

An Energy-Efficient MAC Protocol for Ad hoc Networks

by

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ABSTRACT

A mobile ad hoc network (MANET) is a collection of two or more nodes equipped with wireless communications and networking capability without central network control. Nodes in a MANET are free to move and organize themselves in an arbitrary fashion. Energy-efficient design is a big challenge due to the features of a MANET such as distributed control, constantly changing network topology, and the fact that mobile users in MANETs are usually hand-held devices with limited power supply.

The IEEE 802.11 medium access control (MAC) protocol includes a power saving mechanism. However, it has many limitations. A new energy-efficient MAC protocol (EE-MAC) is proposed in this thesis. It is shown that overall, EE-MAC performs better than IEEE 802.11 power saving mode and exceeds IEEE 802.11 with respect to balancing packet delivery ratio and energy savings. The effects of network load, node density and network mobility on the performance of EE-MAC are presented. Performance results under many different conditions show that EE-MAC scales well and can work with different routing protocols.

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List of Abbreviations

ACK	Acknowledgment
AODV	Ad hoc On-demand Distance Vector
ATIM	Ad hoc Traffic Indication Message
CBR	Constant Bit Rate
CDS	Connected Dominating Set
CSMA	Carrier Sense Multiple Access
CTS	Clear to Send
DARPA	Defence Advanced Research Projects Agency
DCF	Distributed Coordination Function
DMA	Direct Memory Access
DPM	Dynamic Power Management
DPSM	Dynamic Power Saving Mechanism
DVS	Dynamic Voltage Scaling
DSDV	Destination Sequenced Distance Vector
DSR	Dynamic Source Routing
GAF	Geographic Adaptive Fidelity
LEAR	Local Energy-Aware Routing
MAC	Medium Access Control
MANET	Mobile Ad hoc Network
MCU	Micro-Controller Unit
PAMAS	Power Saving Medium Access
PAN	Personal Area Network
PARO	Power-Aware Routing Optimization

PCF	Point Coordination Function
PDA	Personal Digital Assistant
PSM	Power Saving Mode
QoS	Quality of Service
RTS	Ready to Send
VCR	Videocassette Recorder

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Chapter 1

Introduction

With the proliferation of mobile computing and communication platforms, such as cell phones, laptops, hand-held digital devices and personal digital assistants, our information society is driven from the Personal Computer age to the Ubiquitous Computing age. A user can utilize, at the same time, several electronic platforms to access all the required information whenever and wherever needed [40]. The nature of ubiquitous devices makes wireless networks one of the most important tools for their interconnection and, as a result, wireless communications, both technology and market, has experienced rapid development in the last decade. Not only are the mobile devices themselves getting more affordable, more capable and more powerful, but many new applications are being developed as wireless data communications becomes available. The bandwidth is easily 10 to 100 times more than that just ten years ago.

As applications using the Internet become familiar to a wider class of people, those people will naturally expect to use network services even in the geographic area where networking connections are not available. For instance, people using laptop computers at a conference in a hotel want to communicate among themselves without routing across the public network or through some fixed access points. Since current Internet protocols are not suitable for this requirement, a new alternative for self-configured multi-hop wireless networks is needed. As compared to traditional cellular voice/data networks, multi-hop wireless networks do not require fixed infrastructure support or centralized control. Multi-hop relays can overcome the inherent constraint of wireless communication range and thus

increase service availability.

A Mobile Ad hoc Network (MANET) is an autonomous collection of mobile users that communicate over bandwidth-constrained wireless links. Without an inherent infrastructure, the mobile nodes manage the necessary control and networking jobs by themselves, generally through the use of distributed control algorithms [16]. More and more attention has been given to MANETs for many reasons. They are flexible and can be rapidly deployed and configured. They can also be tailored to specific applications. Furthermore, they are highly robust because of their distributed management and node redundancy. In the future, it is expected that mobile ad hoc networks will experience explosive growth.

In MANETs, in order to facilitate untethered communication, most mobile ad hoc network devices are battery-powered and operate on an extremely constrained energy budget. Moreover, under some circumstance, MANETs have to be deployed in remote or hostile areas. Thus, it may be impossible to replace or recharge the batteries. Even in the case that wireless devices can extract energy from the environment by converting solar power or mechanical vibration into electronic power [29], it is desirable to keep the energy-dissipation level as low as possible to avoid frequent battery replacement. Therefore, the lack of battery energy coupled with the need for continuous radio transmission poses the research challenge to design and evaluate energy-efficient protocols for mobile ad hoc networks.

In this thesis, we investigate the issue of power management in mobile ad hoc wireless networks. The study is based on the fact that wireless devices can have significantly lower power consumption in sleep states. Nowadays, most wireless devices can be put into different power states, including work, idle and sleep mode, to conserve energy. Power management, which turns devices to low-power states when they are not in use, is a most direct and efficient technique to save energy. The objective of this thesis is to design a power management scheme by putting idle devices into sleep mode and balancing the energy consumption of all devices to prolong network lifetime while minimizing the resulting performance penalty.

1.1 Mobile Ad hoc Networks and Their Applications

A mobile ad hoc network is a collection of two or more nodes equipped with wireless communications and networking capabilities without central network control, namely, an infrastructureless mobile network. Nodes in a mobile ad hoc network are free to move and organize themselves in an arbitrary fashion. Each user is free to roam about while communicating with others. The path between each pair of users may have multiple links, and the radio connection between them can be heterogeneous. Mobile ad hoc networks can operate in a stand-alone fashion or could possibly be connected to a larger network such as the Internet.

All nodes in a MANET are able to move, dynamically connect or disconnect to the network in an arbitrary way, and all nodes can act as a source, destination or router. In contrast with infrastructure based wireless networks, such as cellular phone systems and wireless local area networks, MANETs have peer-to-peer communication, distributed networking and control functions among all nodes, and multi-hop routing. Typical mobile nodes in MANETs are laptop computers equipped with a wireless interface. With advances in technology, smart cell phones, personal digital assistants (PDAs) and pocket PCs have joined this group.

Mobile ad hoc networks were initially designed for military applications and much of the pioneering research work was supported by the Defence Advanced Research Projects Agency (DARPA) [37][28][22]. Recently, with improved techniques and the increasing popularity of mobile devices, MANETs have become very appealing for commercial systems because they eliminate much of the investment required to deploy and run the network. In what follows we give some MANET uses.

1.1.1 Home Networking

Home networks will provide very exciting and attractive experiences. The interconnection of PCs, laptops, cordless phones, security and monitoring systems, smart appliances and

so on can lead to many useful and interesting applications. For example, using a PDA in the bedroom, one could search stored movies on a PC and pick a favorite one to play using a TV in the bedroom, read the daily news from the Internet, set up a VCR to record a soccer game at night, and start the oven and rice cooker. A peer-to-peer mobile ad hoc network is a perfect choice for home networking since much of the communication in home networks happens between peer devices. In home networking, energy-efficient design is an important issue since many devices will be low-power or battery-driven. Furthermore, the design needs to leverage the power in unconstrained devices so that they can take on the heaviest networking tasks.

1.1.2 Mobile Conferencing

Mobile conferencing is perhaps the prototypical application based on the establishment of a mobile ad hoc network. When conference attendees gather in some hotel outside their normal office environment, or when project team members want to exchange and share data at an airport, network infrastructure is often unavailable. However the need to quickly set up a network is very urgent. As a particular case of MANETs, IEEE802.11a [3], b [4] and g [5] wireless LANs are suitable solutions for these situations. Clearly, energy saving is also a key point here.

1.1.3 Personal Area Networks

The idea of a personal area network (PAN) is to create a very localized network populated by some network nodes that are closely associated with a single person [27]. In other words, these nodes form a network around a person. Although they may not need to connect with the Internet, interconnection among the nodes is definitely necessary since they are related to that person's everyday behavior. Usually, only a single-hop network with very short radio range is needed. Bluetooth [7] is one of the best choices in this case. If mobile devices are equipped with bluetooth, up to eight such devices can form a so called piconet, in which a

master will allocate time slots for communications. However, when interactions between several PANs are needed, methods for establishing communications between devices in different PANs can be provided by a multi-hop ad hoc network.

1.1.4 Emergency Services

Independence from a fixed infrastructure makes an ad hoc network an ideal emergency network during natural disasters, loss of local power or other similar situations. Since the Internet has pervaded into every corner of the world, the loss of Internet connectivity may have very serious consequences. In addition, in a calamity, nothing is worse than isolation from the rest of the world. Thus, it is important to keep the network alive even when fixed infrastructure elements have been destroyed. Mobile ad hoc networks could help to overcome network unavailability. By using MANETs, a network could be set up in hours instead of weeks or more, as is required in the case of wired communications. Power supply in disaster areas is usually extremely limited and therefore a good energy-efficient design is required.

1.1.5 Sensor Networks

Recently, more attention has been focused on wireless networks of small, low-cost sensor devices which collect and disseminate environmental data. Such sensors, cheap to produce and able to be deployed in large numbers, could gather detailed information under environmentally dangerous conditions. Each sensor is only capable of a limited amount of processing, but when coordinated with the information from many other sensors, they can provide a detailed picture of specific areas. Thus, a sensor network can be described as a collection of sensor devices which can coordinate with each other to perform some specific action. Unlike traditional networks, sensor networks depend on dense deployment and coordination to carry out complex tasks.

Typical applications of sensor networks include environmental monitoring, condition

based maintenance, habitat monitoring, seismic detection, inventory tracking, etc. For example, we can suppose some poisonous chemicals were dispersed because of an accident. Sending emergency personnel might not be a good idea since they could be exposed to lethal gases. Instead, it would be better to drop sensors into the area so they can form an ad hoc network and gather the desired information. In sensor networks, energy efficiency is a dominant consideration no matter what the problem is simply because sensors usually have a small and finite source of energy and under many situations, an inability to recharge their batteries.

1.1.6 Military Networks

Military applications were the original motivation for mobile ad hoc network research. In a battlefield, especially to a special force undertaking a mission, keeping efficient and reliable communication is very important. A fixed infrastructure is not flexible and can easily be targeted by enemies. Besides, once the backbone infrastructure is destroyed, the entire network will cease to function. Therefore, quick deployment, robustness and distributed control make a mobile ad hoc network an inherent choice for the military. Tactical Internet [27], implemented by the US army in 1997 is by far the largest-scale implementation of a mobile wireless multi-hop packet radio network.

1.2 Technical Challenges in Mobile Ad hoc Networks

Mobile ad hoc networks do not rely on centralized administration, can change their network topology rapidly, may operate in stand-alone fashion or may be connected to the Internet. Nodes in MANETs are free to move randomly, can easily leave or join networks and can organize themselves arbitrarily. However, implementation of such a flexible and convenient network comes at a cost, as described below.

1.2.1 Traditional Wireless Communication Problems

The common difficulties for normal wireless networks clearly also pertain to MANETs. Additional challenges include: the wireless network medium has no absolute boundaries outside of which stations are unable to receive network signals, the wireless transmission environment is time varying and significantly less reliable than wired media, the wireless channel is exposed to many sources of interference, and wireless networks are degraded by hidden-terminal and exposed-terminal phenomena.

1.2.2 Security

One of the primary concerns is to provide secure communication between mobile hosts in a hostile environment. The unique characteristics of mobile ad hoc networks create many challenges to the security design, such as open peer-to-peer network communications, a shared wireless medium and a rapidly changing network topology. These challenges require the development of appropriate security solutions. Unlike central control in fixed networks, distributed control in mobile ad hoc networks means that they are accessible to both legitimate users and malicious attackers. So far, IEEE 802.11i is the only standard concerning security issues in wireless LANs (WLANs) and this situation needs to be improved.

1.2.3 Routing

Routing is the process of delivering a message across a network or networks via the most appropriate path, and is usually done by a device called a router. Routing is essential for a network and an effective routing protocol needs to establish smooth transmissions in the network. Due to the dynamic nature of mobile ad hoc networks, the network topology may change rapidly and unpredictably and the connectivity between mobile nodes may vary with time. The mobile nodes have to dynamically establish routing among themselves as they move about. Therefore, routing protocols for mobile ad hoc networks must adapt to

traffic conditions as well as node mobility. Current routing protocols for fixed networks are not well suited to MANETs, and thus routing poses a great challenge for ad hoc network design [12].

1.2.4 Quality of Service

Quality of Service (QoS) refers to the capability of a network to provide better service to selected network traffic. The primary goal of QoS is to provide priority including dedicated bandwidth, controlled jitter and latency and improved loss characteristics. Providing QoS in a time varying and constantly changing environment is a challenge. The inherent random nature of communication quality in wireless networks makes it difficult to assure fixed and satisfactory guarantees on QoS in ad hoc networks compared to fixed and wired networks.

1.2.5 Scalability

In general, network scalability refers to the ability to provide a satisfactory network performance with a small to large number of nodes in the network. Currently, most feasible mechanisms for mobile ad hoc networks perform acceptably on small networks but do not scale well to large networks. Common routing protocols, such as AODV, DSR and DSDV, suffer from rapid growth in routing overhead as the number of nodes in the network increases [32]. However, many applications today require large size networks with hundreds or thousands of nodes, such as the sensor networks mentioned earlier. Since addressing, routing, location management, configuration management, security and capacity issues all need to be solved, ad hoc network scalability poses a big challenge [12].

1.2.6 Energy Efficiency

Recently, more and more light-weight mobile terminals have appeared on the market and most of these operate on batteries with limited power supply. Thus, energy-efficient design has become a big issue. In mobile ad hoc networks, energy efficiency is more important

than with other wireless networks. Due to the absence of an infrastructure, mobile nodes in ad hoc network must act as routers. Since a MANET is a ‘cooperative’ network, the nodes will join in the process of forwarding packets. Therefore, traffic loads 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 is a cross-layer design issue which should consider the trade-offs between different network performance criteria. For example, routing protocols usually try to find a shortest path from sources to destinations. It is likely that some nodes which are in 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. Later in this thesis, we will give a detailed discussion of energy efficiency in mobile ad hoc networks.

1.3 Outline of The Thesis

The remainder of this thesis is organized as follows.

In Chapter 2, we first give an overview of low-energy design for wireless communication networks. Then, we introduce the energy characteristics of multi-hop mobile ad hoc networks. Related work on energy-efficient ad hoc network is also presented in this chapter.

A power management policy in mobile ad hoc networks needs to make the following decisions:

1. which set of nodes should perform power management,
2. when a power-managed node switches to a low-power state, and
3. when a node in the sleep state switches to the awake state.

In Chapter 3, we propose an energy-efficient MAC protocol to deal with these three problems. The key idea of the protocol is to elect master nodes from all nodes in the network. Master nodes stay awake all the time and act as a backbone to route packets.

Other nodes, called slave nodes, remain in low-power mode and wake up periodically to check whether they have packets to receive or need to become Master nodes. Furthermore, we discuss our simulation environment and present simulation results. We conclude the thesis and give possible future research directions in Chapter 4.

Chapter 2

Background

Energy-efficient wireless communication network design has become an important and challenging issue. It is important because mobile devices rely on batteries with limited energy supply. Moreover, progress on battery technology shows that only small improvements in battery capacity can be expected in the near future [34]. It is challenging because many issues must be considered when designing a low-energy wireless communication network, including amplifier design, coding, modulation design, routing and medium access control strategies. Under these situations, it is very important to manage power utilization effectively without impacting the applications.

Generally speaking, the energy dissipation characteristics of wireless networks can be considered from both a hardware and a system view. Sections 2.1 and 2.2 introduce hardware and system design for low-energy wireless networks, respectively. Section 2.3 presents energy efficiency in mobile ad hoc networks, and Section 2.4 concludes this chapter.

2.1 Hardware Perspective

Almost all commonly used mobile devices in ad hoc networks are typical applications of embedded systems, for examples, PDAs, cell phones and pocket PCs. Thus, in this section, we focus on energy-efficient embedded system design. When designing the architecture of embedded systems used in ad hoc networks, we have to consider more factors than those of

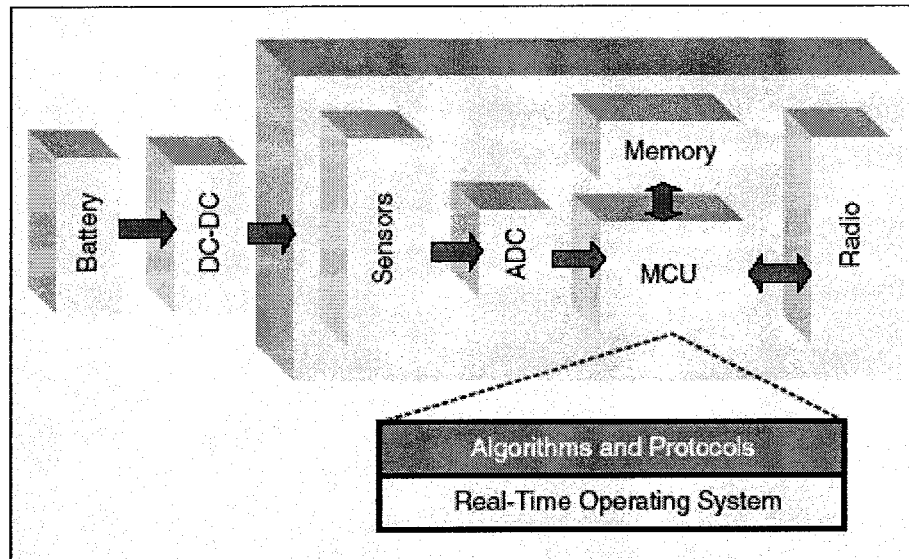


Figure 2.1. System architecture of a typical wireless sensor device [30].

general purpose systems. Consider a wireless sensor node as an example [30]. The system architecture of a canonical wireless sensor node is given in figure 2.1. The node consists of four subsystems:

1. a computing subsystem,
2. a communication subsystem,
3. a sensing subsystem, and
4. a power supply subsystem.

In the power supply subsystem, factors that affect the battery lifetime include the discharge rate from the battery, the efficiency factor of the DC-DC converter, which is responsible for providing a constant supply voltage to the rest of the components, as well as the pattern of discharge. As to the energy consumption of the sensing subsystem, depending on the type of sensing tasks, it can vary from negligible, such as sensing temperature, to significant, such as sonar for detecting targets. Typically, low-energy sensors are used to detect pending events and then trigger the operation of more power-consuming sensors so that they can be put in a low-power state when not required.

2.1.1 Low-Energy Design for Micro-Controller Units

The Micro-Controller Unit (MCU) in the computing subsystem is responsible for the control of all other components in wireless devices, acting as a CPU. For MCUs, consumed energy can be expressed as $\text{Energy} = E_1 + E_2$, in which E_1 is energy required for computation and E_2 denotes energy consumed while idling [24]. From the user's perspective, the faster the computation is done the better. Thus, in order to balance the desire to minimize energy consumption while idling and computing and to maximize throughput when computing, the energy efficiency, F , can be evaluated by the product of energy required per operation and the peak throughput, T

$$F = (E_1 + E_2) \cdot T/N, \quad (2.1)$$

where N is the total number of operations performed during the battery life.

From [41], The energy dissipated in a digital CMOS circuit is dominated by the energy required to charge and discharge circuit nodes. Given the circuit physical capacitance, C , the supply voltage, V , and the number of energy consumption transitions, α , this switching energy can be expressed as

$$\text{Energy} = C \cdot \alpha \cdot V^2 \quad (2.2)$$

Thus, combining (2.1) and (2.2), we get

$$F = (\alpha_1 + \alpha_2) \cdot C \cdot V^2 \cdot T/N \quad (2.3)$$

where α_1 and α_2 are the number of energy-dissipating transitions during computation and idling, respectively.

According to (2.3), the following techniques can be used to reduce energy consumption:

1. Scale the operating voltage, V ,
2. Decrease the physical capacitances, C , and
3. Reduce the number of energy consuming transitions, α_1 and α_2 .

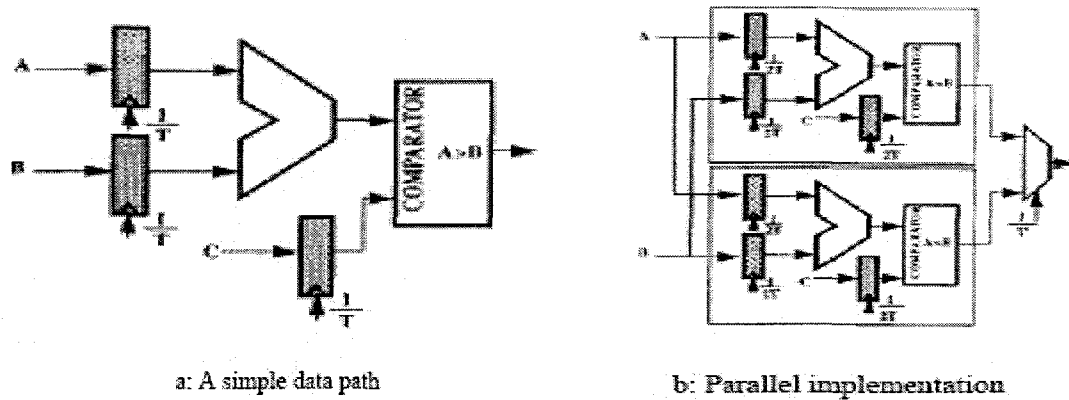


Figure 2.2. *Parallel implementation of a simple data path circuit [9].*

Scaling voltage is the easiest and most effective way to increase energy efficiency. Adjustments to the operating voltage have a quadratic effect on the energy while affecting the delay in a linear manner. According to [24], a common approach to architecture-driven voltage reduction is to couple voltage scaling with clock frequency scaling, such as using parallelism. In a parallel structure, although lowering the voltage will cause a decrease in clock frequency, throughput will remain at the same level with the original design because two or more operations can be completed per clock cycle. In Figure 2.2, we show two circuit designs to implement the same function, which is the addition of A and B and the comparison of this to C . Figure 2.2a is the original design without any power reduction and Figure 2.2b represents parallel implementation. Parallelism allows each unit to work at half the original rate while maintaining the original throughput. In [9], it is shown that power consumption can be decreased by 64%.

Note that when applying voltage scaling, we need to consider the energy overhead required for the extra control and redundant circuits.

To decrease the physical capacitances, C , we first examine the factors affecting capac-

instances: type of functional units, input data width, fabrication technology, layout, logic style and internal module structure. Clearly, reducing these parameters mainly depends on low-level optimization techniques, but there are several powerful ways to do this at the architectural level, such as hardware distribution [29], hardware localization [33] and bus load reduction [18].

Approaches to reducing energy consuming transitions can be classified into reduction of idling transitions and reduction of computing transitions. To do so, optimizing the instruction set architecture, the instruction execution architecture and the micro-architecture [24] can be used. Apart from the above methods, energy saving can be achieved by better instruction branch prediction and using a direct memory access (DMA) controller.

A recently developed MCU is Intel's PXA27x microprocessor family [1], a block diagram of which is shown in Figure 2.3.

PXA27x series supports active, idle, standby, sleep and deep sleep power modes, each of which consists of several power consumption grades according to different working frequencies. This so-called Wireless Intel SpeedStep technology provides the ability to dynamically adjust the power and performance of the processor based on CPU demand. This results in a significant decrease in power consumption for wireless hand-held devices to increase standby and talk-time. In active mode, PXA27x has a peak power consumption of 925mW at 624MHz CPU frequency and can scale to a low power mode of 44.2mW at 13MHz CPU frequency. In deep sleep mode, the processor only consumes 0.1014mW. The core of speedstep technology is dynamic power management (DPM) and dynamic voltage scaling (DVS). The former technique is able to put devices into one of several sleep or deep sleep modes in the absence of events while the latter is responsible for dynamically adapting the processor supply voltage and operating frequency to meet instantaneous processing requirements in active mode. Furthermore, Intel XScale core, on which the PXA27x series is based, with an experience based instruction branch target buffer and a mini D-cache can provide additional energy savings. Finally, using a DMA controller offers additional help to control energy consumption.

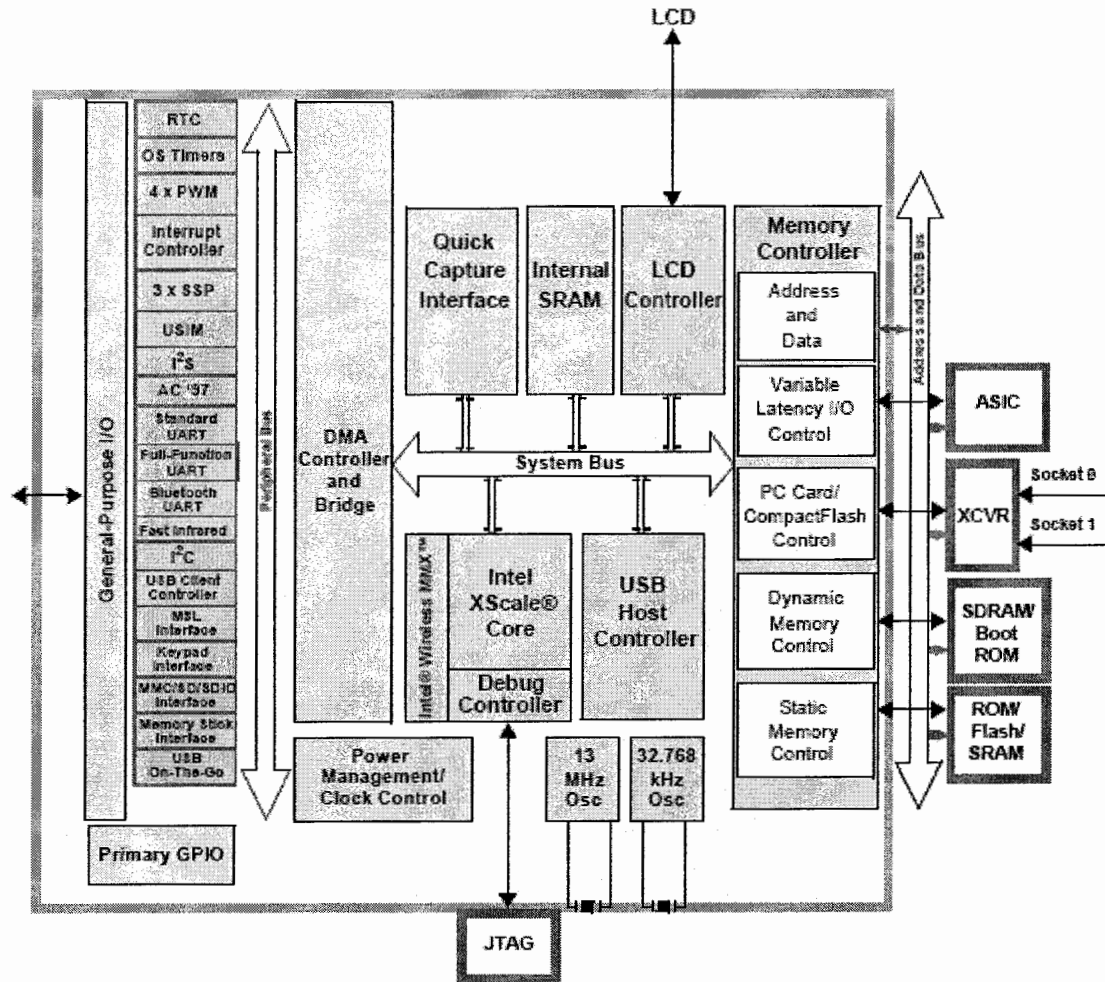


Figure 2.3. Intel PXA27x processor block diagram [1].

2.1.2 Energy Consumption of the Communication Subsystem

The major concern of this thesis is the energy consumption of the communication subsystem. It can be classified into two parts, the radio electronics and the RF output. The overall power consumption of the communication subsystem is determined by the modulation scheme, the data transmission rate, the transmission power and the operating mode, typically one of transmit, receive, idle and sleep. According to [35], for short range transmission in the GHz carrier frequency range, the energy consumption of the communication subsystem is dominated by the radio electronics, which is on the order of 10-100mW. On

the other hand, the output transmit power is only about 1mW for a typical bit error rate (BER) of 10^{-5} at 1Mbps. In [35], the average power consumption of the radio in active mode is characterized as

$$P_{active} = N_{tx}[P_{tx}(T_{on-tx} + T_{st}) + P_{out}T_{on-tx}] + N_{rx}[P_{rx}(T_{on-rx} + T_{st})], \quad (2.4)$$

where $N_{tx/rx}$ is the average number of times per second that the transmitter/receiver is used, $P_{tx/rx}$ is the power consumed by the transmitter/receiver, P_{out} is the output transmit power, $T_{on-tx/rx}$ is the actual data transmission/reception time, and T_{st} is the start-up time of the transceiver. Using the free-space propagation model, which is appropriate for short-range communication, P_{out} can be approximated by $\epsilon_{amp} \cdot r \cdot d^2$, where $\epsilon_{amp} \propto (2^b - 1)J/bit/m^2$ is the energy consumed to deliver one symbol, which contains b bits, over one unit distance with an acceptable SNR, r is the data rate and d is the distance of the transmission. $P_{tx/rx}$ is affected by the modulation scheme. The start-up overhead associated with switching from sleep mode to active mode is not negligible in terms of time and energy dissipation. A typical start-up time is on the order of $100 \mu s$. This implies that the control interval of switching between modes should not be too small.

When energy consumption in the idling mode and sleep mode are included, the average power consumption becomes

$$P_{radio} = P_{active} + D_{idle}P_{rx} + D_{sleep}P_{sleep}, \quad (2.5)$$

where D_{idle} and D_{sleep} are the percentage of time in the idle and sleep modes, respectively. P_{rx} approximates the power consumption in idle periods. P_{sleep} is the power consumed in sleep mode and typically $P_{sleep} \ll P_{rx}$. From (2.5), to reduce the power consumption of the communication subsystems, one can reduce the communication-time power consumption P_{active} and/or reduce the idling-time power consumption.

In summary, the hardware characteristics of wireless devices have a great impact on the design of communication protocols for wireless networks. Due to the fundamental limits of communication and computation laws for circuit design and channel capacity, energy saving design for hardware is a big challenge.

2.2 System Perspective

We can easily draw two conclusions from the discussion in Section 2.1. First, it is always desirable to put components in a wireless device into low-power mode to save energy. Second, reducing the transmission range by adjusting the transmission power can only affect the power consumption of the RF output, which may not result in significant power savings in the communication subsystem because the radio electronics dominates power consumption. Furthermore, in current hand-held wireless devices, the power consumption due to network activities is approximately 50% of the overall power consumption [23]. Therefore, system optimization is a key factor in the energy-saving design of wireless networks.

From the system perspective, it is desirable to build a network protocol that maximizes the time the wireless interface works in power-saving mode and maximizes the number of wireless devices which work in power-saving mode. In infrastructure-based networks, such as a radio paging network, this approach is extensively used because much of the complicated communication, computation and synchronization is moved to fixed infrastructures, such as base stations, which allows the wireless devices to be in sleep or low-power mode most of the time. However, in mobile ad hoc networks, this may not be a viable approach. Moreover, in an infrastructure-based wireless network, energy management strategies are local to mobile devices, which means that every node only needs to care about its own energy saving approaches. Similarly, only local consideration is not feasible in mobile ad hoc networks, as nodes must cooperate to guarantee network connectivity and network performance. A simple example is if a node remains most of the time in sleep state without contributing to routing and forwarding, this will maximize its battery lifetime, but may compromise the network lifetime.

