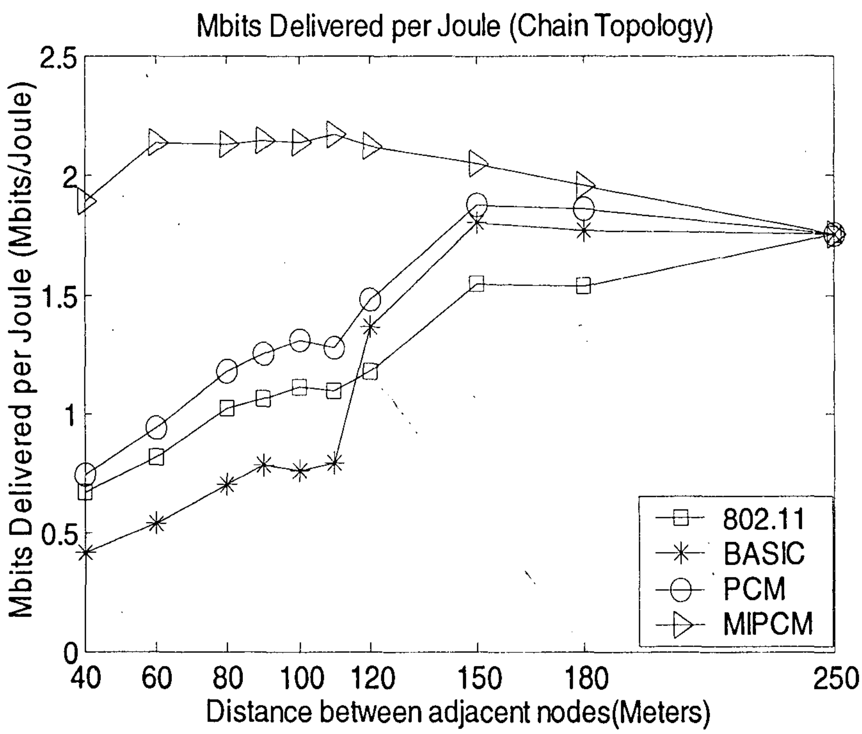

Figure 4.4: Chain topology: Total data delivered per joule at a traffic rate of 1 Mbps (MIPCM).

Figure 4.5 shows the plot of Mbits delivered per second (effective throughput) to the final destination for all the schemes. As shown, the effective throughput of MIPCM scheme is much higher compared to all other schemes at all distances, whereas the effective throughputs of IEEE 802.11 and PCM schemes are comparable and are higher than BASIC scheme. On the other hand, MIPCM scheme delivers more data per joule to the final destination compared to all other schemes as shown in figure 4.6. Therefore, MIPCM protocol is more energy efficient than the others. This means MIPCM protocol conserves a considerable amount of energy, while delivering the same amount of data to the destination node than other schemes.

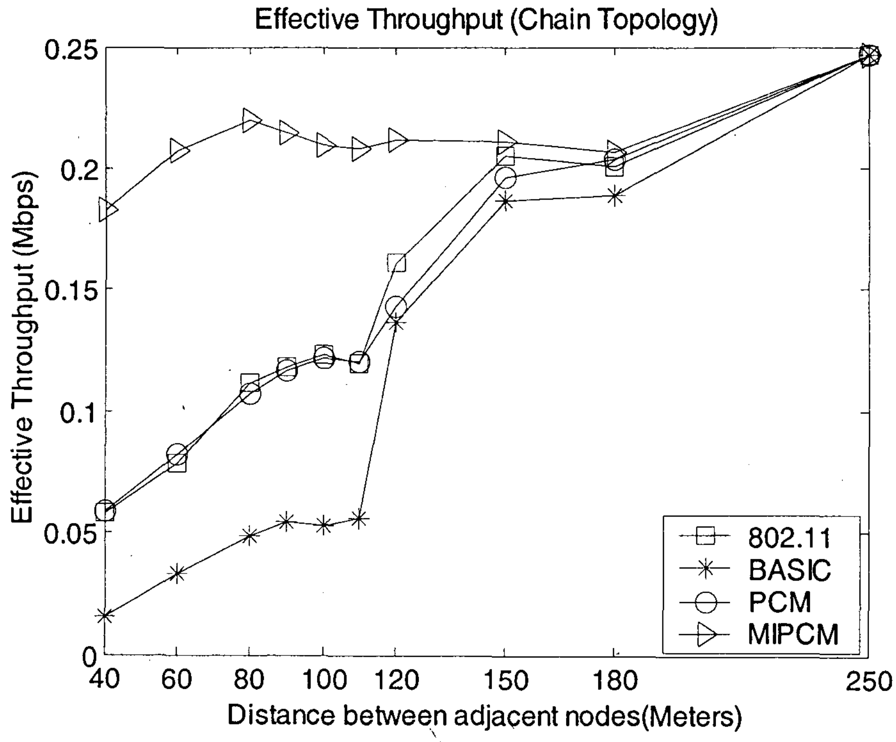

Figure 4.5: Chain topology: Effective throughput at a traffic rate of 1 Mbps (MIPCM).

We also simulate the chain topology using 2 Mbps traffic rate instead of 1 Mbps to show the advantage of the proposed scheme with others. The source node generates traffic at the rate of 2 Mbps. Figure 4.7 shows the aggregate throughput for all four schemes obtained from the simulations. It is clearly shown that MIPCM is effectively better. In general, the remarks about the performances of all the four schemes which can be noticed from this figure are quite similar to those obtained from figure 4.3 for the chain topology with 1 Mbps traffic rate. But it can also be noticed that when the traffic rate increases from 1 Mbps to 2 Mbps there is a considerable improvement in the aggregate throughput of MIPCM scheme for most distances. The aggregate throughput improvement for other schemes is unnoticeable. Since MIPCM provides better spatial reuse with lower interference level compared to others. The better performance in term of the aggregate throughput of the MIPCM scheme is reflected on its energy consumption. Figure 4.8 shows that MIPCM scheme has the highest data delivered per joule among others. The reasons are the same as discussed in the corresponding results obtained for the chain topology with 1 mbps traffic rate.

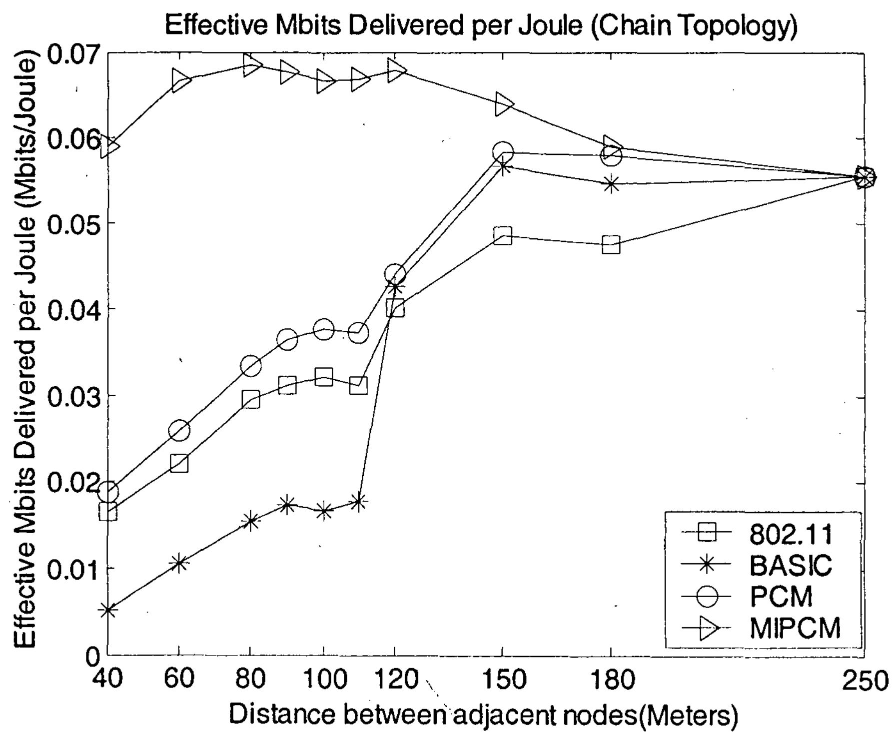

Figure 4.6: Chain topology: Effective data delivered per joule at a traffic rate of 1 Mbps (MIPCM).

Random topology

We now present simulation results of our studies for randomly generated topology by varying the number of traffic flows, network load and packet size. Each flow generates traffic at a rate of 1 Mbps. Figure 4.9 illustrates the aggregate throughput achieved for this network with varying traffic flows. The proposed protocol achieves a much higher aggregate throughput for all the traffic flows compared to others, since it intelligently selects the carrier sensing range, which improves the spatial reuse and reduces interference. The aggregate throughput of IEEE 802.11 and PCM schemes are quite comparable, where as the BASIC scheme performs poorly. Moreover, when observing the total data delivered per joule shown in figure 4.10, the proposed protocol transmits more data compared to other schemes for the same amount of energy consumption. We can also observe a decrease in the data delivered per joule for all the schemes as the number of traffic pairs increases. The reason behind such a decrease is that when the number of traffic pairs increases, collisions also increase. This leads to more retransmissions which reduce the data delivered per joule.

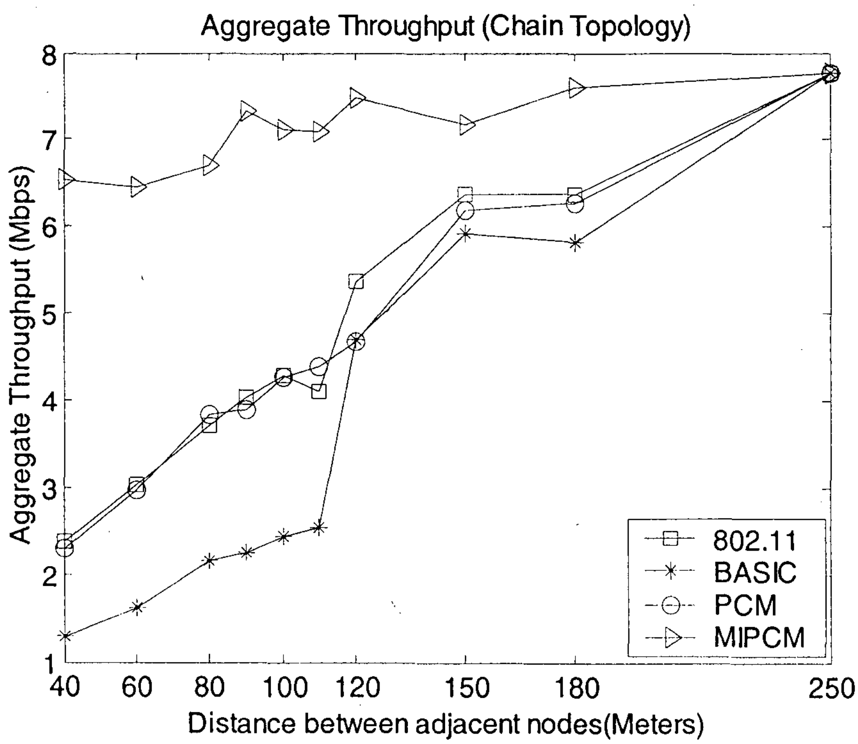

Figure 4.7: Chain topology: Aggregate throughput at a traffic rate of 2 Mbps (MIPCM).

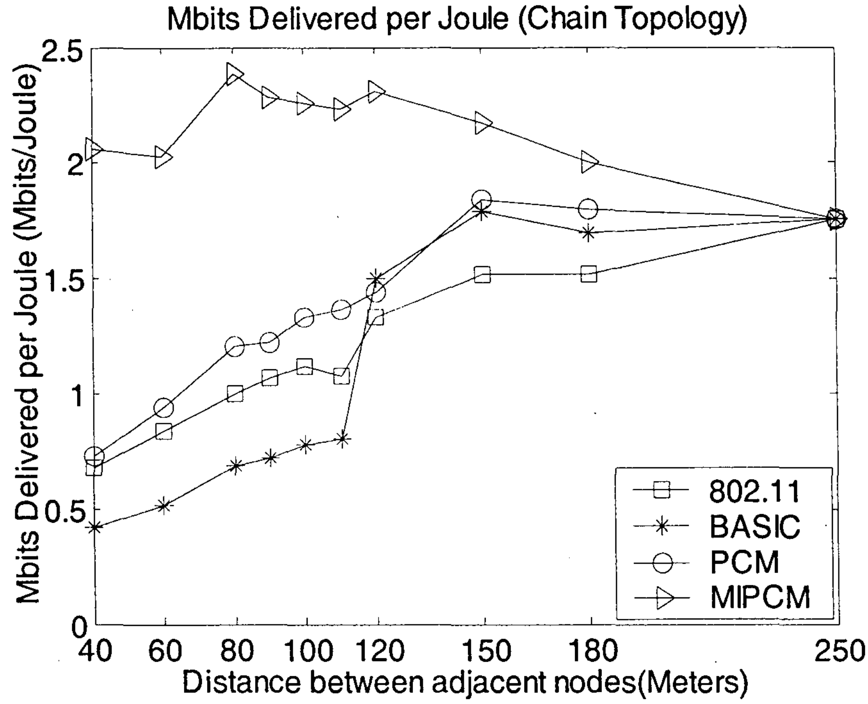

Figure 4.8: Chain topology: Total data delivered per joule at a traffic rate of 2 Mbps (MIPCM).

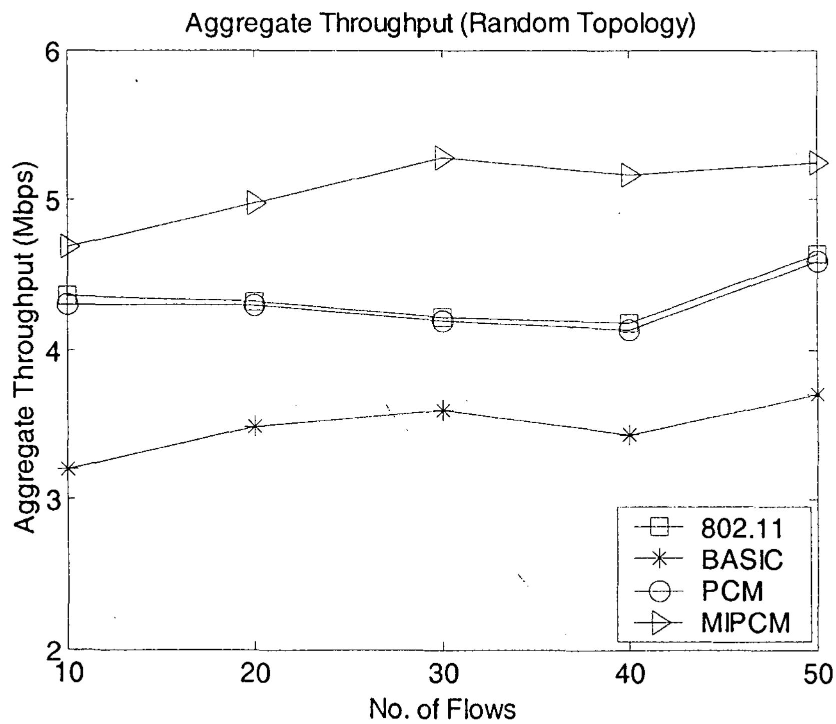

Figure 4.9: Random topology: Aggregate throughput at a traffic rate of 1 Mbps (MIPCM).

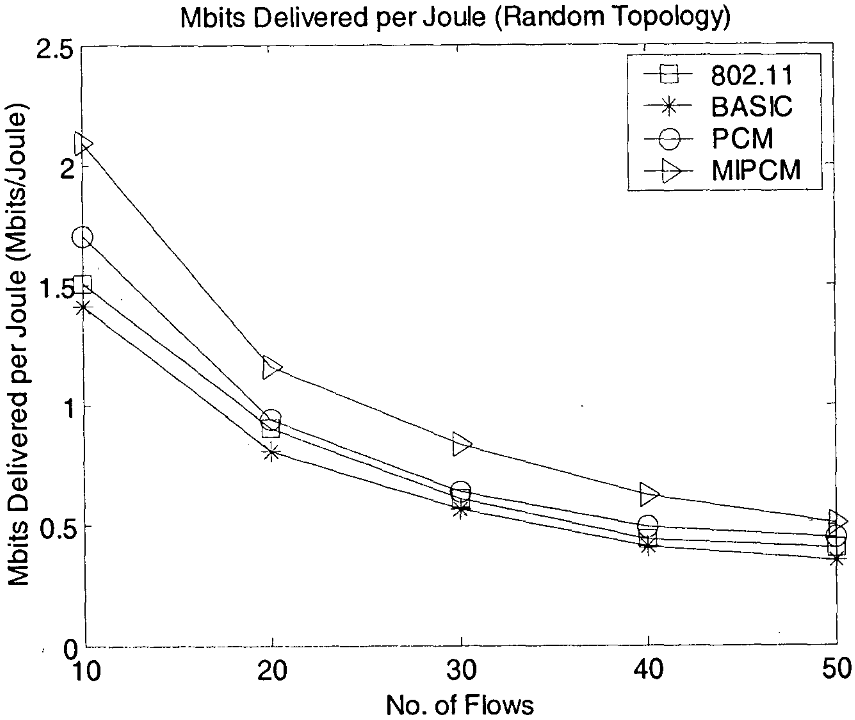

Figure 4.10: Random topology: Total data delivered per joule at a traffic rate of 1 Mbps (MIPCM).

