ABSTRACT

ENABLING COST AWARE ROUTING WITH AUCTIONS
IN WIRELESS AD-HOC NETWORKS

by
Ali Yuksel

Battery power is a precious resource in wireless ad-hoc networks, and most routing protocols that have been proposed so far do not generate cost efficient routes. In this thesis, a novel auction-based cost-aware routing scheme, called CARA, is presented. CARA is designed as an extension of the MAC layer, and is shown to improve the cost efficiency of existing ad-hoc routing protocols through dynamic power control, while introducing only minimal additional overhead. The MAC layer at each node is given the capability to run local sealed-bid second-price auctions for the user data packets that need to be transmitted, and to determine any neighbor nodes that reduce the transmission cost to the next hop identified by the network layer. Existing network layer routing protocols are utilized with no changes or impact on their operation. Self-organized networks, where nodes are greedy and selfish, are being supported through the proposed auction-based framework.

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by
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To my beloved wife, Oya

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CHAPTER 1

INTRODUCTION

1.1 Background

Wireless data communication became more and more popular in the last few years, with the recent technological advances in notebook computers and wireless data communication devices. Mobile computing experienced significant growth, mainly due to the lower prices and higher data rates.

In order to enable wireless communication between mobile hosts, two distinct approaches are being used. The first approach is to use a base station between the hosts, which would in turn be forwarding packets from one host to the other, similar to today's traditional cellular networks or wireless local area networks (WLANs). The second approach is to form an ad-hoc network and to let the users of the ad-hoc network forward each other's packets. This form of networking could either be used as standalone, which would typically be limited in size, or within a hybrid architecture, allowing the nodes also to communicate wired base stations or gateways. Ad-hoc networks do not rely on any existing infrastructure, and can be deployed in places where infrastructure does not exist or cannot be used.

Ad-hoc networking has been one of the most active research fields over the last couple of years. Research in this area is not new; the earliest ad-hoc networks were designed in the early 1970s, mainly for military applications. Within the past few years, though, the wide availability of low cost 802.11 and similar wireless devices triggered a tremendous interest and academic activity in this field, and many commercial possibilities were born.

1.2 Motivation

There is a need in the literature for a new protocol, or a new scheme, for improving the cost and energy efficiency of ad-hoc networks by making use of the existing popular network layer routing protocols, and considering the selfishness and the lack of cooperation of the wireless nodes.

In a traditional cellular network, the wireless communications are enabled through fixed infrastructures, such as base stations. The cost of communications in these networks are associated with providing of this equipment and the air interface resources, and the wireless carriers typically charge the users of the network in order to cover these costs. The situation is quite different in wireless ad-hoc networks, since fixed infrastructure is no longer a requirement. Each wireless node in these networks is expected to forward packets of other nodes in the network in a multi-hop fashion. However, wireless devices that operate in ad-hoc networks are typically battery-powered and have limited processing power. Battery power and processing power is a precious resource for every node in these networks.

Therefore, forwarding of other nodes' packets is not necessarily in the best interest of a given node, simply because it will take away from the node's energy and processing resources, and will force the nodes to act selfishly. Each node in an ad-hoc network incurs a variable amount of *cost* for forwarding other nodes' packets, which depends on several variables, such as the current battery level of the node, cost of recharging the battery, or cost of potential processing delay to node's own message transmission or reception.

Minimizing of the cost of communications in wireless ad-hoc network is a critical *cross-layer* design issue, and therefore has to be taken into consideration at each layer of the protocol stack, including the physical layer, MAC layer, network layer (and routing protocols), and application layer. Efficient utilization of battery power will improve the cost efficiency of the network, and will provide the nodes the ability to continue to communicate longer, by keeping the network connected for longer durations.

Most popular ad-hoc routing protocols that have been studied and proposed in the literature and being subject to standardization within the IETF use the *number of hops* as their metric, and are designed to generate minimum-hop routes, using maximum transmission power levels at the nodes (Johnson et al. 2004), (Perkins et al. 2003), (Perkins and Bhagwat, 1994), (Sinha et al. 2000), (Blazevic et al. 2001), (Karp and Kung, 2000). Since battery power is a valuable resource for all nodes, these minimum-hop routing protocols are energy and cost inefficient, in cases where nodes can dynamically vary their transmission power levels.

Energy or cost efficient protocols using variable-range transmission power levels were studied actively in the research community over the last couple of years. These methods can be divided into two main groups. The methods in the first group either modify or replace the existing popular routing protocols, in order to achieve cost efficiency, such as (Anderegg and Eidenbenz, 2003). The methods in the second group operate below the network layer and designed to work with the existing routing protocols, such as (Gomez et al. 2003) or (Muqattash and Krunz, 2004), but do not consider the selfishness of the nodes, and assume all nodes in the ad-hoc network will always cooperate.

1.3 Objectives

The main objective of this thesis is to improve the cost and energy efficiency of ad-hoc networks, by making use of the existing network layer routing protocols, and considering the lack of cooperation from the nodes. The goal is to meet this objective by introducing a new method, which shall:

- Improve the cost and energy efficiency of wireless ad-hoc networks.
- Improve the lifetime of wireless ad-hoc networks.
- Introduce only minimal overhead to the network.
- Provide support for networks with selfish nodes.
- Make use of the "existing" ad-hoc network layer, without modifying to the underlying routing protocol.

1.4 Contribution of Thesis

In this thesis, a novel method called CARA (Cost Aware Routing with Auctions) is proposed for improving the cost efficiency of routing protocols in ad-hoc networks. The method is designed to operate below the wide-area routing protocols, as an extension of the MAC layer, and utilizes variable range power control and sealed-bid second price auctions to reduce the cost of transmissions.

This new method of cost reduction using existing routing protocols and through auctioning is first in its kind. A very important advantage of CARA is that it utilizes existing routing protocols to achieve cost efficient routing, without modifying or impacting them in any way. CARA takes the selfishness of the nodes into consideration, and supports self-organized networks where nodes are greedy. It brings an auctioning scheme into the network that stimulates nodes to participate in packet forwarding, which in turn reduces the cost of communications. Simulation results show that CARA significantly improves the cost efficiency, energy efficiency and lifetime of the network, while introducing only minimal additional overhead.

1.5 Outline

The remainder of the thesis is organized as follows. Chapter 2 provides an overview of wireless ad-hoc networking, along with its history, applications, challenges, enabling technologies and ad-hoc routing. In Chapter 3, the existing cost efficient approaches in ad-hoc networks are presented. In Chapter 4, the system model with all relevant assumptions is described. Following the system model description, the CARA architecture is introduced in Chapter 5, and the proposed method is explained in detail. The detailed CARA process flows are given in Chapter 6. In Chapter 7, a description of the simulation model and simulation tools is provided. Simulation results are presented and analyzed in Chapter 8. Finally, the main conclusions drawn from this study and suggest areas for future research are presented in Chapter 9.

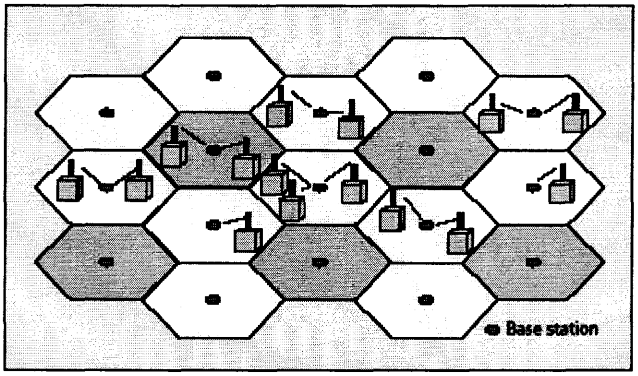
CHAPTER 2

A REVIEW OF AD-HOC NETWORKING

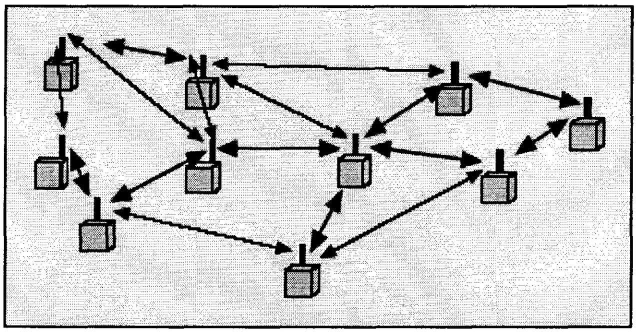
2.1 Overview

A wireless ad-hoc network is a (possibly mobile) collection of wireless communications devices (nodes) that self-configure to form a network without the aid of any established infrastructure or centralized control (Goldsmith and Wicker, 2002), (Kumar and Chockalingam, 2002). The nodes in an ad-hoc network wish to communicate, but have no fixed infrastructure or pre-determined organization of links available. All or some nodes within an ad-hoc wireless network are expected to act as routers for the traffic of other nodes in the network, allowing for wireless communication between parties that are relatively far apart. Mobile hosts in an ad-hoc network communicate in a multi-hop fashion.

Figure 2.1 illustrates the architectures of a traditional cellular network and an ad-hoc network. The first is known as the infrastructured network (i.e. a network with fixed and wired base stations or gateways). In these types of networks, a mobile unit connects to, and communicates with, a base station within its communication range. The mobile will perform an "handoff" (i.e. connect to another base station) as it travels out of the range of one base station and into the range of another, and this capability allows seamless communication throughout the network.



(a) Cellular system architecture.



(b) Ad hoc network structure.

Figure 2.1 Cellular and ad-hoc network architectures.
(Source: Goldsmith et al. 2002)

The second part of Figure 2.1 illustrates an ad hoc, or infrastructureless, network structure. The typical assumption for an ad-hoc network is that not all nodes can directly communicate with each other, and since there are no fixed routers, nodes are expected to relay packets on behalf of other nodes in order to deliver data across the network. Nodes act as both an end-host and a router, which discover and maintain routes to other nodes in the network. As nodes move, the network will have to continuously self-configure itself, utilizing dynamic configurations between nodes in an arbitrary manner, without the assistance of existing infrastructure.

2.2 History

Research in the field of ad-hoc networks has been ongoing for more than 30 years. The earliest ad-hoc networks were designed in the early 1970s. Since then, the work in this area is seen to have developed in three stages.

The first stage was initiated by U.S. Defense Advanced Research Projects Agency (DARPA) in 1972 (Freebersyser and Leiner, 2001). The DARPA-sponsored Packet Radio Network (PRNET) can be seen as the earliest ad-hoc network designed and built (Jubin and Tornow, 1987), (Leiner et al. 1987), (Tobagi, 1987). The PRNET supported ad-hoc networks of moderately mobile hosts communicating via radios. It used a combination of ALOHA and CSMA approaches for medium access, and a form of distance-vector routing, with each node periodically broadcasting a routing update packet, for automatic set up and maintenance of packet switched communication routes.

In the second stage, Survivable Radio Networks (SURAN) was developed by DARPA in the 1980s (Beyer, 1990). The purpose was to address main issues in PRNET, such as network scalability, security, processing capability and energy management. SURAN made significant improvements in the radios by making them small, low-cost and low-powered (Freebersyser and Leiner, 2001). Algorithms were more scalable and the network was more resilient to electronic attacks. The routing protocols were based on highly scalable hierarchical link-state.

The third stage started in the mid 1990s, and with the wide availability of inexpensive 802.11 and similar wireless devices for personal computers, it became the biggest wave of academic activity in this area. The IEEE 802.11 subcommittee adopted the term "ad hoc networks" after the publication of two conference papers (Johnson, 1994), (Perkins et al. 1994), and this can be seen as the beginning the concept of commercial (non-military) ad hoc networking. With the increasing number of non-military possibilities, the research interest in this area grew significantly, and a number of standards activities and commercial standards evolved in the mid to late '90s. Mobile Ad Hoc Networking (MANET) working group was established within the IETF, for the purpose of standardizing routing protocols for ad hoc networks.