There exist several fundamental trade-offs among fidelity, latency and energy consumption in mobile ad hoc networks. By fidelity, we mean the objective quality of the application-layer data. For example, in sound wave tracking applications, fidelity can be defined as the frequency that targets are successfully located to within the required resolu-

tion. In environment monitoring, fidelity is determined by the number of monitored events over a certain time interval. In most cases, packet delivery ratio reflects the level of fidelity in an ad hoc network. Latency is the delay a packet incurs in traveling from source to destination and is associated with the quality of the data. For example, in alerting services, if an alarm arrives too late for the guard to take any action, the information is of little use. In general, the user satisfaction level is a function of both fidelity and latency.

Given the energy, bandwidth and computation constraints, it is very challenging to balance the trade-offs between fidelity, latency and energy consumption. These are illustrated below,

1. Fidelity-latency trade-off

Increasing the fidelity of data in general implies more sophisticated processing. In mobile ad hoc networks, computations can be carried out at the destination nodes or intermediate nodes. For example, to improve the packet delivery ratio in the network, data can be processed at intermediate nodes by some extra processing of the data packets. However, this may require data packets to be buffered at these nodes which incurs longer delays.

2. Fidelity-energy consumption trade-off

As mentioned previously, the power consumed in the communication subsystem is determined by the modulation scheme, the transmission rate and the transmission power level. All these factors affect the quality of the received signal. More sophisticated signal processing techniques for signal detection and error correction bring more computational overhead and thus consumes more energy. Moreover, the longer a node is in sleep state, which can save more energy, the shorter time it will be in active mode to forward data packets, which will definitely affect the fidelity.

3. Latency-energy consumption trade-off

The trade-off between latency and energy consumption spans multiple layers of the system. In the physical layer, the power management modes of the MCUs and radio components affect the per-hop latency of communication. In the medium access control layer (MAC), which is a sublayer of the data link layer right above the physical layer and mainly

responsible for access scheduling of a shared medium, scheduling policies and collision avoidance techniques affect both the latency and the overall energy consumed in delivering packets. In the network layer, power-aware routing determines the route and per-hop transmission power. If more transmission power is used, a shorter route may be found thus incurring less delays.

In this thesis, we explore energy-performance trade-offs in the design and analysis of power management protocols.

2.3 Energy Efficiency in Mobile Ad hoc Networks

In general, 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 will use different mechanisms for energy conservation. According to the power saving approaches, we classify existing energy conservation solutions into three categories:

1. power control,
2. power-aware routing, and
3. power management.

In what follows, we give a brief overview and related work in these categories.

2.3.1 Power Control

1. Transmitter Power Control

In wired networks, the network topologies are fixed and can be easily determined. Conversely, the topology of an ad hoc network is usually changeable, even if no host mobility is present. Adjusting antenna directions and tuning transmission power can change the network topology. Controlling the power of a transmitting node provides two advantages:

1. it can conserve battery energy of the wireless nodes and
2. it can increase spatial reuse of wireless bandwidth and reduce radio interference.

On the other hand, the drawbacks of transmitter power control include lower reliability, higher error bit rate and weaker network connectivity. Thus, balancing these factors is an important issue.

In adaptive power control [6], each node maintains for each destination a weighted history of the received signal strength for successful transmissions and the threshold at which packet loss occurs. If the received signal strength indication is stronger than this threshold, the transmission power will be reduced. If the MAC layer does not receive a response in a certain period of time, the node records this threshold signal strength and retransmits the packet using a higher transmission power until the control traffic is properly exchanged. Simulation results show that in a group mobility environment, energy consumed in transmitting and receiving data traffic is reduced by 10 – 20% and throughput is increased by about 15%, compared to using an unmodified protocol. However, adaptive power control is not as effective in a randomized environment. This is not surprising since power control techniques can take advantage of the fact that most traffic is exchanged locally. Note that this technique cannot be used for broadcast transmissions, as broadcast packets must be transmitted at full power to reach the largest number of users. This means that the route discovery process continues to find routes with the smallest number of hops, rather than minimum energy routes.

Different from the above pure power controls, another technique which incorporates power control into MAC layer protocols is introduced in [6]. It modifies the header formats of the clear-to-send (CTS) and DATA packets to support power control and one of ten transmission power levels can be selected. The receiver informs the sender of the appropriate power level through a modified CTS packet, while the sender informs the receiver using a DATA packet. Hence, during one RTS-CTS-DATA-ACK handshaking period, both sender and receiver can determine the proper transmission power to use, where RTS and ACK refer to ready-to send and acknowledgement packets, respectively.

2. Topology Management

Topology management (also called topology control), means adjusting the transmission power of wireless nodes to minimize the maximum transmission power used in the network while at the same time maintaining network connectivity. It also can provide the benefit of reducing MAC-level interference and increasing traffic carrying capacity [19][20]. Several topology management algorithms have been developed. We describe two representative approaches below.

COMPOW [25] is based on the need to find the minimum common power for topology management. In COMPOW, each node runs multiple instances of a proactive ad hoc routing protocol in parallel, each at a specific power level. Each routing daemon maintains its own routing table by exchanging control messages at the corresponding power level. When a node needs to forward data packets, by comparing the entries in different routing tables, it can determine the smallest power level that ensures maximum connectivity as well as minimum power consumption. The major drawback of COMPOW is the significant routing message overhead incurred since each node has to run multiple daemons, each of which exchanges link state information with its counterparts at other nodes.

In [31], link state topology information is used to maintain a connected topology. If a routing information update indicates that a link failure has happened, which means the network might no longer be connected, the nodes involved will increase their transmission power until the network is reconnected. However, this technique will result in significant overhead because changes in network connectivity can trigger further routing updates.

2.3.2 Power-Aware Routing

Power-aware routing has been a very hot research topic over the last several years. It aims to intelligently choose routes for unicast sessions so as 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-

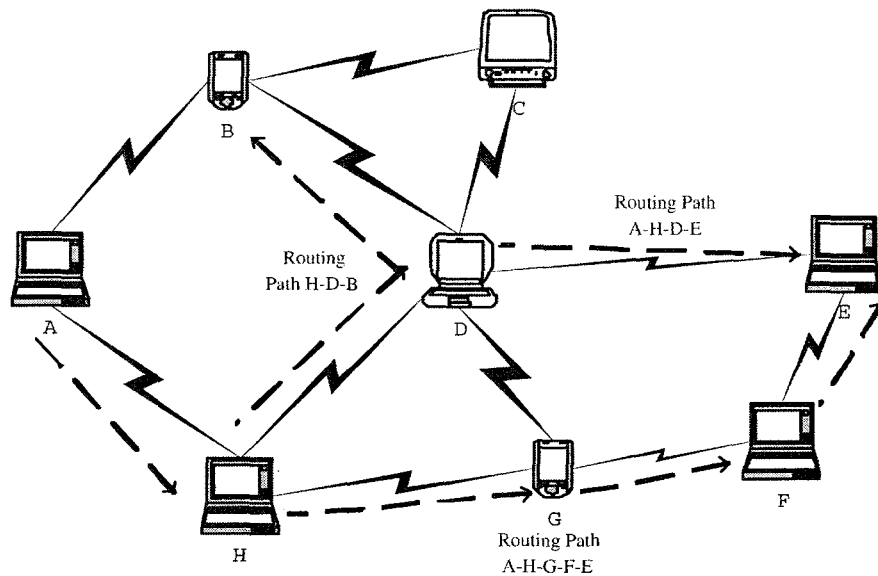


Figure 2.4. *The effect of a power-aware routing protocol.*

aware routing protocols try to balance rather than save energy consumption.

As shown in Figure 2.4, based on the hop-account metric, host A selects the shortest route *A-H-D-E* to reach *E*. Similarly, host *H* chooses *H-D-B* to reach *B*. Both routes go through *D* and thus make *D* drain its energy off quickly. In this case, a power-aware routing protocol may pick *A-H-G-F-E* as the route from *A* to *E*, even though it is not the shortest one.

Before giving some power-aware routing protocols, we state some issues related to these 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, energy awareness can be either implemented at only the routing layer or the routing layer with help from other layers such as the MAC layer. Third, some routing protocols assume node position information is available and under this assumption, finding a low power path becomes a conventional optimization problem.

The local energy-aware routing (LEAR) protocol [42] is based on the DSR routing protocol, where the route discovery requires flooding of route-request messages. The basic

idea of the LEAR protocol is to consider each mobile node's willingness to participate in the routing and the forwarding of data packets on behalf of others. This determination is based on the local information of a mobile node. When a routing path is searched, each mobile node relies on information on remaining battery power to decide whether or not to participate in the selection process of a route path. When a node's remaining battery power is higher than a certain threshold, the route-request message will be forwarded and the node will join the route path selection process; otherwise, the message is discarded. Thus, all intermediate nodes along the route path have good battery levels and the first arriving route message is considered to have followed an energy-efficient as well as a reasonably short path. If any of the intermediate nodes drop the route-request message, which means no nodes are willing to join the route path, the source will not receive a single reply even though a route may exist. To prevent this, the source node will resend the same route request message with a lower threshold.

The power-aware routing optimization (PARO) protocol [17] represents another approach to minimum energy routing. Rather than exchanging connectivity information to determine a minimum energy route path, nodes observe ongoing transmissions and nominate themselves as intermediate nodes for packet forwarding. This means that PARO uses observed information rather than position information to evaluate routes. Simulation results with PARO show that it reduces per-packet energy consumption by between one- and two-thirds compared to fixed power transmissions. The delivery ratio also remains good, except in the case where high mobility is combined with low data rates.

2.3.3 Power Management

All the above approaches only consider reducing the cost of communication and operate in active periods. Meanwhile, power management aims to intelligently put a device's wireless interface into an idle or sleep state. In what follows, we only focus on MAC layer design.

MAC Layer Power Management

The IEEE 802.11 MAC specification describes functions and services for wireless de-

vices to operate in ad hoc and infrastructure networks. It defines low-level support for power management such as buffering data for sleeping nodes and synchronizing nodes to wake up for data delivery. The network interface has five physical states: transmit, receive, idle, sleep and power-off. In the IEEE 802.11 specification, a node can be in one of two power management modes, active mode (AM) or power saving mode (PSM). We will give full details of IEEE 802.11 power-saving mode in the next chapter. Several modified IEEE 802.11 MAC protocols are described below.

The power-saving medium access (PAMAS) protocol [36], which is an RTS/CTS-based MAC layer protocol with separate data and signalling channels for data and control packets, turns off a node's radio when it receives a packet that is not addressed to it. This approach is suitable for radios in which processing a received packet is expensive as compared to listening to an idle medium. In the case of an idle medium, the node must remain on all the time for incoming transmissions. Therefore, the effectiveness of PAMAS is limited to reducing the power consumed in processing unnecessary packets.

By observing that the fixed beacon interval in the IEEE 802.11 PSM leads to energy waste, the dynamic power saving mechanism (DPSM) proposed in [21] uses adaptively changed ad hoc traffic indication messages (ATIMs). Coupled with a separate DATA window, DPSM can control the transition to the low-power state in the middle of a beacon interval. Simulation results show that the proposed approach outperforms IEEE 802.11 PSM in both throughput and the amount of energy consumed.

The on-demand power management for ad hoc networks introduced in [46] bases power management decisions on traffic in the network. The key idea is that transitions from power-saving mode to active mode are triggered by communication events instead of the established beacon interval used in IEEE 802.11 PSM. On the other hand, 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. A node uses HELLO messages to track its neighbor's power management state to decide whether or not send packets.

The geographic adaptive fidelity (GAF) [45] protocol identifies many redundant nodes with respect to routing and turns them off without sacrificing routing fidelity. Each node uses location information based on GPS to associate itself with a virtual grid, where all nodes in a particular grid square are redundant with respect to forwarding packets. One master node in each grid stays awake to route packets. In GAF, nodes could be in three states, sleep, discover 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.

2.4 Summary

In this chapter, we gave a full review of low-energy wireless design from hardware and system perspectives, respectively. Then issues on energy-efficient mobile ad hoc networks, including power control, power-aware routing and power management, were presented. Related work on energy-efficient ad hoc networks was briefly introduced.

Chapter 3

The Proposed Protocol

In this chapter, we propose an energy-efficient MAC (EE-MAC) protocol for mobile ad hoc networks. Our design is based on the observation that most applications of ad hoc networks are data-driven, which means that the sole purpose of forming an ad hoc network is to collect and disperse data. Hence keeping all network nodes awake is costly and unnecessary when some nodes do not have traffic to carry. We thus propose a protocol to conserve energy by turning on and off the radios of specific nodes in the network. It attempts to reduce energy consumption without significantly diminishing network capacity and connectivity.

Our protocol is based on IEEE 802.11 and its mode. Simulation results show that EE-MAC can achieve up to 70% savings in energy as well as much better performance in terms of latency and packet delivery ratio compared to IEEE 802.11 PSM mode.

The rest of the chapter is organized as follows. We present an overview of the IEEE 802.11 protocol and its PSM mode in Section 3.1. Then we describe in Section 3.2 the EE-MAC protocol. The simulation environment and performance evaluations are given in Section 3.3 and 3.4, respectively. Finally, a brief summary is presented in Section 3.5.

3.1 IEEE 802.11 MAC Protocol and its Power Saving Mode

3.1.1 An Overview of IEEE 802.11 MAC Protocol

The IEEE 802.11 protocol covers the MAC and physical layers. The MAC layer is a set of rules that determine how to access the medium and send data, but the details of the transmission and reception are left to the physical layer. In this thesis, we only focus on the MAC layer.

The IEEE 802.11 MAC protocol employs carrier sense multiple access with collision avoidance (CSMA/CA), based on an exponentially increasing random back-off strategy. Access to the wireless medium is controlled by coordination functions. The MAC layer defines two different access methods, the distributed coordination function (DCF) and the point coordination function (PCF). PCF provides contention-free service but can only be used in infrastructure networks. Thus, we only describe DCF in detail.

The DCF is the basis of the standard CSMA/CA access mechanism [15]. Like Ethernet, it first checks to see that the radio link is clear before transmitting. To avoid collisions, network hosts use a random back-off after each frame, with the first transmitter seizing the channel. In the IEEE 802.11 MAC protocol, DCF uses the RTS/CTS handshake to further reduce the possibility of collisions, where RTS stands for request to send and CTS means clear to send.

Before giving more details about IEEE 802.11 MAC protocols, we first present some definitions [15].

Network allocation vector (NAV)

The NAV is a timer that indicates the amount of time the medium will be reserved. Hosts set the NAV to the time for which they expect to use the medium and other hosts count down from the NAV to 0. A nonzero NAV value indicates that the medium is busy and a NAV value of 0 indicates that the medium is idle.

Short inter-frame space (SIFS)

The SIFS occurs before the highest-priority transmissions, such as RTS/CTS frames

and positive acknowledgments. High-priority transmissions can begin once the SIFS has elapsed. Once these high-priority transmissions begin, the medium becomes busy, so frames transmitted after the SIFS has elapsed have priority over frames that can be transmitted only after longer intervals.

DCF inter-frame space (DIFS)

The DIFS is the minimum medium idle time for connection-based services. Stations may have immediate access to the medium if it has been free for a period longer than the DIFS.

Contention window or Back-off window

The contention window or back-off window is a period of time following the DIFS. This window is divided into slots and slot length is medium-dependent. The slot time is defined in such a way that a station will always be capable of determining if another station has accessed the medium at the beginning of the previous slot.

3.1.2 Operation of CSMA/CA

In wireless networks, including ad hoc networks, there is a well-known problem, called the hidden node problem. A neighbor of the destination that is out of the wireless range of the source may interfere with the transmission of the source. As shown in Figure 3.1, node *B* can communicate with both nodes *A* and *C*, but *A* is out of range of *C*. From the perspective of node *A*, node *C* is a hidden node. If a simple transmit-and-pray protocol is used, it would be easy for node *A* and node *C* to transmit simultaneously, resulting in node *B* being unable to communicate. Furthermore, neither node *A* nor node *C* realizes that interference has occurred.

To prevent collisions from occurring, every data communication is preceded by an exchange of control packets, RTS/CTS/ACK, but only when the data packet size exceeds a particular threshold. When a source *S* wants to transmit to a destination *D*, it first senses the local channel (physical carrier sensing). If the channel is busy, it backs-off using an exponentially increasing back-off window algorithm. Otherwise, if the channel is idle for more

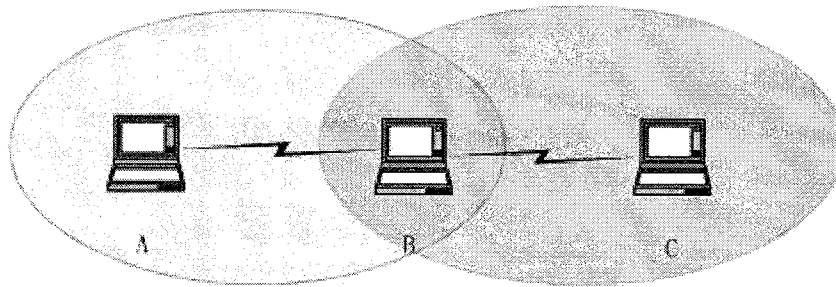


Figure 3.1. *The hidden node problem in a wireless network.*

than DIFS, the source transmits an RTS control message to the destination. If the local channel around D is free, D replies with a CTS message. After this exchange, data packets can be transmitted from S to D , and an acknowledgment (ACK) packet transmission from D to S follows the data packets. If the channel around D is busy, S times out waiting for the CTS message and retransmits the RTS packet.

Both RTS and CTS packets contain the proposed duration of upcoming transmissions. Nodes located in the vicinity of communicating pairs will overhear one or both of these control messages and must defer transmission for this proposed duration. This is called virtual carrier sensing which is performed in addition to the physical carrier sensing mentioned earlier. It is implemented by means of the NAV. A node updates the value of its NAV with the duration field specified in the RTS and CTS. Thus the nodes lying within the transmission range of the transmitter or the receiver do not initiate any transmission while the communication is in progress. The RTS and CTS packets thereby reserve the local channel for the upcoming data transmission by silencing all nodes in the vicinity of the transmitter and the receiver. This in turn solves the hidden node problem.

It should be noted that the RTS/CTS procedure can be controlled by setting the RTS threshold. The RTS/CTS exchange is performed for frames larger than the threshold. Frames shorter than the threshold are simply sent. Figure 3.2 shows how the CSMA/CA protocol works.

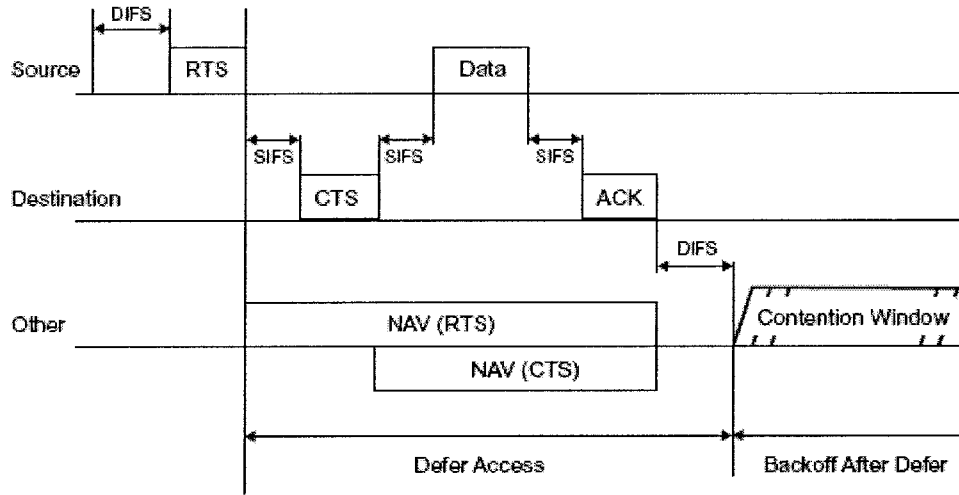


Figure 3.2. Operation of the CSMA/CA protocol.

3.1.3 Random Back-off Time

The CSMA/CA MAC protocol uses a back-off interval to resolve channel contention. When a node needs to transmit data or control frames, it senses the local medium. If the medium is busy, the node will defer transmission until the medium is free for DIFS. After DIFS, if the node's current back-off value is zero, the node will choose a random back-off time and then transmit packets. This process reduces the possibility of collisions when many nodes try to access the medium simultaneously. In mathematical terms:

$$\text{Back-off time} = \text{Random}() \times \text{slot time}, \quad (3.1)$$

where $\text{Random}()$ is a random integer in the range $[0, cw]$ and cw represents the contention window which varies between cw_{min} and cw_{max} .

After the sender S chooses a back-off time, it will decrement its back-off counter by one after every idle slot time. When the back-off counter reaches 0, S transmits its packet. If the transmission from S collides with other transmissions, S increases its cw exponentially, and chooses a new random number from the new window range and then attempts retransmission. Note that collision of an RTS packet can be detected by the absence of a

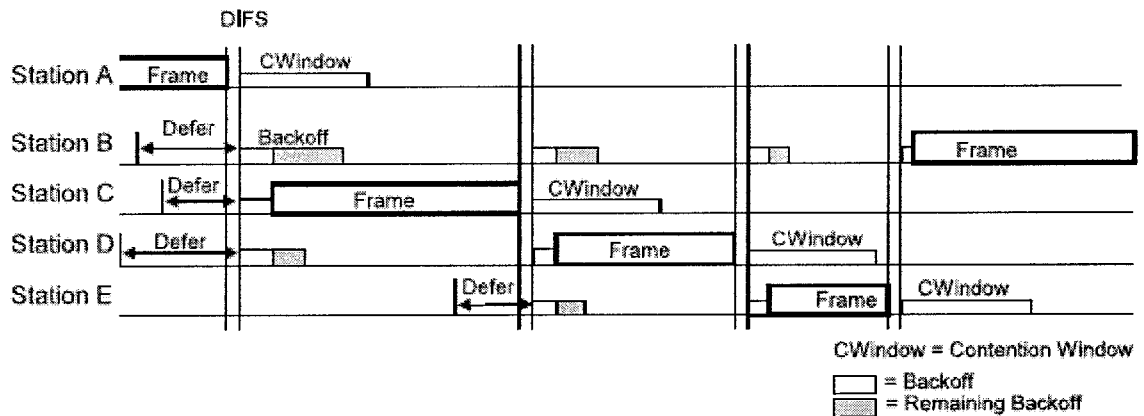


Figure 3.3. *The back-off procedure [2].*

CTS within a timeout value. The contention window size doubles after every collision until it reaches a maximum threshold, cw_{max} , and cw will remain at this value until it is reset. In the back-off stage, if a node senses the channel is busy it freezes its back-off counter. When the channel becomes idle once again for DIFS, the back-off counter resumes counting down from its frozen value. Thus the back-off procedure is invoked only when the channel has been sensed to be idle for DIFS duration. Resuming the back-off counter from its frozen value ensures that nodes that have deferred access to the channel for a longer time have a higher probability to access the channel. Note that the contention window size is always 1 less than a power of 2. Figure 3.3 illustrates the back-off procedure.

3.1.4 IEEE 802.11 Power Saving Mode

Power management can achieve great savings in infrastructure networks. All traffic for mobile stations must go through access points, so they are ideal locations to buffer traffic. However, in ad hoc networks, far more of the burden is placed on the sender to ensure that the receiver is active or awake. Receivers must also be more available and cannot sleep for the same length of time as in infrastructure networks.

Power management in IEEE 802.11 power saving mode (hereafter referred to as PSM),

is based on traffic indication messages. Nodes use ATIMs to notify other nodes to prepare to receive data. All nodes have to wake up periodically to listen for ATIMs and check whether they have packets to receive.

In PSM, time is divided into beacon intervals and each beacon interval starts with an ATIM window. This window is the period during which nodes must remain active and no stations are permitted to power down their wireless interface. The ATIM window is a parameter that can be set. Setting it to 0 means no power management is used. There are four possibilities for a node in terms of ATIMs: the node has transmitted an ATIM, received an ATIM, neither transmitted nor received, or both transmitted and received. Nodes that transmit ATIM frames must not sleep because transmitting an ATIM indicates an intent to transmit buffered traffic. Nodes to which an ATIM is addressed must also keep awake so they can receive data packets from the ATIM sender. A node that both transmits and receives of course needs to be active. Thus, only those nodes that neither transmit nor receive an ATIM can go to sleep after the ATIM window. Figure 3.4 illustrates the basic PSM operations. Nodes *A* and *B* have packets advertised in the ATIM window by sending ATIMs and receiving ATIM-ACKs, both of which are subject to the DCF rules described earlier. Therefore nodes *A* and *B* remain awake for the rest of the beacon interval. The transmission of data packets from nodes *A* and *B* take place during the beacon interval. The node that has no packets to transmit can go into the sleep state at the end of the ATIM window if it does not receive an ATIM during the window. In the example in Figure 3.4, node *C* enters sleep mode after the ATIM window, thus saving energy. All sleeping nodes wake up again at the start of the next beacon interval.

The beacon and ATIM window size can affect the performance of PSM. Since no data packets are transmitted in the ATIM window, overhead in terms of energy consumption and bandwidth is incurred. If we use a small ATIM window to improve energy savings, there may not be enough time to advertise all buffered data packets. On the contrary, using a big ATIM window may unnecessarily waste bandwidth and not leave enough time to transmit buffered data. Moreover, PSM also suffers from long packet delivery latency: for each hop

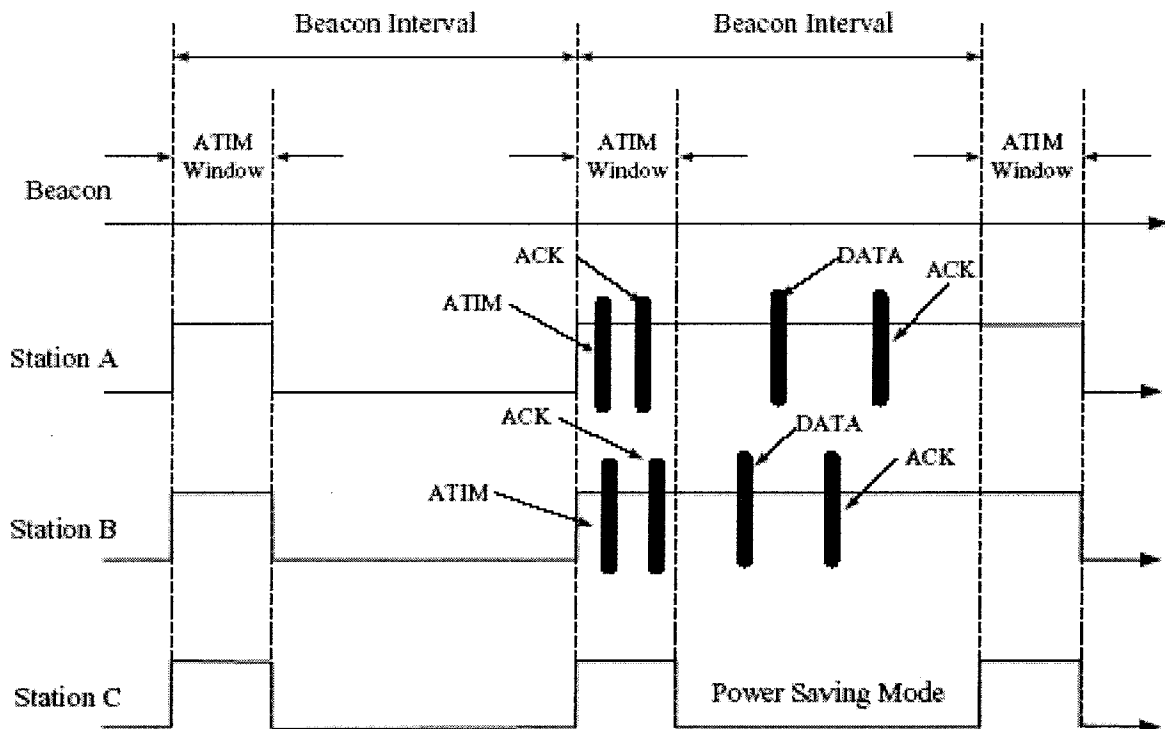


Figure 3.4. Basic IEEE 802.11 PSM operation.

that a packet traverses, the packet is expected to be delayed for at least a beacon period.

3.2 The Proposed Energy-Efficient MAC Protocol

The goal of an energy-efficient MAC protocol is to reduce energy consumption without significantly sacrificing network capacity and connectivity. By using EE-MAC, nodes that do not carry any traffic can enter a sleep state and conserve energy.

The key idea of EE-MAC is to elect master nodes from all nodes in the network. Master nodes stay awake all the time and act as a virtual backbone to route packets in the ad hoc network. Other nodes, called slave nodes, remain in an energy-efficient mode and wake up periodically to check whether they have packets to receive. To be fair, a rotation mechanism between masters and slaves is used. EE-MAC uses some features of PSM, such

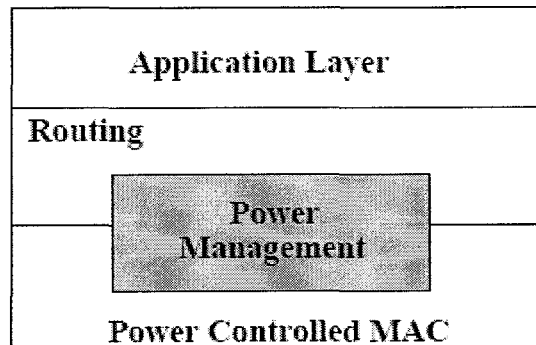


Figure 3.5. *EE-MAC power management location in the protocol stack.*

as periodically waking up at the beginning of the beacon interval.

3.2.1 A Cross-layer Design for Power Management

Power management in ad hoc wireless networks can benefit from a cross-layer design that leverages network layer and MAC layer information. EE-MAC can provide knowledge and guidance to the route lookup process, because only master nodes can be selected along a routing path. On the other hand, EE-MAC requires a mechanism to awaken a sleeping receiver when packet delivery is imminent. This is usually handled by low-level mechanisms at the MAC or physical layers. In EE-MAC, if a node has been asleep for a while, packets addressed to it are not lost but stored at one of its upstream nodes, usually a master. When the node awakens, its master can send buffered data to it, and this is a typical PSM feature which is used in our protocol. Figure 3.5 shows EE-MAC's location in the protocol stack.

3.2.2 Design Criteria

We first give some basic but important design criteria.

- The algorithm must ensure enough master nodes are elected to build the backbone of the network so that every node has at least one master in its vicinity. A collection

of masters can be described as a connected dominating set (CDS). All nodes are either a member of the CDS or a direct neighbor of at least one of the members of the CDS. Nodes in the CDS serve as the routing backbone and remain active all the time. All other nodes are slave nodes and can choose to sleep. Since slave nodes do not join in the process of route discovery or packet forwarding, the network's level of connectivity is decreased. To prevent a dramatic decrease in throughput, we do need an acceptable set of masters that can maintain global connectivity with some redundancies.

- The master nodes election algorithm is based on local information, which is a decentralized approach. Each node only consults its local table to determine whether it will become a master. Due to the characteristics of distributed management in ad hoc networks and the two essential requirements, low overhead and fast convergence, the algorithm for finding a CDS should be localized.
- The algorithm must have a fair way to rotate masters and slaves in order to ensure that all nodes share the job of providing global connectivity roughly equally. Overusing some critical nodes will severely decrease the network lifetime of an ad hoc network. Thus, if some alternative nodes appear, masters can step down and give the new nodes a chance to serve as masters to balance node energy consumption.