Figure 4.11 and figure 4.12 show the performance in terms of the aggregate throughput and the total data delivered per joule for the random topology with 50 flows and varying network load. When the network is lightly loaded, the aggregate throughputs of IEEE 802.11, PCM and MIPCM schemes are identical as shown in figure 4.11. But the aggregate throughput for BASIC scheme is relatively low and when the data rate per flow is more than 30 Kbps, BASIC scheme performs worse. For the data rate per flow more than 30 Kbps, BASIC scheme performs worse. Figure 4.12 shows the total data delivered per joule for all the schemes. Even when the aggregate throughput of IEEE 802.11, PCM and MIPCM schemes are the same, the total data delivered per joule for MIPCM scheme is better than other schemes. Further, PCM scheme performs slightly better than IEEE 802.11 scheme as it always performs better than IEEE 802.11 and BASIC. Whereas due to additional collisions and retransmissions the BASIC scheme is always worst.

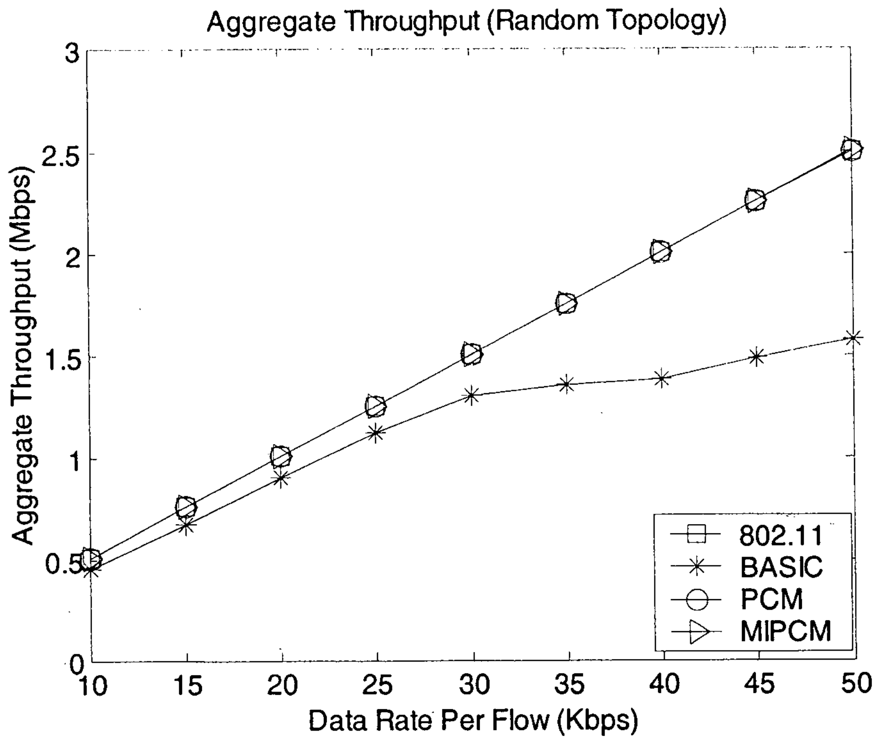

Figure 4.11: Random topology: Aggregate throughput with different network load (MIPCM).

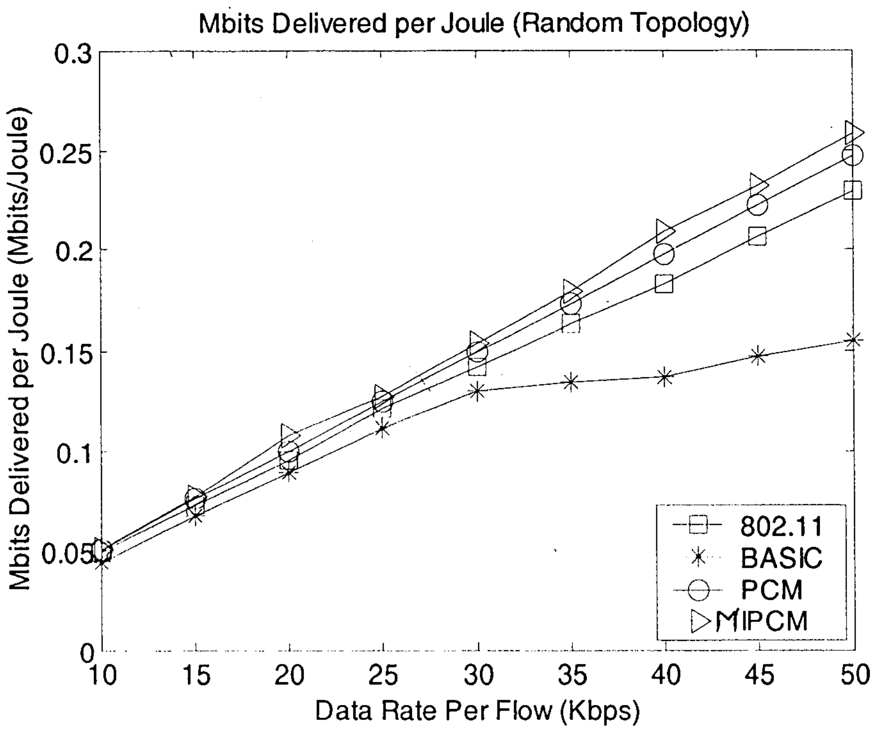

Figure 4.12: Random topology: Total data delivered per joule with different network load (MIPCM).

Figure 4.13 and figure 4.14 show the simulation results for a random topology with 50 flows and varying packet size. Simulated packet sizes are 64, 128, 256, and 512 bytes. Each flow generates traffic at the rate of 50Kbps. The results of these figures present an interesting evaluation of the proposed protocol. Figure 4.13 shows that the aggregate throughput of MIPCM scheme is better than all other schemes with packet size 64, 128 and 256 bytes. For the larger packet size (512 and 1024 bytes), the aggregate throughput of IEEE 802.11, PCM and MIPCM schemes are identical. The BASIC scheme performs poorly in all the cases. It is well known that, the reason behind the bad performance of BASIC scheme is the hidden terminal problem, collisions and retransmissions. With lightly loaded network (50 Kbps) and small packet size, MIPCM scheme allows more concurrent transmissions that reflect on its aggregate throughput. For large packet size and lightly loaded network, data to the overhead increases for all schemes and hence the number of transmission packets reduces compared to small packet size to send the same amount of data. This reduces the number of collisions which leads to an aggregate throughput identical to IEEE 802.11 and PCM schemes. The aggregate throughput of all the schemes is also reflected on their total data delivered per joule as shown in figure 4.14. The performance of MIPCM scheme is better than all other schemes. Even with the same throughput, the total data delivered per joule for MIPCM is marginally better than PCM, since it uses optimum power for all packets and smaller periodic pulse power compared to PCM scheme. The PCM scheme performs better than IEEE 802.11, and BASIC scheme performs the worst.

4.2 Comparative Study of Our Proposed Protocols

This section presents a comparative study of our proposed power saving schemes. We compared the two COMPOW based protocols proposed in chapter two namely PCM/COMPOW and IPCM/COMPOW power saving schemes and MIPCM protocol proposed in this chapter. The objective of this comparative study is to show how each one of the proposed protocols perform compared to others. Before going through the results of this study let us briefly compare the basic operations of the three proposed schemes. The PCM/COMPOW scheme uses the common power to transmit the control packet and optimum power for DATA and ACK packets. On the other hand, the power level of DATA packets is periodically raised to the common power level. The IPCM/COMPOW scheme transmits all the packets with the optimum power. On the other hand, the power level of DATA packets is periodically increased to a suitable level. This level is determined by using the optimum power, distance between the sender and receiver, and the common power. The MIPCM protocol proposed in the first part of this chapter is similar to the IPCM protocol used in the IPCM/COMPOW except that the power level of the periodic pulse power for the latter is determined using measured SINR at the receiver and sender respectively. It should be noted that PCM/COMPOW and IPCM/COMPOW are specially designed for multi-hop ad hoc networks whereas MIPCM protocol is designed for multi-hop or single-hop network.

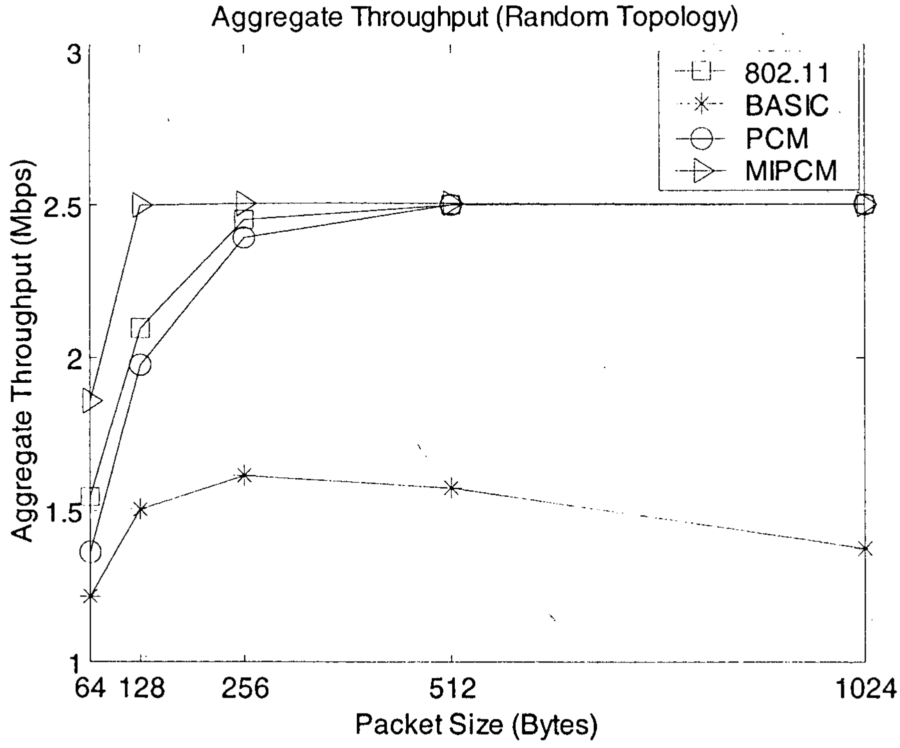

Figure 4.13: Random topology: Aggregate throughput with different packet size and 50 Kbps data rate per flow (MIPCM).

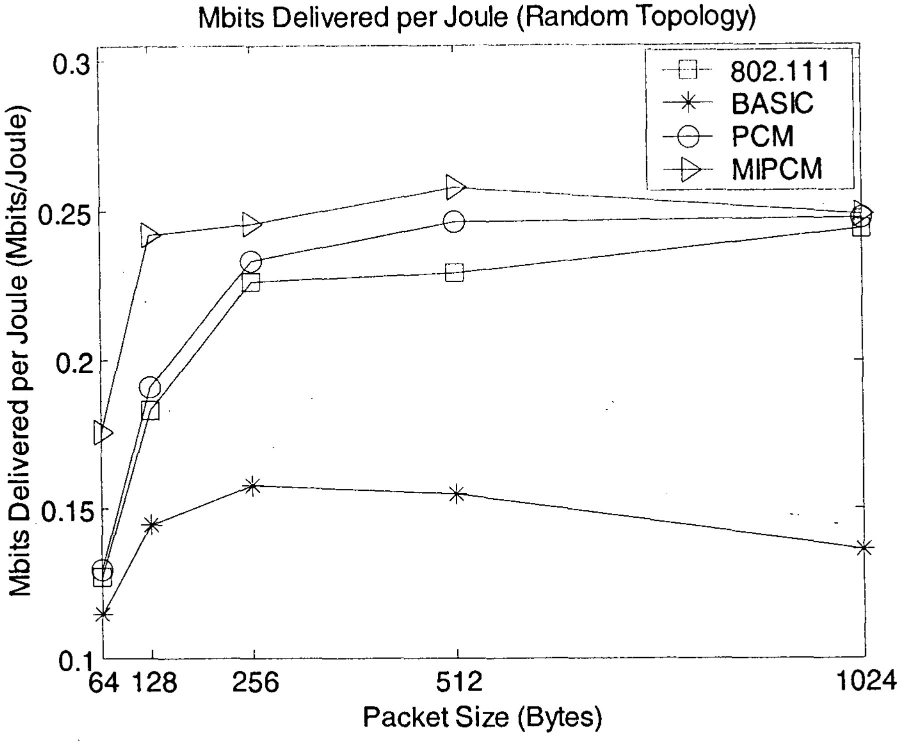

Figure 4.14: Random topology: Total data delivered per joule with different packet size and 50 Kbps data rate per flow (MIPCM).

4.2.1 Simulation

The same experiments carried out in chapter three for PCM/COMPOW and IPCM/COMPOW schemes under the random multi-hop topology are repeated for MIPCM protocol in conjunction with MINPOW routing protocol. This scheme is referred to as MIPCM/MINPOW scheme. The results obtained from these experiments and the results of PCM/COMPOW and IPCM/COMPOW schemes are plotted on the same graph. The graphs formed the base of this comparative study under the random multi-hop topology. On the other hand, the results obtained from the experiments carried out using the MIPCM protocol under the chain topology in section 4.1.4.3 and the corresponding results of PCM/COMPOW and IPCM/COMPOW schemes are also plotted on the same graphs. Similarly, these graphs also formed the base of comparative study under the random multi-hop topology.

4.2.2 Results and Discussions

This section discusses the results obtained from the study carried out for the chain and random multi-hop topologies. The results of this comparison are presented in graphs. These graphs also included the IEEE 802.11, BASIC and PCM schemes. Each of the proposed power saving schemes have been individually evaluated and compared with these schemes previously. Therefore, the current study is only concentrated on comparing the performance of our proposed schemes.

Chain topology

The simulation results obtained from the experiments carried out for the chain topology show that MIPCM protocol achieves higher aggregate throughput compared to all other schemes as shown in figure 4.15. This is because MIPCM uses an optimum carrier sensing range using current *SINR* at the sender and the receiver. The IPCM/COMPOW scheme performs better than PCM/COMPOW scheme since it tries to use a carrier sensing range that improves the spatial reuse and reduces collisions compared to PCM/COMPOW scheme. But the carrier sensing range reserved by the PCM/COMPOW scheme is always constant irrespective of the interference power. Figure 4.16 shows the comparative study in terms of the total data delivered per joule. It clearly shows that the MIPCM protocol scheme consumes lower energy compared to other schemes, since it uses optimum transmission power for all the packets and optimum periodic pulse power which increases the transmitted data and reduces collisions. On the other hand, IPCM/COMPOW scheme performs better than PCM/COMPOW, since it uses optimum levels for both control packets and periodic pulse power compared to the PCM/COMPOW scheme.

The simulation results obtained from the chain topology, considering only the data delivered to the last node are presented in figure 4.17 and figure 4.18. The results show that the performance of these schemes in terms of effective throughput and data delivered per joule to the final destination is similar to the aggregate throughput and the total data delivered per joule shown in figure 4.15 and figure 4.16. As shown in figures, the curves of the effective throughput and the data delivered per joule to the final destination of MIPCM protocol are always at the top. Whereas the performance of IPCM/COMPOW scheme is better than PCM/COMPOW scheme.

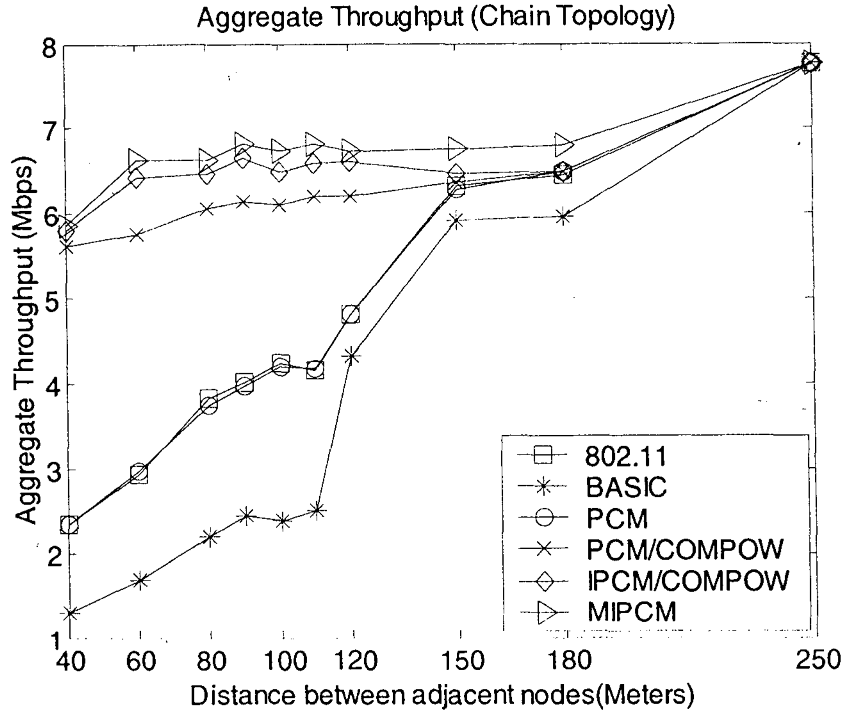

Figure 4.15: Chain topology: Aggregate throughput (Comparative study).