2.3 Ad-Hoc Networking Applications

Ad-hoc networks can operate in a stand-alone fashion or could operate in hybrid-architectures, possibly allowing the users to connect to larger networks through wired gateways or base stations. Initial research on ad-hoc networks was mainly for military scenarios, where there is usually no infrastructure for communication. But recently many commercial possibilities were born, along with the dramatic increase in the deployment of low-cost 802.11 networks, and interest in this field grew significantly.

In infrastructure-less areas, ad-hoc networks provide a convenient of quickly establishing temporary network connectivity and communications. Typical examples would be situations where infrastructure is either not available, not trusted, or should not be relied on in times of emergency, such as military environments, disaster relief, or emergency search-and-rescue operations. In addition, ad-hoc networks can be deployed more readily and at lower expense in environments where infrastructure is poor, for example in rural or developing areas, or in buildings without appropriate cabling infrastructure. Other examples of infrastructure-less network examples are, notebook computers in a conference or campus setting where users wish to quickly share information; and temporary offices such as campaign headquarters; the forestry or lumber industry; rare animal tracking; space exploration (Ramanathan and Redi, 2002).

Another very promising applications for wireless ad-hoc networking is sensor networks. A sensor network is composed of a large number of small sensor nodes, which are typically densely (and randomly) deployed inside the area in which a phenomenon is being monitored (Chlamtac et al. 2003). A large number of sensors can self-organize into ad hoc networks, and relay their observations to a conveniently located base station (Min, 2003). Because of the large number of nodes, the network will be robust and fault-tolerant to the loss of individual nodes, making maintenance unnecessary.

Sensor networks are ideal for any number of inhospitable or unreachable terrains. For example, sensors can be dropped from airplanes over contaminated areas or earthquake zones and be used to register activity. Sensors scattered throughout a city for biological detection; undersea operations; facilities that produce toxic radiation or chemical vapors; the lands of extreme desert or Arctic climates; and even the surface of foreign moons and planets, are other candidates. A comprehensive coverage of sensor networks is available in a recent survey (Akyildiz, 2002).

In infrastructure rich areas, ad-hoc networking can reduce dead spots, lower power consumption (Chen et al. 2004), and increase network capacity and throughput rates (Tacconi et al. 2004) when used within hybrid architectures, allowing the nodes also to communicate wired base stations or gateways.

Table 2.1 Ad-Hoc Networking Applications

Applications	**Descriptions/services**
Tactical Networks	• Military communication, operations • Automated Battlefields
Emergency Services	• Search and rescue operations, as well as disaster recovery • Replacement of a fixed infrastructure in case of earthquakes, hurricanes, fire etc. • Policing and fire fighting • Supporting doctors and nurses in hospitals; e.g., early retrieval and transmission of patient data (record, status, diagnosis) from/to the hospital
Sensor Networks	• Home applications: Smart sensor nodes and actuators can be buried in Appliances to allow end users to manage home devices locally and remotely • Environmental applications include tracking the movements of animals (e.g., birds and insects), chemical/biological detection, precision agriculture, etc. • Tracking data highly correlated in time and space, e.g., remote sensors for weather, earth activities
Commercial Environments	• E-commerce: electronic payments anytime and anywhere • Business: dynamic database access, mobile offices • Vehicular services: road or accident guidance, transmission of road and weather conditions, taxi cab network, inter-vehicle networks • Sports stadiums, trade fairs, shopping malls • Networks of visitors at airports
Home and Enterprise Networking	• Home/office wireless networking • Conferences, meeting rooms • Personal area networks (PAN), Personal networks (PN) • Networks at construction sites
Educational Applications	• Universities and campus settings • Virtual classrooms • Ad hoc communications during meetings or lectures
Entertainment	• Multi-user games • Wireless P2P networking • Robotic pets • Outdoor Internet access • Theme parks
Location aware services	• Follow-on services, e.g., automatic call-forwarding, transmission of the actual workspace to the current location • Information services: o Push, e.g., advertise location specific service, like gas stations o Pull, e.g., location dependent travel guide; services (printer, fax, phone, server, gas stations) availability information
Coverage extension	• Extending cellular network access • Linking up with the Internet, intranets, etc.

(Source: Hoebeke et al. 2004)

End user applications used in ad hoc networks will differ based on the specific needs of each scenario. For example, in a sensor network this might be periodic transfer of collected measurement data, while at a conference or spontaneous meeting the applications could be file sharing, or even web browsing and email.

Some commercially oriented applications already starting to appear, such as MeshNetworks and SPANworks. Research examples of multi-hop networks include MIT's Roofnet (Aguayo et al. 2003), Microsoft's MUP (Adya et al. 2003), the Digital Gangetic Plains Project (Bhagwat et al. 2004) and UCAN (Luo H. et al. 2003).

2.4 Challenges in Ad-Hoc Networks

The autonomous and infrastructure-less architecture makes ad-hoc networks quite different then wired networks. Ad hoc networks can be described as a dynamic, unpredictable, random and multi-hop technology, which do not depend on any established infrastructure or centralized administration. Because of these attributes, the following main characteristics of ad hoc networks are observed (Toh, 2001):

Limited security and lack of cooperation: An ad-hoc network is a system relying on the cooperation of autonomous nodes to achieve a communal goal. Experience has shown that in these types of systems, some fraction of the nodes will almost always "cheat" by consuming global resources without faithfully carrying out their obligations to contribute (Mahajan et al. 2004). In addition, wireless ad-hoc networks are generally more vulnerable to security threats, compared to infrastructured networks, providing a larger possibility for spoofing, denial-of-service attacks etc.

Dynamic topology: Nodes are free to move about arbitrarily. In addition, radio conditions and the network topology change rapidly over time.

Bandwidth constraints and variable link capacity: The capacity of wireless links is significantly lower than that from wired network, due to many factors including signal interference, noise and multipath fading. The effective throughput is often less than radio's maximum transmission capability.

Energy constrained operation: Mobile nodes typically depend on battery power for proper operation. Therefore, battery power is a precious resource for every node in ad-hoc networks, and may even force the nodes to act selfishly. Efficient utilization of battery power will have great influence on overall network performance, and will provide the nodes the ability to continue to communicate longer, by keeping the network connected for longer durations.

Multi-hop communications: Not all nodes can directly communicate with each other, and since there are no fixed routers, nodes are expected to relay packets on behalf of other nodes in order to deliver data across the network. Nodes act as both an end-host and a router, which discover and maintain routes to other nodes in the network.

These characteristics and constraints described above pose significant challenges in ad-hoc network design. Figure 2.2 is included as a reference, to present the huge amount of research activities on ad hoc networks.

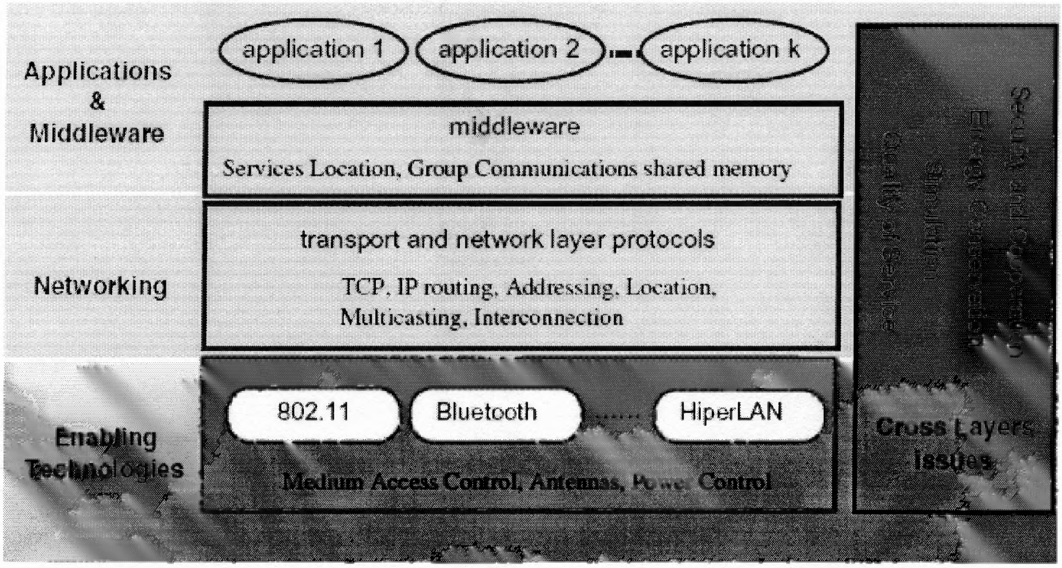


Figure 2.2 Ad-hoc networking research areas.
(Source: Chlamtac et al. 2003)

The objective of this thesis is to improve the cost efficiency of ad-hoc networks, by making use of the existing network layer protocols routing, and considering the lack of cooperation from the nodes. As its sown in the above figure, these are cross-layer design issues, and therefore have to be taken into consideration at each layer of the protocol stack, including the physical layer, MAC layer, network layer (and routing protocols), and application layer. The following related areas will be reviewed in the following sections:

- Enabling technologies.
- Routing protocols.
- Energy and cost efficiency strategies.
- Strategies for security and node cooperation.

For rest of the research areas, (Chlamtac et al. 2003) provides an excellent overview to the interested reader.

2.5 Enabling Technologies

Body Area Networks (BAN), Personal Area Networks (PAN) and Local Area Networks (LAN) wireless technologies constitute the Enabling technologies for ad hoc networking. A list of these technologies is given in Table 2.2. Most of these technologies are already common on the market, and they allow constructing or prototyping multi-hop ad hoc networks.

Table 2.2 Wireless Ad-Hoc Network Enabling Technologies

Technology	Theoretical bit rate	Frequency	Range	Power consumption
IEEE 802.11b	1, 2, 5.5 and 11 Mbit/s	2.4 GHz	25–100 m (indoor) 100–500 m (outdoor)	~30 mW
IEEE 802.11g	Up to 54 Mbit/s	2.4 GHz	25–50 m (indoor)	~79 mW
IEEE 802.11a	6, 9, 12, 24, 36, 49 and 54 Mbit/s	5 GHz	10–40 m (indoor)	40 mW, 250 mW or 1 W
Bluetooth (IEEE 802.15.1)	1 Mbit/s (v1.1)	2.4 GHz	10 m (up to 100 m)	1 mW (up to 100 mW)
UWB (IEEE 802.15.3)	110 – 480 Mbit/	Mostly 3 – 10 GHz	~10 m	100 mW, 250 mW
IEEE 802.15.4 (for example, Zigbee)	20, 40 or 250 kbit/s	868 MHz, 915 MHz or 2.4 GHz	10–100 m	1 mW
HiperLAN2	Up to 54 Mbit/s	5 GHz	30–150 m	200 mW or 1 W
IrDA	Up to 4 Mbit/	Infrared (850 nm)	~10 m (line of sight)	Distance based
HomeRF	1 Mbit/s (v1.0) 10 Mbit/s (v2.0)	2.4 GHz	~50 m	100 mW
IEEE 802.16 IEEE 802.16a IEEE 802.16e (Broadband Wireless)	32 – 134 Mbit/s up to 75 Mbit/s up to 15 Mbit/s	10–66 GHz < 11 GHz < 6 GHz	2–5 km 7–10 km (max 50 km) 2–5 km	Complex power control

(Source: Hoebeke et al. 2004)

Some commercially oriented solutions using these technologies already starting to appear, such as MeshNetworks (http://www.meshnetworks.com) and SPANworks (http://www.spanworks.com). Research examples of multi-hop networks include MIT's Roofnet (Aguayo et al. 2003), Microsoft's MUP (Adya et al. 2003), the Digital Gangetic Plains Project (Bhagwat et al. 2004) and UCAN (Luo H. et al. 2003).