3.2.3 Master Announcement

To form a CDS, many researchers have proposed different approaches [39][11][43]. In this thesis, we use the algorithm in [44] as the prototype and modify it based on the energy saving condition.

Given a simple graph $G = (V, E)$, where V is a set of nodes and E is a set of links, a link from u to v is denoted by a pair (u, v) . According to [44], a set $V' \subset V$ is a dominating set of G if every node $v \in V - V'$ is connected by at least one node $u \in V'$. For example, in Figure 3.6, the node sets u, v in a and u, v in b are dominating sets of the corresponding

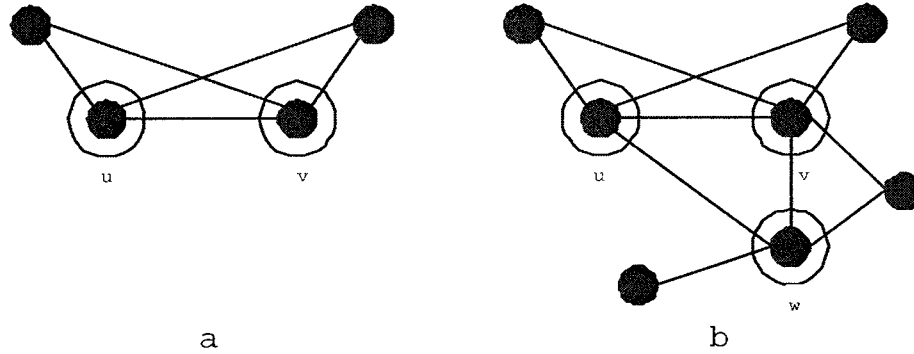


Figure 3.6. Examples of connected dominating sets.

graphs. If all nodes in a dominating set are connected together, it forms a CDS.

To quickly elect masters in an ad hoc network, we use the following steps:

1. Initially assign the marker F to each node u in V .
2. Each node u exchanges its neighbor set $N(u)$ with all its neighbors.
3. u changes its marker to T if there exist nodes v and w such that $(w, u) \in E$ and $(u, v) \in E$, but $(w, v) \notin E$.

Basically, all T -marked nodes can form a connected dominating set and become masters and F -marked nodes become slaves. However, we may not need all T -marked nodes elected to act as the backbone of the network because there are many redundancies in this set. We say a node is covered if its neighbors can reach each other directly or via other connected T -marked nodes. We give a rule to reduce the number of masters based on the idea that if a node is covered by no more than k connected T -marked nodes, we can change the marker of this node to F . Generally speaking, assuming that $V'_k = \{v_1, v_2, \dots, v_k\}$ is the nodes set of a connected subgraph in G' and if $N(u) \subseteq N(V'_k)$ in G , then u can change its marker from T to F . This rule can be simply described as: if every pair of a T -marked node's neighbors can be connected directly or via no more than k other connected T -marked nodes, this node is marked as F .

To avoid simultaneous removal of two T -marked nodes covering each other. Two more issues need to be considered, node connectivity and node energy. We denote the connec-

tivity level of a node i as CL_i . Let N_i be the number of neighbors of node i and C_i be the number of pairs of nodes among these neighbors that can be connected via i if i becomes a T -marked node. Clearly, $0 \leq C_i \leq \binom{N_i}{2}$, and define the maximum as $CL_i = \frac{C_i}{\binom{N_i}{2}}$. The energy level of a node i can be expressed as $EL_i = \frac{E_{ri}}{E_i}$, where E_{ri} is the remaining energy at the node and E_i is the initial energy at the node. Finally, the node id, id_i , will be considered if the two factors given above are identical.

Overall, the rule to reduce redundant T -marked nodes is as follows: assuming $V'_k = \{v_1, v_2, \dots, v_i, \dots, v_k\}$ is the node set of a connected subgraph in G' , the marker of u is changed to F if one of the following condition holds:

1. $N(u) \subseteq N(V'_k)$ in G , and for any node $v_i \in V'_k$, $N(v_i) \not\subseteq N(V'_k - v_i) \cup N(u)$.
2. $N(u) \subseteq N(V'_k)$ in G , and for some nodes $v_1, \dots, v_i \in V'_k$, $N(v_1, \dots, v_i) \subseteq N(V'_k - v_1, \dots, v_i) \cup N(u)$,

- $EL_u < \min\{EL_1, EL_2, \dots, EL_i\}$ or
- $CL_u < \min\{CL_1, CL_2, \dots, CL_i\}$ if $EL_u = \min\{EL_1, EL_2, \dots, EL_i\}$ or
- $id_u < \min\{id_1, id_2, \dots, id_i\}$ if $EL_u = \min\{EL_1, EL_2, \dots, EL_i\}$ and $CL_u = \min\{CL_1, CL_2, \dots, CL_i\}$

After connected dominating set selection and reduction, all T -marked nodes will become masters and the other nodes will become slaves. We use periodically broadcasted HELLO messages to make each node in the network aware of its neighbors' status, including whether or not they are masters, their current masters and their current neighbors. Using a small value for k will increase the network's connectivity but there will be many redundant masters which will consume more energy. Conversely, a large value for k can save significant energy but decrease the robustness of the network. In addition, a large k will usually require more frequent HELLO messages to collect information. To balance the energy saving and network throughput, we use $k = 3$.

3.2.4 Rotation of Masters and Slaves

The rotation of masters and slaves is done to allow every possible node to have a chance to become a master, and let current masters quit their positions to save energy. Each master periodically checks if it should withdraw as a master. Basically, the conditions to trigger a withdrawal are the same as for CDS reduction given above. However, in order to balance the network load evenly, we force some masters to quit even if the conditions to withdraw are not met. After a node has served as a master for some period of time or if its energy level is below the average of its neighbors, it will withdraw even if there are no masters nearby. The only exception is if some neighbors can only be connected to the network via that node.

3.2.5 Features of EE-MAC

In EE-MAC, since masters do not operate in power saving mode and can forward packets all the time, the packet delivery ratio and packet delay can be improved greatly compared to PSM. In this section, we present some features of EE-MAC.

1. Entering sleep mode earlier.

In the original PSM, a node with packets to send will send an ATIM frame to the destination, and both source and destination will keep awake in that beacon interval, no matter how many packets need to be transmitted. While this approach has its advantages, it may result in a much higher energy consumption than necessary. For example, if a source only has one packet pending, they have to waste the whole beacon period to deal with this packet. To avoid this, we add the number of remaining data packets at the sender into every data packet sent to the destination. This information allows the destination to know when it has received all pending packets for it. When the source or destination have sent or received all their packets, they can enter sleep mode until the beginning of the next beacon interval.

2. Priority processing of packets to slaves.

When nodes are trying to send packets, they first deal with those to be sent to slave

nodes. After transmitting all packets to slave nodes, packets between masters can be sent. By using this method, slaves can stay as long as possible in sleep mode.

3. Prolonging sleeping period for slaves.

In EE-MAC, most packets are forwarded by masters and packet routing via slaves is kept to a minimum. To take advantage of this, each slave uses history information to decide their sleep time. When a node observes two consecutive beacon intervals without any packets addressed to it, it will decide to sleep through the next beacon interval. At the same time, this slave's master must store this information since failure to get an ACK does not guarantee a broken link. If the master does not know a slave's situation, it just buffers the packets to that slave. Only when the master does not hear from a neighboring slave for two consecutive beacon intervals does it discard these packets.

4. Additional MAC layer control.

Nodes in an ad hoc networks may move randomly. Thus, to quickly adapt to network topology changes, a node informs its neighbors of its status, master or slave, by using the power management bit in the MAC header. Since the MAC header can be heard anywhere in the network, including RTS/CTS packets, this information will help neighbors to know each other's situation.

3.3 Simulation Environment

Our conclusions are based on the results gathered by extensive simulation of a network model which implements EE-MAC. For the simulations, we used the Network Simulator-2 (NS-2) [38][13]. NS-2 is a popular simulator which has been broadly used in mobile ad hoc network study. For comparison with EE-MAC, we also implemented IEEE 802.11 and its PSM mode.

We considered 25, 50, 75 and 100 nodes moving in a square area of $500m \times 500m$, $750m \times 750m$ and $1000m \times 1000m$ based on a mobility model called *random waypoint* [8]. Initially, each node chooses a random position in the area, chooses a random destination,

Table 3.1. *Power Consumption Model [14]*

Transmit Mode	Receive Mode	Idle Mode	Sleep Mode
1400mW	1020mW	890mW	70mW

chooses a speed at random uniformly distributed between $0m/s$ and $10m/s$, and moves towards the destination at the chosen speed. The node then pauses for a period of time before repeating the same process. Longer pause times reflect lower node mobility in a network and shorter pause times reflect high mobility. Simulations are performed for a duration of 400 seconds as this is long enough to provide sufficient data to evaluate the network performance. In the simulation, the scenario with 400 seconds pause time means no mode mobility.

The nodes have 2Mbps bandwidth and 250 meters radio range. Each source node generate a Constant-Bit-Rate (CBR) flow to the destination with 256 byte packets. We vary the number of sources and the number of packets sent per second to change the network load. A network load of 10% means that the total bit rate of all traffic sources is $2 \times 10\% = 0.2Mbps$. Dynamic Source Routing (DSR) is used as the primary routing protocol, with Ad Hoc On-Demand Distance Vector Routing (AODV) also simulated for one scenario to compare with DSR.

For the energy model, we use the data shown in Table 3.1. All simulation results shown in this thesis are an average of 10 runs.

We use the following metrics to evaluate the network performance.

- **Data packet delivery ratio:** The data packet delivery ratio is the ratio of the number of packets generated at the sources to the number of packets received by the destinations. This metric reflects the network throughput. One of our goals is to design an energy-efficient MAC protocol which can improve energy consumption without suffering a significant loss of capacity. Thus, this metric is useful to measure any degradation in network throughput.
- **End-to-end delay:** This metric not only includes the delays of data propagation and

transfer, but also all possible delays caused by buffering, queuing and retransmitting data packets.

- **Energy efficiency:** We define Energy efficiency as:

$$\text{Energy efficiency} = \frac{\text{Total bits transmitted}}{\text{Total energy consumed}} \quad (3.2)$$

where the total bits transmitted is calculated using application layer data packets only and total energy consumption is the sum of each node's energy consumption during the simulation time. The unit of energy efficiency is *bit/Joule* and the greater the number of bits per Joule, the better the energy efficiency achieved.

We also use the network lifetime to measure longevity of an ad hoc network. It is defined as the time it takes for the data packet delivery ratio to fall to 5%. This metric reflects how long a network can remain operational.

3.4 Performance Evaluation

We now present our simulation results. The figures in this thesis show three curves labeled 802.11, PSM and EE-MAC. The curves labeled 802.11 corresponds to the IEEE 802.11 protocol without using power saving mode. The curves labeled PSM indicate the IEEE 802.11 protocol with power saving mode. The curves labeled EE-MAC represent the protocol proposed in the thesis.

3.4.1 Varying the Network Load

From the simulation results, we observe that network load has a significant impact on all three protocols. However, we show that varying the network load affects these protocols differently in terms of our performance metrics.

In Figures 3.7 to 3.16 we show packet delivery ratio under different network loads from 10% to 40%. When the network load is low (10%), 802.11 performs a little better

than EE-MAC and, while EE-MAC provides a big improvement over PSM. As the network load increases to 40%, all three protocols become worse due to the higher collision rate. However, the performance differences between 802.11 and EE-MAC, and EE-MAC and PSM are also increasing, which means heavier traffic has more impact on EE-MAC than 802.11 because under a heavy network load, the master election algorithm operates more frequently to rotate masters and slaves. Among the three protocols, PSM always performs worst. PSM drops significantly more packets than the others because of the existence of a fixed ATIM window, which wastes bandwidth. When the traffic is high, it is possible that the ATIM window is not long enough to advertise all pending packets, or the buffered data packets cannot all be sent out during a beacon interval. On the other hand, EE-MAC has the advantage of masters which never enter sleep mode, so traffic between masters does not need to be advertised. Coupled with the fact that most of the network traffic is data traffic between masters, EE-MAC can use a shorter ATIM window than PSM and thus offer better performance than PSM. EE-MAC is worse than 802.11 because it still uses an ATIM window in every beacon interval which wastes some bandwidth. Moreover, the overhead of the master election algorithm and using fewer nodes to forward packets also decreases the packet delivery ratio.

In Figures 3.17 to 3.26 we give the average packet delay results. Again, 802.11 performs the best among all schemes and as the network load becomes heavier, the advantage increases. EE-MAC is not far away behind 802.11, but is far superior to PSM. PSM suffers from long packet delays mainly because of its mechanism of *receiving-buffering-advertising-sending*. Thus, each hop in a PSM network corresponds to the length of the beacon interval. In addition, if the network load is high, some packets have to be buffered up to 3 beacon intervals before being sent out. Note that packets are dropped if they have been kept in the buffer for 3 beacon intervals. These factors cause PSM to have poor packet delay performance. Similarly, the overhead of master elections, using ATIM windows and fewer routing nodes makes EE-MAC have higher packet delays than 802.11.

In Figures 3.27 to 3.36, the most interesting metric to us, energy efficiency, is pre-

sented. The results show that EE-MAC perform best among all protocols. This is because EE-MAC allows slave nodes to enter sleep mode when no packets are addressed to them, but there always exist awake nodes (masters) to forward packets. Furthermore, EE-MAC can tell slaves to enter sleep mode once they have finished receiving all data addressed to them in a beacon interval. These benefits allow EE-MAC to nicely balance energy consumption and packet delivery ratio, resulting in much better energy efficiency. PSM does perform better than 802.11 and is comparable to EE-MAC under light network load conditions. As the network load increases, PSM becomes worse very quickly due to high data packet loss. Moreover, more nodes need to participate in packet forwarding under a heavy network load, which more nodes must keep awake all the time, causing high energy consumption. Comparing energy efficiency between EE-MAC and 802.11 under different network loads is somewhat complicated because it is related to both network throughput and energy consumption. Since the difference in power consumption among transmit, receive and idle modes is not significant, the energy savings achieved is highly dependent on the network node density, the ratio of time in sleep mode to other modes, and the ratio of masters to slaves. EE-MAC gains by reducing the number of awake nodes. However, in some cases, for example Figure 3.31, 802.11 can outperform EE-MAC because at least 20 of 50 nodes in the network can never enter sleep mode. Conversely, with 75 nodes and 5 sources, EE-MAC is 3 times better than 802.11 as shown in Figure 3.35.

3.4.2 Impact of Mobility

From all the results shown, it is clear that high mobility decreases the performance of all three protocols. Overall, mobility has a greater impact on EE-MAC than the other two protocols. For example, in Figure 3.8, with low mobility EE-MAC provides a 7% lower packet delivery ratio than 802.11 and a 22% higher packet delivery ratio than PSM. With high mobility, these numbers change to 12% and 19%, respectively. The reason is that with high mobility, the network topology changes rapidly and links between nodes may break often. Thus, the master election algorithm has to be operated more frequently

to reelect masters, which introduces more overhead than with low mobility. Although mobility impacts EE-MAC greatly in terms of packet delivery ratio, it still performs better than PSM. In terms of energy efficiency, PSM performs very badly because under high mobility, frequent route discovery messages cause a node to stay awake most of the time.

3.4.3 Varying the Node Density

We define node density as the number of nodes within radio range [10], which is an area of $\pi \times 250^2$ square meters in this simulation. Clearly, high density can significantly improve network performance with all three protocols. They will have more options to choose a better route, and if a route breaks, it is easier and quicker to find another one. As mentioned above, EE-MAC relies more on node density to enhance its performance than the other protocols because if the number of sources is constant, with high node density, only a small fraction of the nodes need to be elected as masters and most nodes can remain in power saving-mode. This will result in significant energy savings. Furthermore, with high node density, the impact of mobility on EE-MAC is reduced. In other words, the higher the node density, the better EE-MAC performs.

3.4.4 Changing the Number of Source Nodes

In some scenarios, the number of source nodes was changed from 10 to 20. At the same packet rate, doubling the number of sources means doubling the network load, which obviously reduces the network performance. However, we are trying to compare cases under the same network load but with different combinations of number of sources and packet rates. For example 20 sources with 20 packet/s and 10 sources with 40 packets/s results in the same load. The simulation results show that under a 40% network load, a larger number of sources performs slightly worse than a smaller number. This is likely because with more sources, the probability of a node simultaneously acting in two or three roles of source, destination and router increases, and thus the number of congestion points increases, lead-

ing to poorer network performance. This situation is very notable when considering energy efficiency. For EE-MAC, more sources means more nodes have to keep awake to send packets and fewer nodes can enter power-saving mode which lowers the energy efficiency.

3.4.5 Changing the Network Area

Changing the network area from $750m \times 750m$ to $500m \times 500m$ results in increased packet delivery ratio, decreased average packet delay and increased energy efficiency for all three protocols. In a smaller network area, the advantages of EE-MAC are not as prominent because the weaknesses of the other two protocols are reduced. Simulation results show that in an $500m \times 500m$ area, most routes are 2-4 hops long, while in an $750m \times 750m$ area, routes are typically 2-7 hops long, so the routing overhead and packet delay are much less in small size networks. The results show that EE-MAC only gains a little benefit in energy efficiency and is not as superior to PSM as in an $750m \times 750m$ area. When the network size increases to $1000m \times 1000m$, not only is the node density decreased, but also forming a CDS requires more nodes in general and so the CDS can be broken more easily. This causes a degradation of performance.

3.4.6 Static Network

Figures 3.46 to 3.50 show the performance under static network conditions. In particular, energy efficiency and packet delivery ratio are given corresponding to different network loads. These figures give a comparison of the three protocols in an ad hoc network without motion. It is clear that as the network load increases, the packet delivery ratio of PSM drops much more quickly than with EE-MAC and 802.11. The decreased gap between EE-MAC and 802.11 in Figure 3.46, compared to that in Figure 3.48, shows that EE-MAC gains more benefit from a higher node density. Note that in Figures 3.47 and 3.49, with very light network load, PSM performs slightly better than EE-MAC for two reasons. First, PSM has good network throughput under a light network load. Second, EE-MAC needs an

almost constant number of nodes to form a CDS even when the network load is very light and thus has constantly awake nodes unnecessarily. Figure 3.50 shows the network lifetime corresponding to different node densities. The curves are normalized to the lifetime of an 802.11 network. From this figure, the importance of node density to EE-MAC is shown.

3.4.7 Routing Protocol Comparison

As mentioned previously, the simulations presented above used DSR as the routing protocol. However, EE-MAC can work with other routing protocols, such as AODV. Figure 3.51 presents the simulation results with AODV and DSR. Overall, AODV performs slightly better than DSR under a light network load, which is also shown in [26].

3.5 Summary

In this chapter, we described the IEEE 802.11 protocol including the power saving mode (PSM). An energy-efficient MAC protocol for mobile ad hoc networks was presented, including the design criteria, implementation and features. An NS-2 based simulation environment and simulation results under different scenarios were introduced. It is clear that the proposed protocol, EE-MAC, can save energy consumed in the network while not significantly reducing the network throughput. EE-MAC performs best in a mid-sized network with relatively high node density, in which case EE-MAC outperforms IEEE 802.11 and PSM with respect to balancing network packet delivery ratio and energy savings.

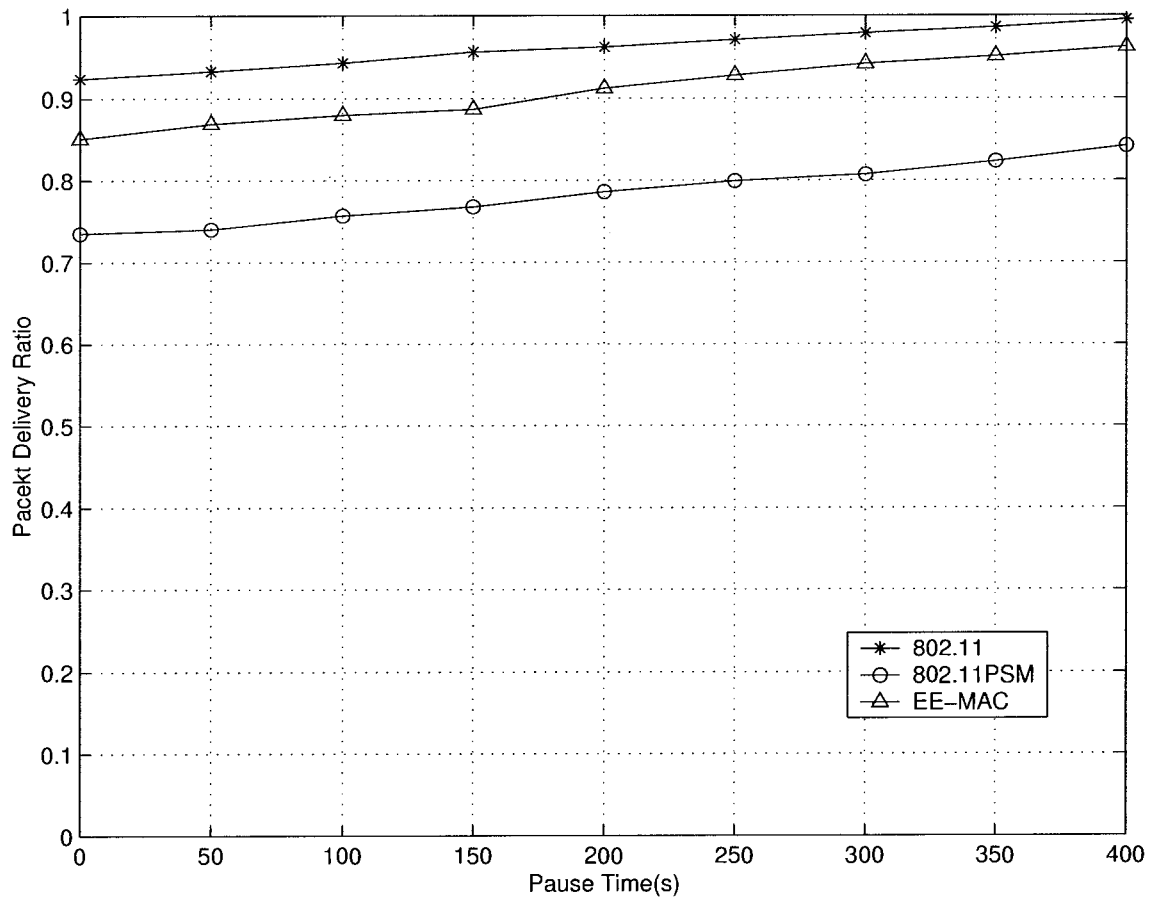


Figure 3.7. Packet delivery ratio with 50 nodes, 10 sources and 10 packets/s in an area of $750m \times 750m$.

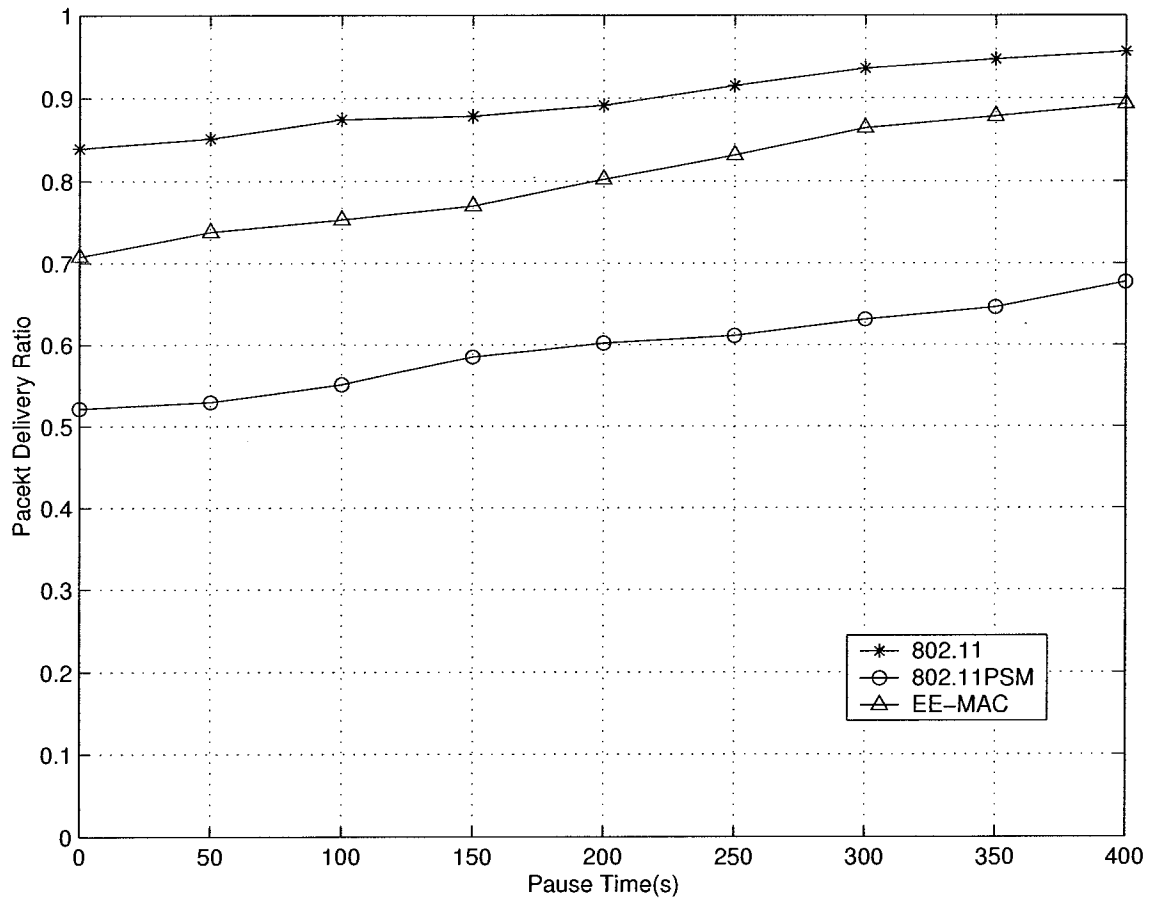


Figure 3.8. Packet delivery ratio with 50 nodes, 10 sources and 20 packets/s in an area of $750m \times 750m$.

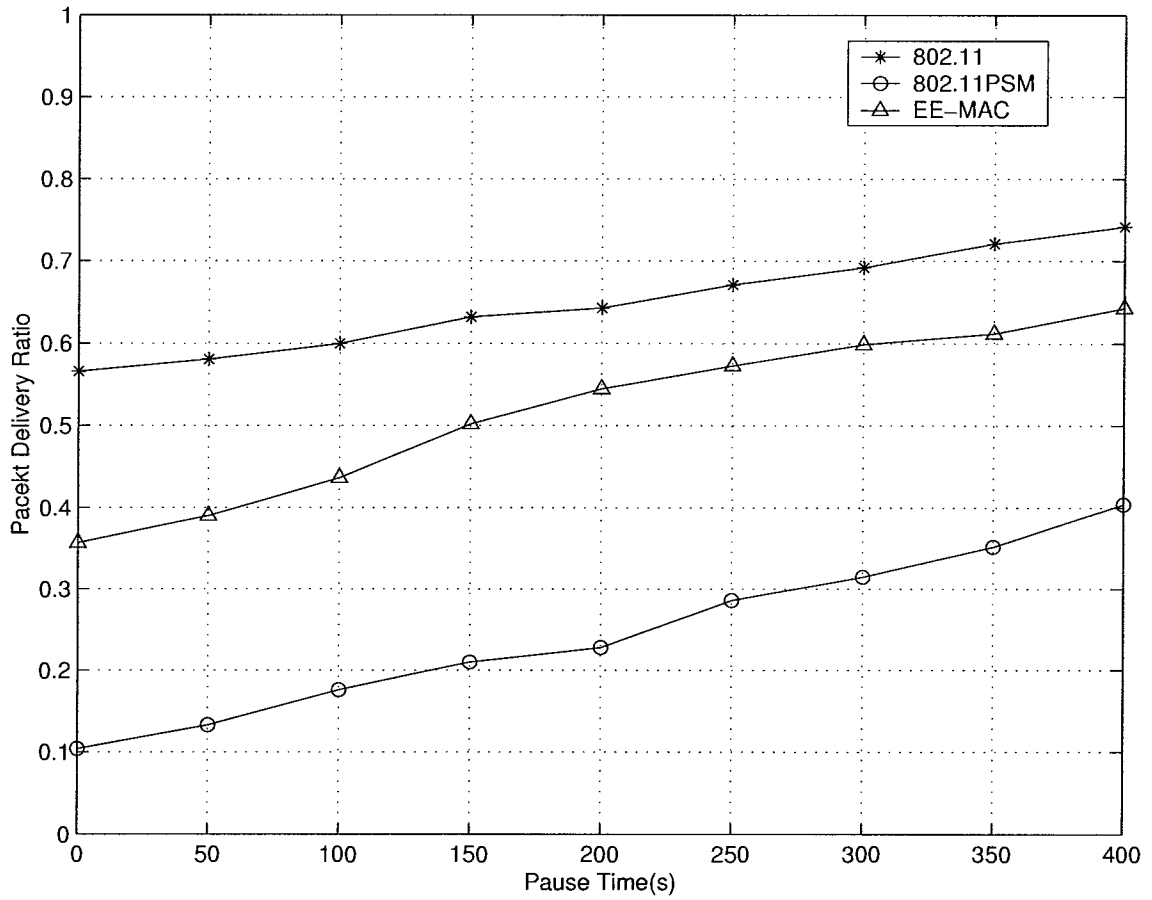


Figure 3.9. Packet delivery ratio with 50 nodes, 10 sources and 40 packets/s in an area of $750m \times 750m$.