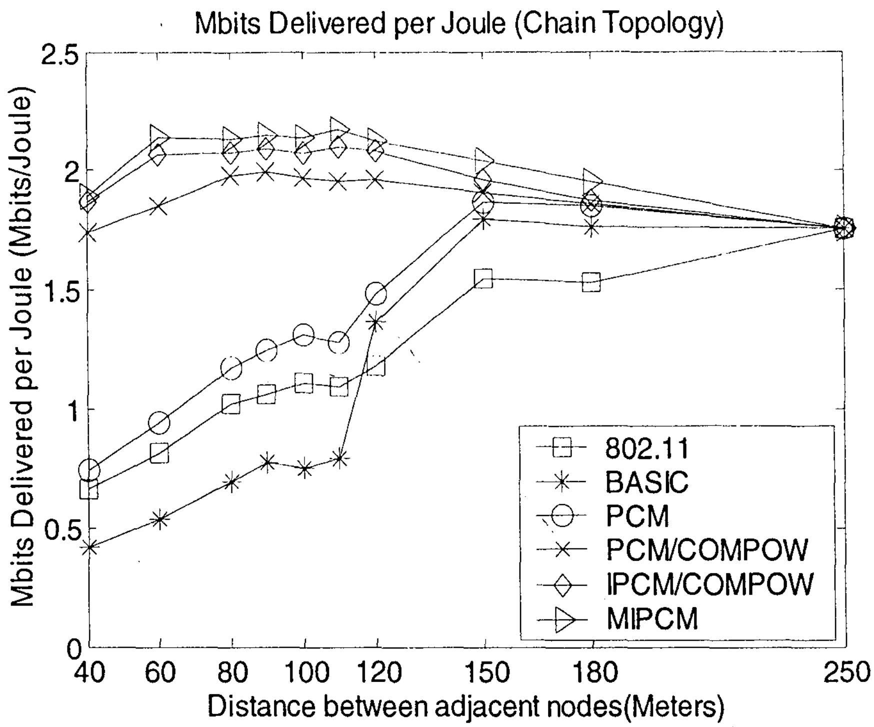

Figure 4.16: Chain topology: Total data delivered per joule (Comparative study).

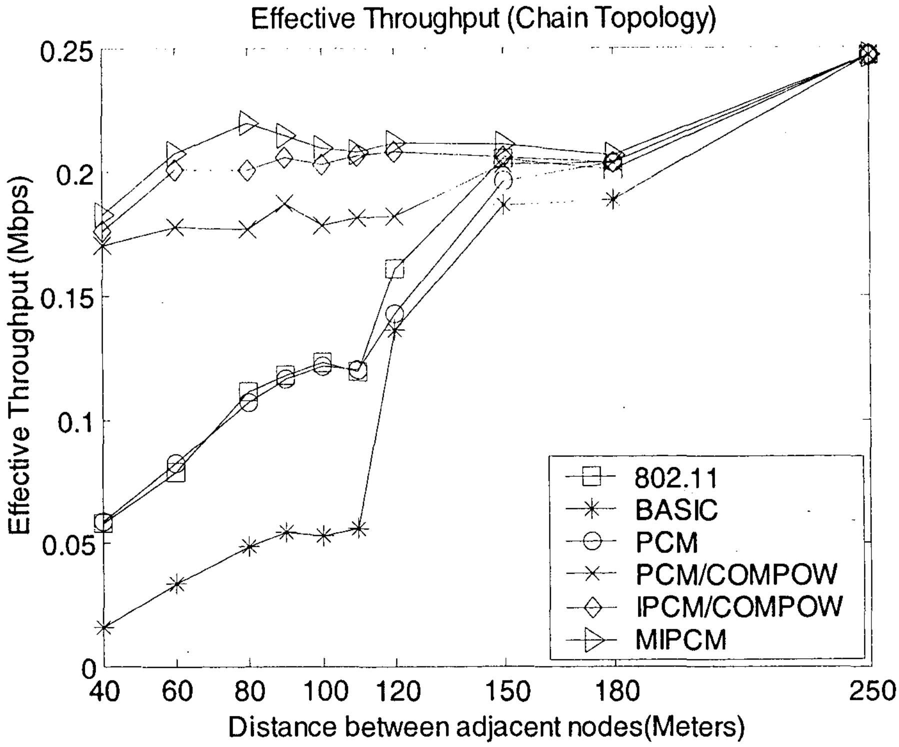

Figure 4.17: Chain topology: Effective throughput (Comparative study).

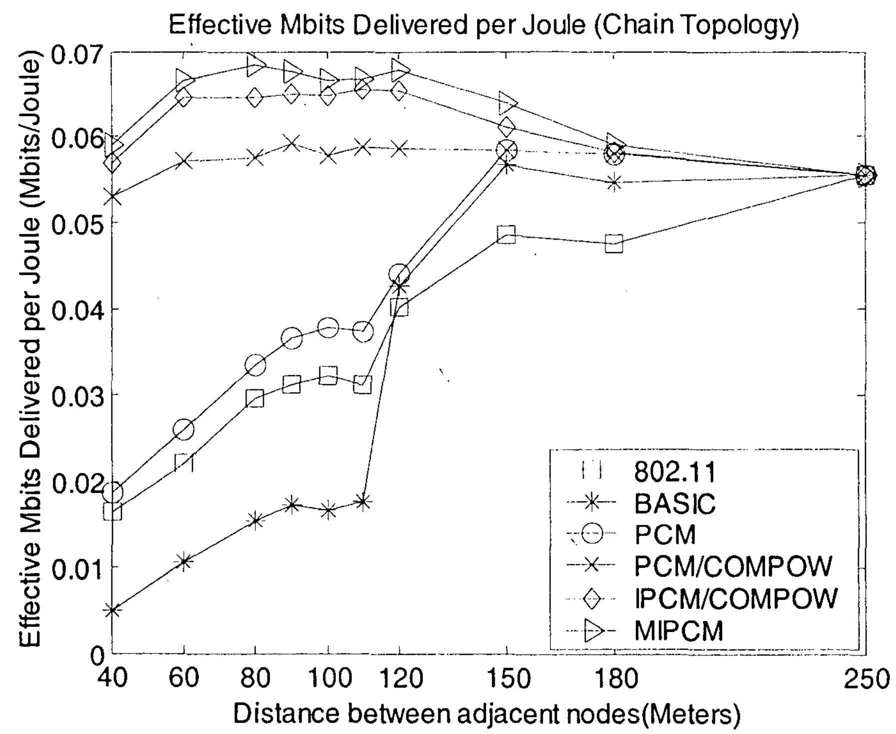

Figure 4.18: Chain topology: Effective data delivered per joule (Comparative study).

Random multi-hop topology

The simulation results obtained from the experiments carried out under the random multi-hop topology using MIPCM protocol in conjunction with the MINPOW routing show that the performance of MIPCM/MINPOW scheme is more efficient in terms of the aggregate throughput and total data delivered per joule than IPCM /COMPOW and PCM/COMPOW schemes. Figure 4.19 show that the MIPCM/MINPOW scheme achieves a much higher aggregate throughput than others. A MINPOW routing protocol selects a route that minimizes the aggregate transmit power on a path from a source to a destination. Therefore, the selected route can be longer than the shortest path selected by conventional ad hoc routing protocols. In other words, there can be more number of hops between a source and a destination. The MINPOW along with PCM protocol which uses minimum necessary transmit power for the transmission of DATA and ACK packets and maximum carrier sensing range, can save more energy compared to IEEE 802.11. But PCM power control does not provide spatial reuse among the nodes on a path that have to be shared, and the channel bandwidth to be competed. Therefore, the throughput achieved is comparable to that of the IEEE 802.11 without power control. On the other hand, the MINPOW along with MIPCM protocol which uses minimum necessary transmit power for all packets and optimum carrier sensing range can improve the aggregate throughput compared to all other schemes as shown in figure 4.19. This is because the carrier sensing range used here is able to provide spatial reuse among the nodes on a path from a source to a destination. This allows more data delivery over the multi-hop path from a source to a destination. As a result this leads to higher data bits delivered per unit of transmit energy in case of MIPCM/MINPOW in comparison to others as shown in figure 4.20.

Further, the simulation results have been obtained from the random multi-hop topology considering only the data delivered to the final destination. The results show that the performance of these schemes in terms of effective throughput and data delivered per joule to the final destination is the same as the aggregate throughput and total data delivered per joule shown in figure 4.19 and figure 4.20. As shown in figure 4.21 and figure 4.22, the effective throughput and data delivered per joule to the final destination of MIPCM/MINPOW scheme are always the highest. Whereas the performance of IPCM/COMPOW scheme is better than PCM/COMPOW scheme, since IPCM/COMPOW provides better spatial reuse compared to PCM/COMPOW as it uses smaller carrier sensing range. On the other hand, it saves more energy than PCM/COMPOW since it uses lower transmit power for the control packets.

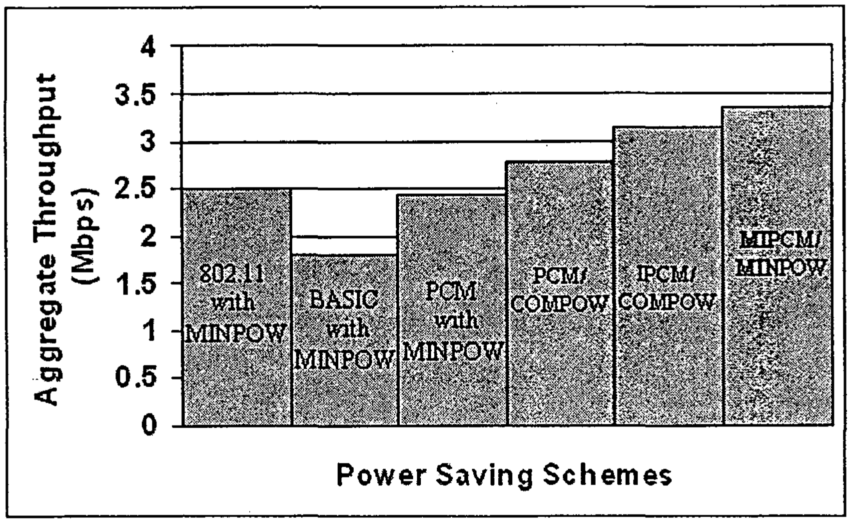

Figure 4.19: Random multi-hop topology: Aggregate throughput (Comparative study).

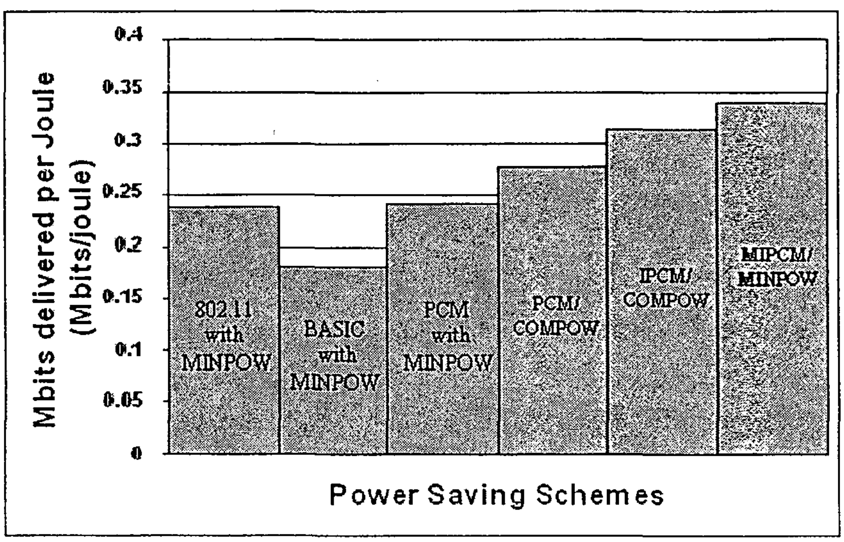

Figure 4.20: Random multi-hop topology: Total data delivered per joule (Comparative study).

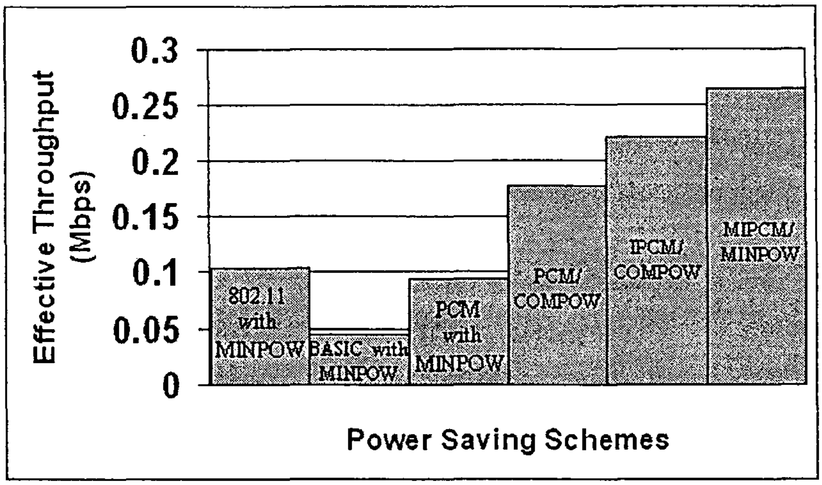

Figure 4.21: Random multi-hop topology: Effective throughput (Comparative study).

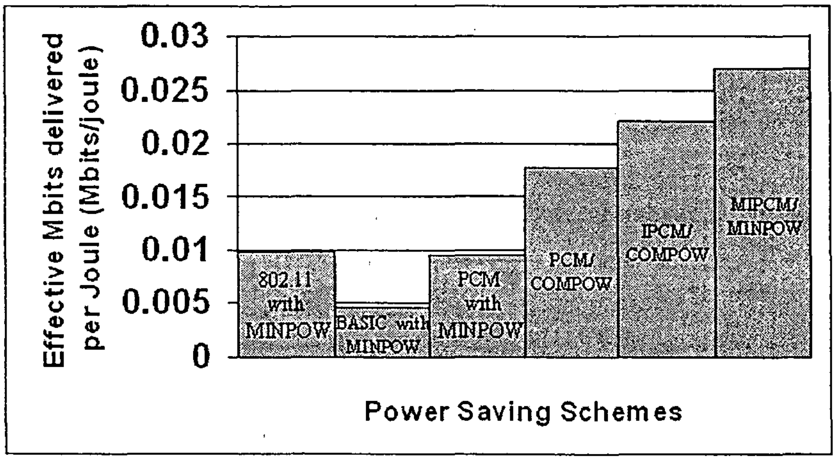

Figure 4.22: Random multi-hop topology: Effective data delivered per joule (Comparative study).

The outcome of the comparative study for the random multi-hop topology with varying data packet size of 64, 128, 256, 512 and 1024 bytes at a traffic rate of 1 Mbps are shown in figure 4.23 and figure 4.24. The results show that the performance of MIPCM/MINPOW schemes is better than IPCM/COMPOW and PCM/COMPOW with varying packet size. As shown in the figures, the throughput and the total data delivered per joule for MIPCM/MINPOW are higher compared to others, since it avoids collisions and retransmissions, and allows better spatial reuse.