A detailed review of these technologies is given in (Chlamtac et al. 2003) and (Jurdak et al. 2004). In this study, the 802.11 technology will be reviewed in more detail.

The IEEE 802.11 (ANSI/IEEE Std 802.11, 1999) standard is, by far, the most dominant MAC protocol for wireless ad-hoc network design in the literature. Most notebook computers today have 802.11 capabilities, and tens of millions of 802.11 devices is sold in a single year. Low cost and simple 802.11 technologies is the main cause of Wireless LANs (WLANs) being a major growth factor for the network industry in the recent years. Using these low cost radio devices, analysts predict 100 million people will be using WLAN technology by 2006 (The Economist, June 10, 2004).

CSMA/CA is the fundamental access method used by the Distributed Coordination Function (DCF) of the IEEE 802.11 standard. In CSMA/CA access mechanism, a station listens to the medium before beginning a transmission. If the medium is busy, the station will wait for random period before attempting to transmit again, determined by a binary exponential backoff algorithm. In addition to the physical carrier sensing, the DCF implements a method for virtual carrier sensing, by exchanging of RTS/CTS (request-to-send/clear-to-send) handshake packets between the transmitter and the receiver, and by including the duration of the packet transmission in the header of RTS, CTS, and DATA frames. This duration is used to infer the time when the source node would receive an ACK (acknowledgement) frame from the destination node, and the medium would be idle again. The minimal frame exchange consists of two frames, a DATA frame from the source to the destination and an ACK frame from the destination to the source. RTS/CTS handshaking for media reservation is optional, and may not be used when the length of the DATA frame to be transmitted is less than a certain threshold.

2.6 Routing in Ad-Hoc Networks

Wireless ad-hoc networks require efficient routing protocols for establishing communication paths between nodes in a multihop fashion, with minimal excessive control traffic overhead or computational burden on the power constrained mobile nodes. In addition, routing protocols need to support efficient utilization of battery power at the nodes, in order to minimize the use of this precious resource and improve network lifetime as much as possible.

A large number of protocols have already been proposed in the literature, some of them being subject to standardization within the IETF. There are several different criteria for designing and classifying routing protocols for wireless ad hoc networks (Zou et al. 2002). A common criterion in the literature is whether or not geographical position information is being used by the protocol to make the routing decisions, as shown in Figure 2.3.

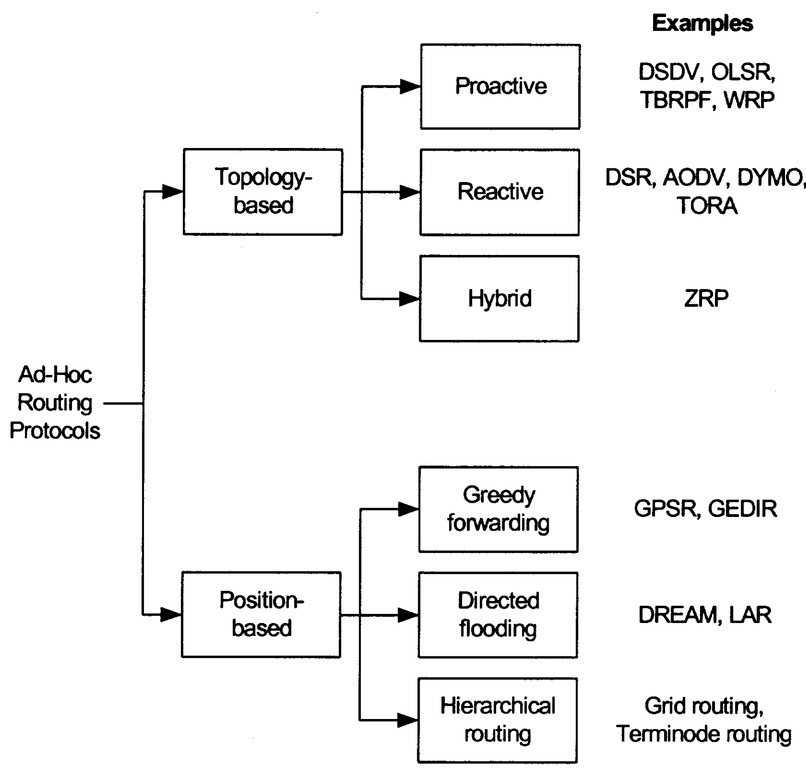


Figure 2.3 Classification of ad-hoc routing protocols.

Topology-based Routing

Topology-based routing protocols make routing decisions according to the logical arrangement of the network nodes. They do not make use of location information, opposed to the position-based protocols. These protocols are generally considered as not to scale with larger networks with more than several hundred nodes. Topology-based routing algorithms work in two phases. During the first phase, which is called route discovery phase, a route between the source and the destination is created. The actual data transmission takes place during in the second phase. Topology-based routing algorithms can be further subdivided into three classes: *proactive*, *reactive* and *hybrid*, as shown in the figure. These three classes of routing algorithms differ in their functioning during route discovery phase.

Proactive routing is also called *table-driven* routing (Royer and Toh, 1999). In this method, all nodes compute the routes to all destinations even if they have no data to send, and all nodes constantly maintain routes to all other nodes in the network. The advantage of this approach is that when a source needs to send packets to a destination, the route will likely be readily available. This approach requires nodes need to store the entire or partial information about link states and network topology. In order to keep the information up to date, nodes need to update their information periodically or whenever the link state or network topology changes (e.g., triggered by links breakages). The disadvantage of this approach is the additional overhead introduced to the system, since some routes may never be used. Some examples of proactive protocols are: Destination-Sequenced Distance-Vector (DSDV) (Perkins and Bhagwat, 1994), Optimized Link State Routing (OLSR) (Jacquet et al. 2003), Topology Dissemination Based on Reverse-Path Forwarding (TBRPF) (Bellur and Ogier, 1999), (Ogier et al. 2004) and Wireless Routing Protocol (WRP) (Murthy and Garcia-Luna-Aceves, 1996).

In reactive routing protocols, the path to reach a destination is discovered by a node only when needed, i.e. when a node wishes to transmit, it starts a route discovery process in order to find a path to the destination. These protocols are also called *on-demand* routing protocols. The main purpose of this approach is to reduce the overhead of constantly maintaining routes to all nodes in the network. Most of the time, it is not necessary to have an up-to-date route to all other nodes. Therefore, routes are built on-demand and are maintained exactly as long as they are needed. The process of detecting route breakage and rebuilding the route during data transmission phase is called route maintenance. The major advantage of reactive routing is that it significantly reduces the overhead and saves resources, when compared to the proactive routing protocols. On the other hand the disadvantage of on-demand routing is the large latency at the beginning of the transmission caused by route discovery. Some examples of reactive protocols are: Dynamic Source Routing (DSR) (Johnson and Maltz, 1996) (Johnson et al. 2004), Ad hoc On Demand Distance Vector (AODV) (Perkins et al. 2003), Dynamic MANET On-demand Routing Protocol (DYMO) (Chakeres et al. 2005), and Temporally Ordered Routing Algorithm (TORA) (Park and Corson, 2001).

In addition to proactive and reactive protocols, another class of topology-based routing protocols is hybrid protocols, which try to combine the advantages of both proactive and reactive techniques. Therefore, some aspect of establishing routes may be reactive while others are proactive. The Zone-Based Hierarchical Link State Routing Protocol (ZRP) (Sinha et al. 2000) is a hybrid protocol and uses a composition of reactive and proactive approaches: each node maintains a zone (e.g., with a 2 hop radius) wherein it uses proactive routing, while for nodes outside this zone it uses reactive routing. This strategy helps to limit the overhead since the proactive route maintenance only concerns the zone (the local neighborhood of a node), and the latency is also reduced since active route search is limited to querying a set of selected nodes.

Position-based Routing

Using position-based routing protocols, nodes make routing decisions based on the geographical position of packet's destination. This technique requires that information about the physical position of the participating nodes be available (Mauve et al. 2001), and using this additional information, it eliminates some of the limitations of the topology-based routing protocols. Its much more scalable than topology-based routing protocols, even if the network is highly dynamic, since maintenance of explicit routes is not required. The key requirement is that the sender node should be able to obtain the current geographical position of the destination node. This capability is provided through a *location service*, used by the sender when it needs destination's position. Sender node includes destination's current position in each packet sent, and all nodes along the end-to-end route, in order to make the routing decisions, use this information. The nodes have neither to store routing table nor to transmit messages to keep routing tables up to date.

Three main strategies can be identified in position-based routing protocols (Chlamtac et al. 2003): *greedy forwarding*, *directed flooding* and *hierarchical routing*.

Greedy Perimeter Stateless Routing (GPSR) (Karp and Kung, 2000) and the geographical distance routing (GEDIR) (Stojmenovic and Lin, 1999) adapted the greedy forwarding strategy. With this strategy, a node tries to forward the packet to one of its neighbors that is closer to the destination than itself. If more than one closer node exists, different choices are possible. If, on the other hand, no closer neighbor exists, new rules are included in the greedy strategies to find an alternative route.

DREAM (Basagni et al. 1998) and LAR (Ko and Vaidya, 2000) are two routing protocols that utilize the directed flooding strategy. With directed flooding, nodes forward the packets to all neighbors that are located in the direction of the destination. LAR uses directed flooding only for route discovery, while DREAM applies a restricted flooding for packets delivery.

The Terminode routing protocol (Blazevic et al. 2001) and the GRID routing protocol (Liao et al. 2001) are examples of hierarchical routing protocols. In these type of protocols, routing is structured in two layers: long-distance routing and short-distance routing. Different rules are applied for both of these layers, in a hierarchical methodology. Typical approach is that position-based routing is used for routing on long distances, while when a packet arrives close to the destination (one or two hops distance) a proactive distance vector scheme is followed.

CHAPTER 3

COST EFFICIENT APPROACHES IN AD-HOC NETWORKS

3.1 Introduction

Wireless devices have maximum utility when they can be used "anywhere at anytime" (Jones et al. 2001). This goal determines one of the greatest resources of a wireless ad-hoc network: battery power. Wireless devices that operate in ad-hoc networks are typically battery-powered and have limited processing power. Battery power and processing power is a precious resource for every node in these networks.

In a traditional cellular network, the wireless communications are enabled through fixed infrastructures, such as base stations. The cost of communications in these networks are associated with providing of this equipment and the air interface resources, and the wireless carriers typically charge the users of the network in order to cover these costs. The nodes of a cellular network use their battery power and processing power for their own message transmission or reception.

The situation is quite different in wireless ad-hoc networks, since fixed infrastructure is no longer a requirement. Each wireless node in these networks is expected to forward packets of other nodes in the network in a multi-hop fashion, and expected to use their battery power and processing power not only for their own message transmission or reception, but also to enable other nodes' communication.

Therefore, forwarding of other nodes' packets is not necessarily in the best interest of a given node, simply because it will take away from the node's energy and processing resources, and will force the nodes to act selfishly. Each node in an ad-hoc network incurs a variable amount of ***cost*** for forwarding other nodes' packets, which depends on several variables, such as the current battery level of the node, cost of recharging the battery, or cost of potential processing delay to node's own message transmission or reception.

Cost-Efficiency is a Cross-Layer Design Issue

Minimizing of the cost of communications in wireless ad-hoc network is a critical cross-layer design issue, and therefore has to be taken into consideration at each layer of the protocol stack, including the physical layer, MAC layer, network layer (i.e. routing protocols), and application layer. This study mostly considers the impacts of MAC layer and network layer on achieving cost-efficiency.

Network layer has a significant impact on the cost of communications, since routing protocol determines the nodes that will be forwarding packets along the end-to-end route from source to destination. Most popular ad-hoc routing protocols that have been studied and proposed in the literature do not support true cost-efficiency of the network, as it's defined in the above paragraphs.