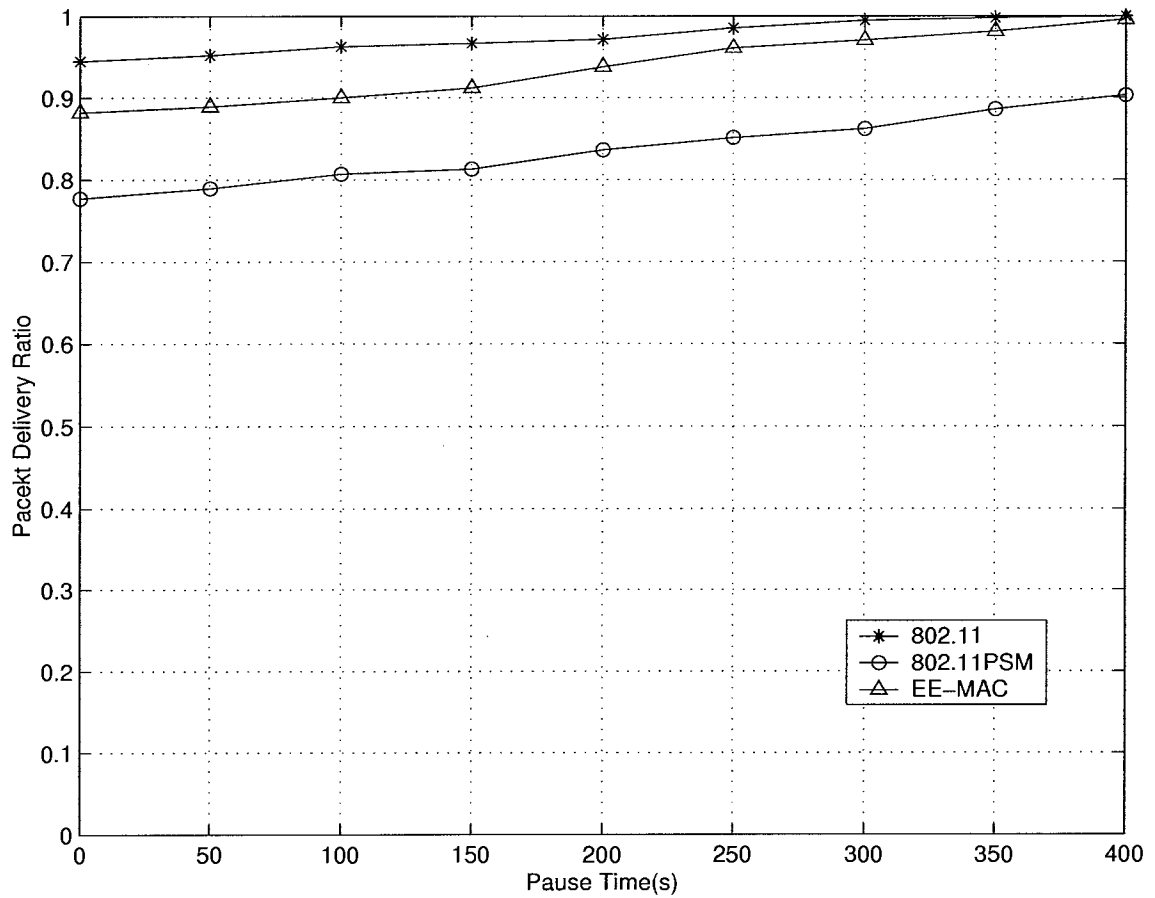


Figure 3.10. Packet delivery ratio with 50 nodes, 5 sources and 20 packets/s in an area of $750m \times 750m$.

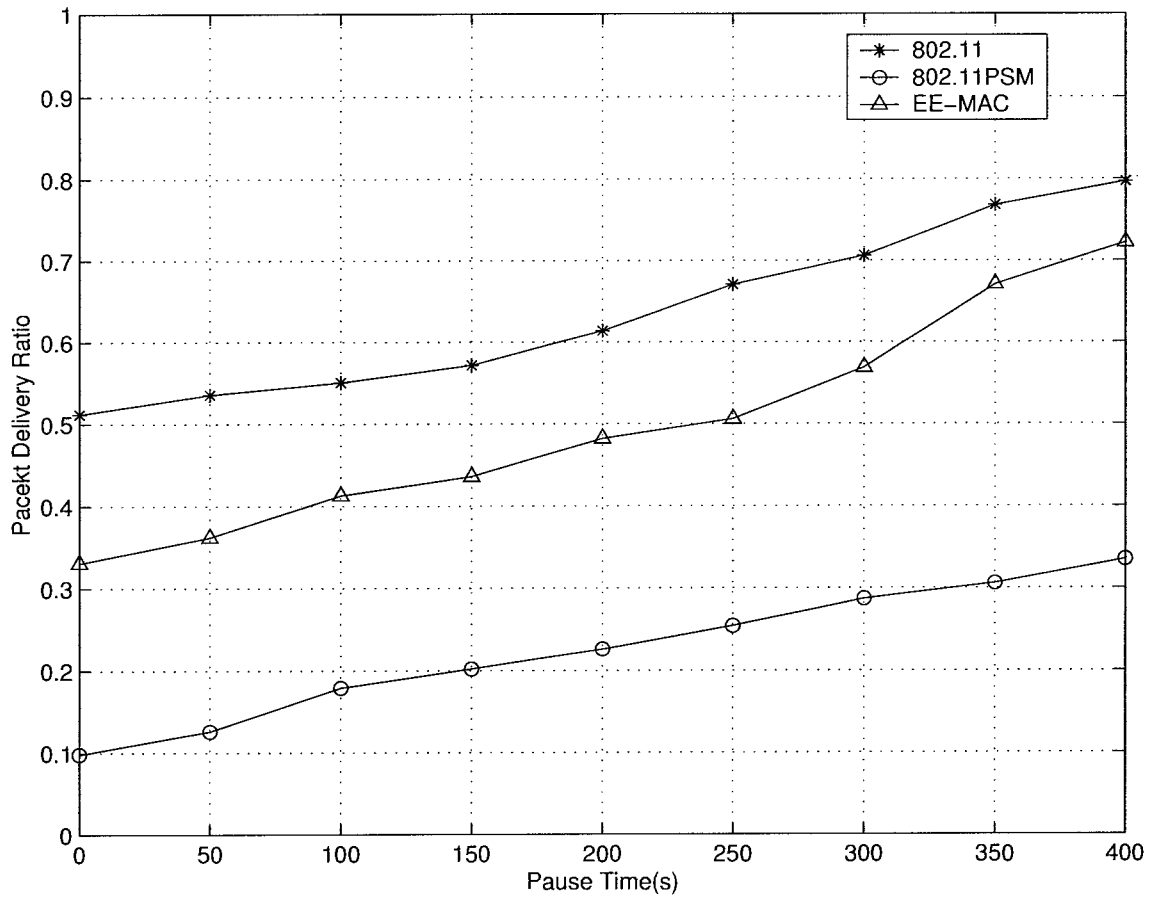


Figure 3.11. Packet delivery ratio with 50 nodes, 20 sources and 20 packets/s in an area of $750m \times 750m$.

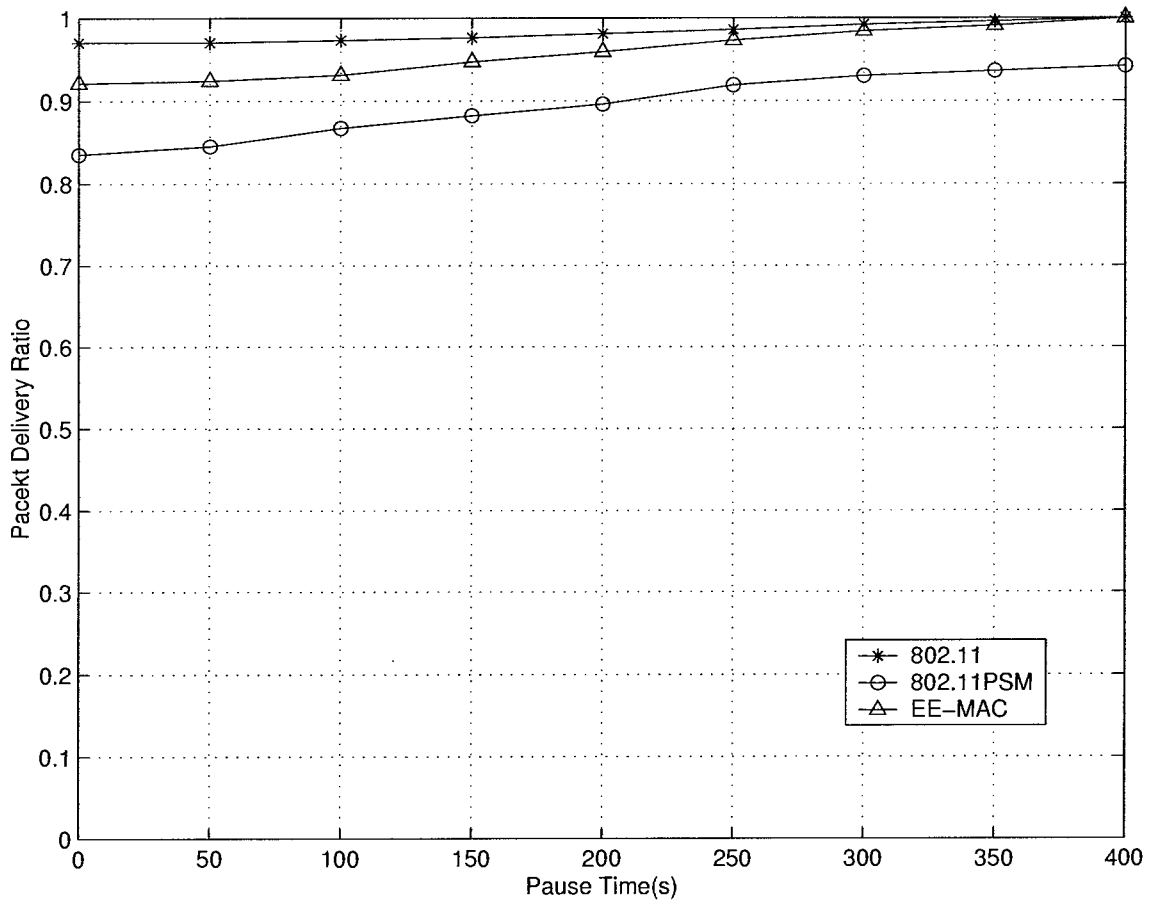


Figure 3.12. Packet delivery ratio with 75 nodes, 10 sources and 10 packets/s in an area of $750m \times 750m$.

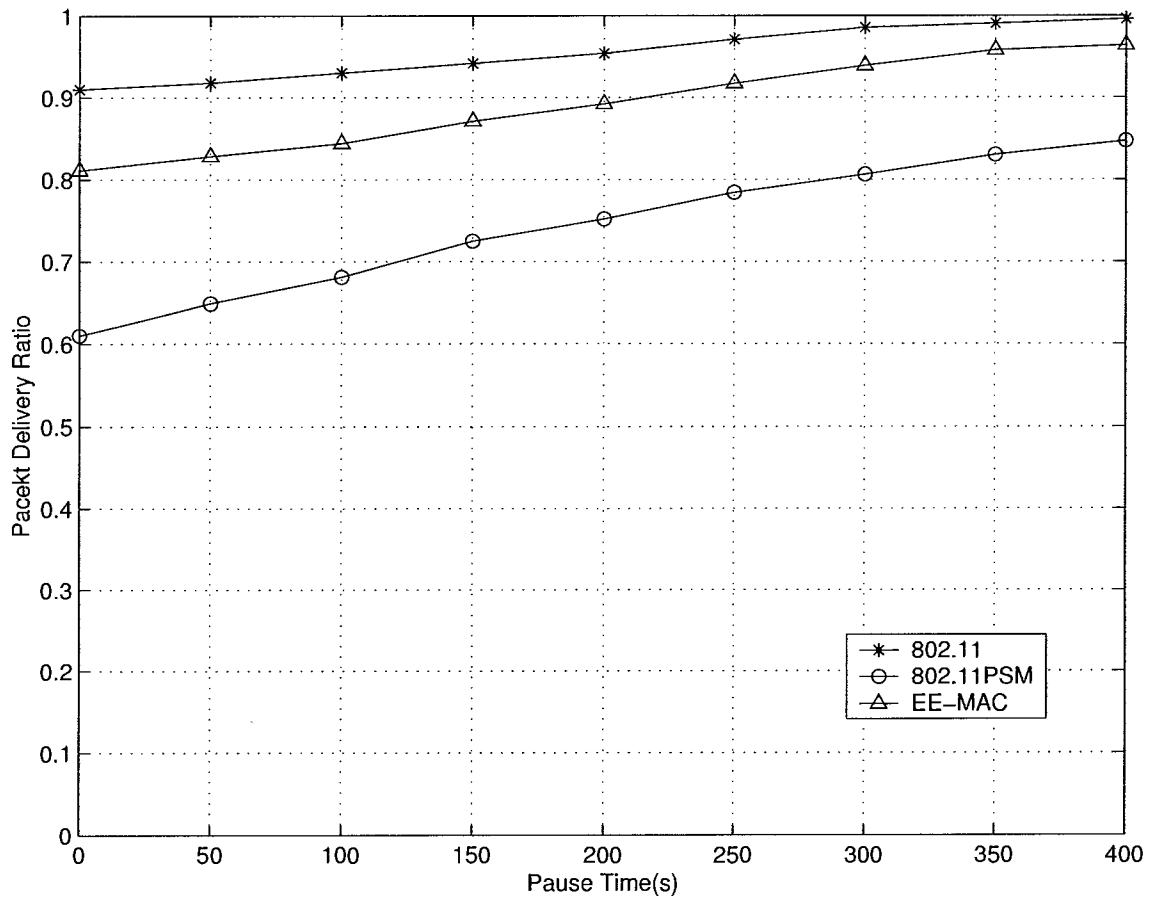


Figure 3.13. Packet delivery ratio with 75 nodes, 10 sources and 20 packets/s in an area of $750m \times 750m$.

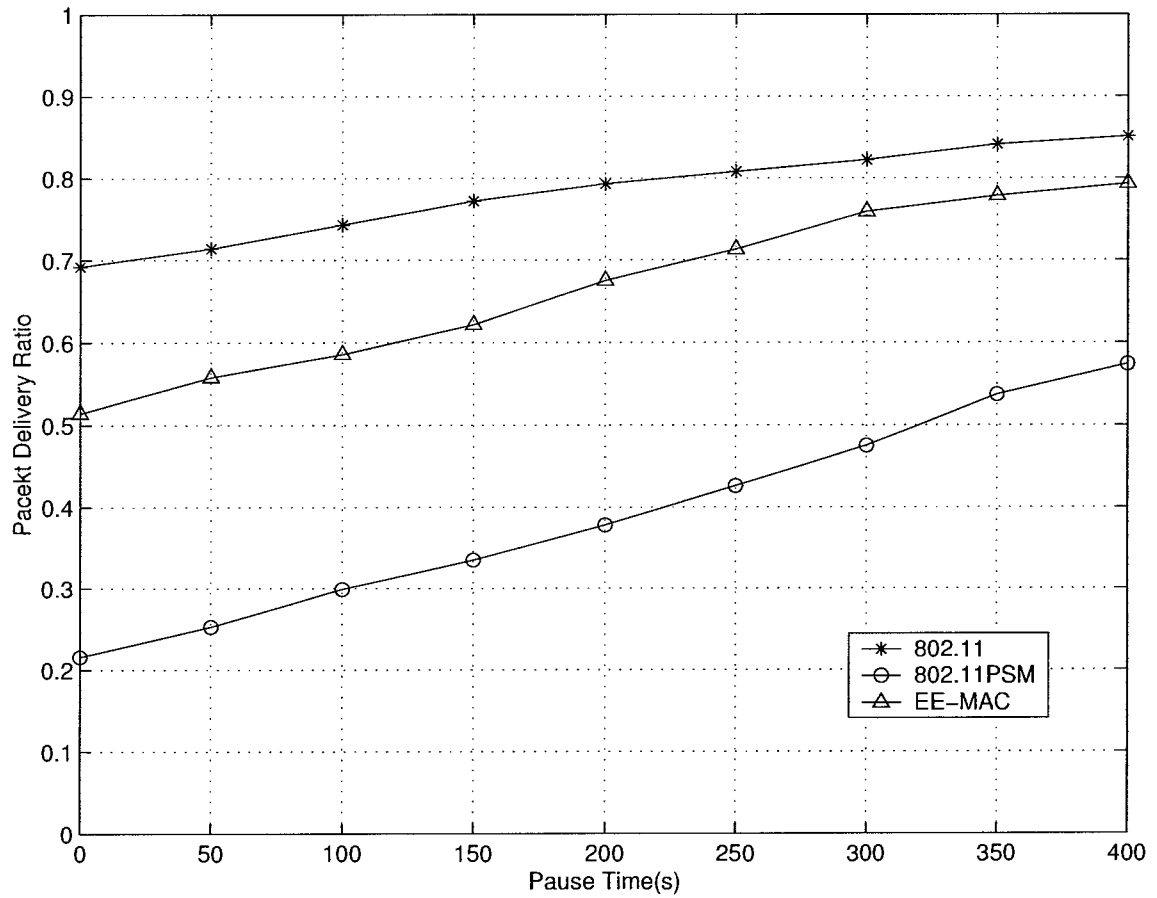


Figure 3.14. Packet delivery ratio with 75 nodes, 10 sources and 40 packets/s in an area of $750m \times 750m$.

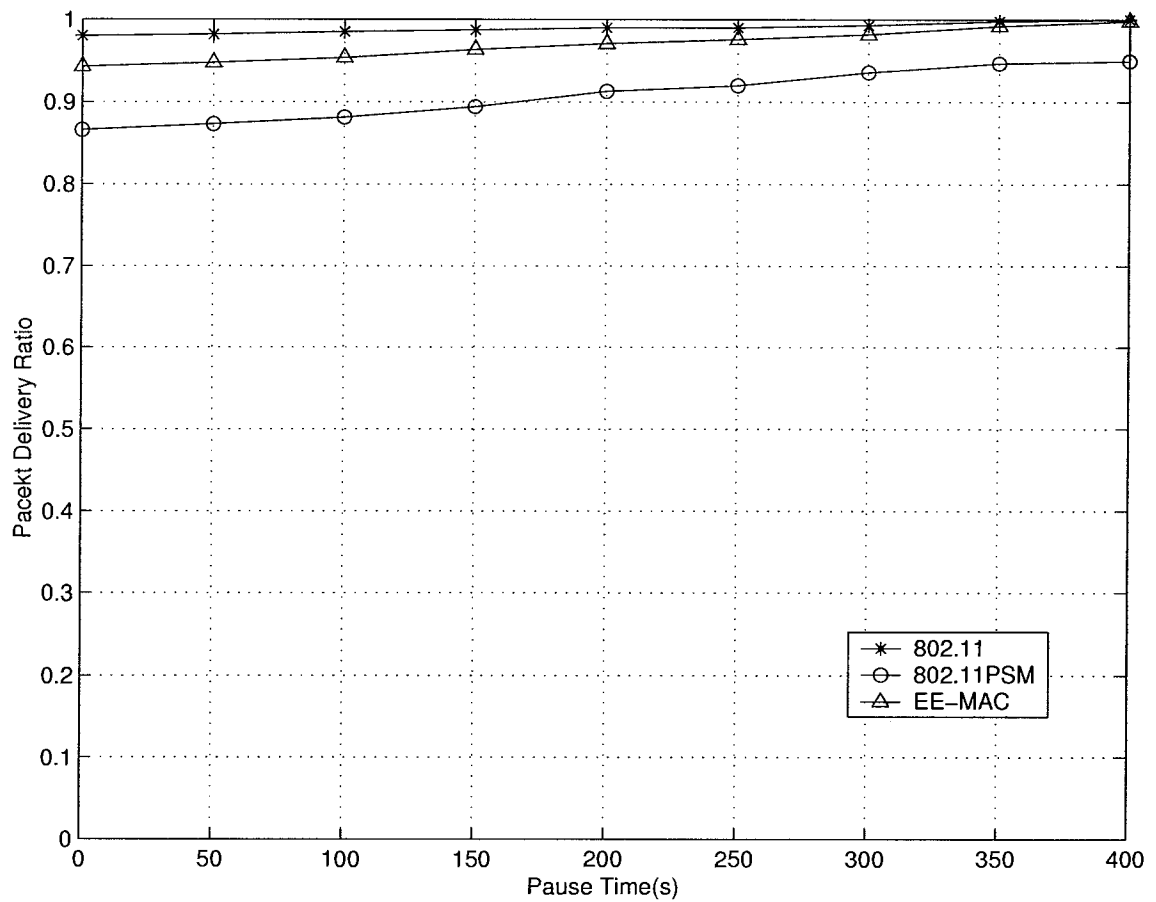


Figure 3.15. Packet delivery ratio with 75 nodes, 5 sources and 20 packets/s in an area of $750m \times 750m$.

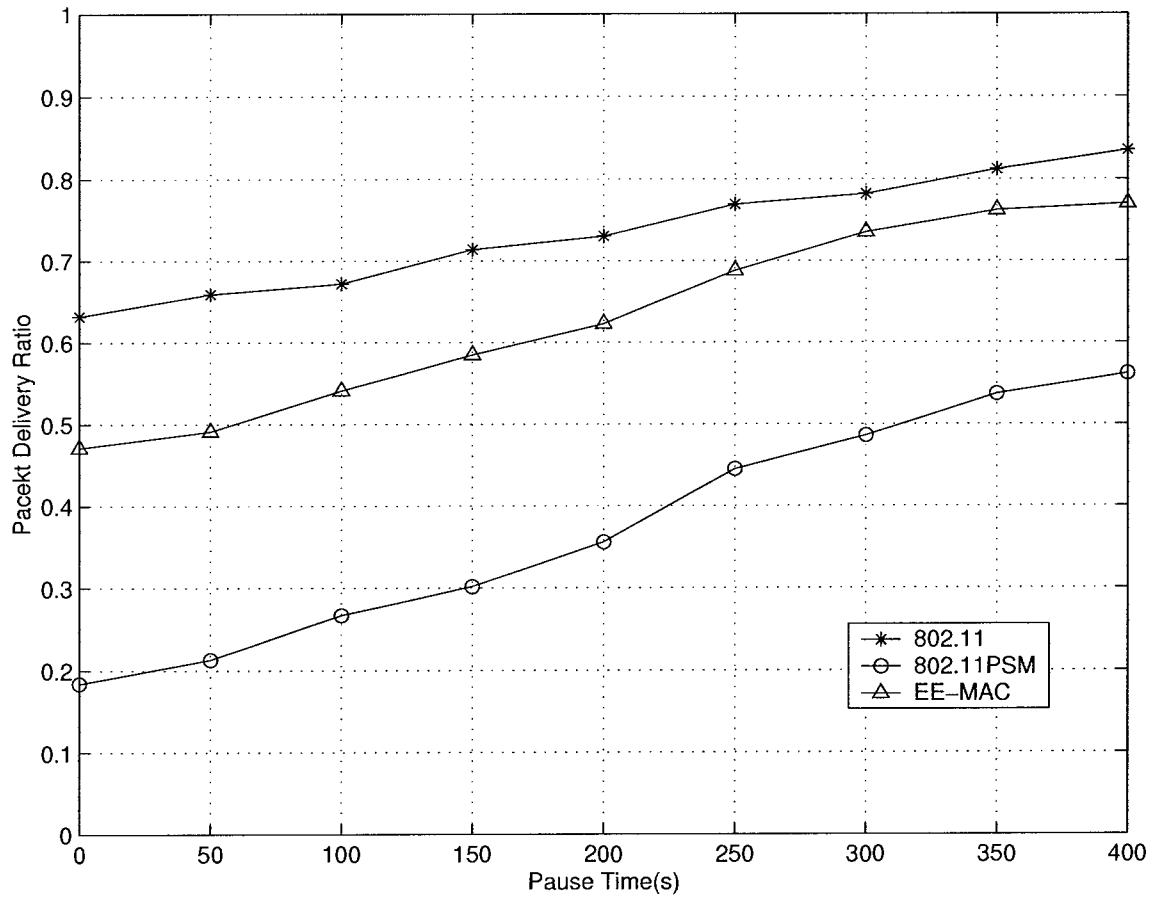


Figure 3.16. Packet delivery ratio with 75 nodes, 20 sources and 20 packets/s in an area of $750m \times 750m$.

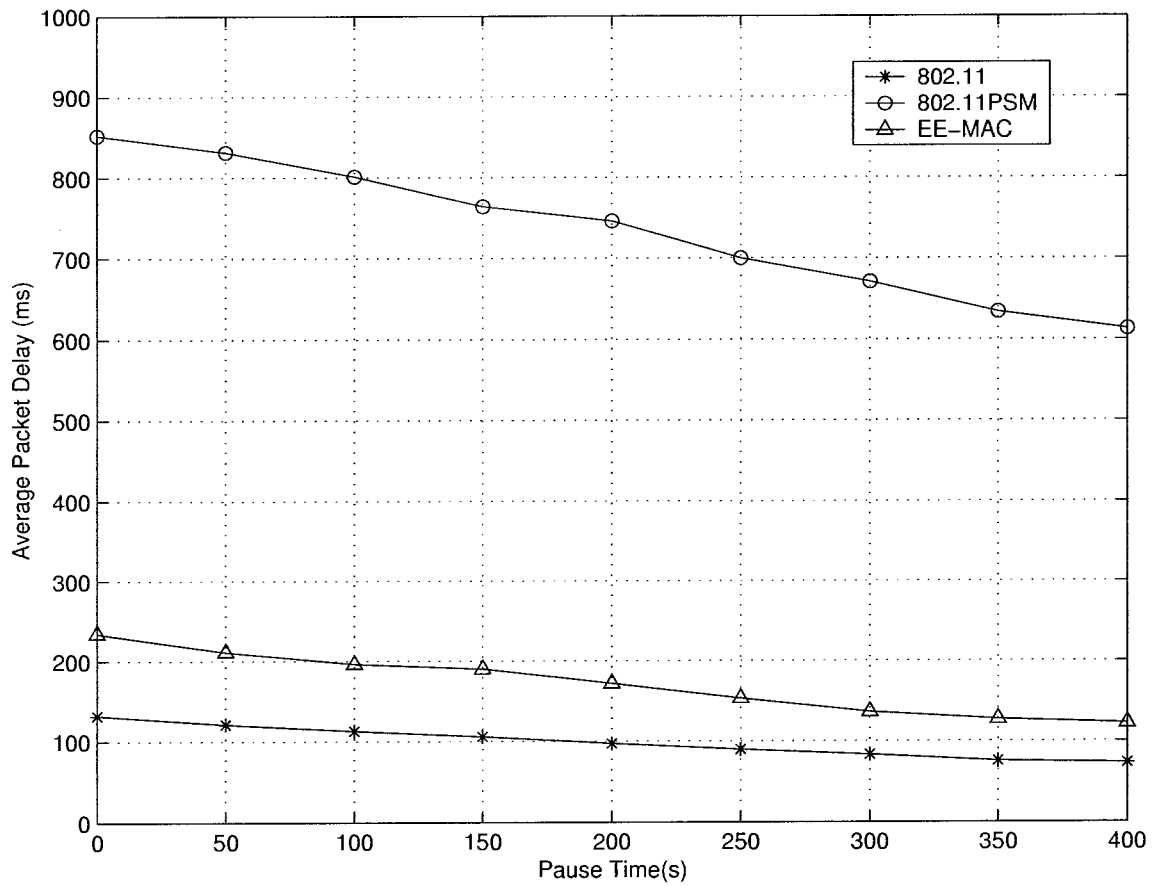


Figure 3.17. Average packet delay with 50 nodes, 10 sources and 10 packets/s load in an area of $750m \times 750m$.

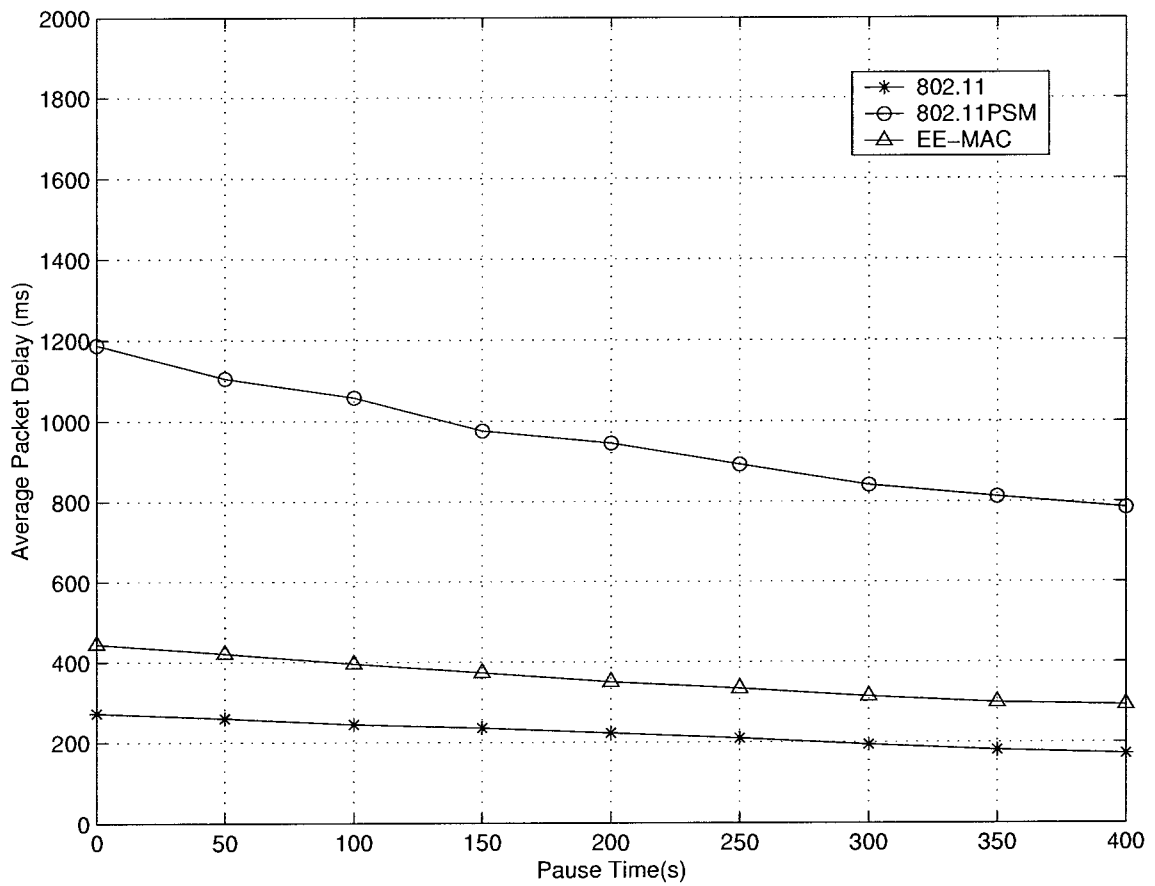


Figure 3.18. Average packet delay with 50 nodes, 10 sources and 20 packets/s in an area of $750m \times 750m$.

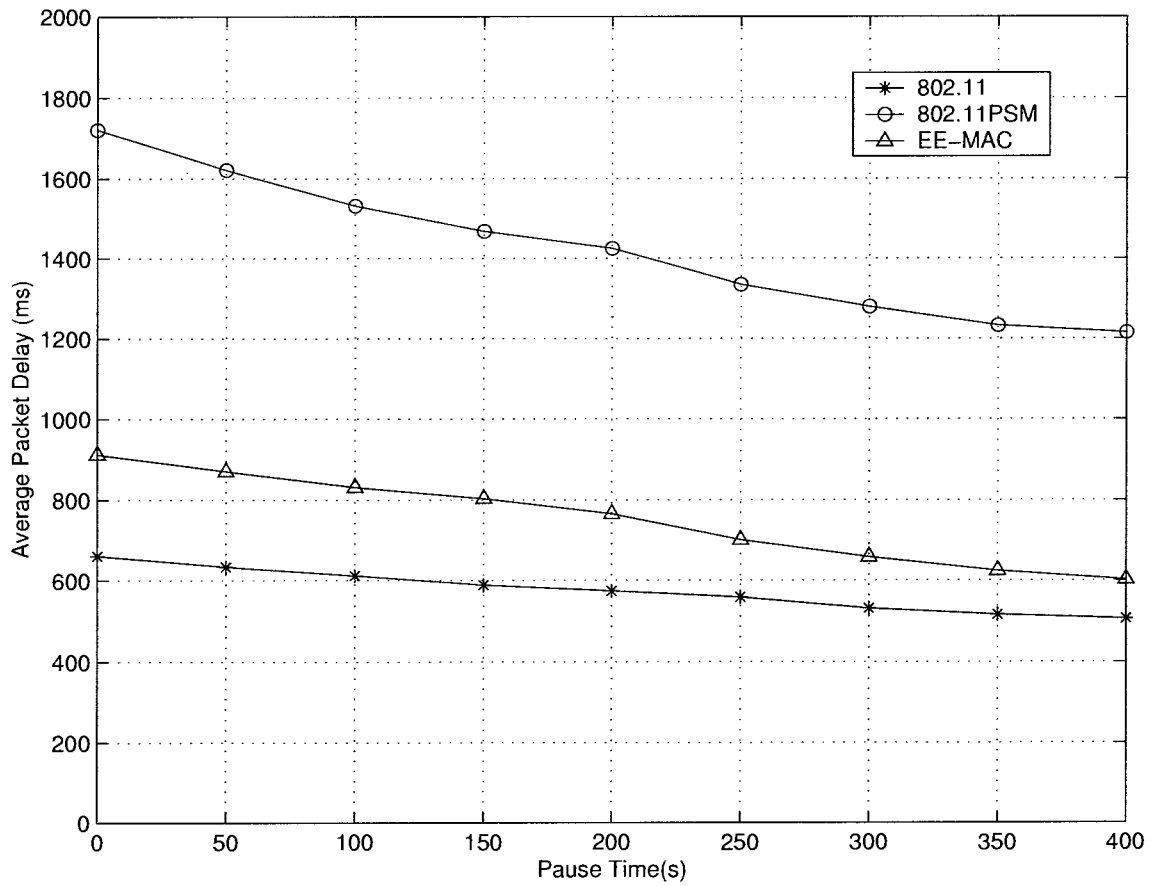


Figure 3.19. Average packet delay with 50 nodes, 10 sources and 40 packets/s in an area of $750m \times 750m$.