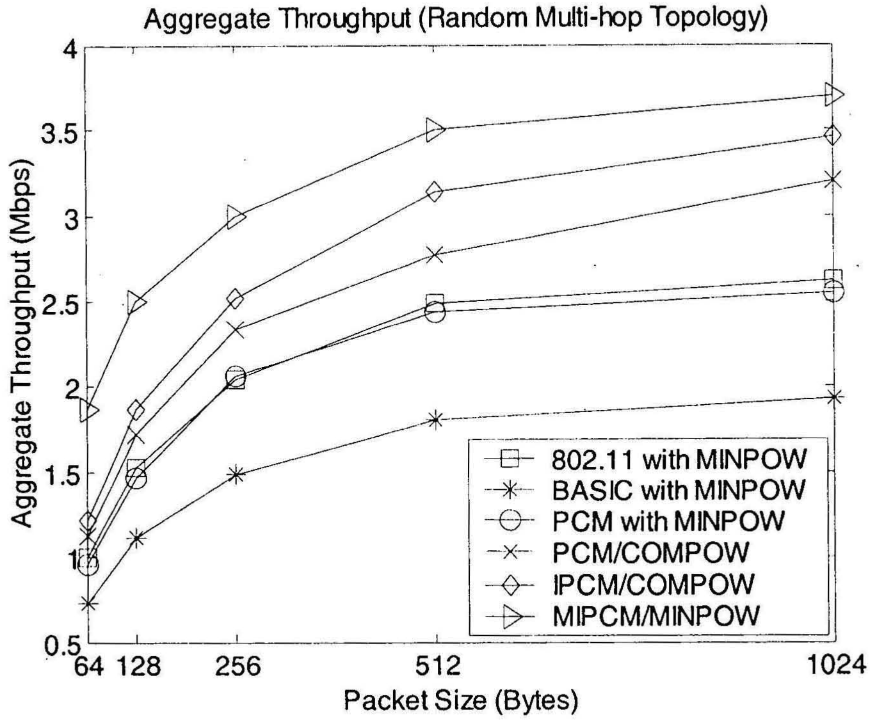

Figure 4.23: Random multi-hop topology: Aggregate throughput with different packet size (Comparative study).

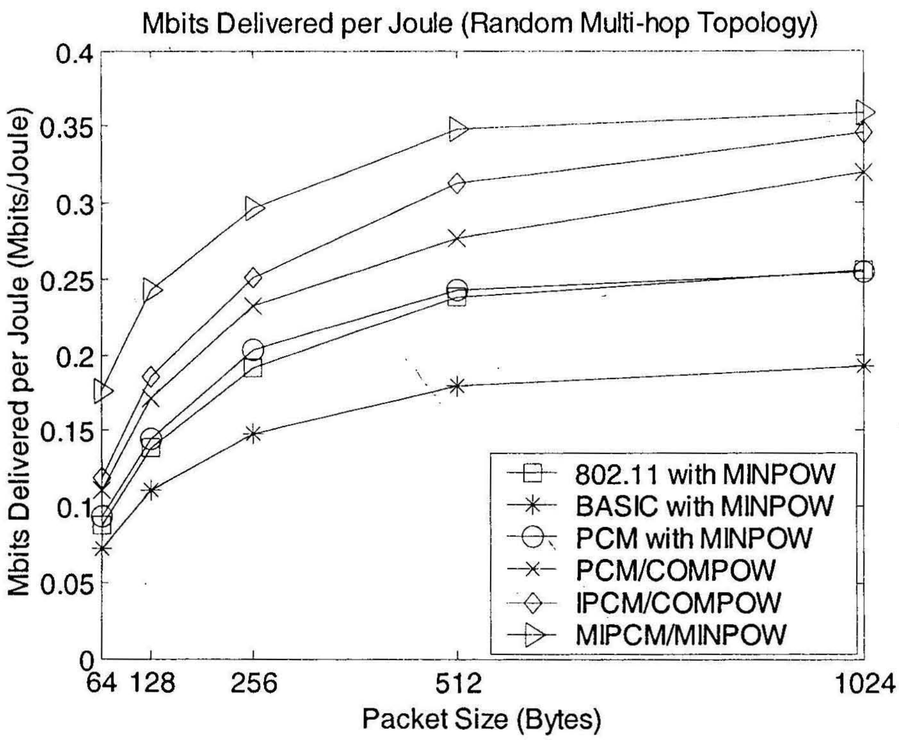

Figure 4.24: Random multi-hop topology: Total data delivered per joule with different packet size (Comparative study).

The performance of multi-hop wireless ad hoc network using the proposed MIPCM/MINPOW power saving scheme is also evaluated and compared with IPCM/COMPOW, PCM/COMPOW and conventional ad hoc routing protocols in conjunction with IEEE 802.11, BASIC and PCM schemes. The results show better performance of MIPCM/MINPOW in terms of aggregate throughput compared to other schemes as shown in figure 4.25. On the other hand, the aggregate throughput of all the schemes is also reflected on their total data delivered per joule as shown in figure 4.26.

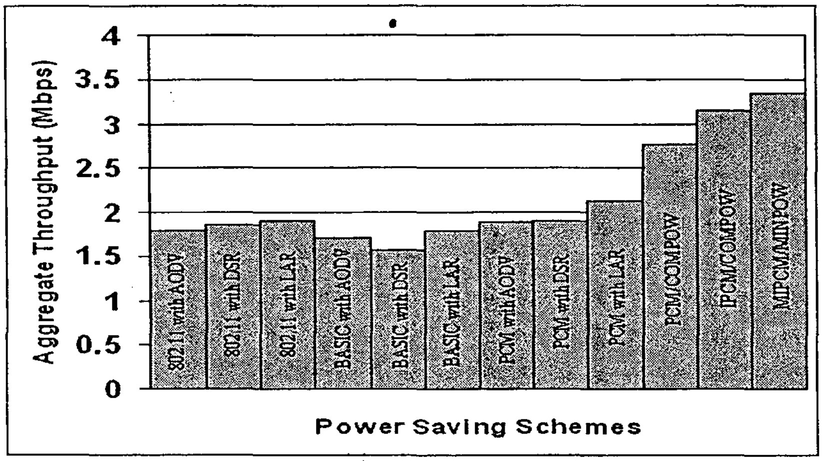

Figure 4.25: Random multi-hop topology: Aggregate throughput using different routing protocols with the power control schemes (Comparative study).

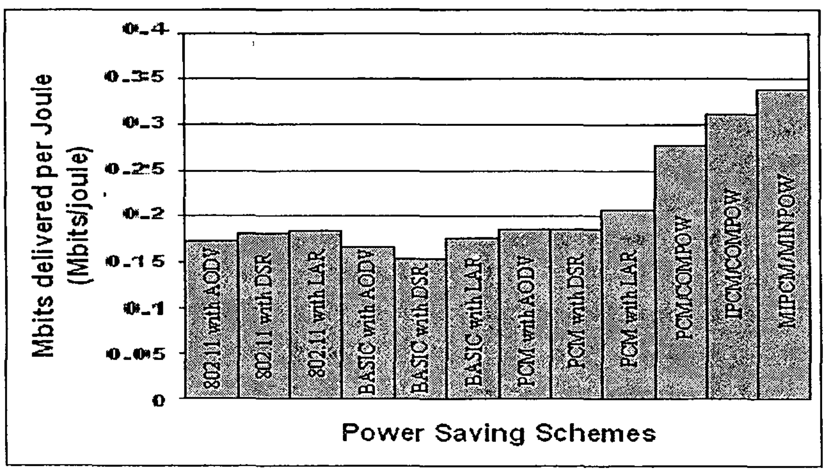

Figure 4.26: Random multi-hop topology: Total data delivered per joule using different routing protocols with the power control schemes (Comparative study).

4.3 Conclusion

In this chapter we have proposed and evaluated the performance of the proposed power control protocol for wireless ad hoc networks called Modified Improved Power Control MAC (MIPCM) protocol. This protocol transmits all the packets with optimum transmission power and periodically increases the power of DATA packets to a suitable level to eliminate the collisions. The periodic pulse power is determined by maximizing the channel capacity and reducing the carrier sensing range. This reduces the number of unnecessary back-off nodes and allows successful concurrent but interference-limited transmissions in the neighborhood of a receiver. We have compared the performance of MIPCM scheme with IEEE 802.11, BASIC and PCM power control schemes. We investigated its performance under different network topologies, different data rates and different packet size. The simulation results show that MIPCM scheme achieved higher total data delivered per joule while maximizing the aggregate and effective throughputs.

Further in this chapter, the proposed power saving schemes PCM/COMPOW, IPCM/COMPOW and MIPCM are compared under random multi-hop topology. The main outcome of this comparative study shows that MIPCM scheme achieves a high reduction in energy consumption. The results also reveal that MIPCM scheme significantly improves the network throughput compared to other schemes. The second outcome of this study is that the performance of IPCM/COMPOW scheme is better than PCM/COMPOW scheme, since IPCM/COMPOW scheme uses smaller carrier sensing range and lower transmit power for sending control packets. In general, the three proposed protocols can be useful for dense multi-hop wireless ad hoc networks where interference and energy consumption, otherwise are more due to collisions. Therefore, these protocols will help in enhancing the life time of a network since they reduce the energy consumption compared to the existing IEEE 802.11, BASIC and PCM schemes.

CHAPTER 5

Adaptive Energy Conserving MAC Protocol

In the literature, several transmit power control MAC protocols have been designed primarily to reduce the energy consumption in wireless ad hoc networks. These protocols usually compromise with throughput of the network. Therefore, many adaptive rate MAC protocols have also been proposed to improve the network throughput. In this chapter, we have presented our proposed energy efficient MAC protocol for ad hoc network based on DCF IEEE 802.11b. This protocol also maximizes the overall network throughput. We call this protocol Traffic Sensing adaptive Rate Power (TSRP) control MAC protocol. In TSRP protocol a sender senses the outgoing traffic based on the traffic load and queue condition rather than matching the channel conditions. Then the MAC layer chooses an energy efficient rate-power combination that is suitable for delivering data packets coming from upper layer. It also schedules the transmission of packets that are waiting in its queue with minimum delay. This chapter presents the detailed design and evaluation of TSRP control MAC protocol based on simulations conducted for different network topologies. We have compared the proposed protocol with various standard data rates and adaptive rate with power control scheme. All analytical and simulation results show that TSRP protocol achieves higher energy saving and gives the maximum throughput [76].

5.1 TSRP Preliminaries

Before dealing with the detailed design and understanding the operations of TSRP protocol, it is important to describe the necessary background on throughput and radio power consumption for DCF IEEE 802.11b based ad hoc networks. It is significant since the design of TSRP has its basis on the outcome remarks obtained from the preliminaries given in the following sections.

5.1.1 Rate Adaptation: Review

Many MAC protocols have been developed that change the transmission rate of the data packets while keeping its power constant. But in adaptive rate MAC protocols, transmission rate is changed in order to improve the network throughput. The adaptive rate schemes use the threshold SNR to predict the appropriate rate (modulation schemes). Several adaptive rate MAC layer protocols for wireless ad hoc networks have been proposed in the literature. Auto Rate Fullback (ARF) [30] is a sender based protocol where a sender selects the best rate based on the information about previous data frame. The adaptive rate MAC protocols such as the Receiver Based Auto Rate (RBAR) [21], the Opportunistic Auto Rate (OAR) [58] and the Adaptive Auto Rate (AAR) [13] are receiver based protocols. RBAR allows a receiver to estimate channel quality and to select an appropriate rate during RTS/CTS frame exchange for the following data frame. OAR and AAR protocols are improved versions of RBAR scheme. The Full Auto Rate (FAR) MAC layer protocol presented in [38] combines sender based and receiver schemes into one. The rate adaptation for RTS/CTS frames is done at sending side, while for Data/ACK frames, it is done at receiving side.

5.1.2 IEEE 802.11b: Physical Layer Overview

TSRP MAC protocol for wireless ad hoc networks has its basis on IEEE 802.11b standard, since IEEE 802.11b WLAN products have been widely deployed. The basic Medium Access Control of IEEE 802.11b is DCF which employs carrier sense multiple access with collision avoidance. Each node needs to sense the channel before data transmission. The virtual carrier sensing is also employed to avoid collisions, by the exchange RTS and CTS frames. IEEE 802.11b uses Direct Sequence Spread Spectrum (DSSS) mechanism at physical layer operating in the 2.4 GHz ISM (Industrial Scientific and Medical) radio spectrum. It supports four different data rates with three different modulation schemes. They are Differential Binary Phase Shift Keying (DBPSK) for 1 Mbps data rate, Differential Quaternary Phase Shift Keying

(DQPSK) for 2 Mbps data rate, and Complementary Code Keying (CCK) for 5.5 Mbps and 11 Mbps data rates [3].

The signal propagation model used in this work is a combination of the free space propagation model (for short distances) and two-ray ground reflection model (for long distances). From Eq.(2.5), the Signal-to-Noise Ratio (SNR) at the receiving node can generally be written as

$$SNR = \frac{P_t C}{N_{th}} * \left(d_{crossover} / d \right)^{\alpha} \qquad (5.1)$$

Where N_{th} is the Additive White Gaussian Noise (AWGN) which can be written as $FkT_O B_t$, where F is the noise figure, $k = 1.38 \times 10^{-23}$ J/K is the Boltzman's constant, T_O = 300 Kelvin is the room temperature and B_t is unspread bandwidth of the signal.

For the rate selection algorithm, a simple threshold based technique is used. In a threshold scheme, the rate is chosen by comparing the channel quality estimate against a series of thresholds representing the desired performance bounds for the available modulation schemes. Most of the adaptive rate schemes have considered rate adaptation for DATA packet only, assuming that the control packets are always transmitted at a low basic rate. The basic rate set normally contains only 1 and 2Mbps. In TSRP we have chosen RBAR [21] as adaptive rate MAC protocol, since the channel quality estimation of RBAR scheme is closer to the actual channel conditions. We assumed that RTS and CTS packets are transmitted at 1Mbps, whereas the ACK packet is transmitted at 2 Mbps whenever the transmission rate of DATA packet is equal to or greater than 2Mbps [38].

5.1.3 BER and SNR Relationship

We have used BPSK, QPSK, 16-QAM and 256-QAM modulations for the data rate of 1, 2, 5.5 and 11 Mbps respectively. The 16-QAM and 256-QAM are used instead of CCK modulation because in IEEE standards M-ary QAM modulation is very well documented (as stated in [21], similar results can be expected for the CCK modulation). Bit error rates for BPSK and QPSK [51] are given as:

$$BER = Q\left(\sqrt{2 * SNR * \frac{B_t}{R_b}}\right) \tag{5.2}$$

and for M-ary QAM

$$BER = 4(1 - \frac{1}{\sqrt{M}})Q\left(\sqrt{3\frac{\log_2 M}{(M-1)} * SNR * \frac{B_t}{R_b}}\right) \tag{5.3}$$

Where R_b is the maximum bit-rate of the modulation scheme.

Figure 5.1 shows the theoretical relationship between BER and SNR for various data rates specified by IEEE 802.11b standards. It is clear that for a given data rate (modulation scheme), BER increases as SNR decreases. Also for a given SNR, an increase in data rate resulted in an increase in BER. For example, given an SNR of 5 dB, a packet transmitted at 1 Mbps experience a BER of 10^{-4}, in comparison to $\approx 10^{-2}$ for the same packet transmitted at 2 Mbps. From this figure we can find the most suitable modulation scheme based on the measured SNR at the receiver and the specific BER value. This BER value is considered as one of the quality of service parameter. The better communication service with negligible error is possible at lower BER (usually $\leq 10^{-5}$). This knowledge can be used to set the threshold SNR for selecting transmission rate based on the received SNR. For example, if the maximum BER is set to 10^{-5} and the current measured SNR falls below the required threshold value for the modulation scheme used, the sender node needs to adjust its rate. In this work we used BER value 10^{-5} to set the threshold SNR for different transmission rates. The results compiled from the Eq.(5.2) and Eq(5.3) are used for further simulations in the rest of the chapter.

5.1.4 Throughput Calculation

Consider a simple model with one active single-hop under the assumptions that there is no loss either due to collisions or buffer overflow, the transmission medium is always frees to content, and the sender has sufficient packets to transmit. The same pattern is repeated with a specific cycle for a given data rate [23] as shown in

Figure5.2. This figure shows how the data packets are transmitted in IEEE 802.11b which is based on CSMA/CA with RTS-CTS-DATA-ACK handshake.

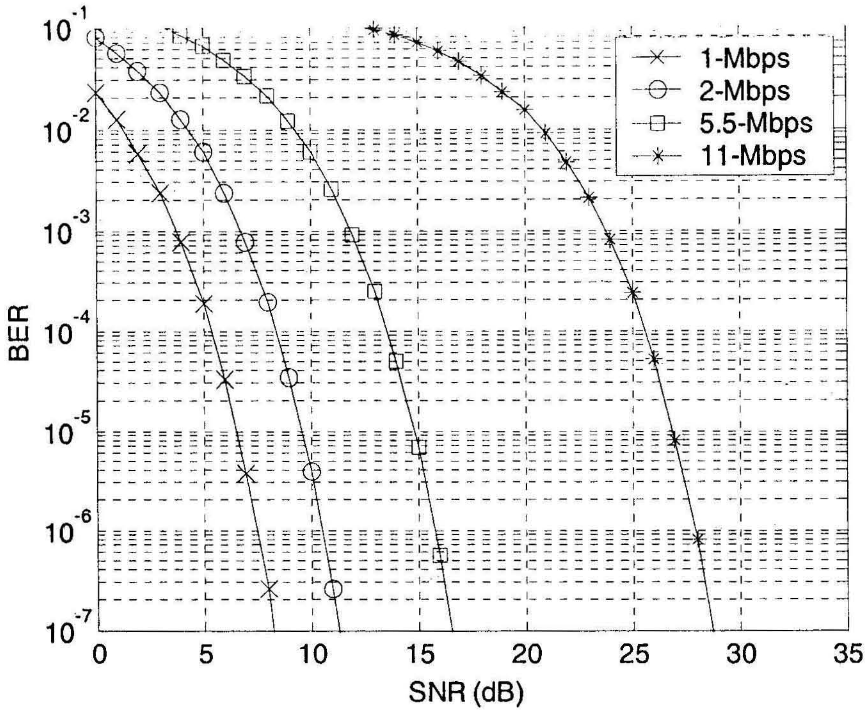

Figure 5.1: Theoretical Bit Error Rate (BER) as a function of Signal to Noise Ratio (SNR) for several data rates used in IEEE 802.11b.