Recently, several new schemes and protocols have been proposed (will be presented in the following sections), which operate below these routing protocols and improve their cost efficiency. However, most of these schemes do not consider selfishness of the nodes and lack of cooperation. The objective of this study is to improve the cost efficiency of ad-hoc networks by utilizing existing routing protocols and also providing support for selfish nodes and lack of cooperation. CARA, the proposed auction-based cost-improvement scheme in this thesis, operates as an extension to the MAC layer, and improves the cost efficiency of the network layer protocols.

3.2 Metrics Used by Popular Routing Protocols

Several different metrics are used by the popular ad-hoc routing protocols that have been proposed in the literature, in order to determine the end-to-end routes from source to destination. These metrics are shown in Table 3.1. Unfortunately, none of these routing protocols are designed to support cost-efficiency. As defined in the above paragraphs, each node in an ad-hoc network incurs costs for forwarding other nodes' packets, because of the battery and processing power used.

Table 3.1 Metrics Used by Popular Routing Protocols

Name	Metrics	Type	IETF status	Reference
AODV	hop count	topology-based, reactive	RFC3561	Perkins et al. 2003
DSDV	hop count	topology-based, proactive	N/A	Perkins et al. 1994
DSR	hop count	topology-based, reactive	internet draft	Johnson et al. 2004
DYMO	hop count	topology-based, reactive	internet draft	Chakeres et al. 2005
OLSR	hop count	topology-based, proactive	RFC3626	Jacquet et al. 2003
TBRPF	link quality hop count	topology-based, proactive	RFC3684	Ogier et al. 2004
TORA	hop count	topology-based, reactive	internet draft	Park and Corson, 2001
WRP	hop count	topology-based, proactive	N/A	Murthy et al. 1996
ZRP	hop count	topology-based, hybrid	internet draft	Sinha et al. 2000
GPSR	geographic direction, most forward within radius	position-based, greedy forwarding	N/A	Karp and Kung, 2000
GEDIR	geographic direction, most forward within radius, minimize spatial distance	position-based, greedy forwarding	N/A	Stojmenovic et al. 1999
DREAM	geographic direction	position-based, directed flooding	N/A	Basagni et al. 1998
LAR	geographic direction	position-based, directed flooding	N/A	Ko and Vaidya, 2000
Terminode	geographic direction	position-based, hierarchical	N/A	Blazevic et al. 2001

As it can be seen it Table 3.1, most topology-based mobile ad-hoc routing protocols that have been proposed so far have utilized hop count as their route selection criteria, and use maximum transmission power levels at the nodes. This approach minimizes the total number of transmissions required to send the packet to the final destination, however, in scenarios where the nodes can dynamically vary their transmission power levels, minimum-hop routing approach may not generate cost efficient routes. Cost of forwarding packets will be different at each node, depending on the transmission power level used, and possibly many other parameters such as remaining battery level of the node. Cost of forwarding other nodes' packets will naturally be high at nodes that have relatively low battery levels.

Position-based routing protocols are designed to use the geographic direction to the target node as their routing metric. A typical strategy of these protocols is that a node tries to forward the packet to one of its neighbors that is closer to the destination than itself. When more then one closer node exists, the most common policy used is the Most Forward within Radius (MFR) policy (Takagi and Kleinrock, 1984) maximizes the progress by forwarding the packets to the node closest to the destination. Therefore, cost efficiency of the nodes is not considered. On the other hand, the Nearest with Forward Progress (NFP) scheme (Hou and Li, 1986) applies a selection of the next node that tries to maximize the success probability. This strategy could improve cost efficiency of the network, because it takes into consideration that the transmission at the maximum distance implies the maximum transmission power (and hence the maximization of the collision probability with other nodes). However, none of today's popular ad-hoc networks use this strategy.

3.3 Energy-Efficient Approaches

Because most popular ad-hoc protocols are not designed for energy efficiency, several energy efficient algorithms were developed to improve the efficiency of these protocols. Energy efficient methods and algorithms can help to save battery power of mobile devices in ad hoc networks. This can be accomplished by efficient variable range power control by altering the transmitter power to use just that amount needed to maintain an acceptable signal-to-noise ratio (SNR) at the receiver. In (Gomez, and Campbell, 2004), it is shown that variable range power control positively impacts system performance metrics such as the traffic carrying capacity and power conserving properties of wireless ad hoc networks. Altering the transmission power also reduces the amount of interference caused to other networks operating on adjacent radio frequency channels.

Nodes in an ad-hoc network are power constraint, since they typically operate on battery power. Conserving power in these networks is crucial since battery life determines whether a network is operational or not. At the same time, military ad-hoc networking requires to maintain a low probability of intercept and/or a low probability of detection. Therefore, it is advantageous if nodes transmit at low power levels in order to decrease the probability of detection or interception.

A radio transceiver would typically be in one the following four states: *transmit*, *receive*, *listen* or *sleep*. The power consumption of a radio transceiver will depend on its state.

During the transmit state, the transceiver will have to set the transmission power level high enough so that the packet will be successfully received by the destination node.

According to the simple path loss model, this transmit power level required at the sender primarily depends on the distance between the source and the destination and is given by:

$$p^{tx} = c_1 + c_2 d^k \quad , k \geq 2 \tag{3.1}$$

where d is the distance between the sender and the receiver, c_1 and c_2 are constants, k is the path loss exponent, and $k \geq 2$ for outdoor propagation models (Rappaport, 2002).

As it can be seen from this equation, there is a tradeoff between the transmission range and the energy consumption. Since the transmit power falls as $1/d^k$, as given by the path loss model, relaying information between nodes may result in lower power transmission than communicating over large distances (Rodoplu ans Teresa, 1999). This is illustrated in a simple scenario in Figure 3.1.

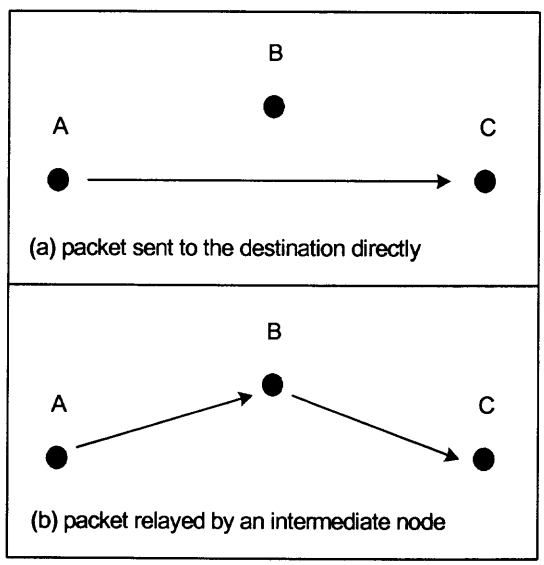


Figure 3.1 A simple scenario of relaying a packet.

In this figure, the total amount of energy required in scenario (a) may be much larger compared to the total amount of energy required in scenario (b), depending on the geographical locations of these three nodes.

A common property of most routing protocols that have been proposed in the literature and standardized in IETF is that they try to minimize the number of hops required between the source and the destination, and they typically use maximum transmit power levels. In order to minimize the number of hops, the nodes running these protocols will typically follow scenario (a) of the above figure. This causes significant amount of extra energy being spent during the transit state of the transceivers.

The amount of power required in the receive state for receiving a single packet is typically a constant and depends on the radio technology. For common technologies, such as 802.11, the receive power is comparable to the transmit power for small distances (tens of meters) (Jain, 2003). The amount of power spent in the listen state can also be substantial and comparable to the receive power. However, in the sleep mode, almost all of the circuitry in the transceiver is off (the radio can not perform any function), and the power consumption is almost zero in this state.

Some of the proposed energy saving algorithms in the literature conserve battery power at nodes by intelligently powering off nodes (or switching nodes into sleep state) that are not actively transmitting or receiving packets, such as PAMAS (Singh and Raghavendra, 1998) or BECA (Xu et al. 2000).

3.4 The Approach of CARA

This thesis introduces a novel method, CARA, for improving the cost efficiency of wireless ad-hoc networks with selfish nodes. Since an important variable in determining the cost is the amount of energy used, CARA is also seen to improve the energy efficiency of the network. The method runs below existing routing protocols, without impacting them in any way, and uses auctions to stimulate additional intermediate nodes to forward packets at the MAC level without involving the routing layer.

When CARA is enabled, the MAC layer at each node (along the end-to-end route determined by the routing layer) places sealed-bid second-price auctions for stimulating and identifying any "additional" intermediate nodes that could reduce the cost of communications. This is particularly useful in cases where routing protocol does not consider the "true" cost of the route as a metric. The metrics used by popular routing protocols were reviewed in the above sections. "True" cost of forwarding packets will be different at each node, depending on the transmission power level used, and possibly many other parameters such as remaining battery level of the node. Cost of forwarding other nodes' packets will naturally be high at nodes that have relatively low battery levels.

The approach of CARA is illustrated in Figure 3.2. Network layer end-to-end route is determined by the routing protocol at the network layer, based on the metrics it uses (such as hop-count, or geographic direction). This end-to-end route is shown in part (a) of the figure. Note that this end-to-end route will not be cost effective for most popular routing protocols, as discussed in the above sections. When CARA is enabled, each node on the end-to-end network layer route initiates sealed-bid second price auctions (by modifying the MAC header of the user packet that is being transmitted), looking for other nodes that could help reduce the cost of transmissions. These packets that are used to initiate auctions carry information regarding how costly the existing transmission is for the auctioneer nodes.

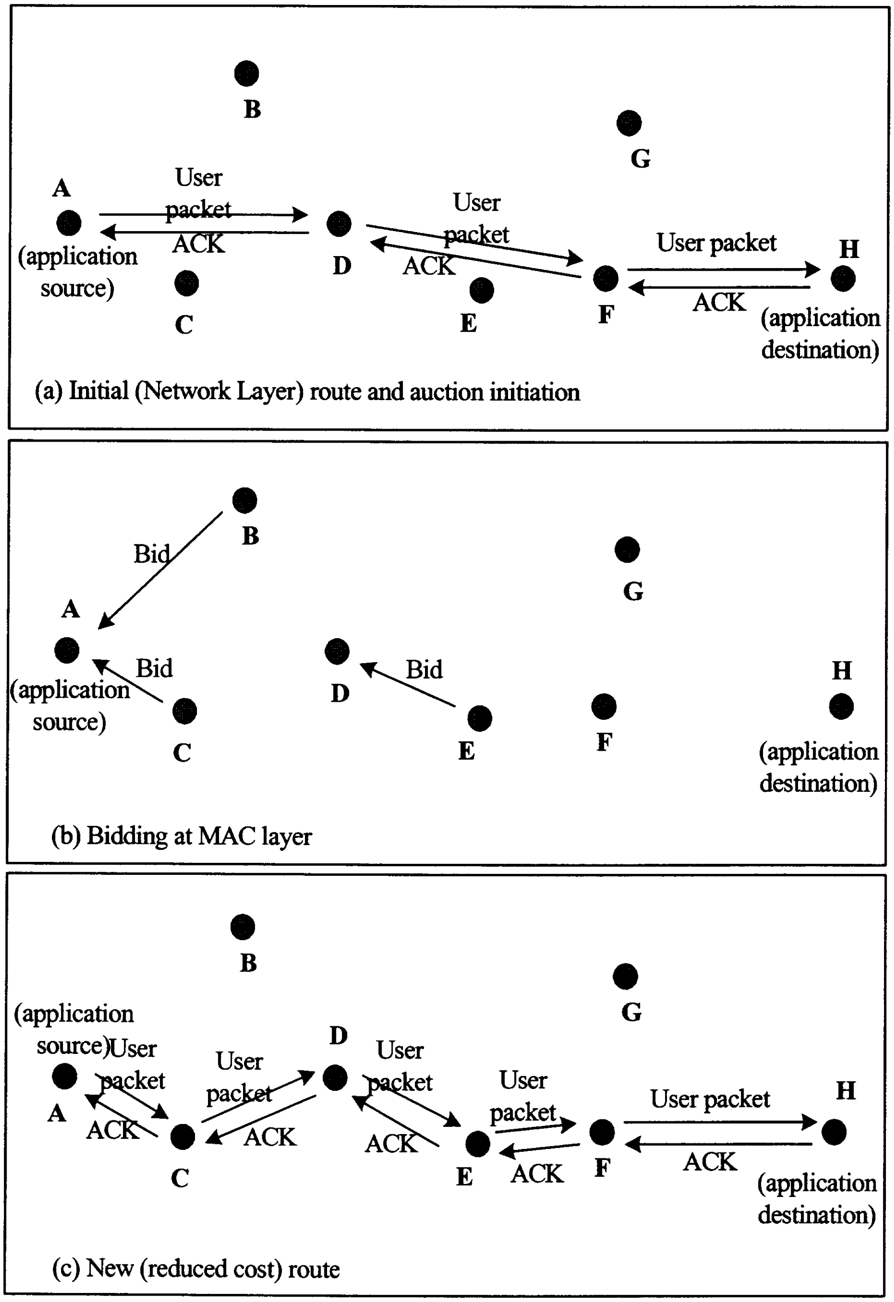


Figure 3.2 The approach of CARA.