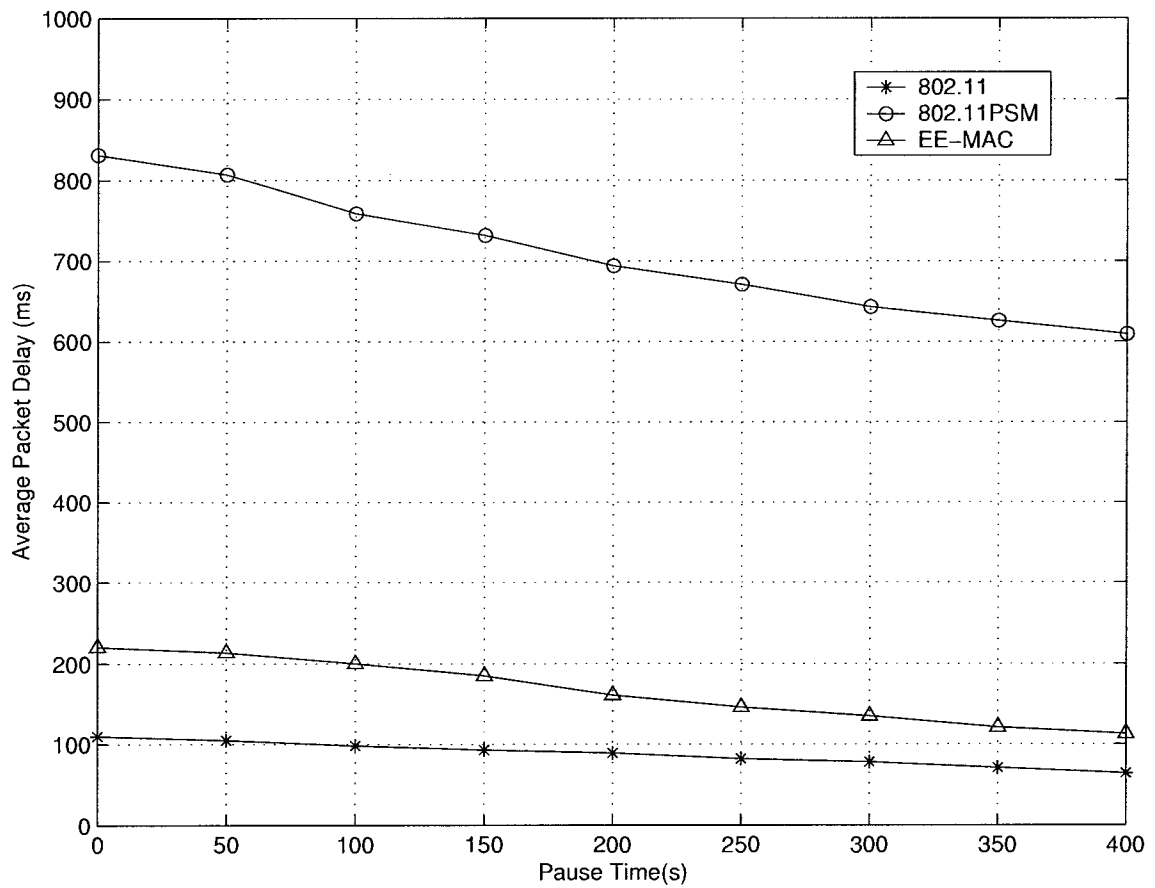


Figure 3.20. Average packet delay with 50 nodes, 5 sources and 20 packets/s in an area of $750m \times 750m$.

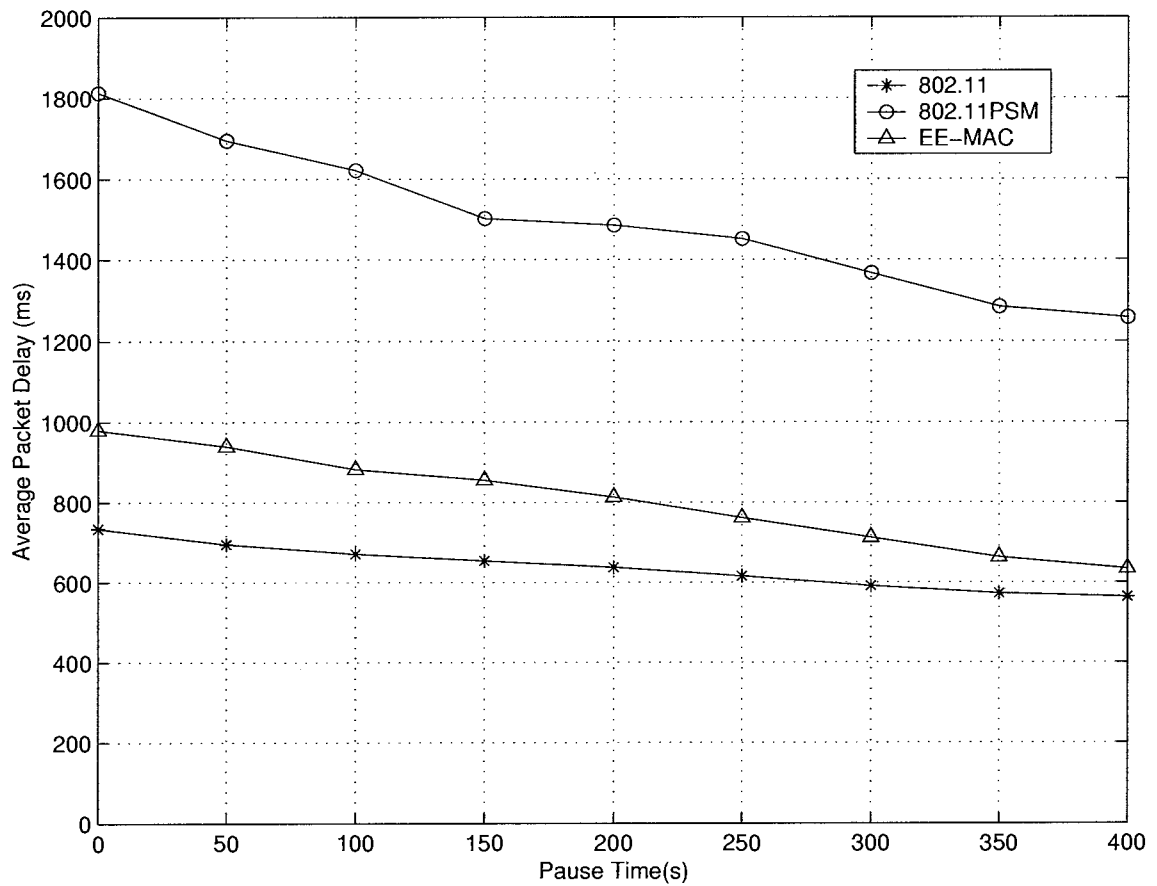


Figure 3.21. Average packet delay with 50 nodes, 20 sources and 20 packets/s in an area of $750m \times 750m$.

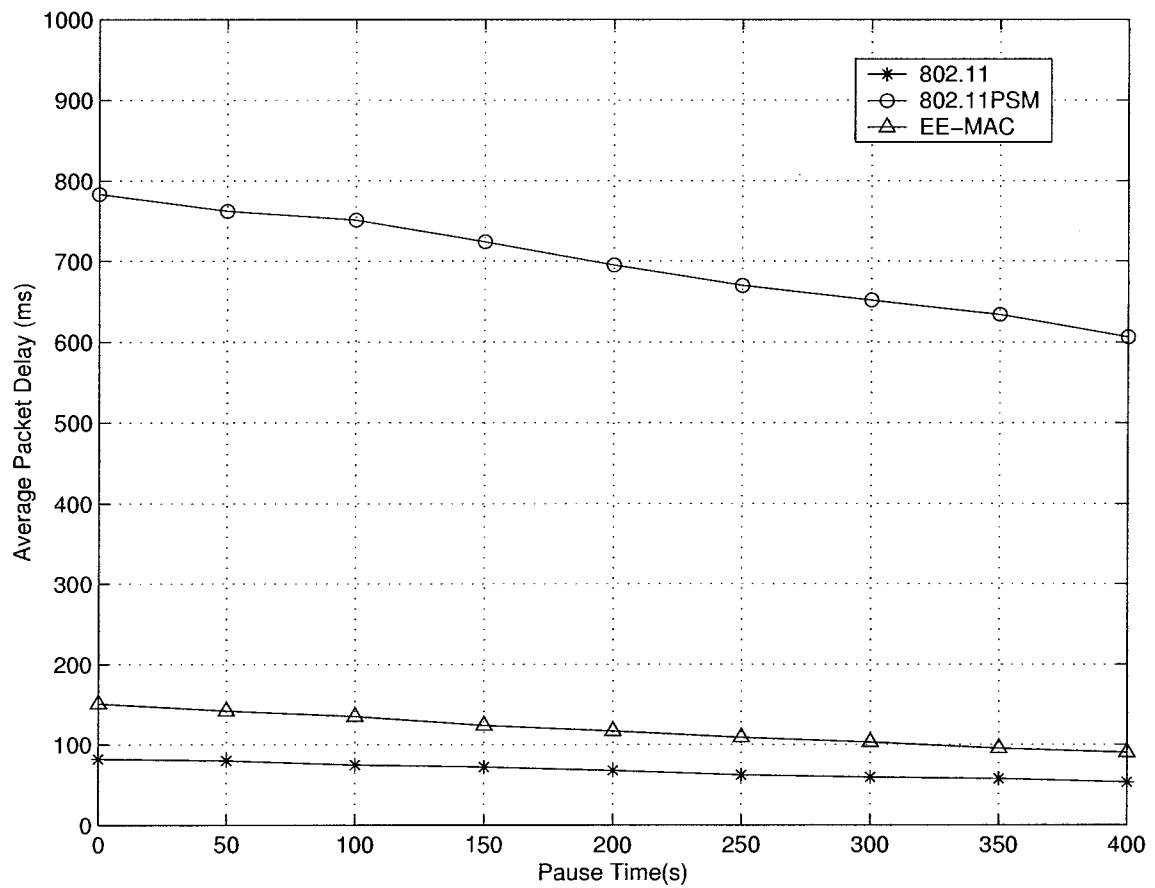


Figure 3.22. Average packet delay with 75 nodes, 10 sources and 10 packets/s in an area of $750m \times 750m$.

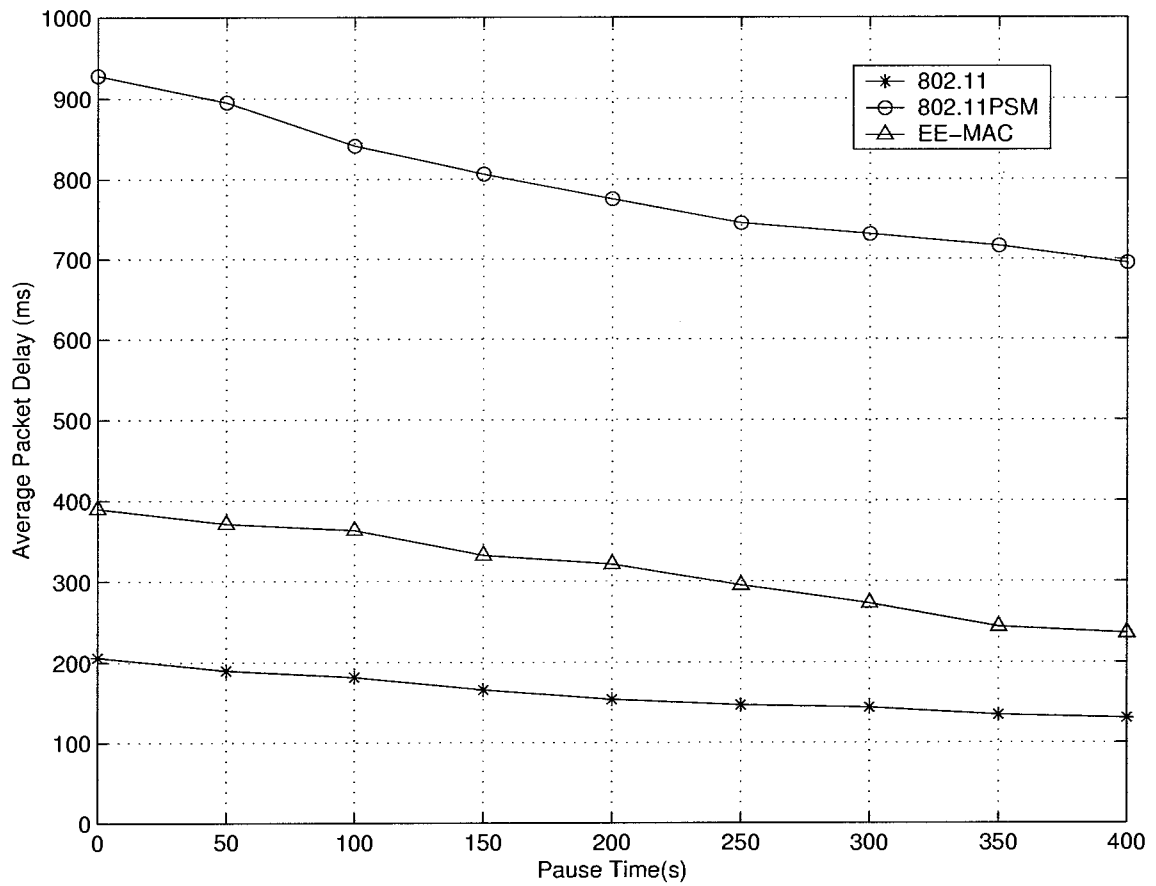


Figure 3.23. Average packet delay with 75 nodes, 10 sources and 20 packets/s in an area of $750m \times 750m$.

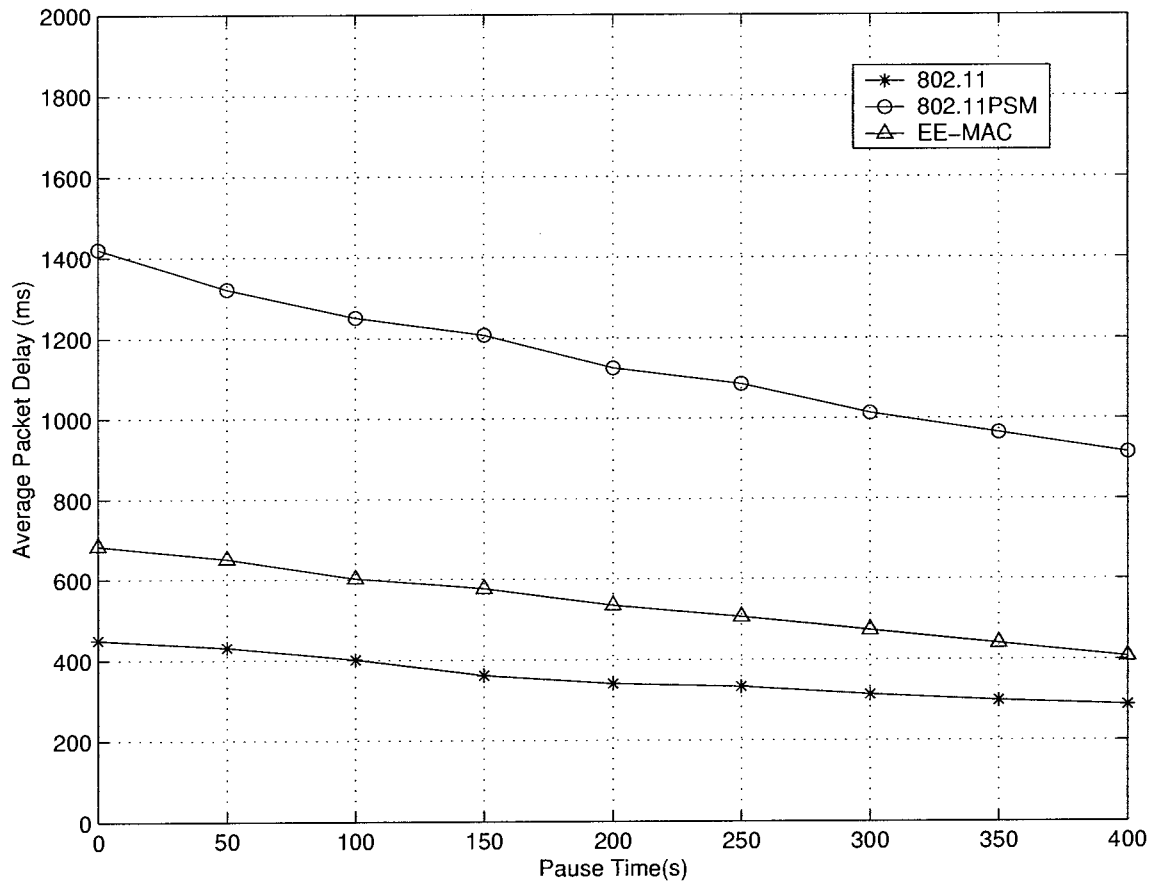


Figure 3.24. Average packet delay with 75 nodes, 10 sources and 40 packets/s in an area of $750m \times 750m$.

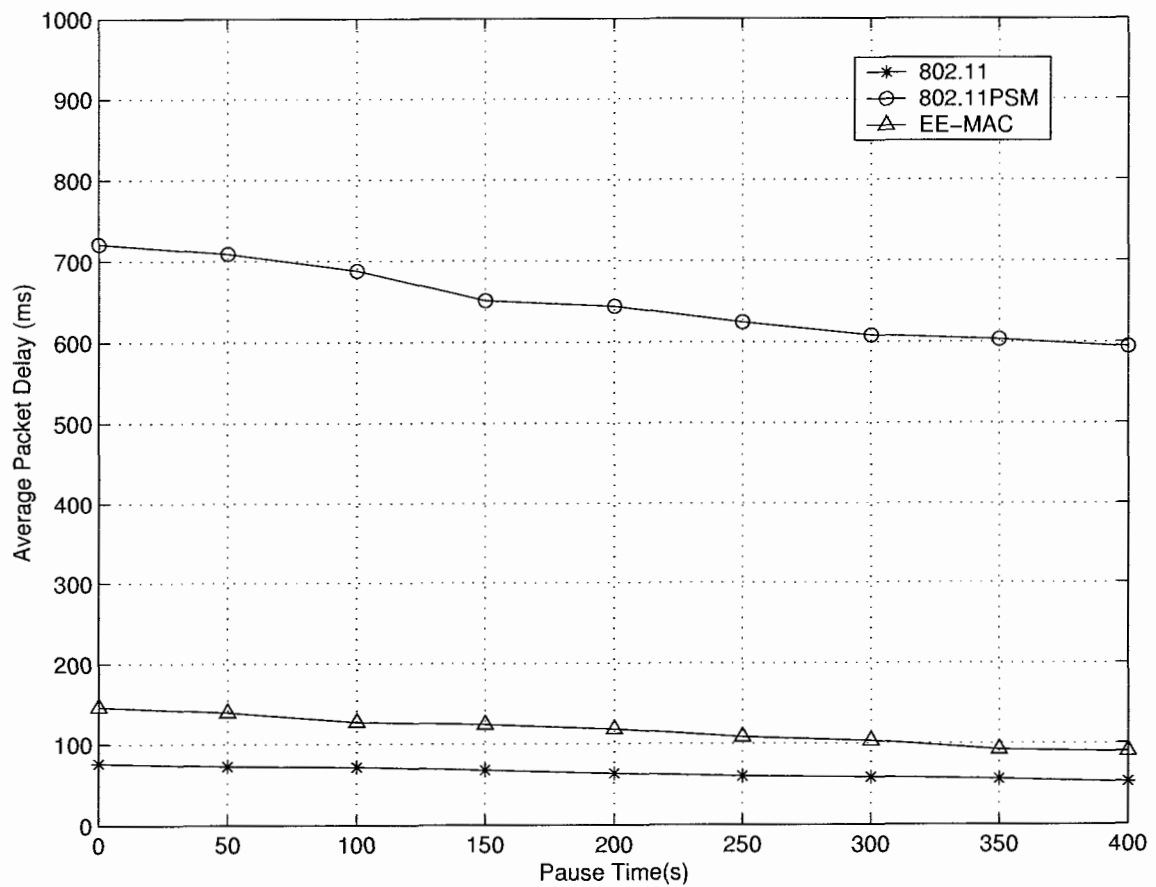


Figure 3.25. Average packet delay with 75 nodes, 5 sources and 20 packets/s in an area of $750m \times 750m$.

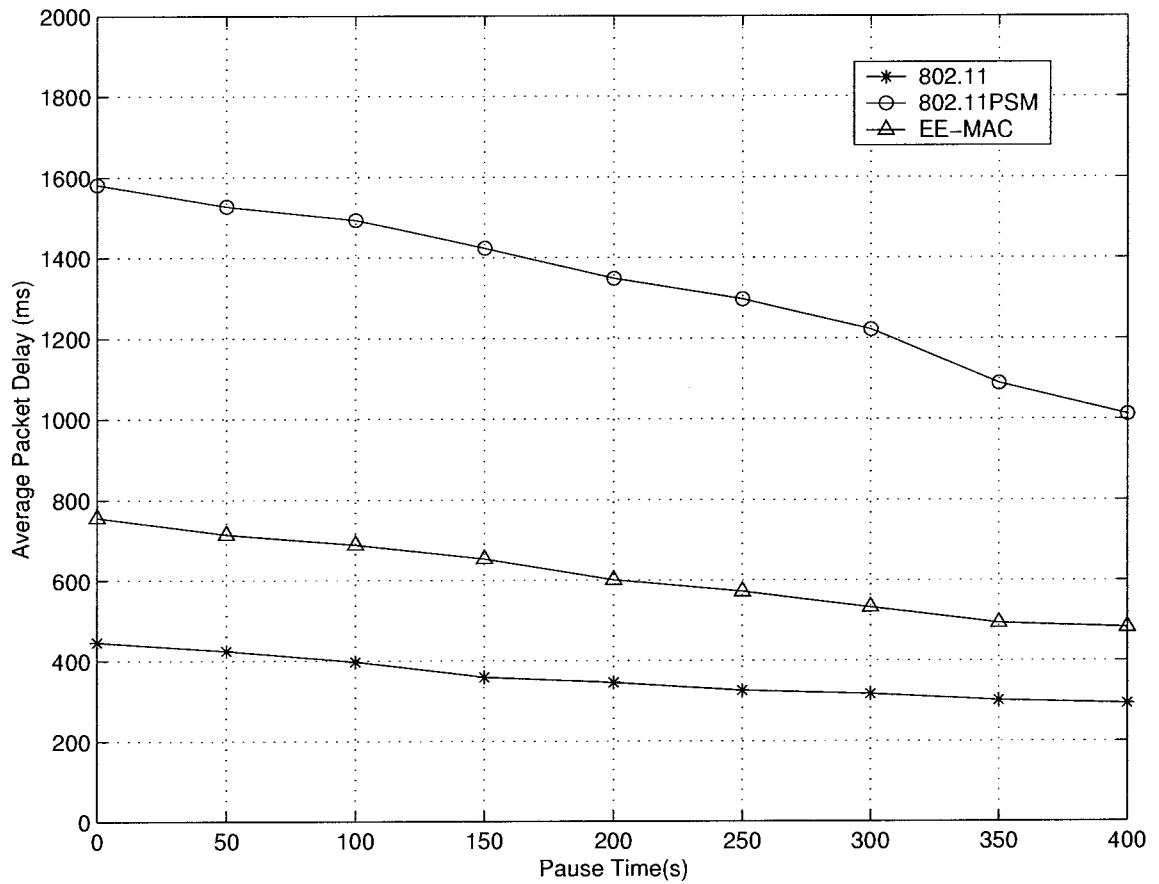


Figure 3.26. Average packet delay with 75 nodes, 20 sources and 20 packets/s in an area of 750m \times 750m.

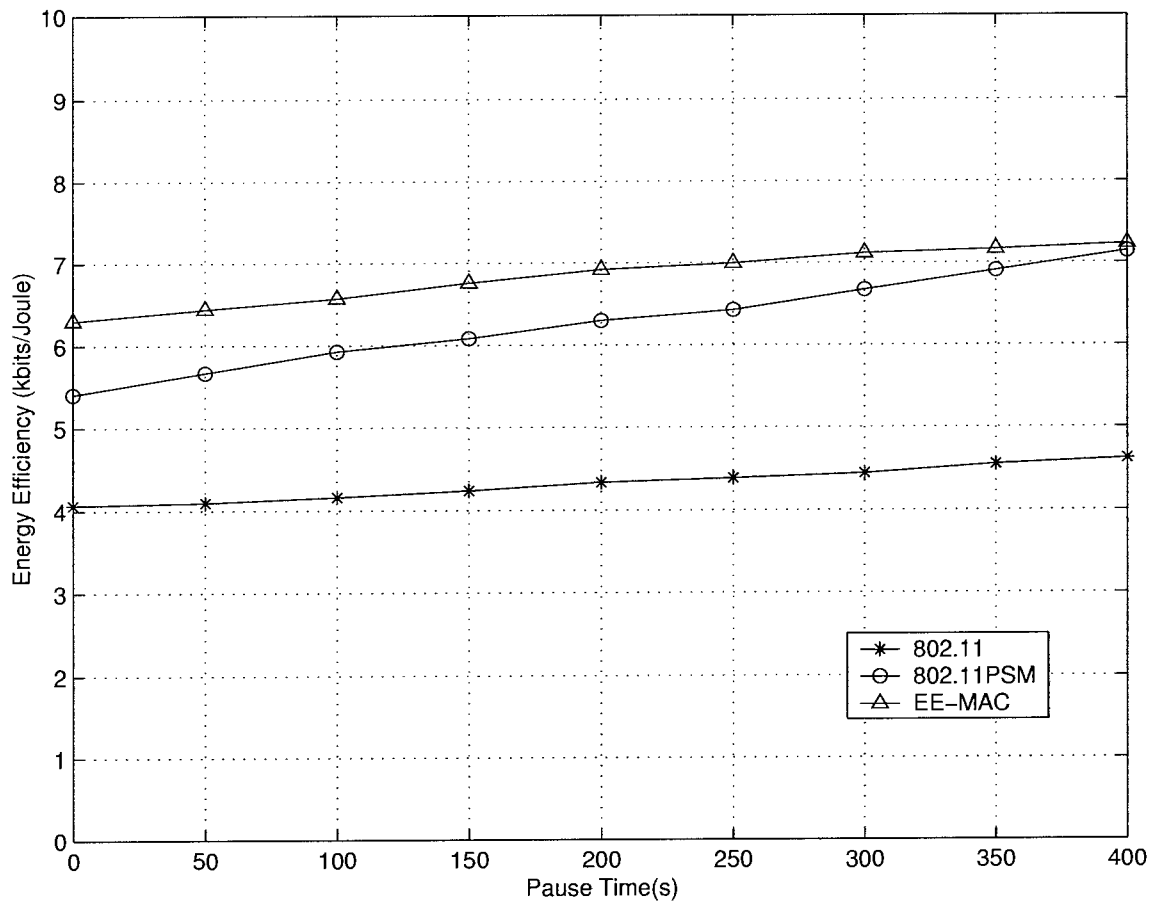


Figure 3.27. Energy efficiency with 50 nodes, 10 sources and 10 packets/s in an area of $750m \times 750m$.

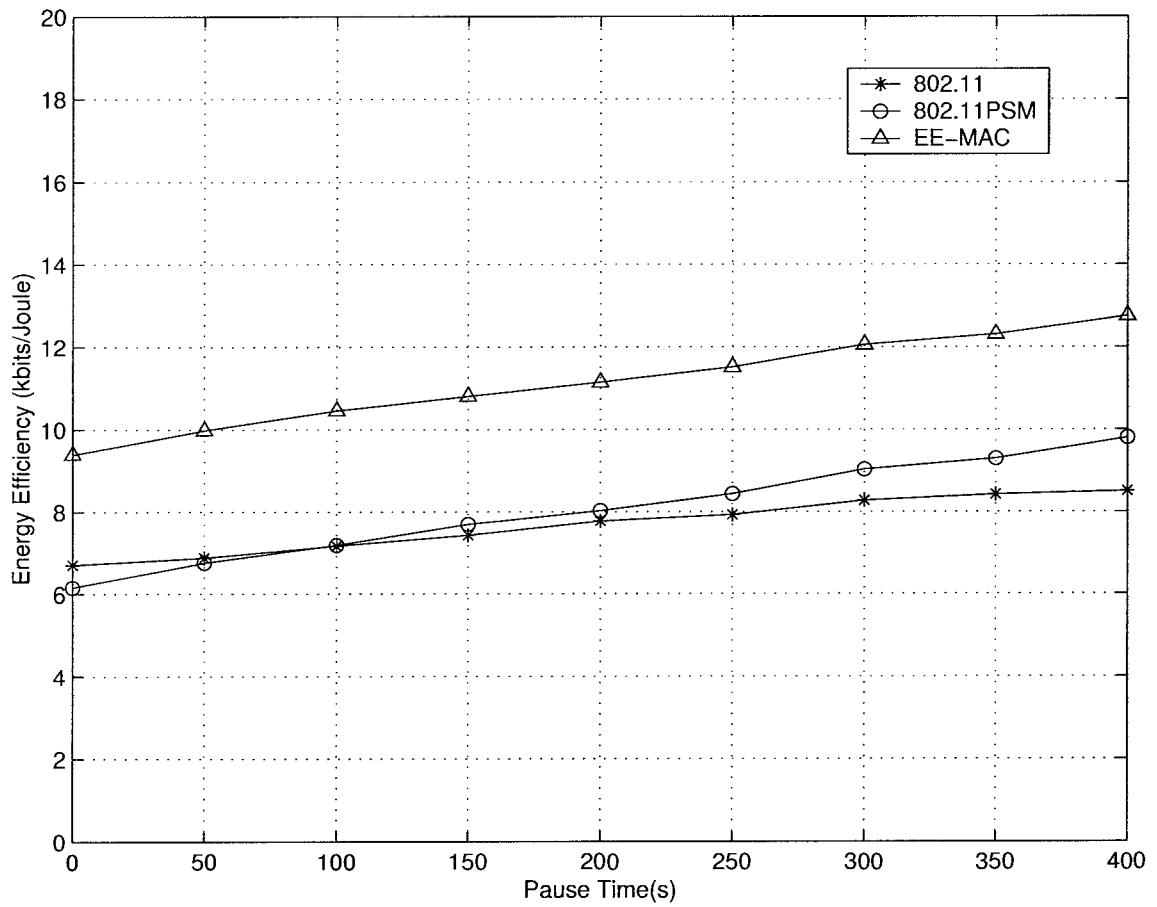


Figure 3.28. Energy efficiency with 50 nodes, 10 sources and 20 packets/s in an area of $750m \times 750m$.