The average time T required to transmit one packet [38] is:

$$T = T_{BO} + 3 \times T_{SIFS} + T_{RTS} + T_{CTS} + T_{DATA} + T_{ACK} + T_{DIFS} \tag{5.4}$$

Where T_{BO} , T_{SIFS} , T_{RTS} , T_{CTS} , T_{DATA} , T_{ACK} and T_{DIFS} are back-off, IEEE 802.11 short inter-frame space, RTS transmit, CTS transmit, DATA transmit, ACK transmit and DCF inter-frame space times, respectively.

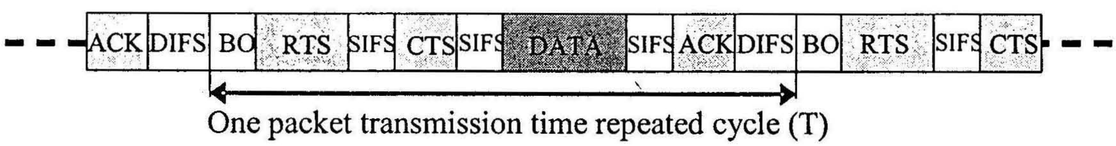

Figure 5.2: Timing diagram for the CSMA/CA with the RTS-CTS-DATA-ACK handshake.

The back-off time T_{BO} is selected randomly following a uniform distribution from $(0, CW_{min})$ giving the expected average value of $(CW_{min}/2) \times T_{slot}$, where T_{slot} is the slot time in microseconds. The transmission times taken by RTS, CTS and ACK depend on the packet size (in bits) specified by the MAC layer, PHY header attached to these packets, and the corresponding rates (in Mbps) assigned by the MAC layer. These times are given in the following equations:

$$T_{RTS} = \frac{8 \times (RTS + PHY\_Hdr)}{R_{RTS}} \quad (5.5)$$

$$T_{CTS} = \frac{8 \times (CTS + PHY\_Hdr)}{R_{CTS}} \quad (5.6)$$

$$T_{ACK} = \frac{8 \times (ACK + PHY\_Hdr)}{R_{ACK}} \quad (5.7)$$

Where RTS, CTS, ACK, are packet size (in Bytes) and R_{RTS} , R_{CTS} and R_{ACK} are corresponding rates (Mbps) of RTS, CTS and ACK packets respectively. The PHY_Hdr is the header (Bytes) added by physical layer to these packets. On the other hand, the time taken by DATA packets depends on the packet size (bits) specified by the upper layer, MAC layer header, PHY header, and the corresponding data rate chosen by the MAC layer as given in the following equation:

$$T_{DATA} = \frac{8 \times (L + MAC\_Hdr + PHY\_Hdr)}{R_{DATA}} \quad (5.8)$$

Where L is size (in Bytes) of the data packet handed over by upper layer. MAC_Hdr and PHY_Hdr are headers (Bytes) added by the MAC and physical layers to the data packet. R_{DATA} is the data rate selected by MAC layer. The numerical results and the simulation model for IEEE 802.11b presented in this chapter depend on the specific setting of IEEE 802.11b protocol parameters [62]. Table 5.1 gives the values for different parameters used to obtain the results presented in the following sections.

We have used one active single-hop model to generate bit errors according to the distance between the sender and the destination. For this work, we assumed an AWGN channel which can be considered as a worst case channel regardless of the channel coding. The AWGN channel always results in an equal and independent distribution of bit errors over time. Hence the SNR at a receiver is the function of communication distance for a given data rate and transmit power. As a result the throughput is affected by this SNR value. Therefore, the maximum theoretical throughput given by the following equation:

$$MaximumThroughput = \frac{L \times 8}{T} \tag{5.9}$$

can be rewritten as:

$$MaximumThroughput = \frac{L \times 8}{T} \times PSR \tag{5.10}$$

Where *PSR* is the Packet Success Rate (*PSR*=(1-BER)$^{L'}$), where *L'* represents the complete data packet size during transmission (*L'=L+MAC DATA Header+ PHY Header*).

T_{slot}	20 μsec
T_{SIFS}	10 μsec
CW_{min}	$31 \times T_{slot}$
T_{DIFS}	50 μsec
RTS Packet Size	20 Bytes
CTS Packet Size	14 Bytes
ACK Packet Size	14 Bytes
MAC DATA Header	28 Bytes
PHY Header	24 Bytes
DATA Packet Size	512 Bytes
Operating frequency	2.4 GHz

Table 5.1: IEEE 802.11b parameter values used in simulations.

Figure 5.3 shows the theoretical throughput for the single-hop model as the function of SNR for different data rates supported by IEEE 802.11b. It is clearly shown that higher data rate provides higher maximum throughput compared to the lower data rates at extremely high SNR. However, using lower data rates gives better performance than the higher data rates at lower SNR. Figure 5.4 shows the maximum throughput as the function of communication distance for different modulation schemes and adaptive rate. This throughput is obtained by simulating a single-hop model. The source node generates CBR traffic at the rate of 5 Mbps. The figure gives the exact relation between the data rate and the transmission range. It is noticed that the higher data rate provides higher throughput but its transmission range is smaller compared to lower data rates. This transmission range improves as the data rate decreases. As shown in the figure 5.4 the adaptive rate scheme always tries to dynamically choose the highest data rate that satisfies the estimated channel conditions. This simple threshold technique is widely used in many adaptive rate protocols [47].

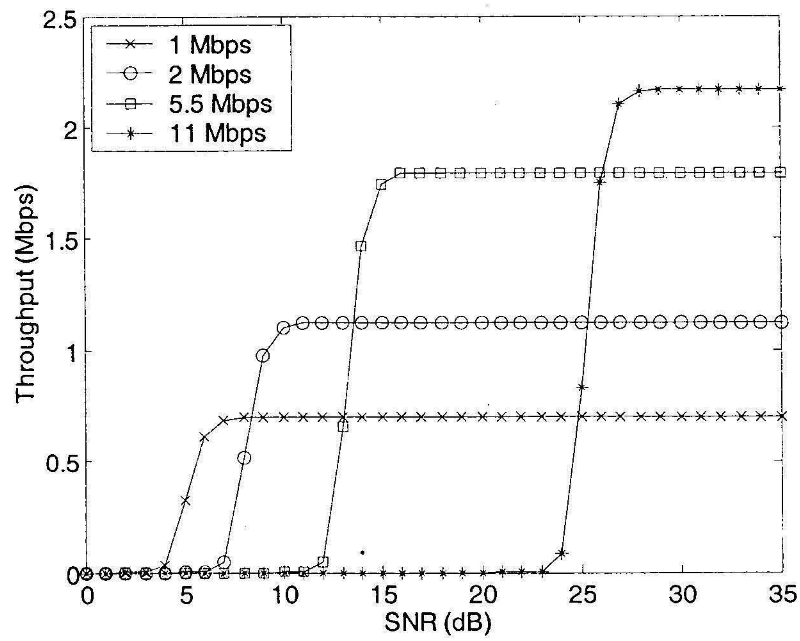

Figure 5.3: Maximum theoretical throughput in IEEE 802.11b for the different data rates as a function of SNR (dB).

5.1.5 Energy Consumption Calculation

We used data delivered per joule as an evaluation metric in this work. We have considered only the energy consumed in transmission of RTS, CTS, ACK and DATA packets. The energy consumed by the nodes in idle or receiving states are not considered. The power control schemes considered in this work is PCM which transmits RTS-CTS at maximum power, P_{max}, but sends DATA/ACK at minimum necessary power P_{min}. Therefore, the energy consumed for transmitting one data packet with its control packets is expressed in the following equation:

$$Energy\,Consumed\,/\,Packet = P_{\max}(T_{RTS} + T_{CTS}) + P_{\min}(T_{DATA} + T_{ACK}) \qquad (5.11)$$

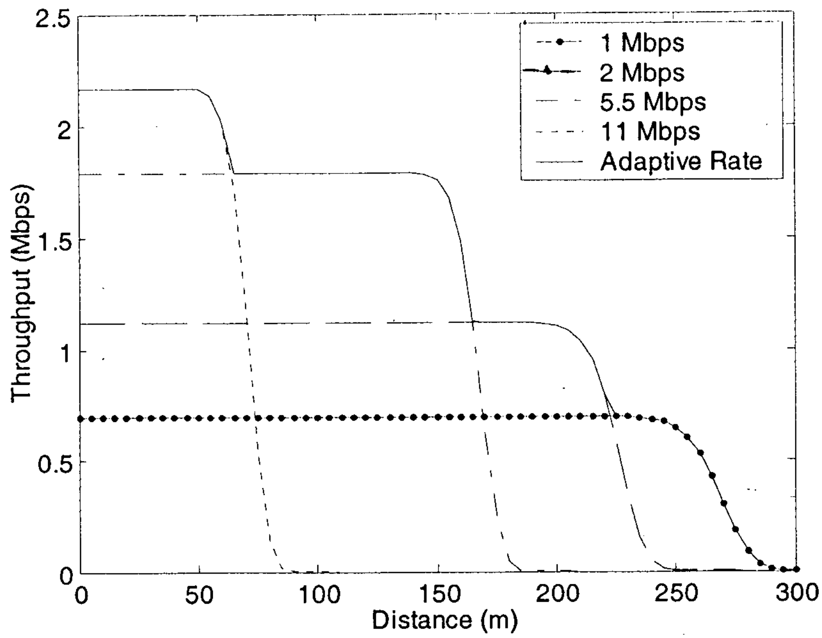

Figure 5.4: Maximum theoretical throughput in IEEE 802.11b for the different data rates and adaptive rate as a function of distance.

Figure 5.5 shows the maximum data delivered per joule in IEEE 802.11b as the function of distance, taking BER into consideration corresponding to the maximum throughput shown in figure 5.4 for the single-hop model. In the simulation, we consider different data rates supported by IEEE 802.11b standard and adaptive rate. In this evaluation, IEEE 802.11b with different data rates and adaptive rate scheme has been simulated using maximum power P_{max}, (without power control). The IEEE 802.11b with constant data rates has also been simulated using PCM power control scheme. We used 10 transmit power levels as given in table 2.3 with maximum transmission range of 250 m at the basic data rate of 1 Mbps. As shown in figure 5.5, higher data rate delivers more data with the same amount of energy used than the lower data rate if power control technique is not used. Conversely as the communication distance increases, the lower data rate provides better data delivered per joule than the higher data rate. The adaptive rate scheme without power control dynamically follows the highest data rate that satisfies the estimated channel conditions. Different data rates with power control technique perform better than the corresponding rates without power control, since with the same data rate power control scheme uses less power so the energy consumption is reduced. When the distance increases, the power control scheme tries to increase its transmission power to satisfy the required higher SNR. When the transmit power reaches its maximum level, the energy consumption performance of some data rate with power control scheme exactly follow the curve of the same data rate without power control technique as clearly shown for the 11 Mbps data rate in figure 5.5. Data rate of 5.5 Mbps, 2 Mbps and 1 Mbps gives better performance but their throughput as shown in figure 5.4 is not acceptable over all distances unlike the throughput of adaptive rate. For the data rate of 2 Mbps and 1 Mbps energy consumption performances alternately change with each other at distance ≤200m but for the rate of 2 Mbps throughput is better at those distances. At distance >200 m, for 1 Mbps rate, throughput and energy consumption performance are better than all other rates, since it is the only data rate that provides the maximum transmission range.

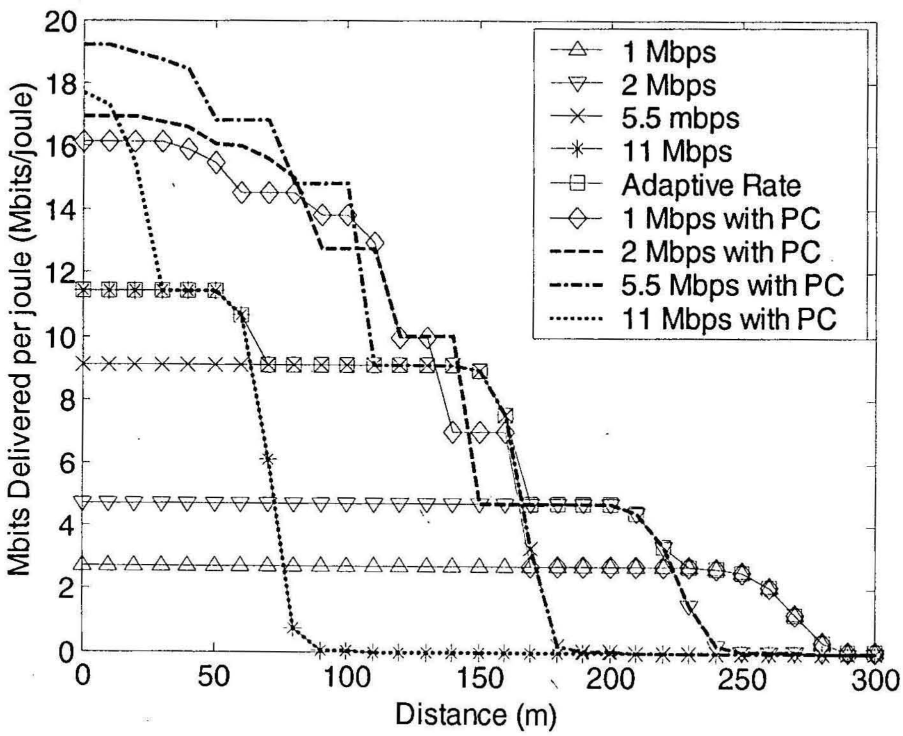

Figure 5.5: Maximum data delivered per joule in IEEE 802.11b for the different data rates with/without power control and adaptive rate as a function of distance.

5.2 Traffic Sensing Adaptive Rate Power (TSRP) Control MAC Protocol

TSRP control MAC protocol selects the best rate-power combination for each data frame. The selected rate-power gives the required SNR at the receiver, maximizes the throughput and saves the energy. The main characteristic of TSRP protocol is that rather than just matching the channel conditions, a sender chooses an energy efficient rate-power combination that is suitable to schedule the transmission of packets in its queue with minimum delay.

5.2.1 Important Remarks

From the equations 5.1-5.11 given in the previous section and their outcome results, it is noticed that the throughput and the energy consumption metrics are related to each other strongly. The selection of higher data rate based on the estimated channel quality provides higher throughput. But this higher data rate requires more transmit power to satisfy the required channel quality since the energy consumption is directly proportional to the transmit power and inversely to the data rate. Therefore, higher data rate improves the throughput but it may not minimize the energy consumption. The energy efficient rate-power combination satisfies the required channel conditions, and required throughput, and gives minimum power to rate ratio. Therefore it is not necessary that the highest selected rate as suggested for adaptive rate is energy efficient. If the required network throughput is low, which based on the traffic load, lower data rate that can satisfy the required channel condition combined with selected transmit power is also energy efficient.

5.2.2 TSRP Protocol Basics

The important remarks made in the previous section forms the basis of the proposed protocol design. Initially, this new MAC layer protocol determines the optimum highest data rate that can satisfy the channel conditions. This rate is declared after the successful exchange of RTS-CTS control packets using the maximum transmission power and the basic rate. Next, this protocol determines the optimum lowest data rate that can satisfy the traffic load and schedules all the data packets waiting in MAC layer queue with minimum delay. Then, it builds up a table containing all the data rates within the optimum highest and lowest rates (optimum lowest rate ≤ data rates ≤ optimum highest rate). A set of transmit power corresponding to selected data rates are computed and added in the table. Therefore, the table contains a set of all possible rate-power combinations that can satisfy the current channel conditions and achieves the required throughput. Finally, a sender node selects the most suitable rate-power combination that can consume less energy. Therefore, TSRP protocol tries to sense the outgoing transmissions by considering the traffic load and the number of waiting packets.