The neighboring nodes that receive these initial user packets, and also the acknowledgements from the destination nodes, can make a determination on whether or not they can reduce the cost of transmission, send bidding messages to the auctioneers as appropriate. The details of this method will be explained in detail in the following chapters.

3.5 Enforcing Cooperation in Ad Hoc Networks

An ad-hoc network is a system relying on the cooperation of autonomous nodes to achieve a communal goal. Experience has shown that in these types of systems, some fraction of the nodes will "cheat" by consuming global resources without faithfully carrying out their obligations to contribute (Mahajan et al. 2004).

Most of the existing routing protocols simply assume that nodes will act cooperatively. This may be a valid assumption for military applications. However, for commercial networks, mechanisms are required to encourage the cooperative behavior and discourage the non-cooperative behavior or punish cheaters. One of the proposed solutions in the literature is implementing of a payment-based model, where nodes are awarded payments for forwarding packets of other nodes at the network layer, and participating in network layer routing procedures. In this scheme, the amount of payment each node receives must cover the cost the node incurs for contributing to those routing layer operations. Payment-based models and the problem of making the actual payments to the nodes is a different research thread. Some example studies include Nuglets (Buttyan and Hubaux, 2003) or Sprite (Zhong et al. 2003).

CHAPTER 4

MODEL DESCRIPTION

4.1 General Assumptions

As discussed in earlier sections, CARA improves the cost efficiency of ad-hoc routing protocols by stimulating the nodes to setup and participate in auctions for forwarding packets at the MAC level. Before going into mechanism descriptions and architectural details, the assumptions and layout of the proposed model will be presented.

A mobile ad-hoc network is assumed, with a set of nodes hosting a number of user applications that require sending of data packets to the applications hosted at other nodes in the network.

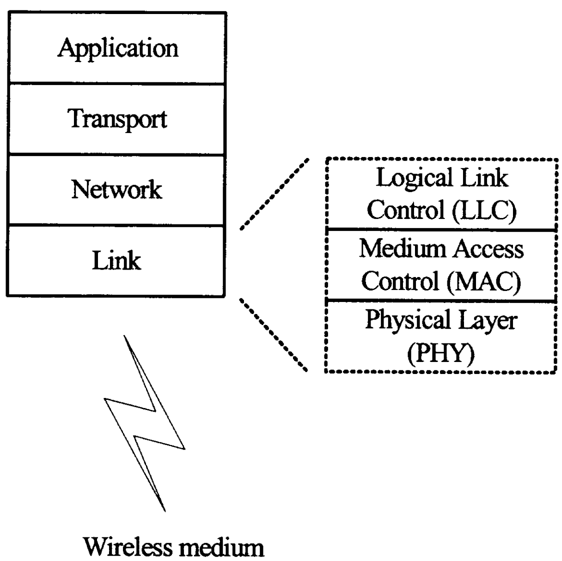


Figure 4.1 Assumed protocol stack.

Nodes are equipped with wireless transmitter/receiver devices, and they share the same wireless medium and a common protocol stack shown in Figure 4.1. The link layer provides peer-to-peer links between nodes within transmission range, and consists of three sub-layers: Logical Link Control (LLC), Medium Access Control (MAC), and Physical Layer (PHY). These sub-layers have similar functionality as explained in 802.11 (ANSI/IEEE Std 802.11, 1999), which is the dominant standard used in wireless ad-hoc network designs. The ad-hoc routing protocols reside on the network layer, which offers end-to-end routing services, and a simple datagram service over multiple links. The transport layer provides reliable communications between nodes in the ad hoc network. And finally, the application layer provides the desired application services the user.

Proper operation of the ad-hoc network requires cooperation of the nodes at all layers of the protocol stack. However, nodes in the network are assumed to be selfish and not willing to forward other nodes' packets and not willing to contribute to critical routing related operations such as route discovery, when there is no direct incentive. This non-cooperative behavior is a reasonable assumption since a node could simply save its resources by not forwarding the traffic of other nodes, resulting in lower energy consumption and longer operation.

4.2 Network Layer Assumptions

The objective of this study is not to design a new network layer routing protocol, or modify existing routing protocols. Instead, the intent is to improve the cost efficiency of the network layer without making any changes to the routing protocol already in use. As discussed in earlier sections, one of the main design goals behind CARA is to improve the cost effectiveness of existing routing protocols. Therefore, it is assumed that all nodes within the mobile ad-hoc network are using a common routing protocol at the network layer. Required network layer routing functionality, and necessary stimulation or incentive mechanism for nodes to cooperate at the network layer, is provided by this network layer protocol, allowing the nodes to communicate with one another in an end-to-end multi-hop fashion.

Biggest improvements in cost efficiency will be achieved when CARA is introduced in networks that are not designed for cost or energy efficiency. Several of these protocols were reviewed in earlier chapters. Typical examples are popular topology-based protocols designed to generate minimum-hop routes, and position-based protocols that are designed to use geographic direction as their routing metric.

Currency Based Incentive Scheme

Since the nodes in the network are assumed to be non-cooperative, a stimulation mechanism is required for the existing routing protocol to operate properly. The second assumption for the network layer is that the stimulation issue on the network layer has already been addressed. It is assumed that the network layer addresses this problem by implementing a payment-based model, where nodes are awarded payments for forwarding packets of other nodes at the network layer, and participating in network layer routing procedures. In this scheme, the amount of payment each node receives must cover the cost the node incurs for contributing to those routing layer operations. Payment-based models and the problem of making the actual payments to the nodes is a different research thread. Some example studies include Nuglets (Buttyan and Hubaux, 2003) or Sprite (Zhong et al. 2003).

This is a reasonable assumption since the design goal behind CARA is to enhance the cost effectiveness of "already existing" end-to-end communications in the network, by adding more intermediate nodes to forward the user data packets at the MAC level.

Required stimulation at the MAC layer for determining these additional intermediate nodes will be addressed by CARA, through its auction-based framework, which will also determine the amount of payments that need to be paid to each of these nodes forwarding at MAC level.

4.3 Protocol Stack Usage in a Typical Ad-Hoc Network

Figure 4.2 illustrates routing in a typical ad-hoc network. As in most popular ad-hoc routing protocols, nodes transmit with their maximum power levels, and therefore their transmission ranges are set to maximum. Dotted circles in the figure represent the transmission range of the transmission by each node in the 2D space. For simplicity, *omnidirectional antennas* are assumed at all nodes.

The arrows between nodes indicate the traffic flows. In this example, the source application running at node A is communicating with the destination application running on node H (i.e. the final destination). As can be seen in the second part of the figure, these two nodes use all layers of their protocol stack, up to the application layer. The nodes that are colored in dark (node E and node F) are the intermediate nodes determined by the routing protocol, and forwarding packets at the network layer on the end-to-end route from application source to application destination. These two nodes use the link layer and the network layer of their protocol stack for forwarding these packets.

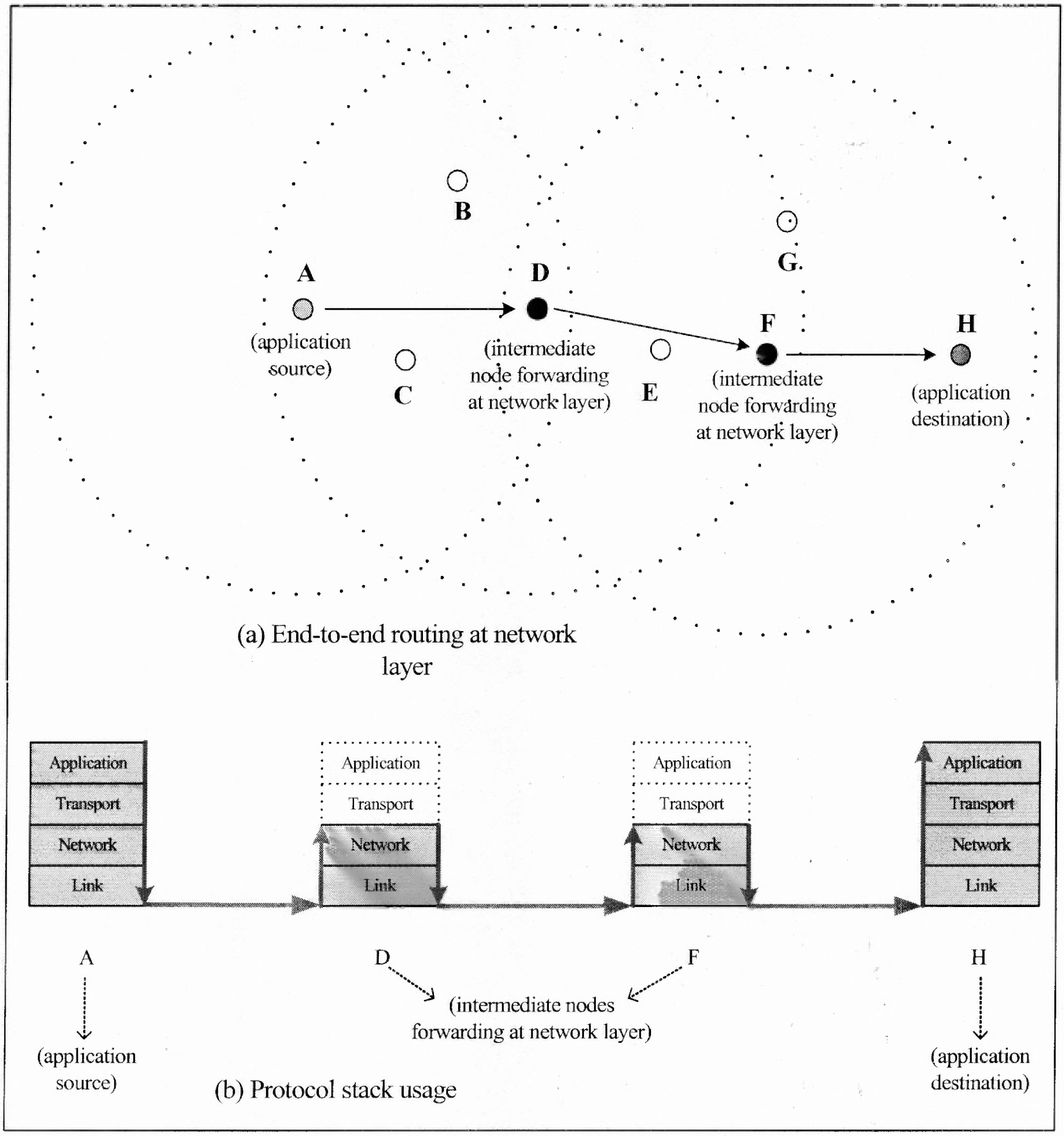


Figure 4.2 Typical end-to-end routing scenario in a mobile ad-hoc network.