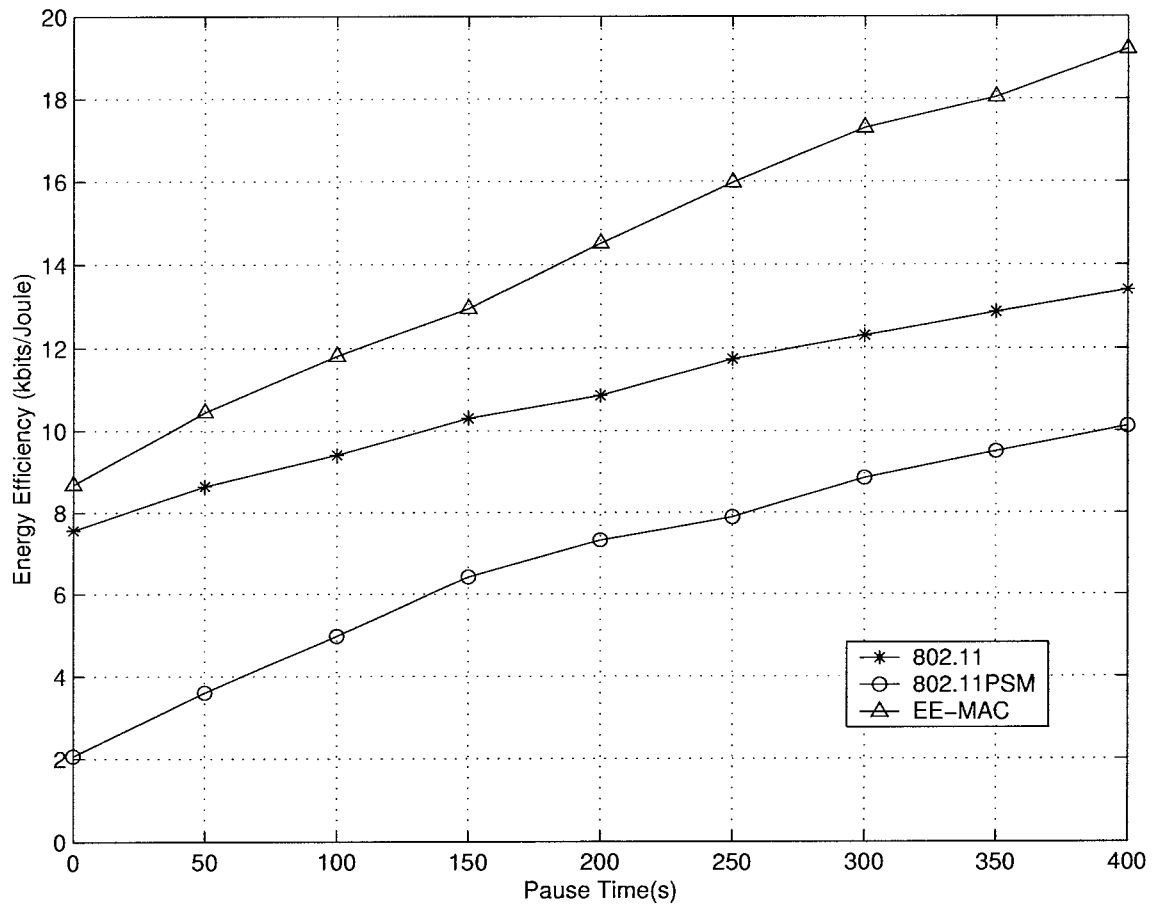


Figure 3.29. Energy efficiency with 50 nodes, 10 sources and 40 packets/s in an area of $750m \times 750m$.

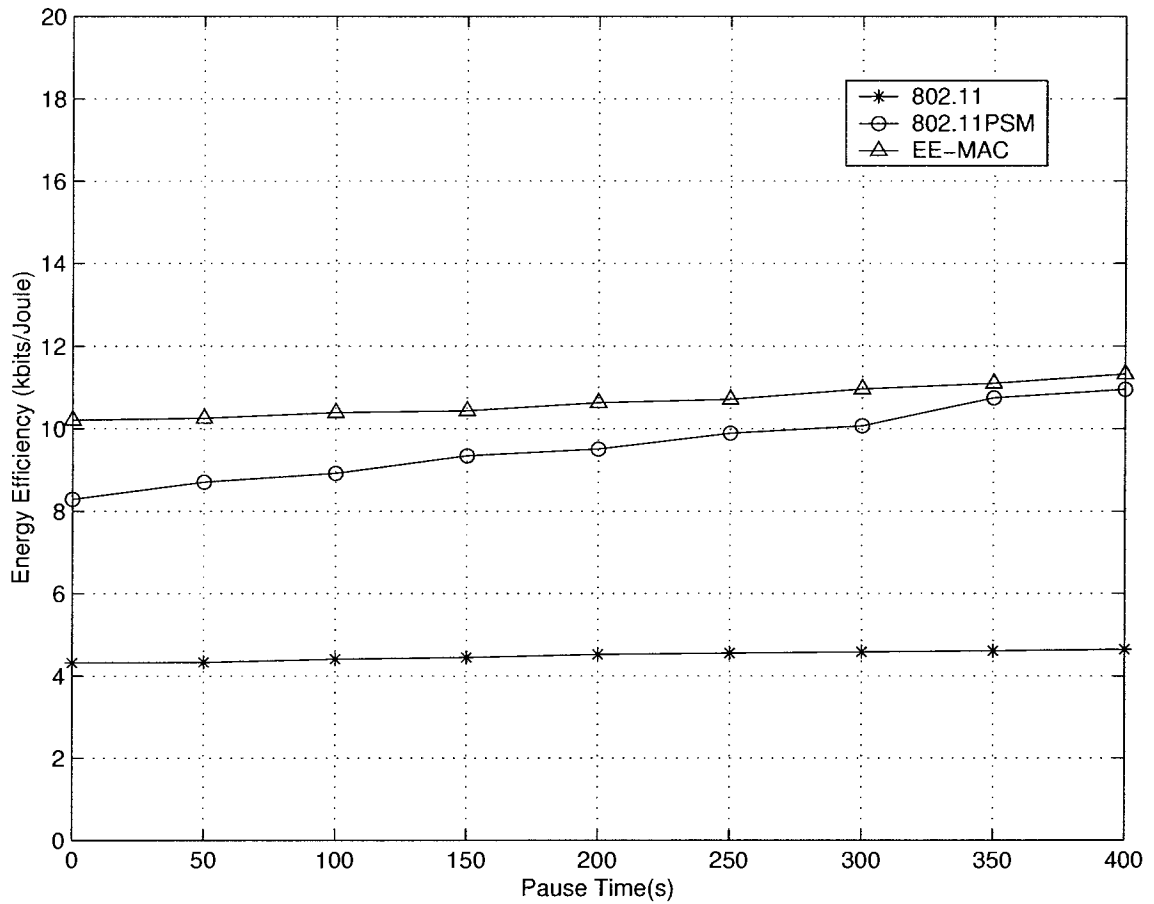


Figure 3.30. Energy efficiency with 50 nodes, 5 sources and 20 packets/s in an area of $750m \times 750m$.

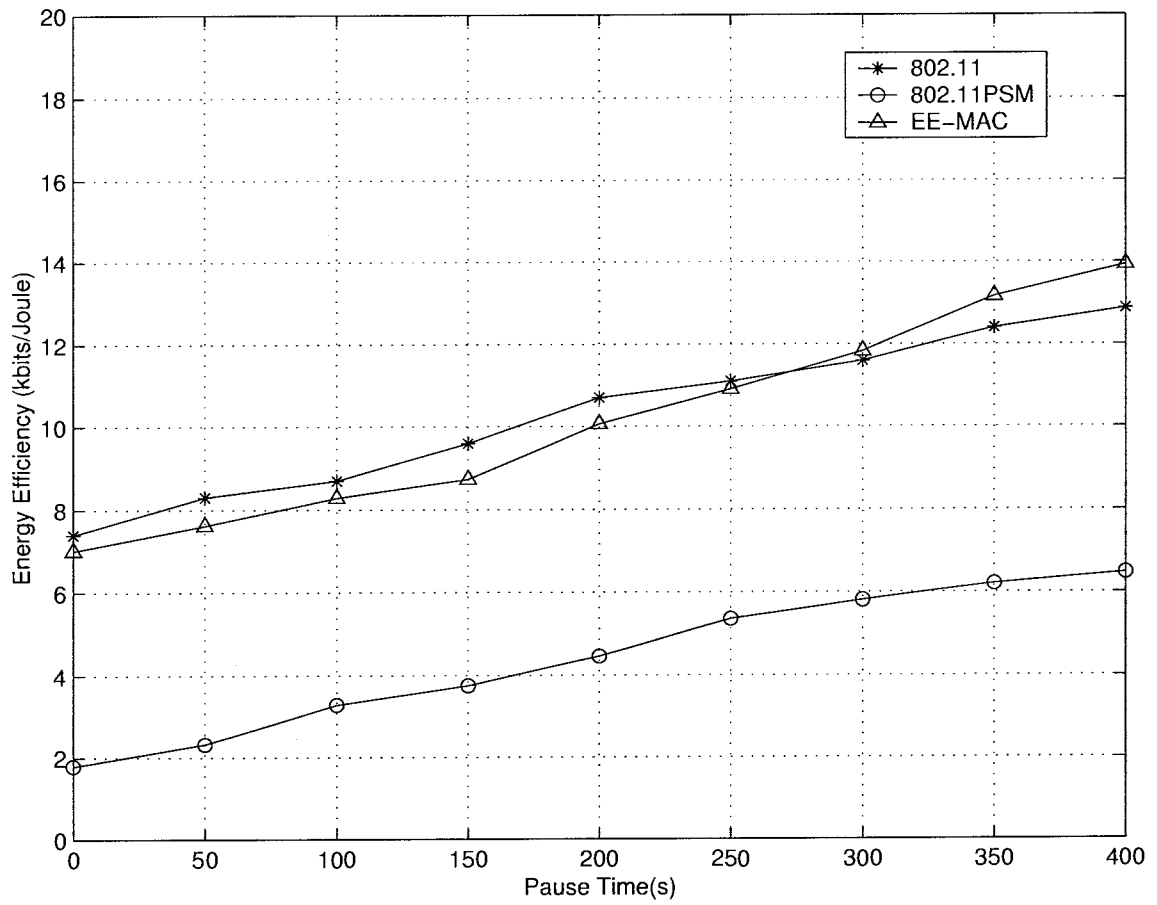


Figure 3.31. Energy efficiency with 50 nodes, 20 sources and 20 packets/s in an area of $750m \times 750m$.

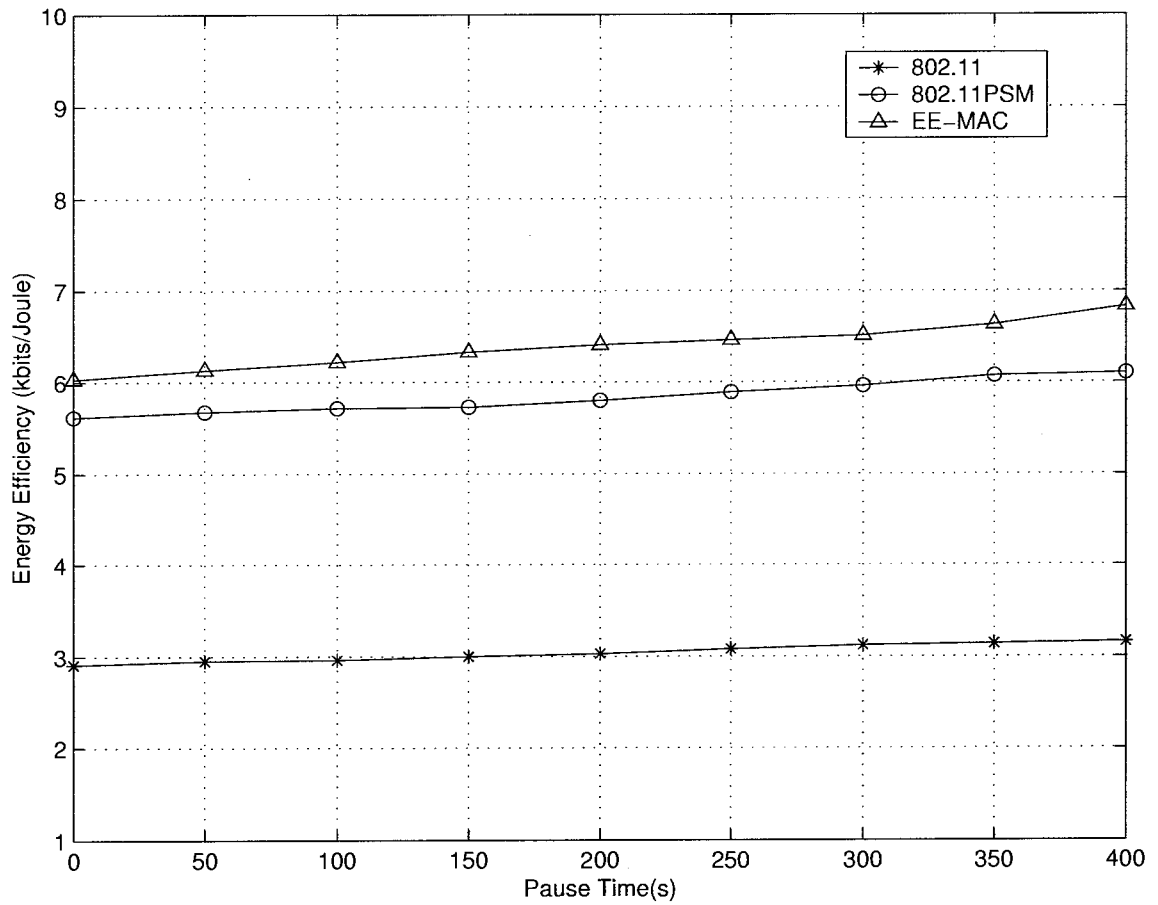


Figure 3.32. Energy efficiency with 75 nodes, 10 sources and 10 packets/s in an area of $750m \times 750m$.

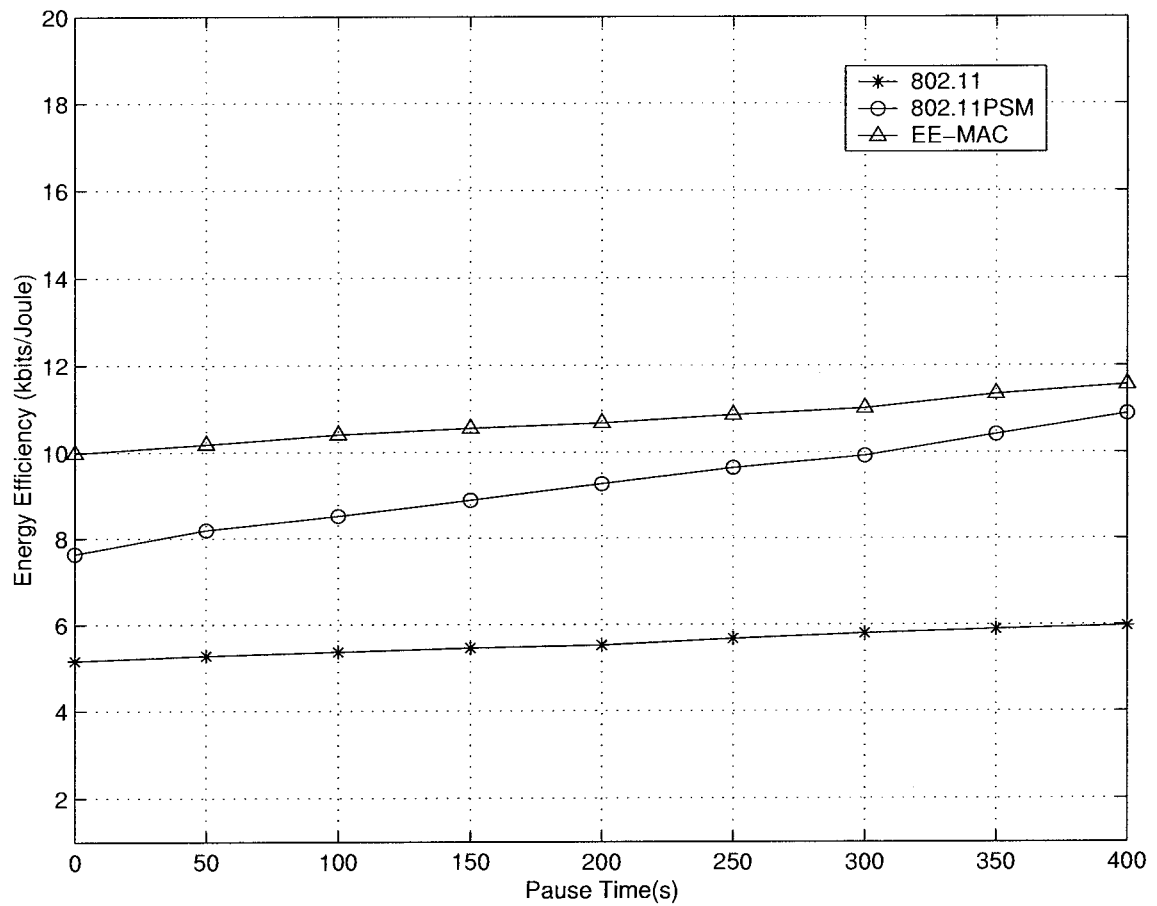


Figure 3.33. Energy efficiency with 75 nodes, 10 sources and 20 packets/s in an area of $750m \times 750m$.

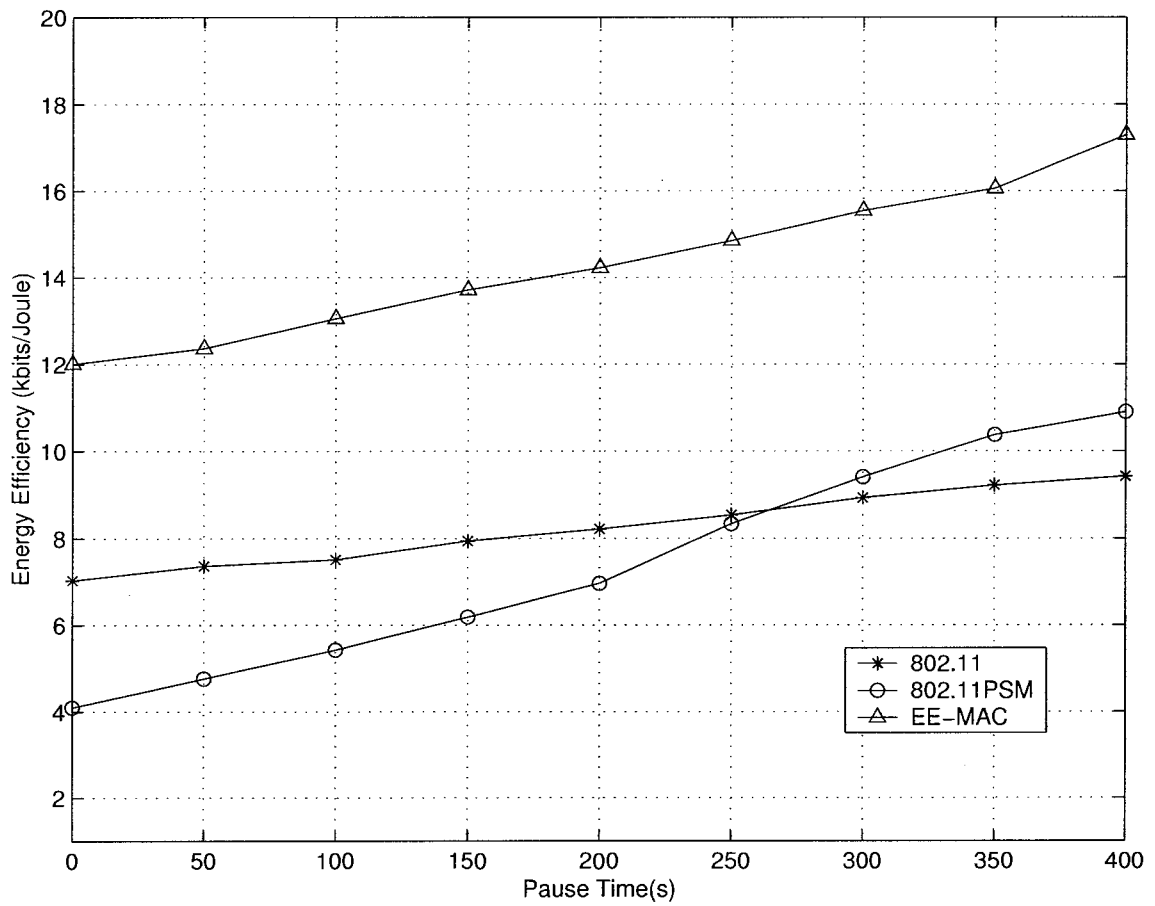


Figure 3.34. Energy efficiency with 75 nodes, 10 sources and 40 packets/s in an area of 750m × 750m.

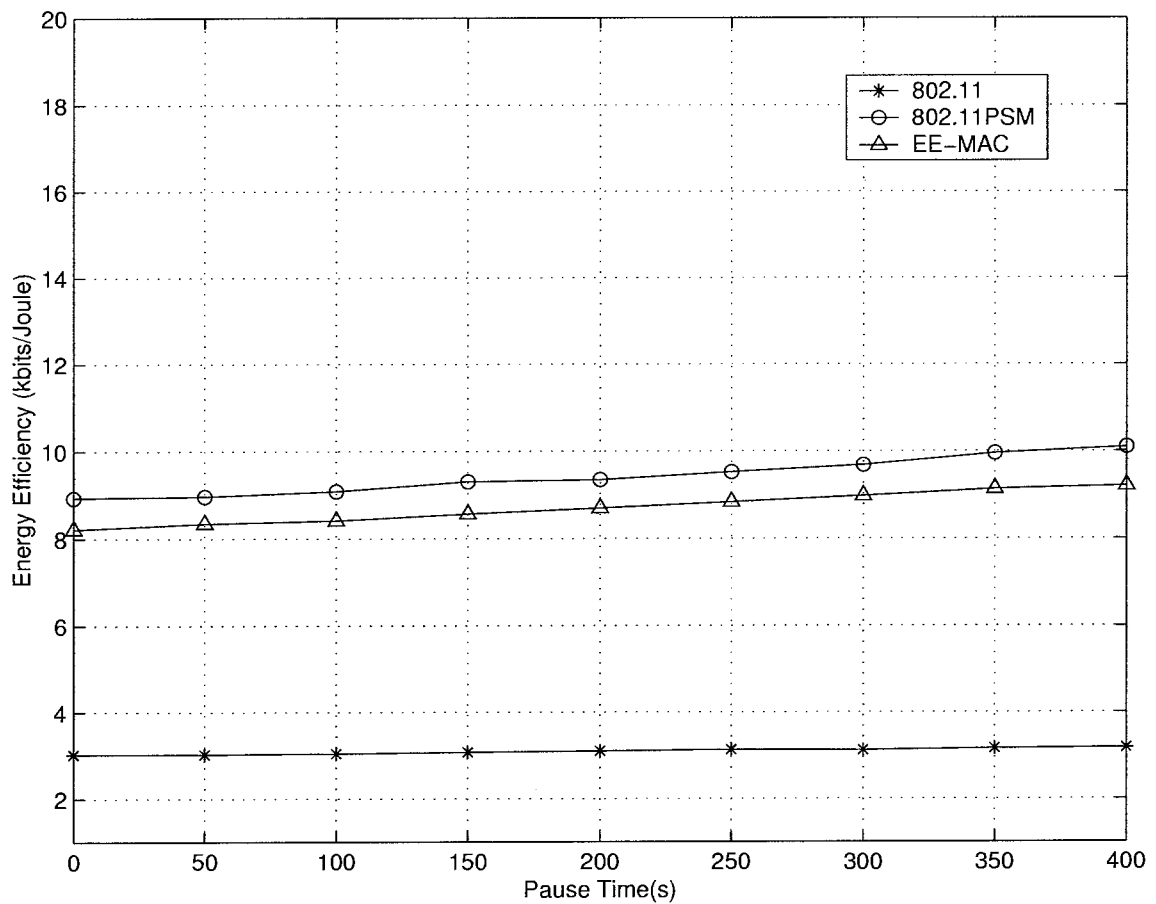


Figure 3.35. Energy efficiency with 75 nodes, 5 sources and 20 packets/s in an area of $750m \times 750m$.

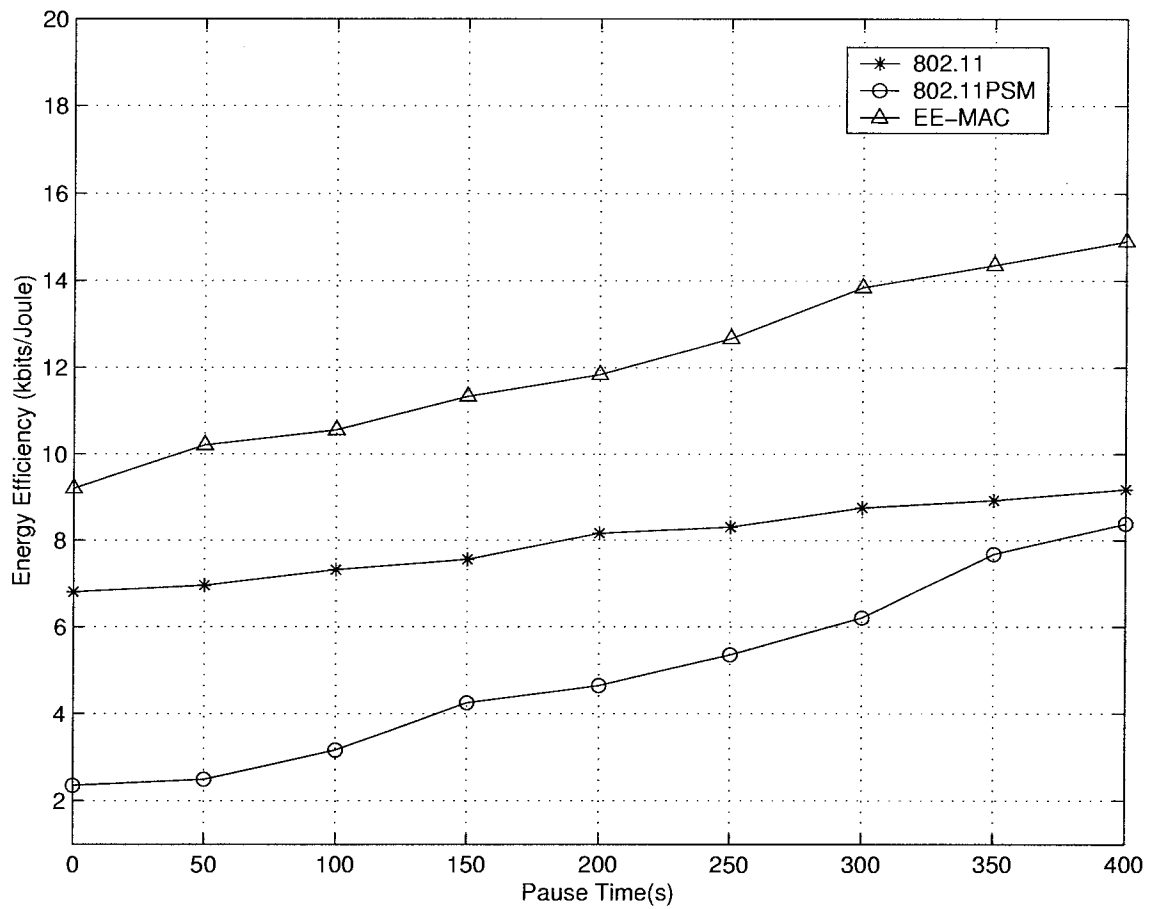


Figure 3.36. Energy efficiency with 75 nodes, 20 sources and 20 packets/s in an area of $750m \times 750m$.

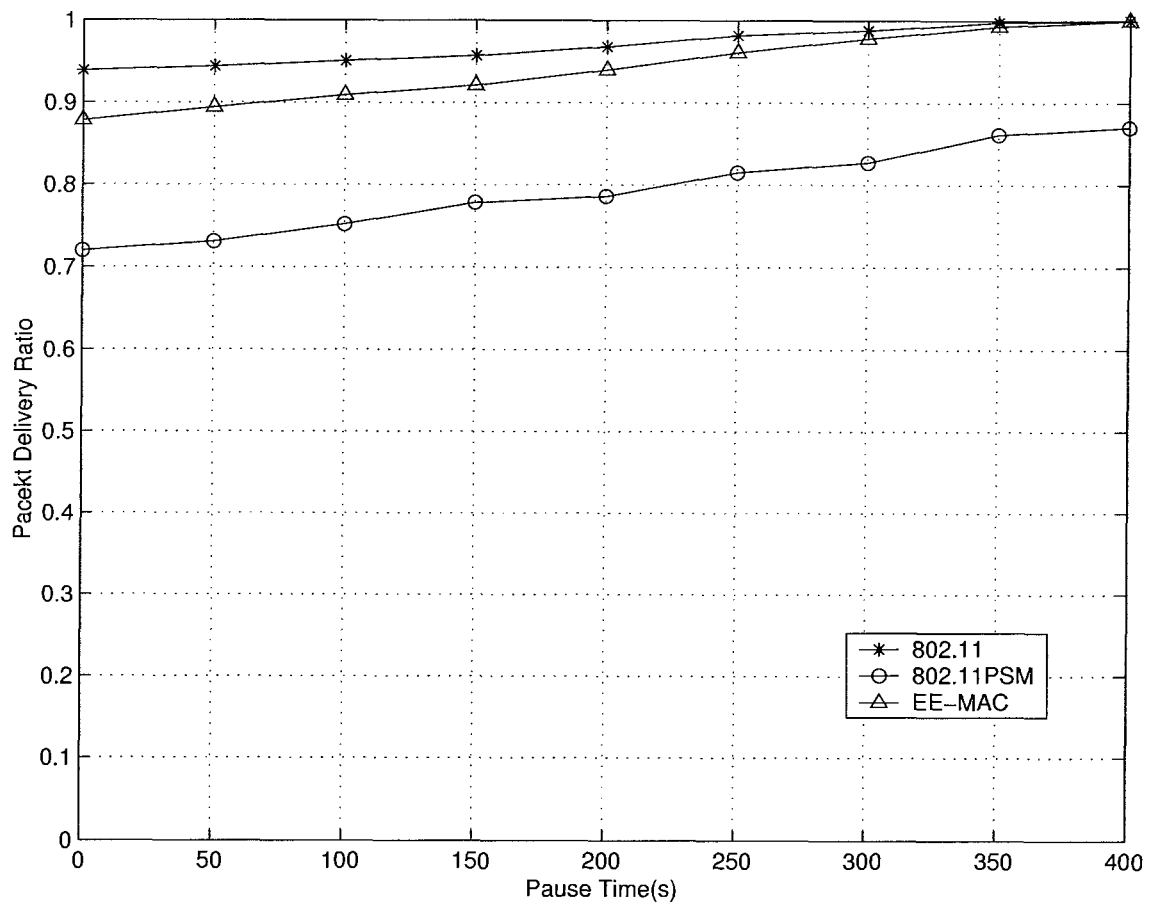


Figure 3.37. Packet delivery ratio with 100 nodes, 10 sources and 20 packets/s load in an area of 750m \times 750m.