Now suppose that a source node is ready to send data. It has no waiting packet(s) in its queue and it also found the medium free to content. The estimated measured SNR(t) at the receiver is high and the required throughput can be easily achieved by the lowest data rate (1 Mbps). Under these conditions, TSRP MAC protocol selects the most energy efficient rate-power for transmitting the packets coming from upper layers. As shown in figure 5.6, the traffic load is too low so that the inter-arrival time (λ=packet_size*8/traffic_load) between successive packets is larger than the time required for transmitting a data packet with lowest data rate (1 Mbps). Therefore, the sender selects a data rate along with corresponding transmit power, which is energy efficient combination. As the measured SNR(t) at the receiver decreases or the traffic load increases, the elements of the rate-power set reduce so the choice of energy efficient rate-power combination becomes limited. This new protocol is more effective at higher SNR(t) and lower traffic load.

Let us now consider the operations of the proposed protocol under more complicated situation. In this situation, either a sender node finds the medium busy or the node has packet(s) waiting in its queue. To understand the idea of the proposed protocol, let us explain an example of two source nodes sharing the same transmission medium. The timing diagrams of such example are illustrated in figure 5.7. Suppose that each source node generates a traffic load at the same rate (packet_size*8/λ in bps). It is noticed that the first packet generation of both sources are not shown in figure 5.7(a). At the beginning of the second packet generation, the first packet is already generated and ready for the transmission.

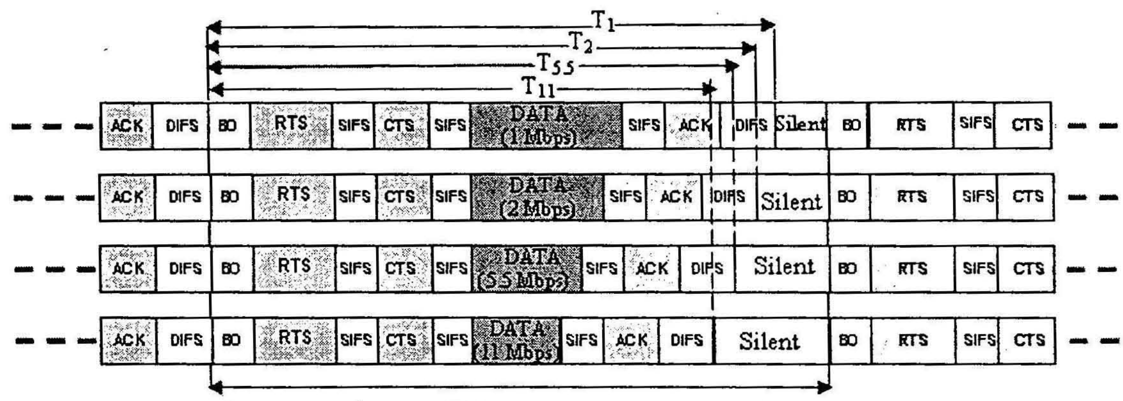

Figure 5.6: Timing diagram for the CSMA/CA with the RTS-CTS-DATA-ACK handshake with the different data rates.

Assume that at certain SNR(t), the main set contains 1 Mbps, 2 Mbps, 5.5 Mbps and their corresponding transmits power. It is found that the 1 Mbps is more energy efficient, than 2 Mbps when there is no packet(s) waiting in the queue. Therefore, a sender selects 1 Mbps data rate to send the data packets using its corresponding transmit power. According to CSMA/CA, if a source 1 has reserved the medium to transmit its packet, it selects 1 Mbps data rate as it can achieve the required throughput and energy efficient. Source 1 did not have any idea that source 2 is also sharing the same medium. But source 2 senses the medium busy, therefore, its packets have to wait as shown in figure 5.7(b). Using the waiting time and the remaining time before the next packet is available for transmission; source 2 selects 5.5 Mbps as the transmission rate. Even 5.5 Mbps is not energy efficient rate in the main set but it provides the required throughput. This scenario continues between source 1 and source 2 since contention of transmission medium in CSMA/CA is random between the shared nodes. If source 1 has reserved the medium, it transmits at 1 Mbps and source 2 at 5.5 Mbps. On the other hand, if source 2 has reserved the medium, it uses

1 Mbps and source 1 uses 5.5 Mbps. With such a technique, the throughput of the network is maximize and more energy is saved.

Now consider another case, when the current SNR(t) is quite small. Suppose the main set contain only 1 Mbps and 2 Mbps rate and 1 Mbps rate is more energy efficient. In this case, if source 1 has reserved the medium to transmit its packet, it will select 1 Mbps data rate as it is energy efficient and can achieve the required throughput. Source 2 will select 2 Mbps to achieve the required throughput. Suppose source 1 again reserves the medium for transmitting its second packet, even the second packet has waited for some time. Source 1 finds that 1 Mbps is still suitable to transmit this packet and can achieve the required throughput. This scenario continues between source 1 and source 2. However, the selection of data rate depends on the packet waiting time and the remaining time for the next packet arrival based on the traffic load as shown in figure 5.7(c). If more than one packet are waiting in the queue, the rate is selected in a manner that the waiting packets are delivered with minimum delay. This protocol is also applicable to nodes engaged in packet transmission in multi-hop wireless ad hoc networks.

5.2.3 TSRP Protocol Description

Figure 5.8 diagrammatically shows the insertion of TSRP-control in the standard IEEE 802.11b MAC protocol. The state-machine is simplistic and is given only to ease the understanding of fundamental mechanism of the proposed protocol at the MAC layer. The MAC layer is modeled as a finite state-machine, and shows the permissible transitions. The functioning of the state-machine is as follows. If a node has a packet to send and is in idle state, it changes its state to wait for NAV and wait for DIFS. In case, the medium continues to be idle after DIFS period, node enters the backing off state. Otherwise, the node sets its back-off counter and goes back to the idle state. After backing off period, the node enters RTS transmission state and starts transmitting RTS packet using the maximum power level and the basic rate. On completion of RTS transmission, node enters waiting for CTS state. In case, the node fails to receive CTS packet within specified time, it goes back to the idle state. Otherwise, the node enters the TSRP- control state. At this state, the sender node executes TSRP-control protocol to find an energy efficient rate-power to transmit the DATA packet. After determining rate power combination, the node moves to data transmission state where it transmits the DATA packet. At the end of data transmission, the node moves to waiting for ACK state. Finally, the node returns to the initial state on receiving an ACK or expiry of waiting time for ACK.

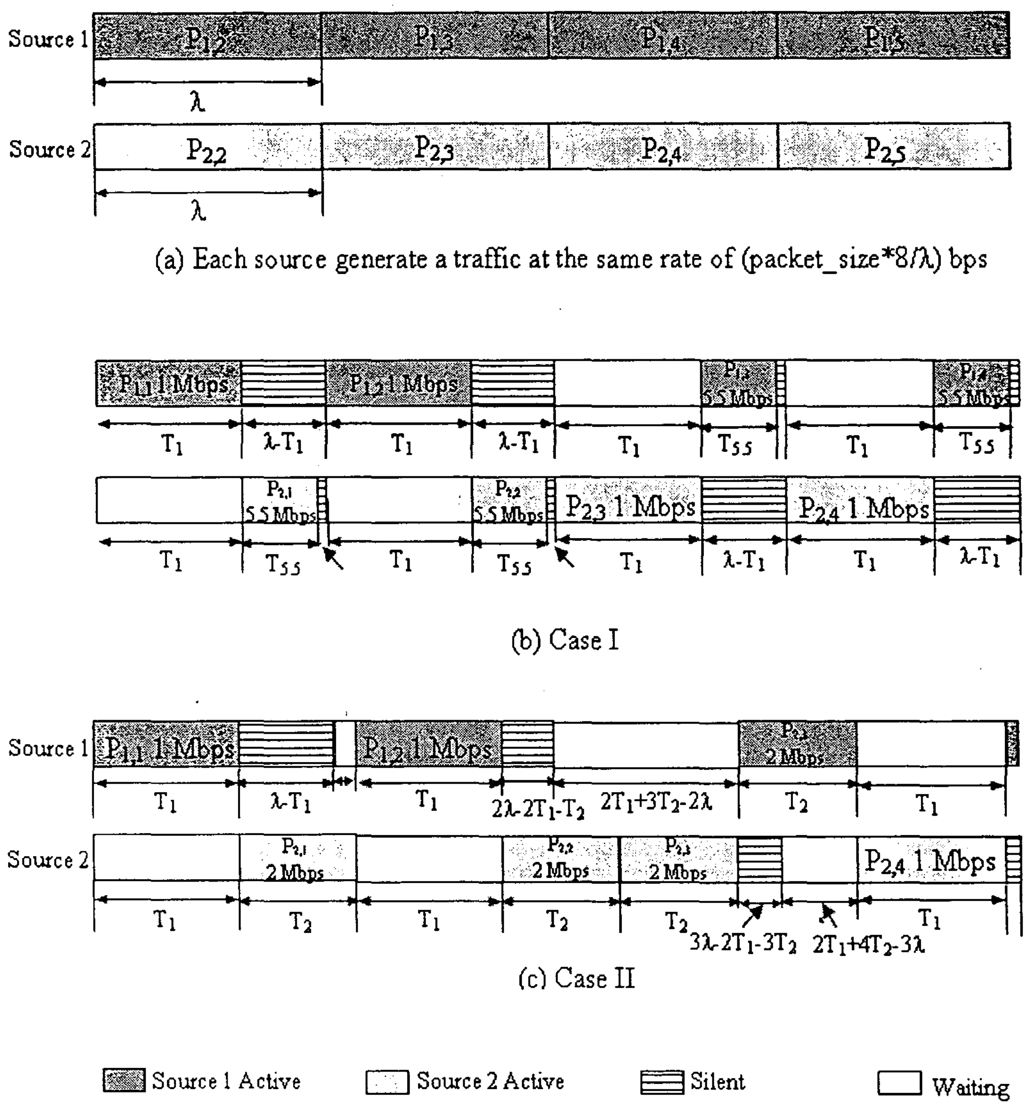

Figure 5.7: Timing diagrams show adaptive operations of TSRP scheme to achieve higher throughput with optimum energy consumption, when two sources with two flows share the same transmission medium.

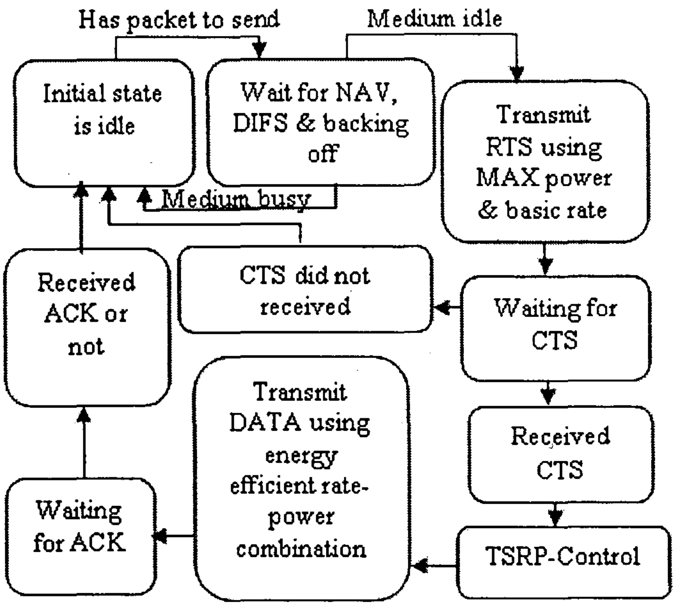

Figure 5.8: MAC state transition diagram of a sender with TSRP-Control protocol.

The proposed TSRP control MAC protocol operations can be summarized in the following steps:

- Transmitter sends RTS packet with maximum power level and using basic rate.
- Receiver decodes the RTS packet; estimates the current channel conditions by measuring the SNR at that time.
- The receiver sends CTS packet with the maximum power level including the measured SNR.
- Using the estimated SNR extracted from the CTS packet, the transmitter finds the highest data rate that satisfies the estimated channel conditions. This highest rate is found by comparing the extracted SNR with the series of SNR thresholds correspond to all the rates.
- Using the number of waiting packets in the queue, and node's waiting time to content for the medium, the transmitter finds the lowest rate that can deliver all the data packet with minimum delay and maximize the network throughput
- The transmitter builds a table that contains a subset of rate-power

combinations. This subset includes rates that fall between the highest and lowest rates, i.e. highest rate≤ rate ≤ lowest rate.

The data packet is transmitted using the most energy efficient rate-power combination selected from this subset.

The TSRP-control protocol finds the most energy efficient rate-power combination by executing three main steps from point 4 to 7 above. These steps are explained as follows. In the first step, it determines the maximum rate that satisfies the current channel conditions whereas the second step determines the minimum rate that can achieve the required throughput. In the third step, TSRP-control tries to find the rate-power combination which can satisfies the current channel conditions and achieve the required throughput with minimum cost factor. The cost factor used in the protocol is defined as the ratio of the transmit power to the transmission rate. If the required throughput can not be achieved by any permissible rate, a rate which can provide the maximum expected throughput is selected as the transmission rate.

5.2.4 Simulation and Results

We simulated IEEE 802.11b with power control using different standard rates, adaptive rate power, and TSRP control protocol. The IEEE 802.11b along with TSRP is simulated using MATLAB based on discrete event approach for a limited network scenario. Here, CSMA/CA technique based on DCF access method as regulated by IEEE is modeled. In this simulation we evaluated our proposed protocol under two scenarios: single flow single-hop and two sources two flows sharing same transmission medium. Further, to investigate the performance of TSRP in full network scenario, we used Glomosim-2.03 to simulate IEEE 802.11b with power control scheme for different standard rates, adaptive rate with power control, and TSRP control protocol. In these simulations, three different scenarios: single flow chain topology, single-hops random topology, and single flow multi-hop topology are considered.

5.2.4.1 Simulation Environment

In this section, we present different parameters and inputs considered in our simulations. The simulations considered different transmit power levels and their approximate corresponding transmission ranges as given in table 2.3. Table 2.4 gives the values of various parameters used in the simulations. It is assumed that all nodes in the network have same characteristics and propagation properties. The signal propagation model used in this work is a combination of free space propagation (for near distances) and two-ray ground reflection (for far distances) model. We performed simulations using different CBR traffic generated at a rate as specified in the results obtained. The packet size is 512 bytes unless otherwise specified. We also performed some simulations for varying packet size as well. Each simulation runs for 1000 seconds for both the scenario - single flow single-hop and two sources two flows sharing the same transmission medium. For single flow chain, single-hops random, and single flow multi-hop topologies, each output result is an average of 10 simulation runs. The duration of each run is 20 seconds.

5.2.4.2 Experimentation

The performance of TSRP control protocol and others protocols under study are evaluated in terms of aggregate throughput, packet delivery ratio, total and effective data delivered per joule. In the evaluation, we have considered energy consumed in transmission of RTS, CTS, and ACK packets for the calculation of total and effective data delivered per joule. Further, experiments are also carried out for five different scenarios: single flow single-hop, two sources two flows sharing same transmission medium, single flow chain topology, single-hop random topology, and single flow multi-hop topology. In the first scenario, there is one sender and one destination, whereas in the second scenario, there are two senders wishing to communicate with their corresponding destinations at the same time. The chain topology consists of 31 nodes with equal spacing and 30 flows. The first node of the chain is considered as the sender and the last node of the chain is considered as the destination. The rest of the experiments used a random topology consisting of 100 nodes randomly distributed in an area of 1000 x 1000 m^2. In case of single-hop random topology, a single-hop traffic pairs have randomly been selected with a distance between them varying from 0 to 250 m. We have selected 50 traffic pairs such that there are 5 pairs in each distribution range of 0-40, 40-60, 60-80, 80-90, 90-100, 100-110, 110-120, 120-150, 150-180 and 180-250 meters. For the single flow multi-hop topology, two nodes are randomly selected, where one is considered as a sender and the other as a destination. These two nodes are selected in such a manner that they are located near the opposite corner of the simulation area. The source node finds its route to the destination using MINPOW routing or AODV and DSR conventional ad hoc routing protocols.

5.2.4.3 Results and Discussions

This section discusses the results obtained from the simulations carried out for five different scenarios considered under the study.

Single Flow Single-hop Scenario

Figure 5.9 shows the throughput obtained from the simulation of single flow single-hop. The distance between the sender and the destination nodes varies, and the sender node generates traffic at the rate of 1 Mbps. The figure shows the comparison of throughput of IEEE 802.11b with power control for different data rates, power control with adaptive rate, and with TSRP. It is clearly visible that, only 1 Mbps rate is not able to provide the maximum throughput required at distance <230m. But its performance is better than other rates as the distance increases toward the maximum transmission range. For this, even the data rate and the traffic rate are same, but due to MAC and PHY overheads, the throughput is reduced. All other rates, adaptive rate, and TSRP are able to achieve the same traffic rate. Excluding 1 Mbps rate since its throughput is low, the proposed scheme is more energy efficient compared to others as shown in figure 5.10. TSRP protocol adaptively selects the rate-power combination that can improve the throughput and energy conservation of the network.