It is assumed that the medium access method used by the link layer is CSMA based (i.e. similar to 802.11 MAC operation), allowing all nodes within the transmission range overhear a transmission. For example in Figure 4.2, nodes B and C can overhear the transmissions from nodes A and D, and will simply discard them unless the transmissions are marked as broadcast or directed to them. This is achieved through the

MAC destination address within the MAC header of the packets, set by the transmitting node. A node checks the destination MAC address for every packet it receives. If destination MAC address matches its own MAC address, it will pass the packet to the higher layers for further processing, otherwise it will simply discard it.

4.4 Protocol Stack Usage in a CARA-Enabled Ad-Hoc Network

The overall cost of sending of a packet from the source application to the destination application will depend on the individual costs that each node on the route incurs for participating the routing procedure. The main goal to achieve by enabling CARA in the network is improving this overall cost by adding more intermediate nodes to the route that forward packets at the MAC level (therefore not impacting the routing layer operation, i.e. network layer route remains unchanged), along with dynamically varying the transmission power levels (i.e. not necessarily transmit at maximum power level, and change it dynamically to allow for cost reduction).

Figure 4.3 illustrates this approach, where additional nodes (node C and node F) have been added to the end-to-end route, when compared to the scenario presented in Figure 4.2. These two nodes participate in packet forwarding only at the MAC level as indicated in the protocol stack usage of the nodes, in part (b) of the figure. Also note that transmission power levels, and therefore the transmission ranges, now vary depending on the distance to the next node on the route (indicated by the dotted circles), allowing an overall cost reduction. Again, omnidirectional antennas are assumed at all nodes.

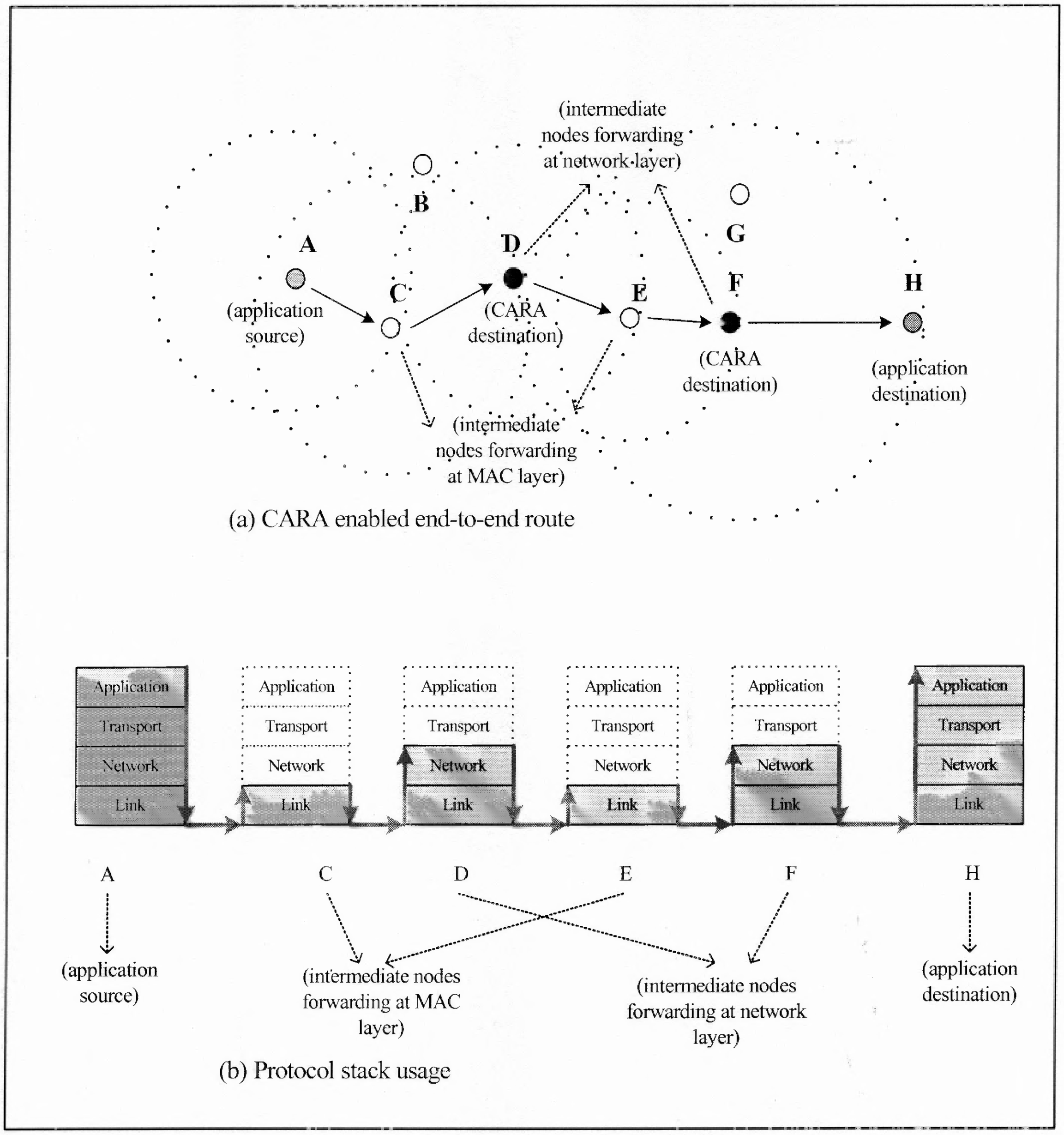


Figure 4.3 Routing in a CARA-enabled mobile ad-hoc network.

According to CARA scheme, the additional intermediate nodes, which are performing packet forwarding at the MAC level, are determined through an auction-based method. Each node that are on the initial network layer route (expect the final destination, i.e. nodes A, D and F in the above example) place sealed-bid second-price auctions at the MAC level for stimulating and identifying any intermediate nodes that will be helping to lower the cost of the auctioneers and also helping to reduce the overall cost of the end-to-end route, without affecting the routing layer operation. The additional nodes that are forwarding packets at the MAC layer (nodes C and F in the above example) has won the auctions placed by some of the auctioneers, and receive payments from them for their cooperation. The details of this method will be presented in detail in later sections.

A key difference between this scenario (Figure 4.2) and the previous scenario (Figure 4.3) is that the link layer at the nodes do not necessarily pass the received packets to higher layers just because the MAC destination address matched. For example the MAC layer at node C and node E in Figure 4.3 redirects the packets to the next hop without involving their network layers at all. CARA achieves this by introducing a new type of address in the MAC header, the *CARA destination address*. Upon receiving a packet, the MAC layer at the node checks not only the MAC destination address, but also the CARA destination address in the MAC header. If the MAC destination address matches its own MAC address, and there is a valid CARA destination address also included in the header, the MAC layer at the node will simply redirect this packet to the indicated CARA destination, after validating that it was indeed a bidder of the associated auction that was previously placed by the sender node.

4.5 Cost Function

It is assumed that the cost a particular node in the network incurs for forwarding other nodes' packets depends on the cost of unit energy consumption on that node, *cost of energy*, in dollars per joule. Cost of energy will naturally be different at different nodes depending on several variables, such as the current battery level of the node, cost of recharging the battery, or cost of potential processing delay to node's own message transmission or reception. Because of the complexity involved, this study does not attempt to formulate the cost of energy based on these variables, but simply assumes that each node is able to determine its cost of energy at any given time. In the simulations, however, a relationship between the cost of energy and current battery level of the node is defined, which is used by the nodes to calculate their cost of energy when required by the simulation.

Assume the ad-hoc network consists of a set of n nodes, $V = \{v_1, \ldots\ldots, v_n\}$. In order to calculate cost of forwarding a particular packet, say packet *n*, node v_j simply multiplies its cost of energy with the duration of the transmission required to transmit the packet, and with the required transmission power level. If the data transmission rate is R (bits/sec), and packet length is L (bits), then forwarding cost of packet *n* at v_j can be calculated as:

$$c_{n,j}^{pkt} = c_j^e \frac{L}{R} p_j^{tx} \quad \text{(dollars)} \tag{4.1}$$

where c_j^e is the cost of energy (dollars/joule) at v_j, and p_j^{tx} (watts) is the transmission power level at v_j.

4.6 Mobility

Mobility may significantly impact the amount of costs that nodes incur for transmitting packets, simply because required transmission power levels will have to be dynamically adjusted to cope with the changes in the propagation environment.

As a simplifying assumption in this study, the nodes in the network are assumed to have relatively low mobility (comparing to the vehicular speeds), either at fixed positions or moving at walking speeds, to minimize the impact on CARA auctioneers, bidders, or winners of previously placed auctions for packet forwarding services at MAC level. With the help of this requirement, it can be assumed that during the course of an auctioned packet forwarding service, which may last up to a few seconds, the packet forwarding costs of participating nodes will change only slightly.

Performance study of CARA under various mobility models will be left as a future work.

4.7 Channel Model and Physical Layer

A typical radio channel propagation model used in wireless systems consists of three components (Rappaport, 2002): Path loss, large-scale variations (modeled by lognormal shadowing model), and small-scale variations (modeled by a Rayleigh distribution model). For the purpose of designing CARA, without loss of generality, only the path loss model is considered, and small-scale variations and large-scale variations are ignored. It is also assumed that the gain between two nodes is the same in both directions, i.e. the channel between the transmitter and the receiver is symmetrical. Having unidirectional links may require additional measures in CARA, possibly use of a security threshold as a power margin, to make the transmissions more reliable. These measures are not considered in this study, and left as future work.

Omnidirectional antennae are assumed at the nodes, and therefore all the nodes within the chosen transmission range of a given node can hear a message sent by that node.

When using the path loss model, it is assumed that the mobile devices have similar antenna heights, and model the received signal using the traditional decay function of the transmitted power and the distance between the transmitter and the receiver:

$$p^{rcv} \propto \frac{p^{tx}}{d^k} \quad , k \geq 2 \tag{4.2}$$

where k is a constant that depends on the propagation medium and antenna characteristics.

A node can successfully receive a packet, and falls within the transmission range, when received power level, p^{rcv}, is above the minimum received power threshold, $p^{rcv}_{\min}$. $p^{rcv}_{\min}$ is constant throughout the network, and known by all nodes. It is also assumed that nodes are capable of measuring the received power levels for the packets they receive or overhear.

4.8 Estimation of Minimum Transmit Power Level

The nodes can estimate the link attenuation, and the minimum transmission power levels required to reach other nodes, using the method described below. This method requires that each node record the transmission power level used within the header of each packet transmitted. Furthermore, it requires that the radio-transceiver can estimate the received power. One of the assumptions in this thesis is that the nodes are indeed capable of measuring the received power levels for the packets they receive or overhear. There are several drivers of products based on the IEEE 802.11 standard provide this information (Bergamo et al. 2004).

Once node v_j receives a packet from node v_i, and measures the received power level $p_{i,j}^{rcv}$, it can calculate the minimum transmission power level required for packet transmission between v_j and v_i, using Equation (4.2), as long as it knows the transmit power level of v_i :

$$p_{i,j}^{\min} = \frac{p_i^{tx}}{p_{i,j}^{rcv}} \; p_{\min}^{rcv} \tag{4.3}$$

where p_i^{tx} is the transmit power level of v_i .