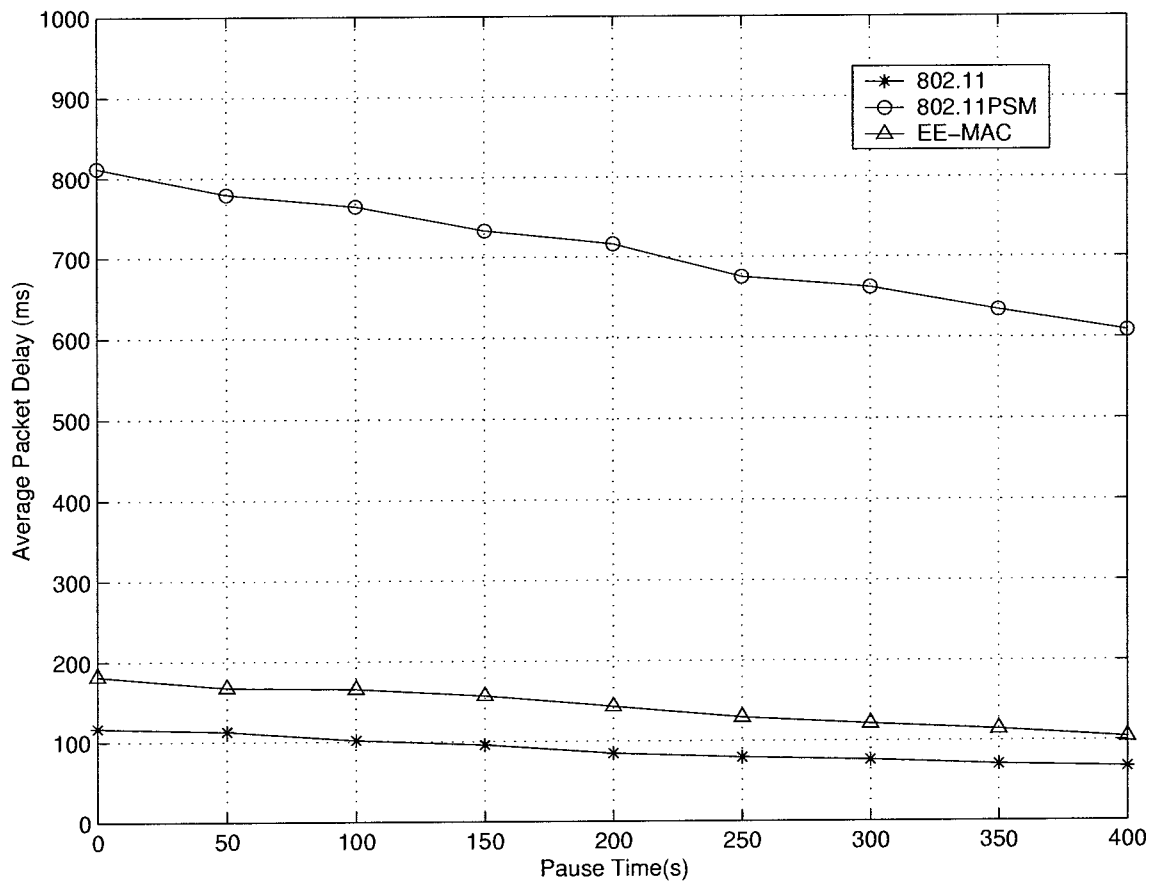


Figure 3.38. Average packet delay with 100 nodes, 10 sources and 20 packets/s load in an area of 750m × 750m.

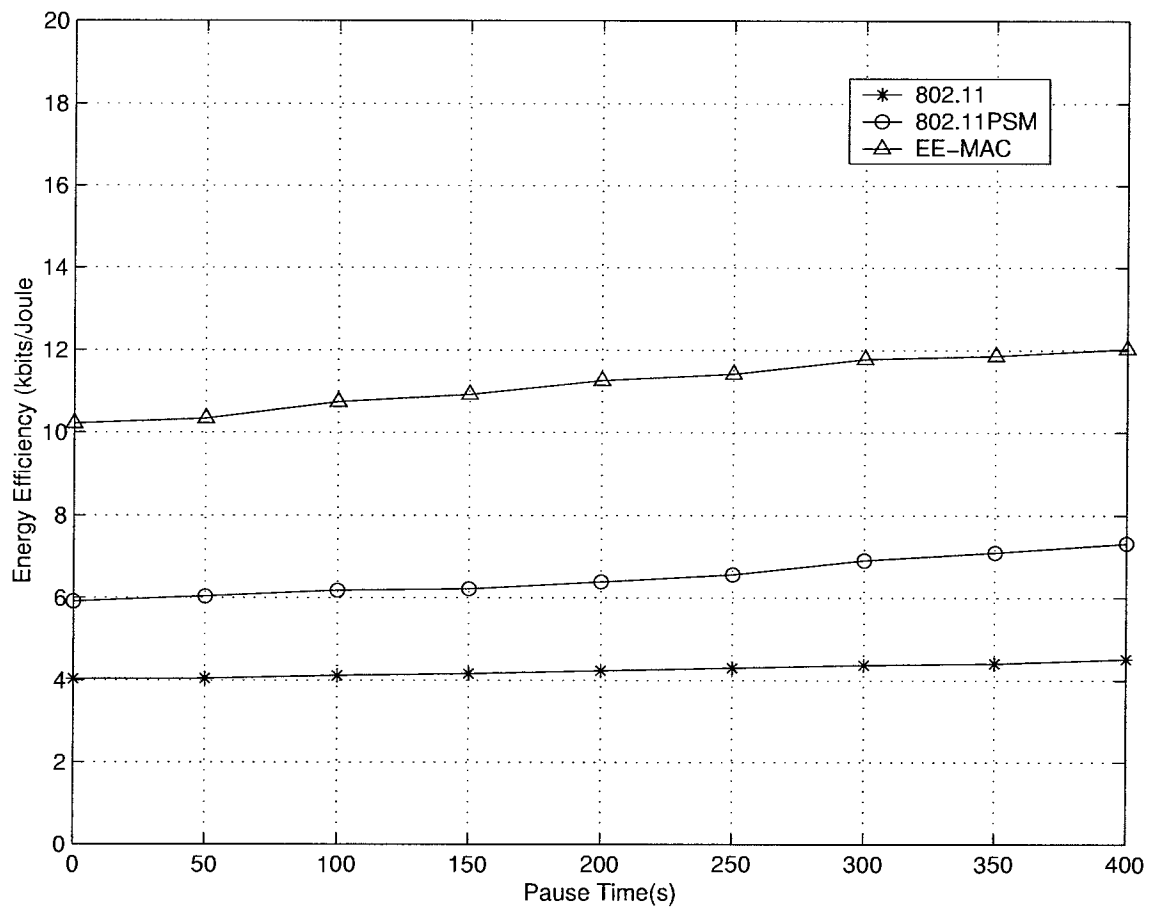


Figure 3.39. Energy efficiency with 100 nodes, 10 sources and 20 packets/s in an area of $750m \times 750m$.

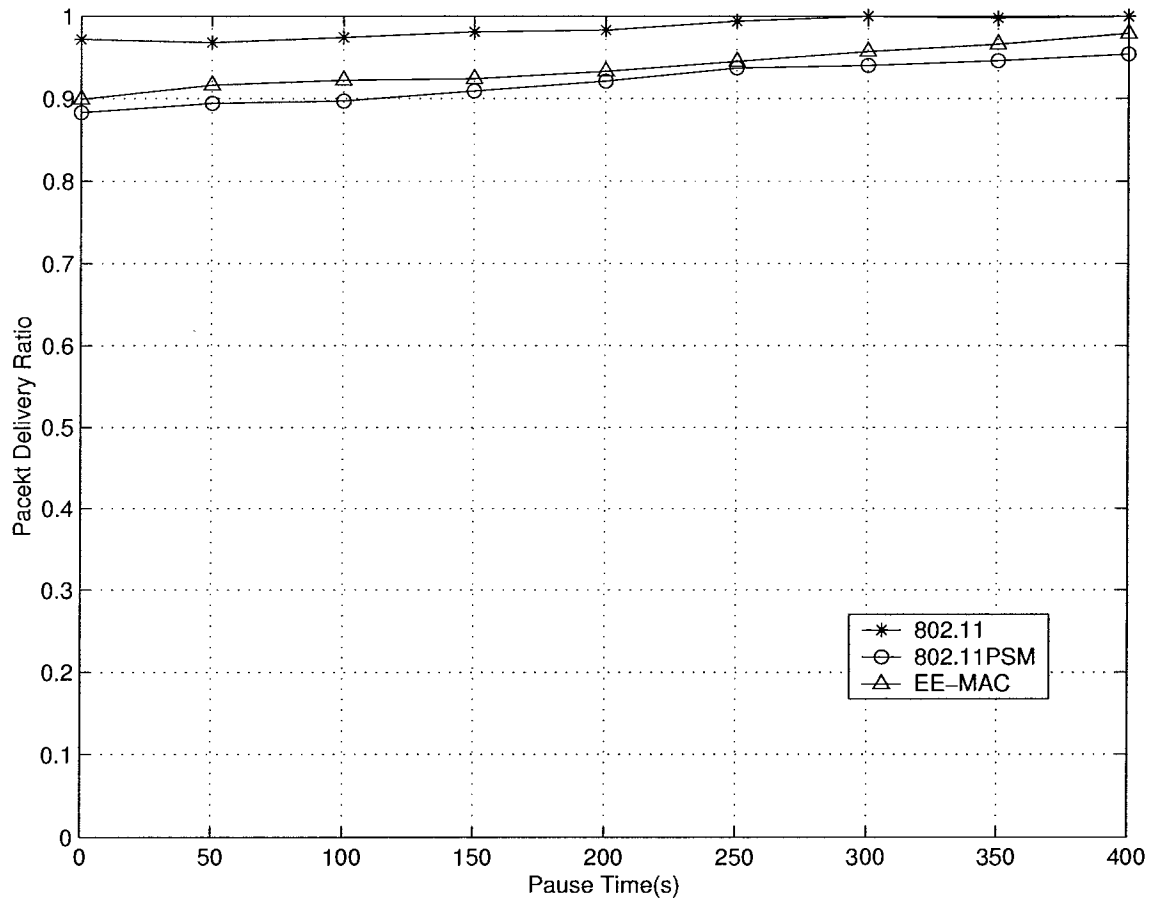


Figure 3.40. Packet delivery ratio with 25 nodes, 10 sources and 20 packets/s in an area of $500m \times 500m$.

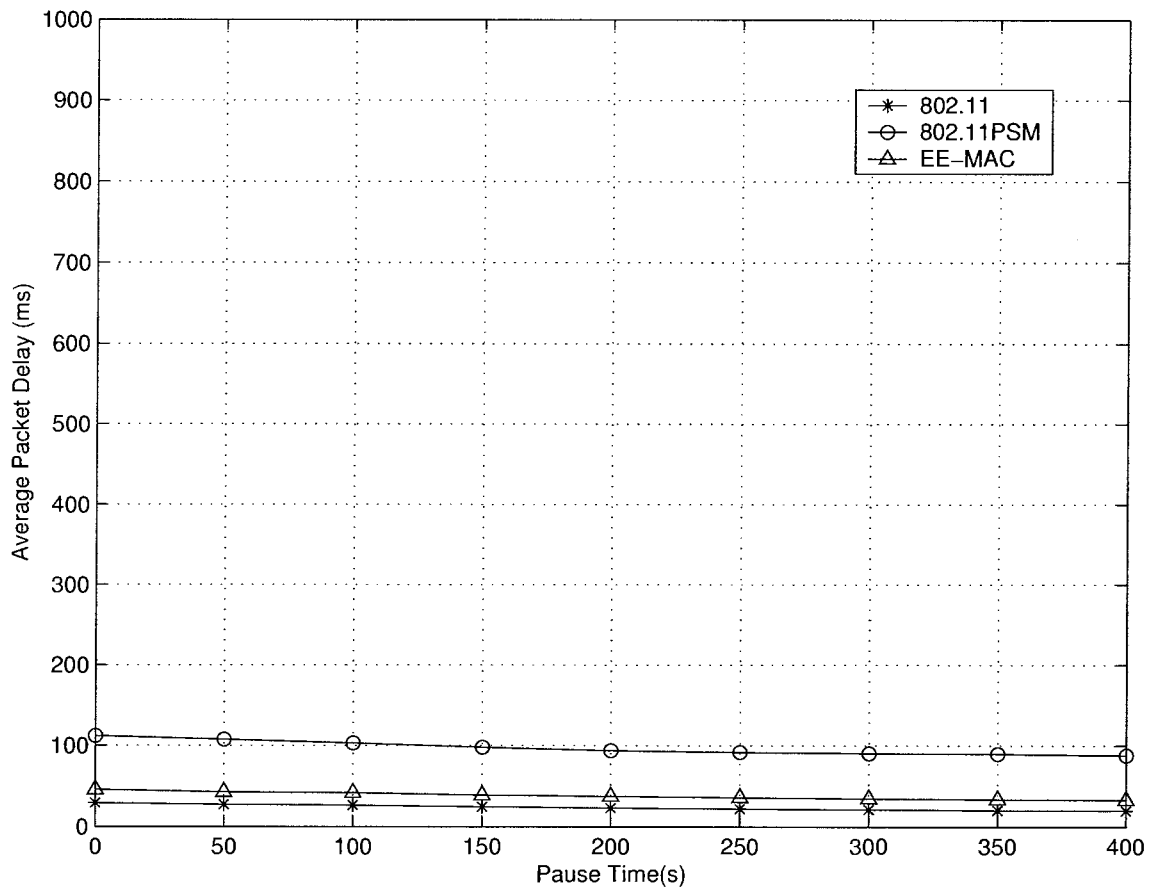


Figure 3.41. Average packet delay with 25 nodes, 10 sources and 20 packets/s in an area of $500m \times 500m$.

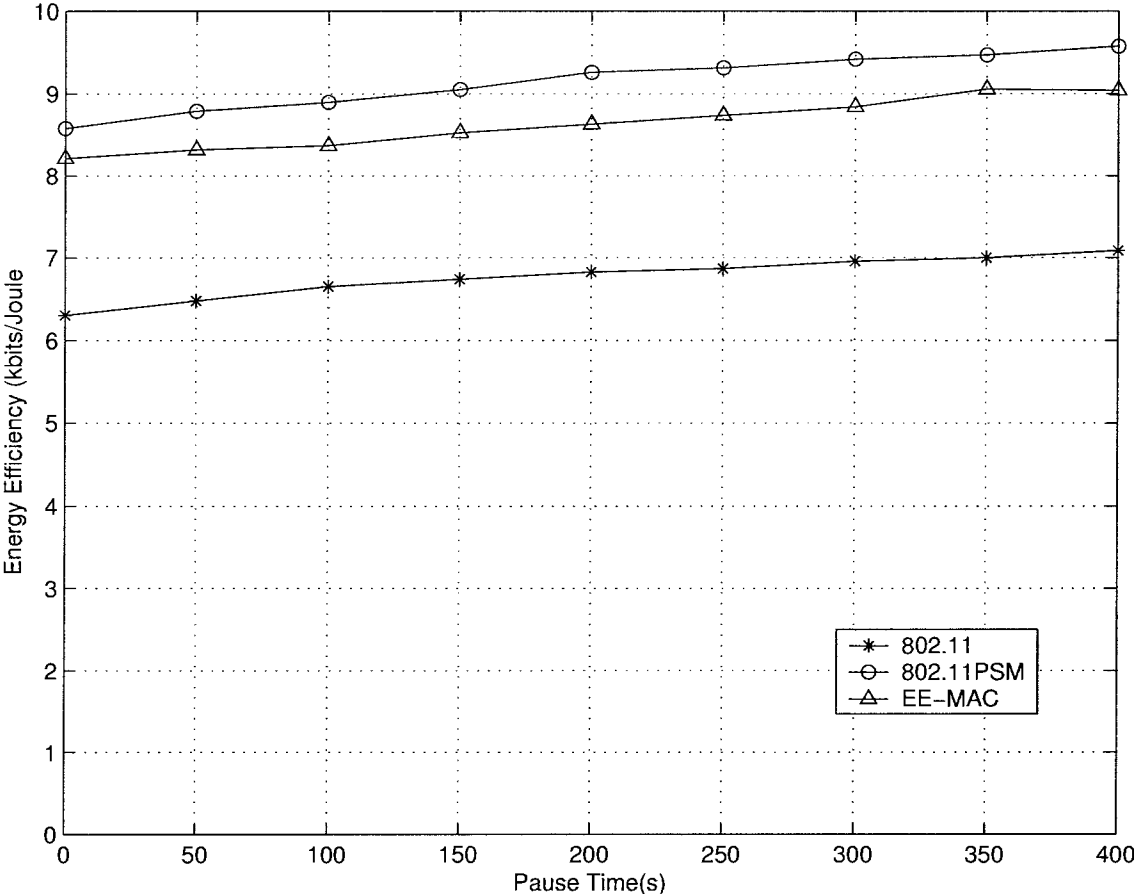


Figure 3.42. Energy efficiency with 25 nodes, 10 sources and 20 packets/s in an area of 500m × 500m.

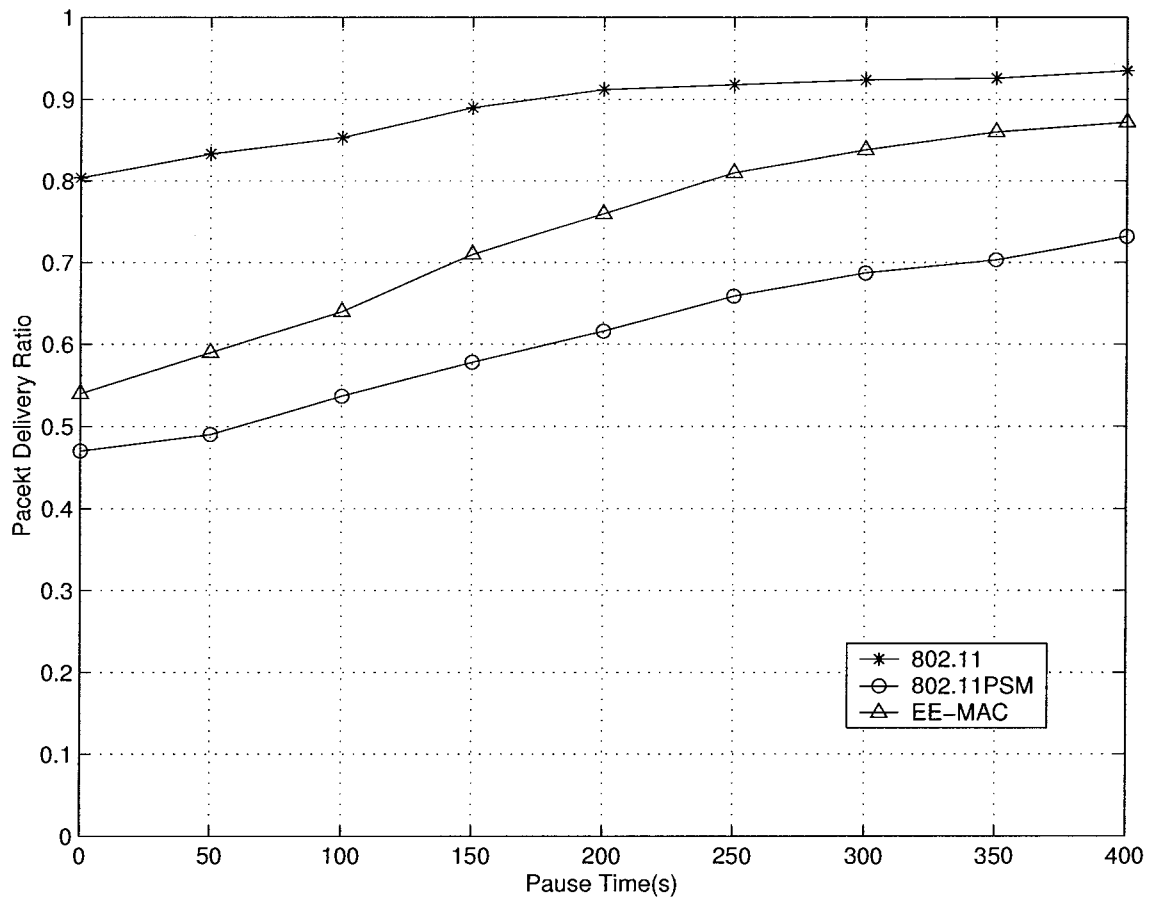


Figure 3.43. Packet delivery ratio with 75 nodes, 10 sources and 20 packets/s in an area of $1000m \times 1000m$.

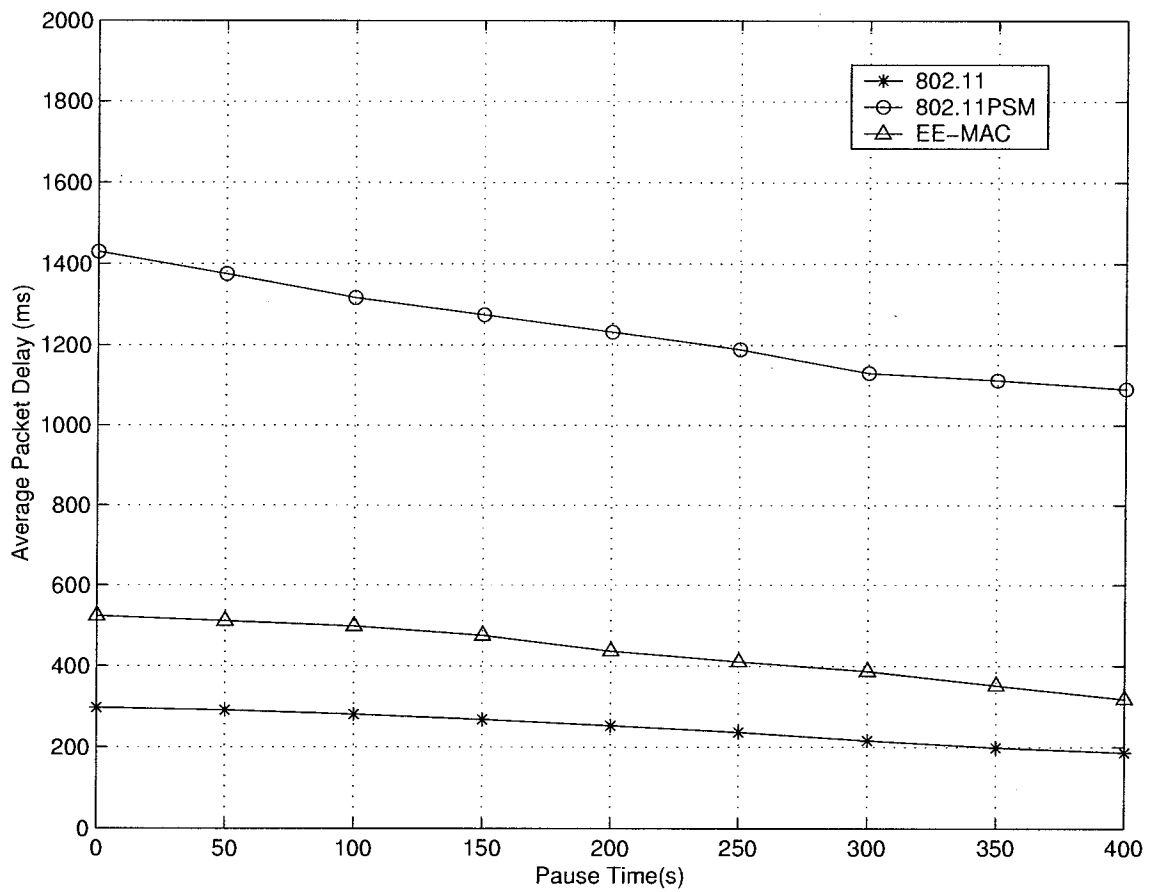


Figure 3.44. Average packet delay with 75 nodes, 10 sources and 20 packets/s in an area of $1000m \times 1000m$.

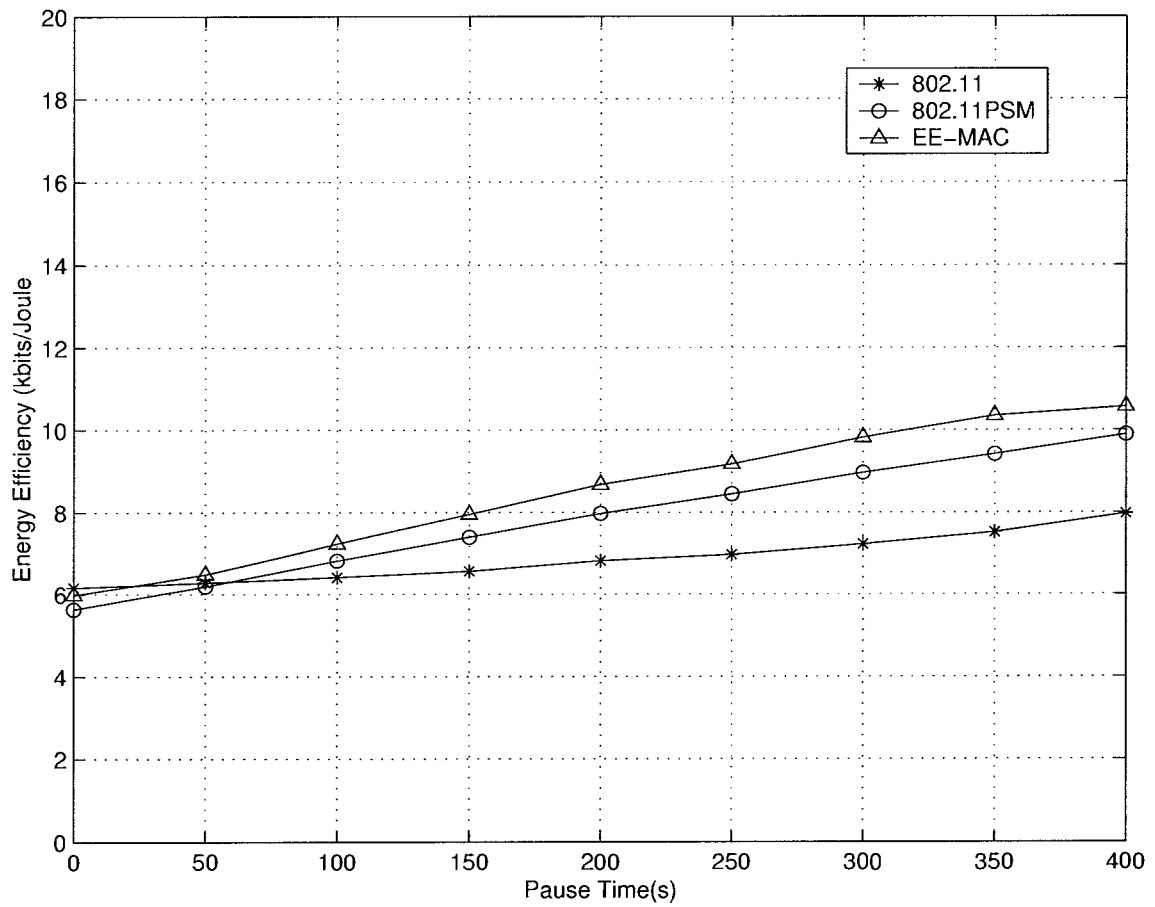


Figure 3.45. Energy efficiency with 75 nodes, 10 sources and 20 packets/s in an area of $1000m \times 1000m$.

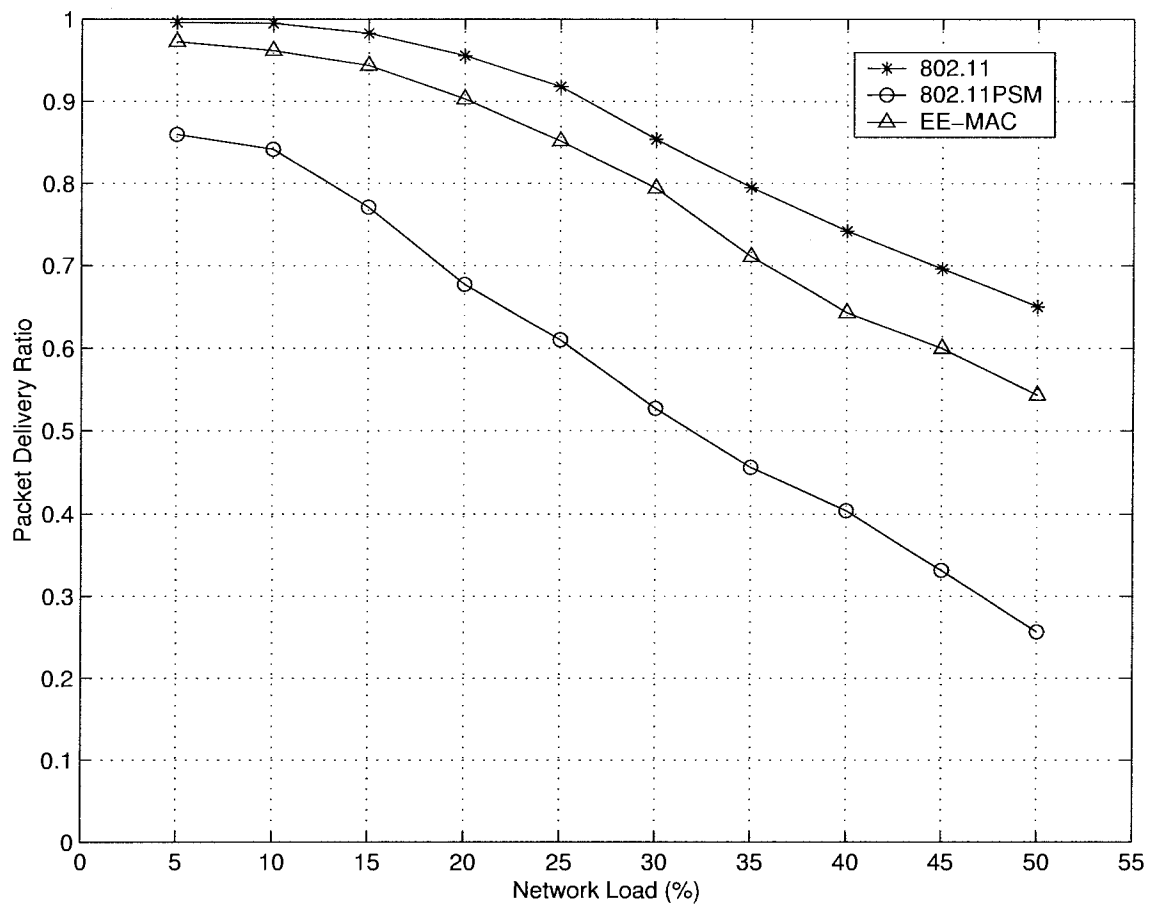


Figure 3.46. Packet delivery ratio with 50 nodes, 10 sources and 5% to 50% network load without mobility in an area of $750\text{m} \times 750\text{m}$.