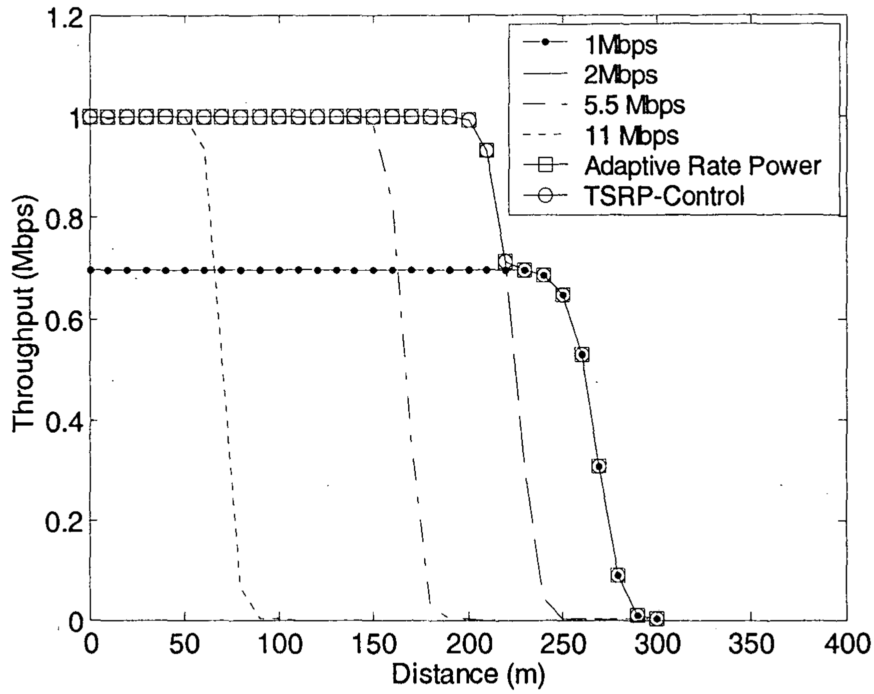

Figure 5.9: Throughput comparisons at 1 Mbps traffic load in case of single flow single-hop.

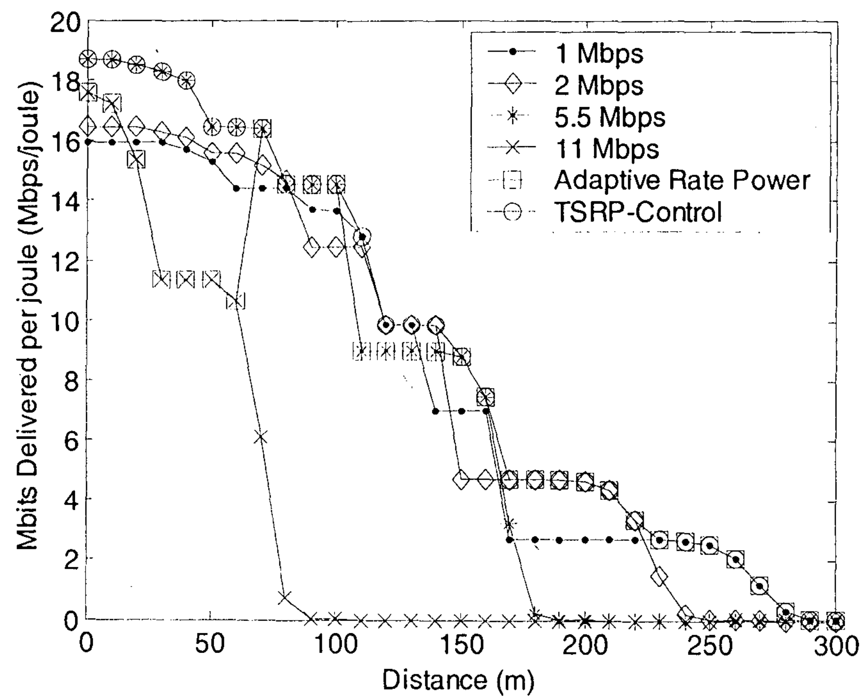

Figure 5.10: Total data delivered per joule comparisons at 1 Mbps traffic load in case of single flow single-hop.

TSRP control technique adaptively selects the rate that can save more energy. However, the adaptive rate scheme always follows the highest rate that satisfies the measured SNR. TSRP protocol always tries to use the rate such that the ratio of power to data rate is the minimum. This is because, as the rate increases, the transmit power also increases and the inverse is also true. This phenomenon is clearly revealed in figure 5.11. This figure shows the transmit power used in single flow single-hop to achieve the required throughput and data delivered per joule as shown in figure 5.9 and figure 5.10, respectively.

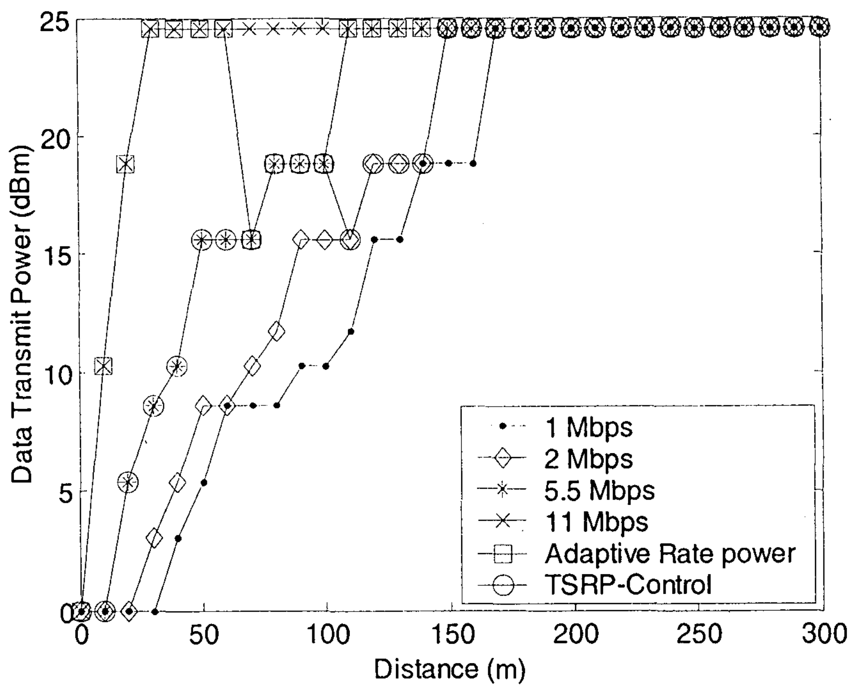

Figure 5.11: Average data transmit power (dBm) comparisons at 1 Mbps traffic load in case of single flow single-hop.

Two Sources Two Flows Sharing the Same Transmission Medium Scenario

In this scenario we considered two source nodes that are sending two different flows to their respective destinations and the nodes are sharing the same transmission medium. Therefore, each source is in the RTS-CTS ranges of the outgoing transmission carried by other source or it is in the carrier sensing range of the other source. Each source generates CBR traffic at the rate of 1Mbps. Since the traffic load is high enough, only 11 Mbps, adaptive rate power and TSRP schemes can deliver all the packets efficiently at short distance as shown in figure 5.12. But it is important to notice that 11 Mbps rate have lower transmission range than other rates. The aggregate throughput achieved for 1 Mbps, 2 Mbps and 11 Mbps rate is better as the distance increases. However, the adaptive rate power and TSRP control protocol generally perform better for all distances. This result is obtained since adaptive rate power control protocol always selects the highest rate that satisfies the channel conditions. Similarly, TSRP control protocol selects the rate that maximizes the network throughput and also consumes energy efficiently.

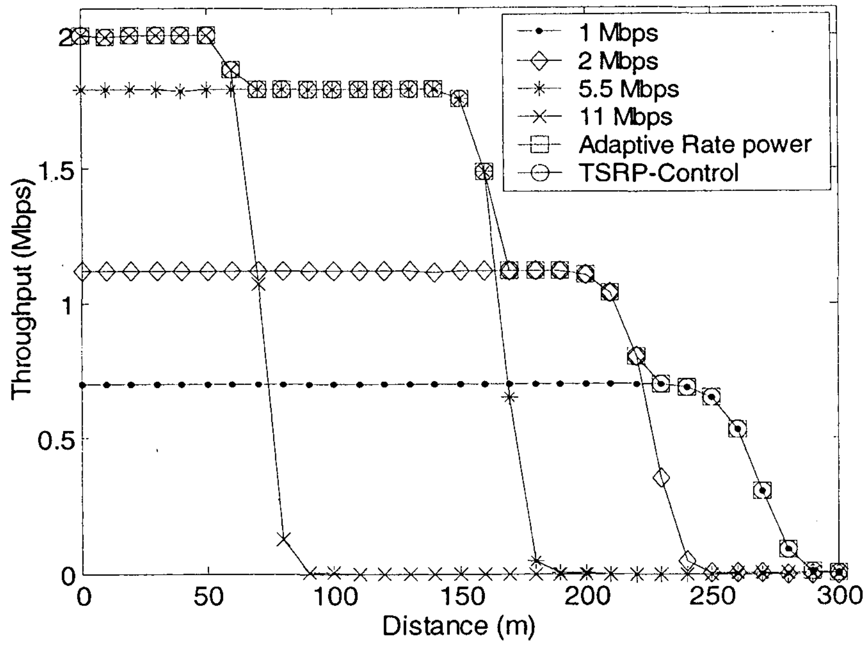

Figure 5.12: Aggregate throughput of two sources each at 1 Mbps traffic load and sharing the same medium in IEEE 802.11b.

Figure 5.13 presents the advantage of TSRP control MAC protocol over adaptive rate, and different data rates supported by IEEE 802.11b. The total data delivered per joule for the proposed protocol is always the maximum compared to others, taking into account the throughput requirement. At distance <60 m, 11 Mbps, adaptive rate power and TSRP proposed schemes only achieve the required maximum throughput as shown in figure 5.12. But TSRP scheme is more energy efficient than 11 Mbps and adaptive rate power schemes as shown in figure 5.13. As the distance increases (at certain distances around 130 m) it seems that 1 Mbps and 2 Mbps rate are more energy efficient than the TSRP control scheme but these rates do not provide the required network throughput. The TSRP protocol always selects a rate that maximizes the throughput and minimizes the energy consumption. Therefore, TSRP protocol saves more energy, without compromising the throughput.

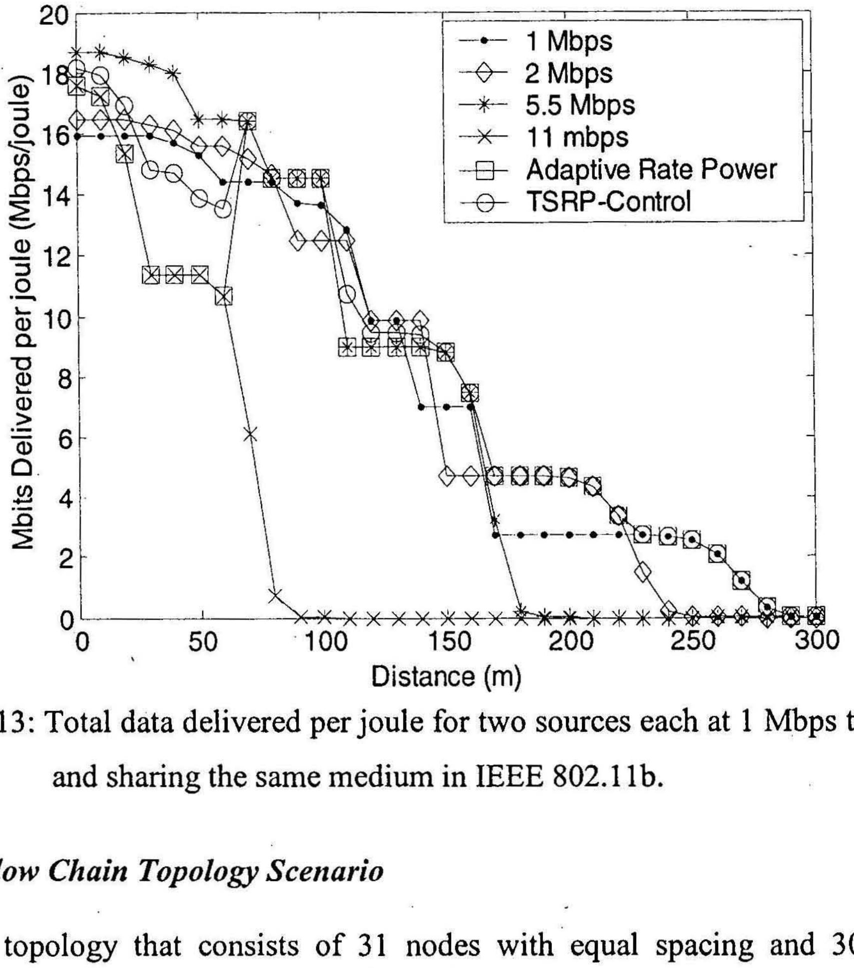

Figure 5.13: Total data delivered per joule for two sources each at 1 Mbps traffic load and sharing the same medium in IEEE 802.11b.

Single Flow Chain Topology Scenario

A chain topology that consists of 31 nodes with equal spacing and 30 flows is simulated. A source generates CBR traffic at the rate of 100 Kbps. The metric packet delivery ratio for the different schemes is shown in figure 5.14. It is clear from the figure that the delivery ratio depends on the data transmission rate. 1 Mbps rate gives the lowest delivery ratio when the distance between adjacent nodes is small. On the other hand, for higher data rates, the delivery ratio falls sharply at lower transmission range compared to lower data rates. Only the adaptive rate power control and TSRP maintain higher delivery ratio at all distances. TSRP-control is also able to deliver more data per joule to the final destination compared to all other schemes as shown in figure 5.15. Unlike the adaptive rate power control, TSRP control scheme does not select the highest rate, but it selects a rate that is sufficient to deliver all the packets with minimum delay and saves more energy.

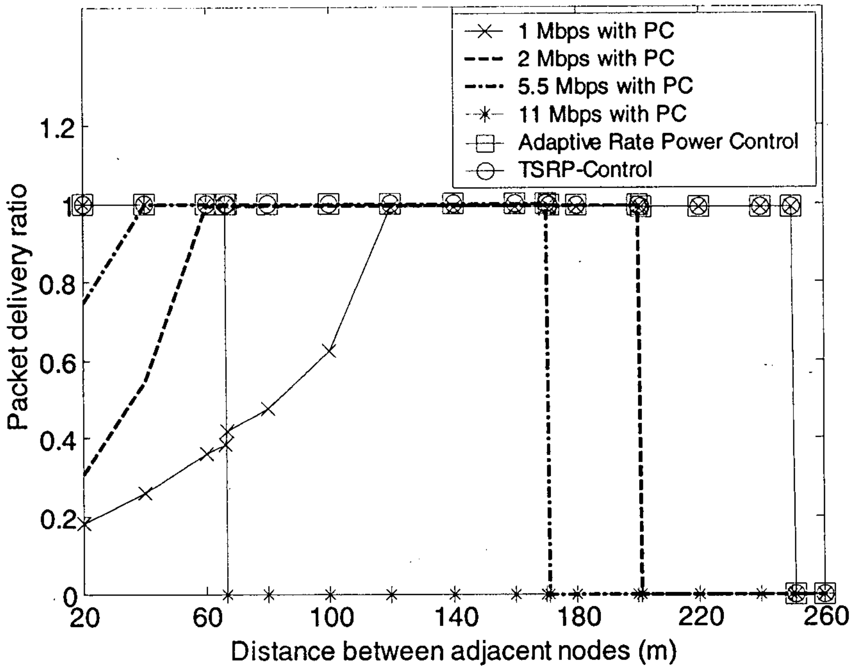

Figure 5.14: Chain topology: Packet delivery ratio at a traffic rate of 100 Kbps.

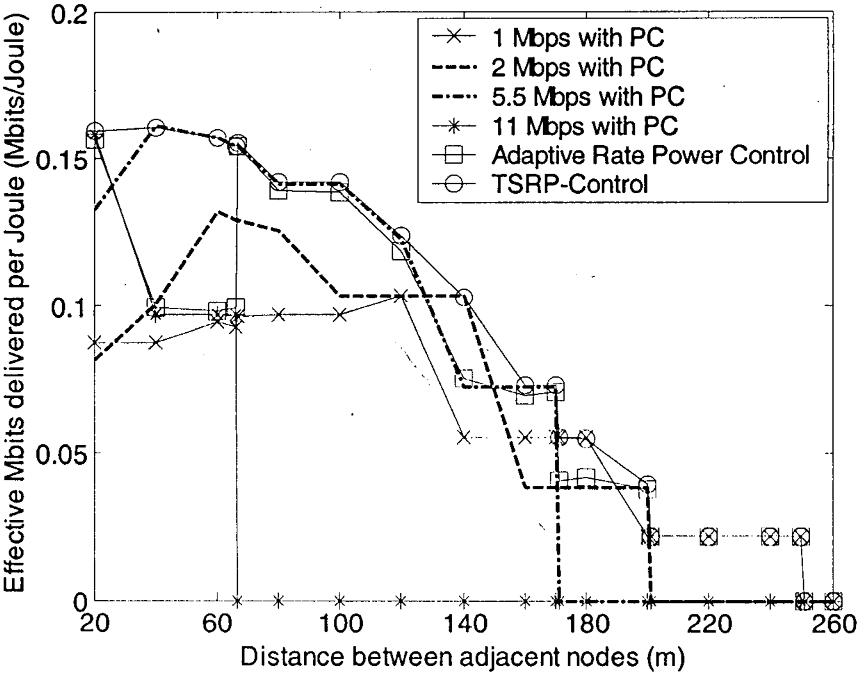

Figure 5.15: Chain topology: Effective data delivered per joule at a traffic rate of 100 Kbps.