A power margin may also be added to the above calculated $p_{i,j}^{\min}$ as a security threshold, to make the transmission more reliable in view of the fact that the channel will not symmetric in real world, and in order to overcome the problem of unstable links due to channel fluctuations and node mobility. For simplicity purposes, in this thesis it is assumed that the channel is indeed symmetric and the links are stable, and therefore no security threshold was used.

This method of estimating minimum transmit power levels required to reach other nodes is widely used by researchers for power control in ad-hoc networks, including (Doshi et al. 2002), (Bergamo et al. 2004), where the authors use roughly the same equation but with the logarithmic (decibel) measures. Similar techniques for power control are also widely used in cellular networks (Rappaport, 2002).

4.9 Variable Transmission Power Levels

It is assumed each node in the network is capable of dynamically varying its transmission power level before transmitting a given packet. This is a key requirement that CARA depends on for proper operation. According to equations (4.1), (4.2), and (4.3), this capability has a direct affect on the forwarding cost and on the transmission range of each packet.

In 802.11 systems, the wireless cards have been found to consume power not only while transmitting or receiving, but also while idling. Some of the proposed algorithms proposed in the literature conserve battery power at nodes by intelligently powering off nodes that are not actively transmitting or receiving packets, such as PAMAS (Singh and Raghavendra, 1998) or BECA (Xu et al. 2000).

A modified version of these algorithms could also be applied to CARA. When the mobile node starts receiving a data packet (which could be the initiation of an auction, and would typically be significantly larger then control packets since it will contain user data), the mobile could first read the header to see if the packet was specifically directed to itself. If the packet was not directed to that node, but it indicates the initiation of an auction, the node stores the necessary auction parameters and temporarily turns off its receiver in order to save power, until the end of the ongoing data transmission.

In this thesis, the issue of reducing power consumption while the radio is in transmission state is being considered. Enhancements for resource saving during receive and idle modes are left as future work.

4.10 Incentive Scheme

As discussed earlier, proper operation of the ad-hoc network requires cooperation of nodes at all protocol layers. CARA assumes that an incentive scheme is used at the network layer for stimulating nodes in participating routing layer procedures and packet forwarding at the network layer, since nodes in the network are assumed to be selfish and non-cooperative.

CARA operates below the network layer, and uses an auction-based incentive scheme for stimulating additional intermediate nodes to forward packets at the MAC level, in order to improve the cost efficiency of the network. The two most common remuneration types used in ad-hoc network incentive schemes are digital currency and reputation (Obreiter et al. 2003). In this design it is assumed the incentive scheme used in the network uses digital currency (payment-based) as remuneration. The mechanism of where and how securely keeping the currency and making the payments is a separate research thread. Some of the proposed architectures are using of some tamper resistant hardware (Buttyan and Hubaux, 2003) or on-line bank service (Zhong et al. 2003).

4.11 MAC Operation

It is assumed that MAC operation is based on CSMA/CA, "carrier sense multiple access with collision avoidance". CSMA/CA is the fundamental access method used by the

Distributed Coordination Function (DCF) of the IEEE 802.11 (ANSI/IEEE Std 802.11, 1999) standard, which is, by far, the most dominant MAC protocol for wireless ad-hoc networks. In CSMA/CA access mechanism, a station listens to the medium before beginning a transmission. If the medium is busy, the station will wait for random period before attempting to transmit again, determined by a binary exponential backoff algorithm. In addition to the physical carrier sensing, the DCF implements a method for virtual carrier sensing, by exchanging of RTS/CTS (request-to-send/clear-to-send) handshake packets between the transmitter and the receiver, and by including the duration of the packet transmission in the header of RTS, CTS, and DATA frames. This duration is used to infer the time when the source node would receive an ACK (acknowledgement) frame from the destination node, and the medium would be idle again. The minimal frame exchange consists of two frames, a DATA frame from the source to the destination and an ACK frame from the destination to the source. RTS/CTS handshaking for media reservation is optional, and may not be used when the length of the DATA frame to be transmitted is less than a certain threshold.

4.12 Other Assumptions

It is assumed that nodes will participate in auctions (by sending bid messages) without receiving payment for it, because of the potential payoff they can get if they win the auction, by receiving payments for forwarding other node's packets. Also, over a long period of time, the application running on each node is assumed to have a large number of messages to transmit. This makes packet forwarding very attractive at each node, in order to collect as much money as possible and to be able to pay for sending its own messages. In addition, it is assumed that the nodes are able to send sealed (i.e. encrypted) bids to the auctioneer. Security in ad-hoc networks is by itself a very large research thread and outside the scope of this thesis.

CHAPTER 5

CARA ARCHITECTURE AND METHOD DESCRIPTION

5.1 Phases of an Auction

CARA improves the cost efficiency of the wireless ad-hoc network through *auctions* placed at the MAC level. An *auction* is a method of stimulating and identifying any intermediate nodes that will be *redirecting* packets at the MAC layer with lower cost, and without affecting the routing layer operation.

An auction consists of three phases; *auction setup* phase, *bidding* phase, and *auctioned route* phase, as shown in Figure 5.1 and Figure 5.2.

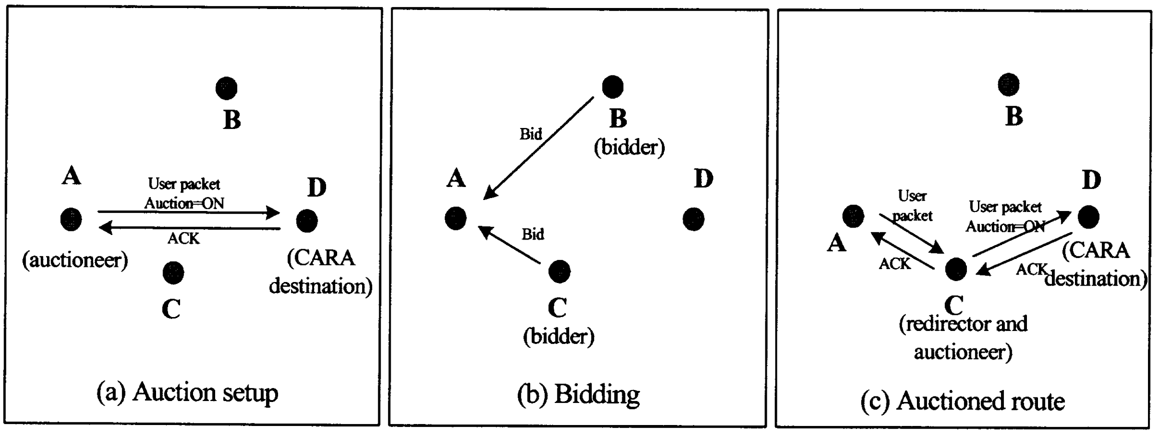


Figure 5.1 Phases of an auction.

Auction Setup Phase

The *auctioneer* initiates this phase, which is typically a node that has at least one data packet to be sent out to some other node in the network, called the *CARA destination*, as introduced in the previous section. Note that for most cases the CARA destination will not be hosting the application that will consume the data packet (i.e. will not necessarily be the final destination on the end-to-end route), but typically a node within the transmission range, determined by the routing protocol as one of the many hops forming the end-to-end route to final destination.

The auctioneer initiates the auction setup phase by sending the first data packet to the CARA destination directly. Within the header of the data packet, the auctioneer includes some of the key parameters of the auction:

- The auctioneer's cost of energy
- The transmission power level used to transmit the packet

The neighboring nodes, which are the potential bidders for this auction, overhear this transmission and store this information in a table, as will be explained later in more detail.

The auction setup phase is completed with the associated acknowledgement frame sent out by the CARA destination node, which includes its own transmission power level in the frame header.

One key point here is that the CARA destination node sets its transmission power level to the minimum value required for reaching the auctioneer. CARA destination node can calculate this minimum using Equation (4.3). The neighboring nodes overhear this transmission also, and can now make a decision on whether or not entering the auction (i.e. bidding), as will be explained in the following paragraphs.

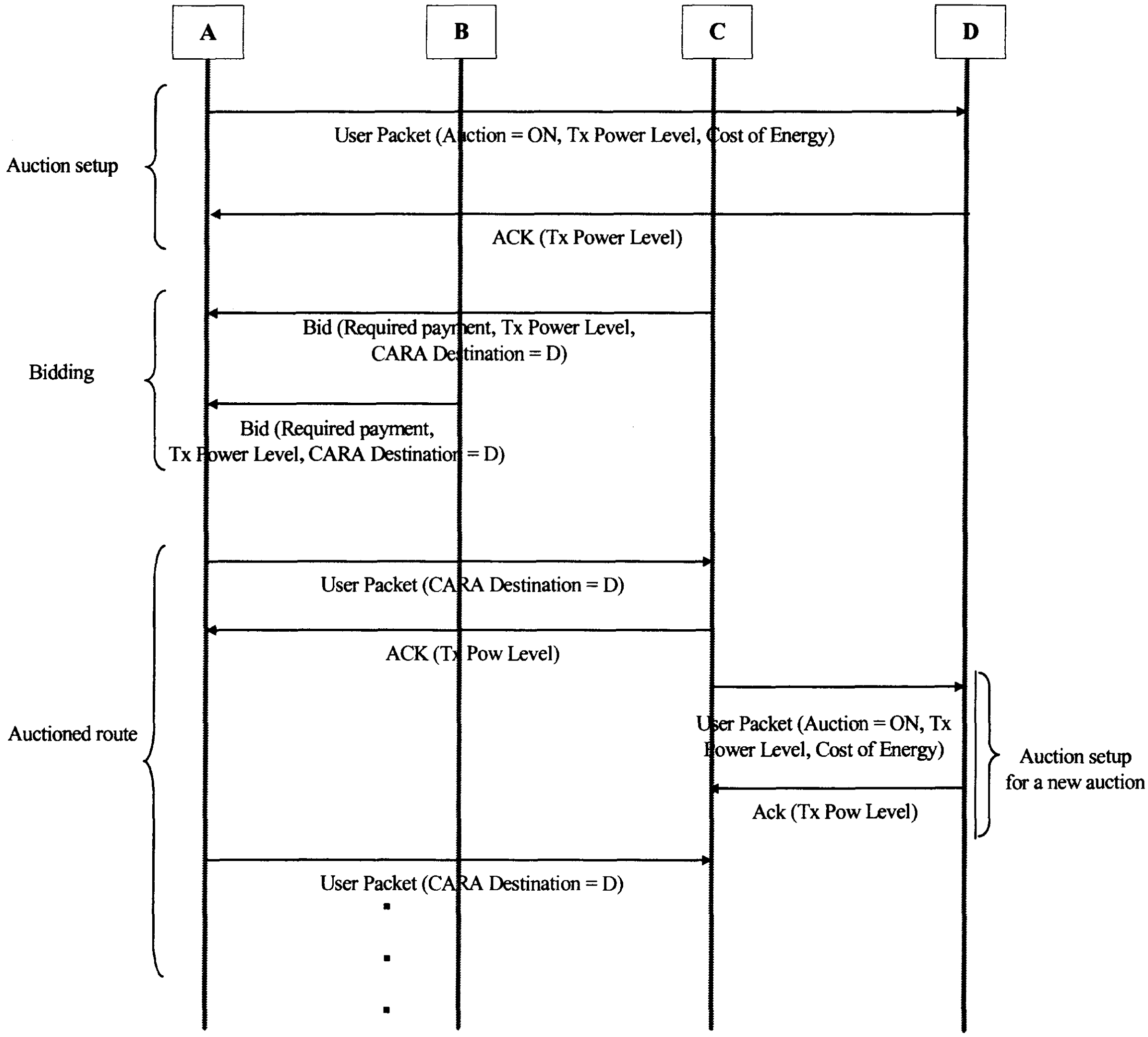


Figure 5.2 Message flow for an auction.