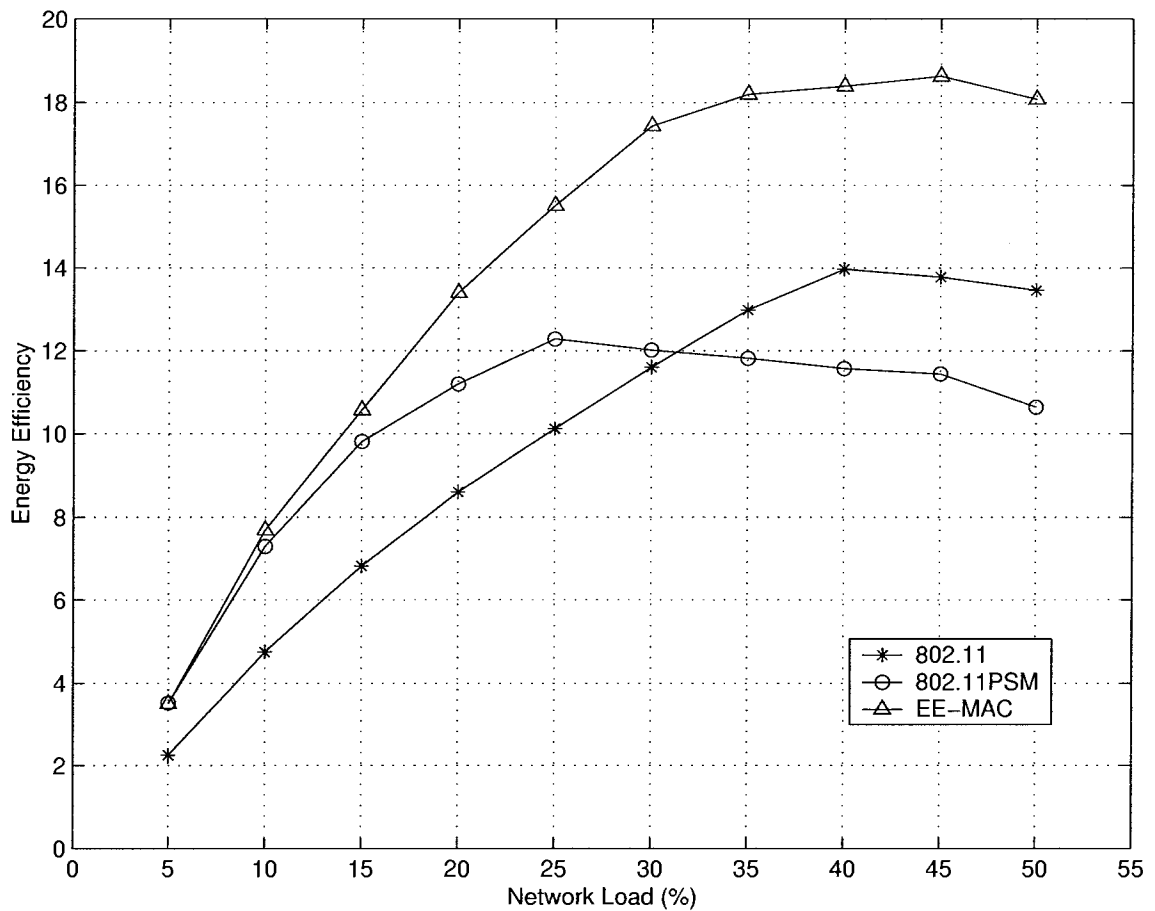


Figure 3.47. Energy efficiency with 50 nodes, 10 sources and 5% to 50% network load without mobility in an area of $750\text{m} \times 750\text{m}$.

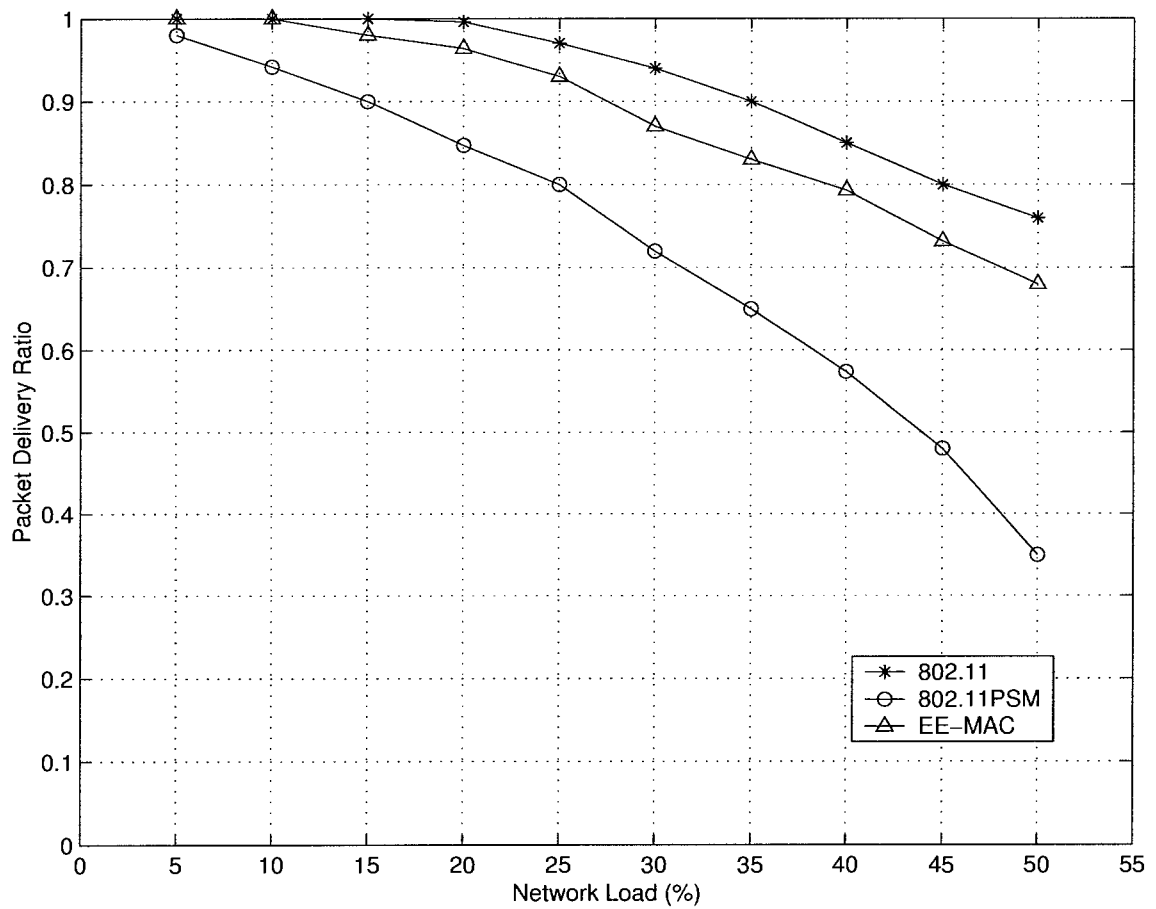


Figure 3.48. Packet delivery ratio with 75 nodes, 10 sources and 5% to 50% network load without mobility in an area of $750m \times 750m$.

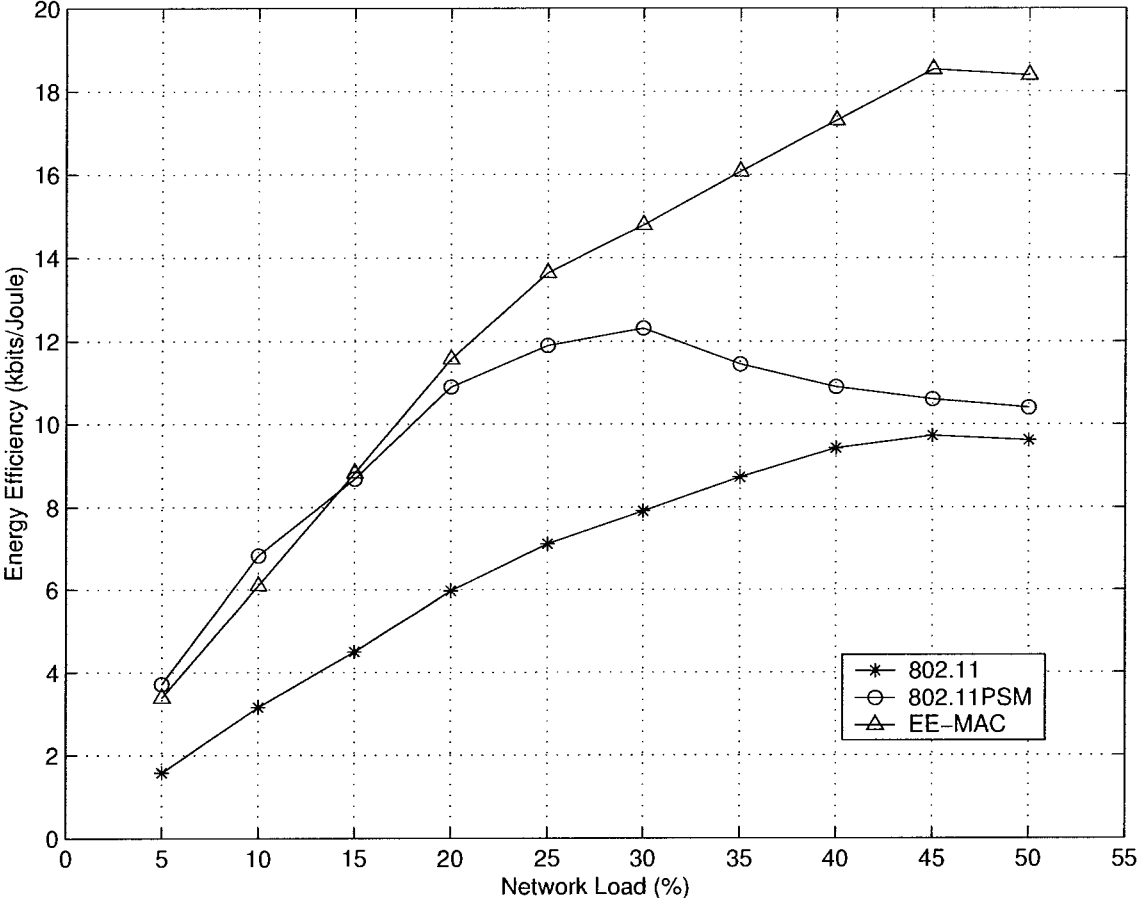


Figure 3.49. Energy efficiency with 75 nodes, 10 sources and 5% to 50% network load without mobility in an area of 750m × 750m.

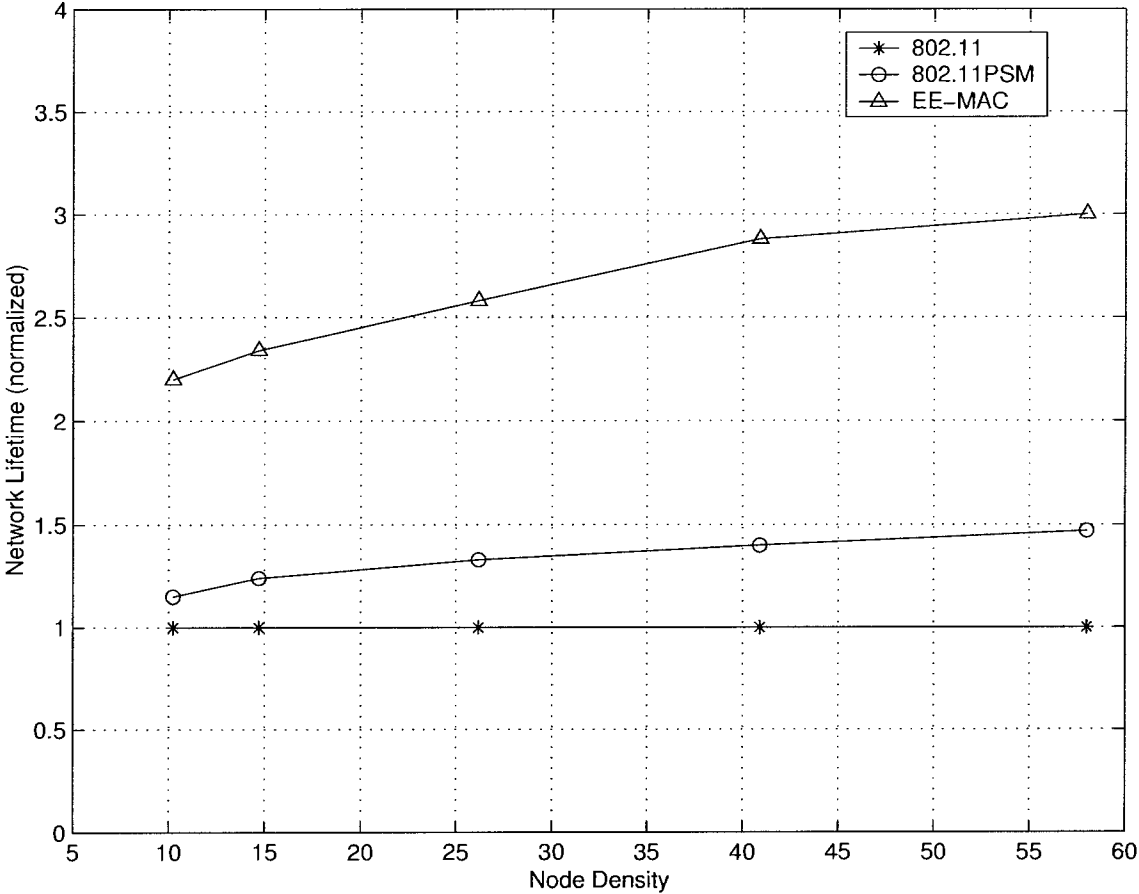


Figure 3.50. Network Lifetime Normalized to IEEE 802.11 with 75 nodes, 10 sources and 10 packets/s without mobility in an area of 750m × 750m.

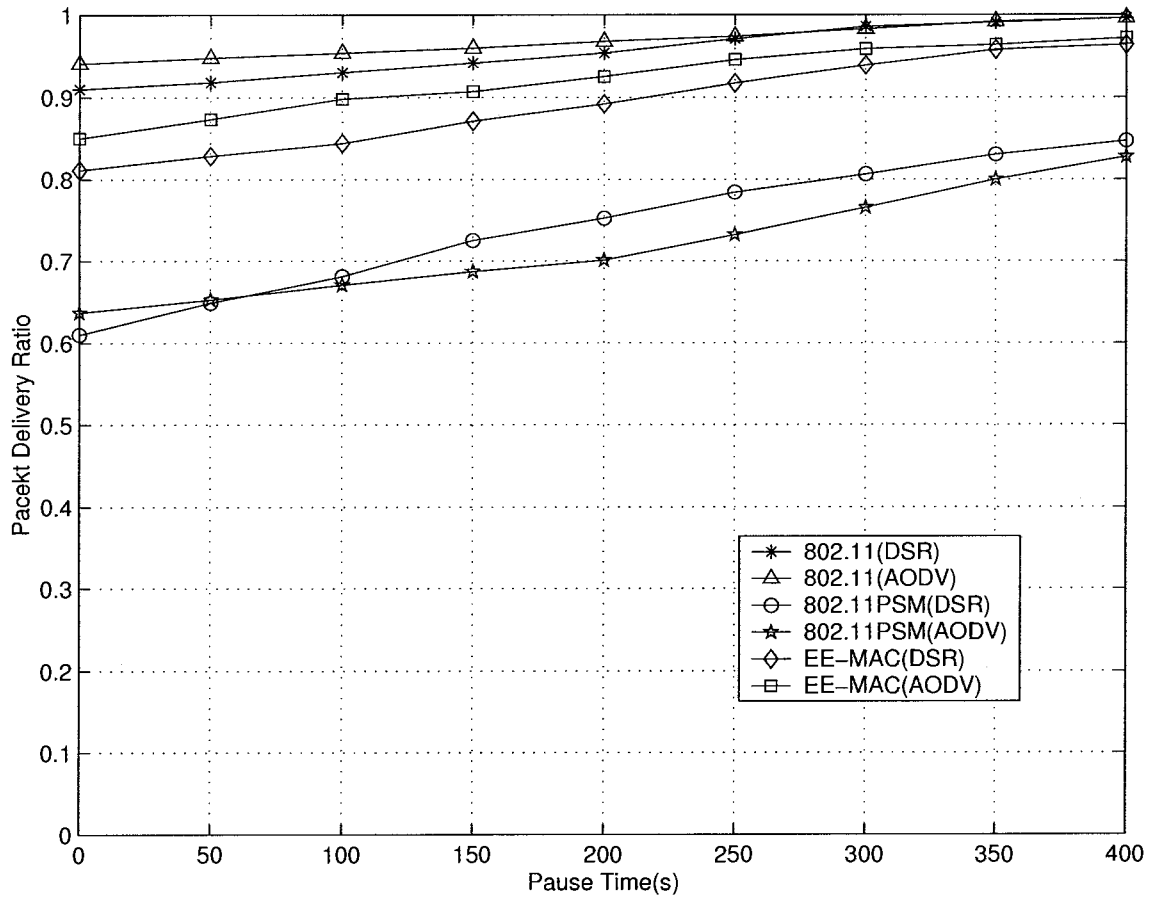


Figure 3.51. AODV vs. DSR with 75 nodes, 10 sources and 20 packets/s in an area of 750m × 750m.

Chapter 4

Conclusions and Future Work

This chapter concludes the thesis and presents some directions for future research.

4.1 Conclusions

This thesis presented EE-MAC, an energy-efficient MAC protocol for mobile ad hoc networks. The goal was to reduce energy consumption in an ad hoc network without sacrificing network throughput.

In Chapter 1, we gave an overview of mobile ad hoc networks, introduced their applications and presented some research challenges. A complete design scheme for energy-saving wireless networks was presented in Chapter 2, from the hardware perspective and system perspective. For the system level, we introduced an energy-efficient design for ad hoc networks which uses power control, power-aware routing and power management. Related research on these topics was also presented.

In this thesis, we focused on energy-efficient MAC protocol design for an ad hoc network. As a basis for our work, the IEEE 802.11 MAC protocol and its power saving mode were described in Chapter 3 in detail. Then, we proposed the EE-MAC protocol. The key idea is to form a connected dominating set and use this as a virtual backbone to route packets, while other network nodes stay in power-saving mode which means a node can go into sleep mode when no data is addressed to it. To form a connected dominating set, we used the algorithm given in [44] and made some modifications. Finally, the features of EE-MAC

were presented.

EE-MAC was simulated using the ns-2 network simulator and the results were compared with IEEE 802.11 and its power saving mode. The results show that IEEE 802.11 performs better than EE-MAC in terms of packet delivery ratio and average packet delay. However, EE-MAC exceeds IEEE 802.11 in energy efficiency and is much better than PSM in overall terms. The network load has a great impact on the behavior of EE-MAC. Under a light network load, EE-MAC is only slightly worse than IEEE 802.11, but as the network load increases, the difference in performance between EE-MAC and IEEE 802.11 increases because EE-MAC needs to rotate masters and slaves more frequently with high traffic. When the node mobility increases, EE-MAC suffers because it requires more frequent reelection of masters. Simulation results also show that the higher the node density, the better EE-MAC performs. In summary, we may say that a mid-sized network with relatively high node density is the best environment to utilize EE-MAC. We also presented simulation results under different conditions to show that EE-MAC scales well compared to other energy efficient protocols.

4.2 Limitations and Future work

The proposed protocol works well in our simulation environments, but this does not necessarily guarantee it can work well under other conditions which could be severe.

In this thesis, the existence of a global synchronization system was assumed, which allows all nodes to wake up at the same time to check whether they have packets to receive. However, achieving and maintaining synchronization is a problem that deserves significant study. Although maintaining synchronization in a single-hop ad hoc network is not so difficult, it is a challenge to achieve synchronization in a multi-hop ad hoc network. Therefore, designing synchronization solutions or an asynchronous wake-up mechanism is a worthwhile project.

Our current work is based on IEEE 802.11 PSM and so there always exists an ATIM

window which occupies some channel resources. Thus, another possible topic is to design a solution that does not use the ATIM window and thus makes full use of the channel bandwidth.

The proposed protocol is based on a connected dominating set (CDS) which can serve as a virtual backbone in the network. However, nodes in the CDS may move away so that the CDS needs to be reformed. Thus, dynamically maintaining the CDS introduces substantial overhead and so designing a quick and low-payoff CDS generation and maintenance algorithm is desirable.

Designing MAC and Network layer protocols to save energy consumed in ad hoc networks is only one direction. Another important direction is to vary the transmission power between nodes so that the signal is just powerful enough to be correctly decoded at the receiver. However, reducing transmission power will cause a reduced transmission range and affect routing performance. Therefore, how to combine this power control into an effective power saving mechanism is challenging.

Mobile ad hoc networks will continue to flourish in future years. An eventual integration of ad hoc networks and other wireless or wired network is inevitable. In the evolution towards fourth generation wireless networks, the ad hoc network will play an important role. Thus, it is desirable to consider these future research directions.

Bibliography

- [1] *Intel PXA27x Processor Family Developer's Manual*. [Online]. Available: <ftp://download.intel.com/design/pca/applicationsprocessors/manuals/2800002.pdf>
- [2] *Information Technology- Telecommunications and Information Exchange Between Systems- Local and Metropolitan Area Networks- Specific Requirements- Part 11: wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*. IEEE Std 802.11, 1999.
- [3] *Supplement to IEEE Standard for Information Technology- Telecommunications and Information Exchange Between Systems- Local and Metropolitan Area Networks- Specific Requirements- Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: High-speed Physical Layer in the 5 GHz band*. IEEE Std 802.11a, 1999.
- [4] *Supplement To IEEE Standard For Information Technology- Telecommunications and Information Exchange Between Systems- Local and Metropolitan Area Networks- Specific Requirements- Part 11: Wireless LAN Medium Access Control (MAC) And Physical Layer (PHY) Specifications: High-speed Physical Layer Extension In 2.4 GHz Band*. IEEE Std 802.11b, 2000.
- [5] *Information Technology- Telecommunications and Information Exchange Between Systems- Local and Metropolitan Area Networks- Specific Requirements- Part 11: wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. Amendment 4: Further High Data Rate Extension in the 2.4 GHz Band*. IEEE Std 802.11g, 2003.
- [6] S. Agarwal, S. V. Krishnamurthy, R. H. Katz, and S. K. Dao, "Distributed power control in ad-hoc wireless networks," in *Proceedings of IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, vol. 2, Sept. 2001, pp. 59–66.
- [7] C. Bisdikian, "An overview of the bluetooth wireless technology," *IEEE Communication Magazine*, vol. 39, no. 12, pp. 86–94, Dec. 2001.
- [8] J. Broth, D. Maltz, D. Johnson, Y.-C. Hu, and J. Jetcheva, "A performance comparison of multi-hop wireless ad hoc network routing protocols," in *Proceedings of the International Conference on Mobile Computing and Networking*, Oct. 1998, pp. 85–

97.

- [9] A. P. Chandrakasan, S. Sheng, and R. W. Brodersen, "Low-power cmos digital design," vol. 27, no. 4, Apr. 1992, pp. 473–484.
- [10] B. Chen, K. Jamieson, H. Balakrishnan, and R. Morris, "Span: An energy-efficient coordination algorithm for topology maintenance in ad hoc wireless networks," in *Proceedings of ACM/IEEE International Conference on Mobile Computing and Networking*, July 2001, pp. 85–96.
- [11] Y. P. Chen and A. L. Liestman, "Approximating minimum size weakly-connected dominating sets for clustering mobile ad hoc networks," in *Proceedings of the ACM International Symposium on Mobile Ad Hoc Networking and Computing*, 2002, pp. 165–172.
- [12] I. Chlamtac, M. Conti, and J.-N. Liu, "Mobile ad hoc networking: imperatives and challenges," *Ad Hoc Networks*, vol. 1, no. 1, pp. 13–64, July 2003.
- [13] K. Fall and K. Varadhan, *NS notes and Documentation*. The VINT Project, UC Berkeley, USC/ISI, LBL and Xerox Parc, 1999. [Online]. Available: <http://www-mash.cs.berkeley.edu/ns>
- [14] L. M. Feeney and M. Nilsson, "Investigating the energy consumption of a wireless network interface in an ad hoc networking environment," in *INFOCOM*, 2001, pp. 1548–1557.
- [15] M. S. Gast, *802.11 Wireless Networks: The Definitive Guide*. O'Reilly & Associates, Inc., 2002.
- [16] A. J. Goldsmith and S. B. Wicker, "Design challenges for energy-constrained ad hoc wireless networks," *Wireless Communications, IEEE*, vol. 9, no. 4, pp. 8–27, Aug. 2002.
- [17] J. Gomez, A. Campbell, M. Naghshineh, and C. Bisdikian, "Conserving transmission power in wireless ad hoc networks," in *Proceedings of the International Conference on Network Protocols*, Nov. 2001, pp. 24–34.
- [18] B. M. Gordon, E. Tsern, and T. H. Meng, "Design of a low power video decompression chip set for portable applications," *Journal of VLSI Signal Process System*, vol. 13, no. 2-3, pp. 125–142, 1996.
- [19] P. Gupta and P. R. Kumar, "Critical power for asymptotic connectivity," in *Proceedings of the IEEE Conference on Decision and Control*, vol. 1, Dec. 1998, pp. 1106–1110.
- [20] P. Gupta and P. R. Kumar, "The capacity of wireless networks," in *IEEE Transactions on Information Theory*, vol. 46, Mar. 2000, pp. 388–404.

- [21] E.-S. Jung and N. H. Vaidya, "An energy efficient mac protocol for wireless lans," in *Proceedings of Joint Conference of the IEEE Computing and Communications Societies*, vol. 3, June 2002, pp. 1756–1764.
- [22] L. Kleinrock and J. Silvester, "Spatial reuse in multihop packet radio networks," in *Proceedings of IEEE*, vol. 75, no. 1, Jan. 1987, pp. 156–167.
- [23] R. Kravets and P. Krishnan, "Power management techniques for mobile communication," in *Proceedings of the ACM/IEEE International Conference on Mobile Computing and Networking*, 1998, pp. 157–168.
- [24] V. G. moshnyaga and K. Tamaru, "Energy saving techniques for architecture design of portable embedded devices," in *Proceedings of ASIC Conference and Exhibit*, Sept. 1997, pp. 163–167.
- [25] S. Narayanaswamy, V. Kawadia, R. Sreenivas, and P. Kumar, "Power control in ad hoc networks: Theory, architecture, algorithm and implementation of the compow protocol," in *European Wireless Conference*, Feb. 2000, pp. 156–162.
- [26] C. Perkins, E. Royer, S. Das, and M. Marina, "Performance comparison of two on-demand routing protocols for ad hoc networks," *IEEE Personal Communications Magazine*, vol. 8, no. 1, pp. 16–28, 2001.
- [27] C. E. Perkins, *Ad hoc Networking*. Addison-Wesley, 2001.
- [28] M. B. Pursley, "The role of spread spectrum in packet radio networks," in *Proceedings of IEEE*, vol. 75, no. 1, Jan. 1987, pp. 116–134.
- [29] J. M. Rabaey, M. J. Ammer, J. L. da Silva Jr., D. Patel, and S. Roundy, "Picoradio supports ad hoc ultra-low power wireless networking," *Computer*, vol. 33, no. 7, pp. 42–48, July 2000.
- [30] V. Raghunathan, C. Schurgers, S. Park, and M. Srivastava, "Energy-aware wireless microsensor networks," *IEEE Signal Processing Magazine*, pp. 40–50, Mar. 2002.
- [31] R. Ramanathan and R. Hain, "Topology control of multihop wireless networks using transmit power adjustment," in *Proceedings of Annual Joint Conference of the IEEE Computer and Communications Societies*, Mar. 2000, pp. 404–413.
- [32] E. M. Royer and C.-K. Toh, "A review of current routing protocols for ad hoc mobile wireless networks," *IEEE Personal Communications*, pp. 46–55, Apr. 1999.
- [33] M. Schoebinger and T. G. Noll, "Low power cmos design strategies," in *Proceedings of the Conference on Design Automation*, 1994, pp. 594–595.
- [34] S. Sheng, A. Chandrakasan, and R. W. Brodersen, "A portable multimedia terminal for personal communications," *IEEE Communication Magazine*, vol. 30, pp. 64–75, Dec. 1992.

- [35] E. Shih, S.-H. Cho, N. Ickes, R. Min, A. Sinha, A. Wang, and A. Chandrakasan, "Physical layer driven protocol and algorithm design for energy-efficient wireless sensor networks," in *Proceedings of the International Conference on Mobile Computing and Networking*, 2001, pp. 272–287.
- [36] S. Singh and C. S. Raghavendra, "Pamas:power aware multi-access protocol with signalling for ad hoc networks," *SIGCOMM Comput. Commun. Rev.*, vol. 28, no. 3, pp. 5–26, 1998.
- [37] F. A. Tobagi, "Modeling and performance analysis of multihop packet radio networks," *Proceedings of the IEEE*, pp. 135–155, Jan. 1987.
- [38] UCB LBNL VINT Group, "Network simulator (version 2)," [Online]. Available: <http://mash.cs.berkeley.edu/ns>
- [39] P.-J. Wan, K. M. Alzoubi, and O. Frieder, "Distributed construction of connected dominating set in wireless ad hoc networks," *Mobile Networks and Applications*, vol. 9, pp. 141–149, Apr. 2004.
- [40] M. Weiser, *The computer for the twenty-first century*. Scientific American, September 1991.
- [41] N. H. E. Weste and K. Eshraghian, *Principles of CMOS VLSI design: a systems perspective*. Addison-Wesley, 1985.
- [42] K. Woo, C. Yu, D. Lee, H. Y. Youn, and B. Lee, "Non-blocking, localized routing algorithm for balanced energy consumption in mobile ad hoc networks," in *Proceedings of the International Symposium in Modeling, Analysis and Simulation of Computer and Telecommunication Systems*, Aug. 2001, pp. 117–124.
- [43] J. Wu and H. Li, "On calculating connected dominating set for efficient routing in ad hoc wireless networks," in *Proceedings of the International Workshop on Discrete Algorithms and Methods for Mobile Computing and Communications*, 1999, pp. 7–14.
- [44] J. Wu and H. Li, "Domination and its applications in ad hoc wireless networks with unidirectional links," in *Proceedings of the International Conference on Parallel Processing*, 2000, pp. 189–197.
- [45] Y. Xu, J. Heidemann, and D. Estrin, "Geography-informed energy conservation for ad hoc routing," in *Proceedings of the International Conference on Mobile Computing and Networking*, 2001, pp. 70–84.
- [46] R. Zheng and R. Kravets, "On-demand power management for ad hoc networks," in *Proceedings of Joint Conference of the IEEE Computer and Communications Societies*, Mar. 2003, pp. 481–491.