Single-hops Random Topology Scenario

A random topology is simulated with 100 nodes distributed over 1000 X 1000 m^2 area. Single-hop traffic pairs are randomly selected with the different distance ranging between 0 to 250 m. We have selected 50 traffic pairs such that there are equal number of pairs within the destination ranges of 0-50, 50-100, 100-150, 150-200 and 200-250 meters. Figure 5.16 and figure 5.17 shows the performance of random topology with varying network load. When the network is lightly loaded, packet delivery ratio for 1 Mbps rate is higher compared to other rates. It is because with 1 Mbps rate and light traffic load, all the sources are able to deliver packets to their destinations. However, for the higher rate, all traffic pair communication may succeed since transmission range decreases as the rate increases. When the traffic load increases, 1 Mbps rate curve falls more sharply compared to 2 Mbps and 5.5 Mbps rates. Although, all the sources may be connected to their destinations at 1 Mbps, but this rate cannot maintain the same delivery ratio at high traffic load. As the traffic load increases, for the data rates of 2 Mbps and 5.5 Mbps, the network maintains the same delivery ratio as it achieves for the same rate at low load for the traffic load ≥ 60 Kbps it tries to fall but slowly, compared to 1 Mbps. The adaptive rate power control and TSRP scheme maintain the highest delivery ratio at various network loads. However, the packet delivery ratio for 11 Mbps is relatively low at any load, even the data rate is high since most of the senders may not be connected with their destination.

Figure 5.17 shows the total data delivered per joule for the random topology scenario for all schemes. Even when the packet delivery ratio for adaptive rate power control and TSRP control schemes are the same, the total data delivered per joule for TSRP is better than the adaptive rate power control scheme. The figure clearly presents the advantage of TSRP control MAC protocol over the adaptive rate power control and IEEE 802.11b with different data rates. For TSRP, the total data delivered per joule is always the maximum compared to other schemes. Therefore, TSRP scheme saves more energy and outperforms the other protocols under study. However, 11 Mbps rate with power control is the worst in terms of the data delivered per joule at any traffic load.

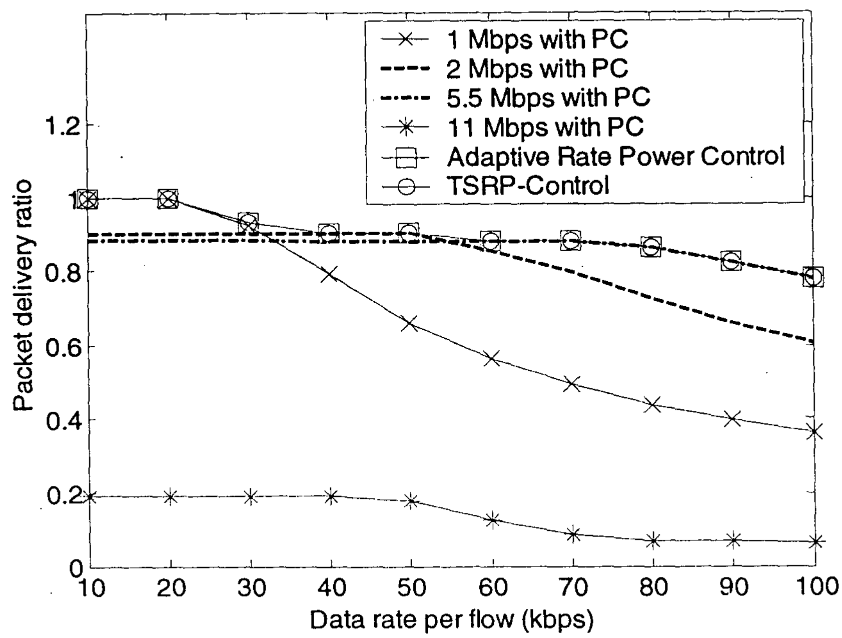

Figure 5.16: Single-hops random topology: Packet delivery ratio with different network load.

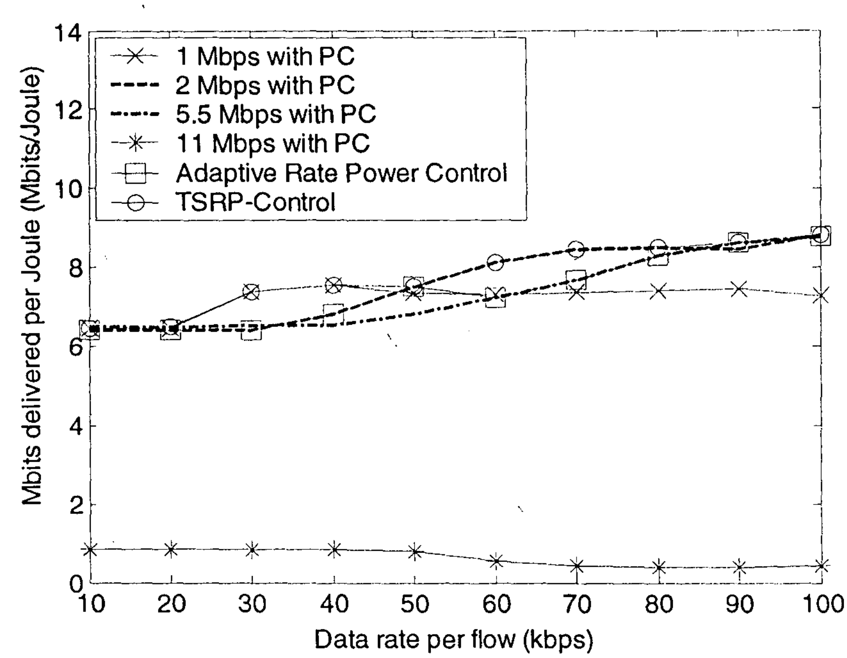

Figure 5.17: Single-hops random topology: Total data delivered per joule with different network load.

Single-flow Multi-hop Topology Scenario

We also simulated single-flow multi-hop random topology with 100 stationary nodes distributed over 1000 X 1000 m^2 area. Two nodes are randomly selected, one is considered as a sender and the other is the destination. These two nodes are located near the opposite corner of the simulation area. The source node discovers a route to the destination using MINPOW routing protocol, AODV and DSR routing protocols. The performance of the proposed scheme with MINPOW as a routing protocol is compared with adaptive rate power control. This adaptive rate power control scheme uses AODV, DSR and MINPOW as the routing protocol. Figure 5.18 and figure 5.19 show the simulation results for varying data packet size of 64, 128, 256, 512 and 1024 bytes at the traffic rate of 100 Kbps. The packet delivery ratio of TSRP control/MINPOW, adaptive rate power control/MINPOW and adaptive rate power control/AODV schemes are identical as shown in figure 5.18. This is because at light traffic rate of 100 Kbps, all the source nodes are able to send packets to their respective destinations. But the delivery ratio for adaptive rate power control/DSR scheme is relatively low when the packet size is less than 512 bytes. The benefits of the proposed protocol compared to others can clearly be noticed from figure 5.19. As shown in this figure, the total data delivered per joule for TSRP control scheme is better than all other schemes with different packet size. This means the scheme conserves more energy compared to others while achieving the maximum throughput with different packet size.

5.3 Conclusion

In this chapter, we have explained the proposed adaptive rate-power control MAC protocol for wireless ad hoc networks and evaluated its performance. We have named this protocol as the Traffic Sensing adaptive Rate Power (TSRP) control MAC protocol. The proposed protocol is mainly designed to conserve more energy while maintaining the same throughput that adaptive rate protocols can achieve. The design of TSRP protocol takes the traffic load and the packets waiting in its queue into consideration. Based on the outgoing traffic flow, TSRP control protocol selects the most energy efficient rate-power combination that can maximize the network throughput and save more power.

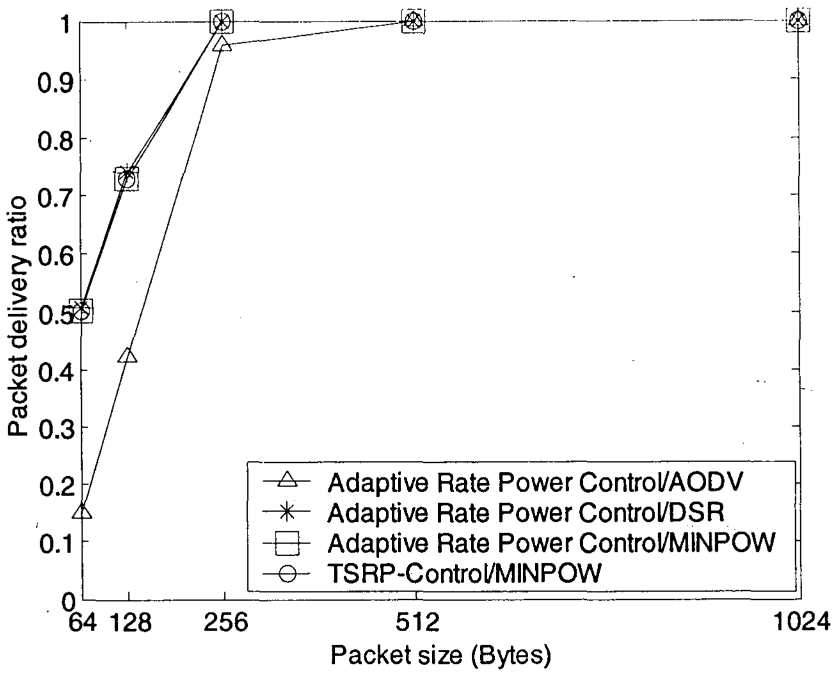

Figure 5.18: Single-flow multi-hop topology: Packet delivery ratio at traffic rate of 100 Kbps.

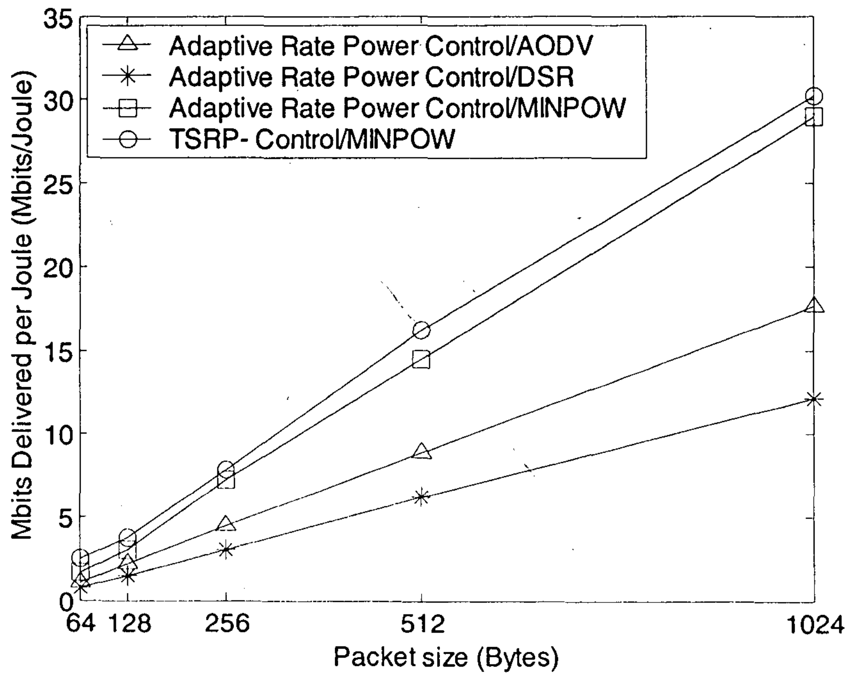

Figure 5.19: Single-flow multi-hop topology: Total data delivered per joule at traffic rate of 100 Kbps.

The initial operations of TSRP are quite similar to the adaptive rate MAC protocols. But instead of selecting the highest data rate that satisfies the channel conditions, it selects the energy efficient rate-power combination that can achieve the required network throughput. We have compared the performance of IEEE 802.11b based TSRP control scheme with IEEE 802.11b supported different rates, and adaptive rate power control protocol. We investigated its performance for five different scenarios under various traffic rates and different packet size. All simulation results show that TSRP design helps in achieving more data delivered per joule while maintaining the packet delivery ratio and the network throughput always the maximum.

CHAPTER 6

Conclusion and Future Work

The goal of the present work has been to reduce energy consumption in an ad hoc network and maximize the network throughput. In this thesis, we have focused on energy efficient MAC protocol design in an ad hoc network. The design of the new proposed protocols presented in the current work is completely different from the previous existing schemes. The IEEE 802.11 MAC protocol and the existing power control (BASIC and PCM) schemes form the basis of our work. The first step in the thesis has been to study the relation between the IEEE 802.11, power control schemes and the interference. Next we have investigated the effect of carrier sensing range on the energy consumption and throughput of the network. Based on these studies, we proposed new MAC protocols and simulated them using Glomosim network simulator to evaluate their performance. Simulation results are compared with IEEE 802.11, BASIC and PCM schemes. The results show that our proposed protocols perform better than the existing schemes in terms of throughput and data delivered per joule. Finally, we took this work further, and used rate adaptation in conjunction with power control to develop protocols that can conserve more energy and maintains the same throughput that adaptive rate protocols achieve.

Contributions

The contributions of this thesis are a set of studies, modifications to the existing protocols and proposing new power saving schemes with the goal to conserve more energy without trading-off the throughput. The major contributions of the work are listed below:

- Explored the effects of the interference and carrier sensing range on the performance of IEEE 802.11, BASIC and PCM schemes in terms of throughput and energy consumption.

- The benefits of the optimum carrier sensing range on the performance of mobile ad hoc networks have been investigated.
- Design of IPCM protocol – an improved version of existing PCM protocol.
- Design of PCM/COMPOW and IPCM/COMPOW power saving schemes by integrating PCM and IPCM with the existing COMPOW protocol for multi-hop ad hoc networks.
- Design of MIPCM protocol – a modified version of IPCM.
- Performance comparison of proposed power saving schemes with the IEEE 802.11, BASIC and PCM schemes.
- Performance comparison of proposed power saving schemes.
- Studied the relationships between the BER, SNR, communicating distance, transmission power, data rate and their influences on the energy consumption and throughput using mathematical concepts.
- Designed TSRP control protocol – an energy efficient MAC for DCF IEEE 802.11b based ad hoc networks.

Findings

Results were obtained through a series of experiments conducted on simulated network. After examining the results of the study the following observations are made:

- The interference has a huge effect on the performance of mobile ad hoc networks.
- An optimum carrier sensing range can greatly enhanced the performance of mobile ad hoc networks in terms of the data delivered per joule and throughput.
- Our proposed power saving protocols – PCM/COMPOW, IPCM/COMPOW and MIPCM have performed better than IEEE 802.11, BASIC and PCM schemes.
- MIPCM scheme gives better results than PCM/COMPOW and IPCM/COMPOW power saving schemes.

- The energy efficiency can be maximized with the large packet size.
- Network throughput can also be maximized together with energy efficiency by carefully designing the energy efficient protocols. As in the literature, most energy efficient protocols have trade-off between the throughput and the energy efficiency.
- Rate adaptation in conjunction with the power control only makes sense in energy conservation if the distance to the intended receiver is smaller and the traffic load is light.
- Energy efficient MAC protocol design based on traffic sensing to determine the data rate can provide better performance than other rate adaptation and power control protocols.

Future Work

No research work can be completed within a specified time specially, within given course duration. We made our modest efforts to accomplish the goals set in the initial proposal. However, some of the objectives remained untouched due to the limited availability of time. Like any other research works, the outcome of the current research has exhibited the possibilities of further extensions. List of the work that can be carried out in future as an extension of current work is given below:

- We focused on energy efficient MAC protocol design and used them with already existing power ware and conventional routings protocols. Designing a network layer protocol compatible with energy efficient MAC layer protocols is our main future direction. Therefore, a protocol design considering issues from both the layers together is an interesting challenge.
- As design of energy efficient protocol is a cross layer issue, therefore, possibilities of investigating challenge from other layer than network affecting the design is another direction of future study.
- All these power saving schemes can be further evaluated for others metrics, such as delay and remaining node energy.
- The impact of the fading and different mobility models on these schemes needs to be investigated.

- The scalability of the proposed schemes needs to be tested.
- We aim at extending TSRP protocol further taking into account the packet size and load-balancing techniques.

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