Bidding Phase

At this phase, the neighboring nodes that have overheard the message exchange between the auctioneer and the CARA destination node can now make an estimate on how much it would cost to the auctioneer to send packets to the CARA destination directly, and compare it with the cost that would be incurred if they acted as redirectors for this transmission.

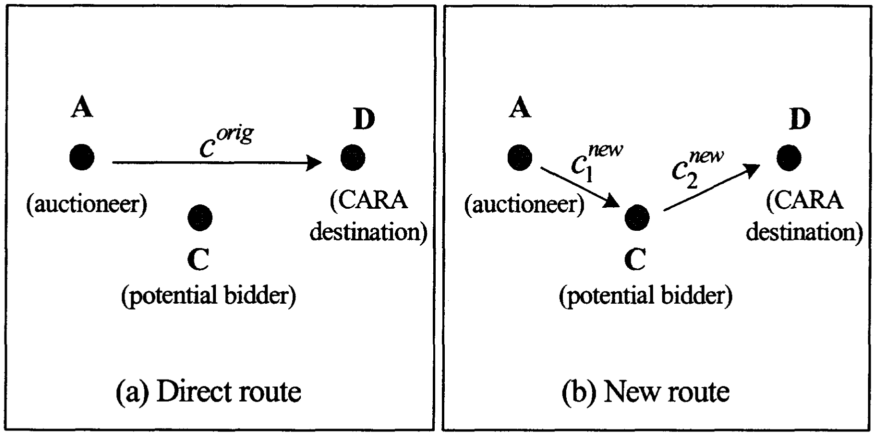


Figure 5.3 Scenarios considered by bidder.

These two options that are considered by the potential bidder is illustrated in Figure 5.3. c^{orig}, shown in part (a) of the figure is the amount of cost the auctioneer would incur for transmitting directly to the CARA destination for unit time. Using Equation (4.1), c^{orig} can be calculated by the potential bidder as:

$$c^{orig} = c_A^e p_{A,D}^{tx} \quad \text{(Dollars/second)} \tag{5.1}$$

where

c_A^e is the cost of energy (dollars/joule) of the auctioneer, and received by the potential bidder in the data packet sent out by the auctioneer when the auction was first initiated.

$p_{A,D}^{tx}$(watts) is the minimum transmission power level required at the auctioneer to reach the CARA destination, which is assumed to be same as the transmission power level included in the acknowledgement frame from the CARA destination node. Note that as mentioned in previous sections, a symmetric radio channel is assumed, where the propagation and fading characteristics is same in both directions between two nodes.

Similarly, the amount of total cost that would be incurred if the potential bidder acted as a redirector for unit time transmission to the CARA destination can be calculated as:

$$c^{new} = c_1^{new} + c_2^{new} = c_A^e p_{A,C}^{tx} + c_C^e p_{C,D}^{tx} \qquad \text{(Dollars/second)} \tag{5.2}$$

where

c_A^e is the cost of energy (dollars/joule) of the auctioneer, received by the potential bidder in the data packet sent out by the auctioneer when the auction was first initiated

$p_{A,C}^{tx}$ (watts) is the minimum transmission power level required at the auctioneer to reach the potential bidder, and can be calculated by the potential bidder using Equation (4.3)

c_C^e is the cost of energy (dollars/joule) of the potential bidder

$p_{C,D}^{tx}$ (watts) is the minimum transmission power level required at the potential bidder to reach the CARA destination, and can be calculated by the potential bidder using Equation (4.3).

The potential bidder will only make a bid if the service it offers reduces the original cost of the auctioneer (otherwise, it's guaranteed that the bidder will loose the auction even if there is no other bidder). Therefore, the following condition must be true in order to place a bid:

$$c^{orig} > c^{new} \tag{5.3}$$

The payment that bidder will require for forwarding auctioneers' packets will be equal to the cost that bidder will incur for those transmissions:

$$c_C^{payment} = c_2^{new} \tag{5.4}$$

Note that if the bidder wins the auction, it will likely receive a larger payment from the auctioneer since this is a second-price auction. Therefore it will be able to make a profit from the auction. The amount of this profit (i.e. the difference between the payment it receives, and the payment it asks for) will depend on how far the difference is between the best bid and the second best bid.

All bidders will prepare the bid frame with the following information in the frame header, and will send the bid frames to the auctioneer.

- Required payment to the bidder.
- The transmission power level used by the bidder to transmit the bid frame
- The CARA destination address

The auctioneer will examine the bids receives for redirecting to a particular CARA destination, and will select the bidder that minimizes its cost, as the winner of the auction. This cost, that the auctioneer is trying to minimize, is the cost of forwarding packets to the bidder plus the required payment that needs to be made to the bidder, for transmission for unit time:

$$c_A = c_C^{payment} + c_A^e p_{A,C}^{tx} \tag{5.5}$$

where

c_A is the cost that the auctioneer incurs (and is trying to minimize).

c_A^e is the cost of energy (dollars/joule) of the auctioneer.

$p_{A,C}^{tx}$ (watts) is the minimum transmission power level required at the auctioneer to reach the potential bidder, and can be calculated by the auctioneer using Equation (4.3).

$c_C^{payment}$ is the requested payment by the bidder, received by the auctioneer in the bid frame.

Since the auction that is placed is a sealed-bid second-price auction, the actual payment that winner receives will depend on the amount of cost the auctioneer would have incurred if it selected the second best bid as the winner:

$$c^{payment} = c_C^{payment} + (c_A^{second} - c_A^{best}) \tag{5.6}$$

where

$c^{payment}$ is the actual payment that winner receives

$c_C^{payment}$ is the payment that the bidder asked for, received by the auctioneer in the bid frame

c_A^{best} is the minimum cost that the auctioneer incurs (i.e. using the best bid)

c_A^{second} is the cost that the auctioneer would have incurred using the second best bid. Note that if there is only one bidder, this will be equal to the amount of cost the auctioneer would incur for transmitting directly to the CARA destination for unit time, which is c^{orig}.

The amount of profit that the winner will make:

$$c^{profit} = c_A^{second} - c_A^{best} \tag{5.7}$$

Auctioned Route Phase

In this phase, the auctioneer starts sending the required user data packets to the CARA destination through the new local route, where the node that made the winning bid acts as a redirector. Note that if there is no winning bid, the auctioned route will be a direct route to the CARA destination (i.e. no redirector). In this model, the auctioneer will not advertise it's cost of energy during the auctioned route phase. This gives the ability to disable further auctions to be initiated by the same auctioneer during this phase, making the architecture and design simpler.

If there was no mobility, and if the cost of energy of the nodes never changed, this phase could potentially continue as long as the auctioneer has packets to send to the CARA destination. However, this is not the case. The cost of energy of the nodes continuously changes based on many variables such as their remaining battery level. Also, the nodes are mobile (even though low mobility is assumed). Therefore, the results of the auction may not be valid after some time, i.e. the auctioneer may find itself spending much more money than what it originally started with, or the winning bidder may find itself losing money even if it started with a profit.

Because of these reasons, the auctioned route phase continues only for a short amount of time (in the range of few seconds), to allow for only very small change in the channel conditions (when having low mobility) and a very small change in the cost of energy of the nodes, but still allow the auctioneer to be able to send potentially many packets on the auctioned route, depending on the size of user data received from the network layer (see Figure 5.6 for an example). After this configurable amount of time, the auctioned route will expire and the auctioneer may initiate a new auction, i.e. nodes will go through another cycle of these phases.

One important point here is that during this phase, the winning bidder (i.e. the redirector) may chose to initiate its own auction to reduce its own cost and further increase its profit. For example in part (c) of Figure 5.1, the winning bidder (node C) initiates a new auction, looking for any bidders which would help him to reduce its cost to transmit to the CARA destination (node D).

5.2 CARA Operation on End-To-End Network Layer Route

Now that all phases of a single auction is presented in detail, the end-to-end example shown in Figure 5.4 will be explained. In this example, source application running at node A has user data messages to be sent to the destination application running at node H. The routing protocol determines a minimum-hop network layer route through nodes D and F, as shown in part (a) of the figure.

The first data packet from the application source to the application destination is sent with no MAC-level redirectors, but used to initiate auctions by node A, node D and node F, in order to find any redirectors that would reduce their cost of transmission. Node A, node D and node F (the auctioneers) advertise their auction related parameters, such as their cost of energy and the transmission power level they use to transmit the packet, in the MAC header of this first data packet.

Note that in this scenario, node D becomes a CARA destination (which is defined earlier) for node A, node F becomes a CARA destination for node D, and node H becomes a CARA destination for node F. The setup phase of these auctions is completed with the associated acknowledgement frames sent out by the CARA destination nodes, which includes their own transmission power level in the frame header.

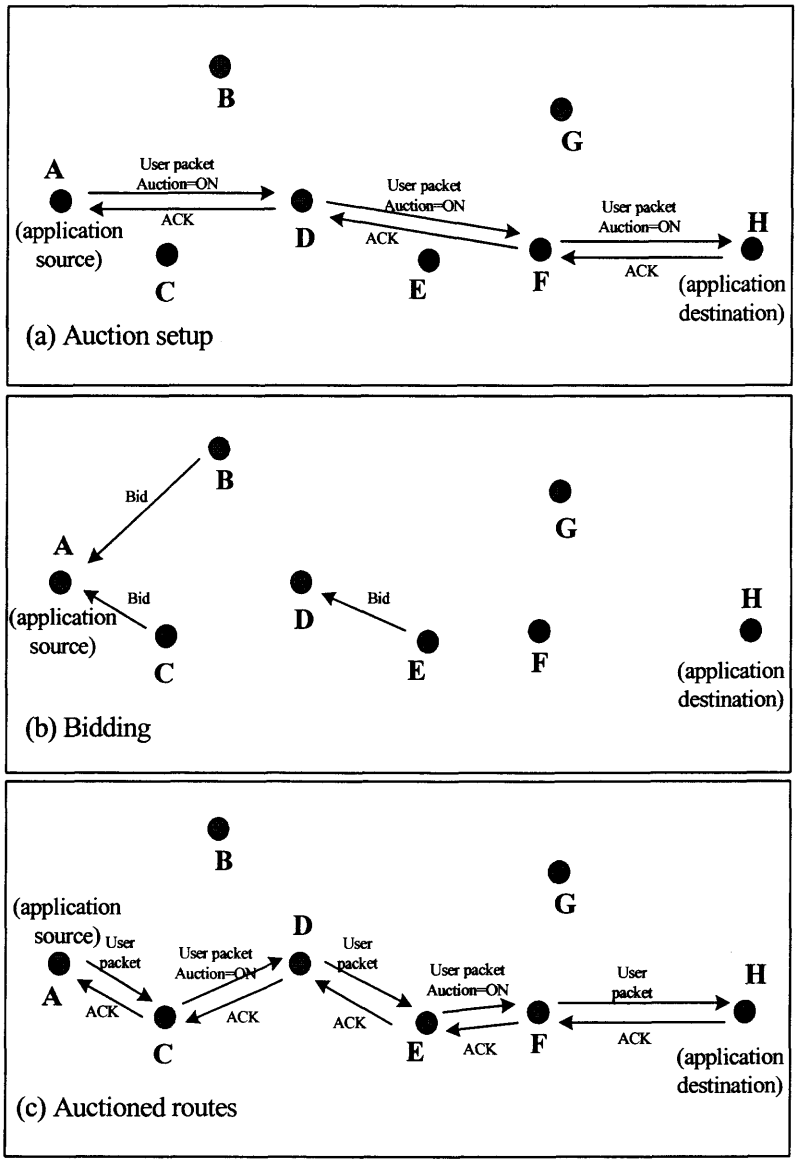


Figure 5.4 CARA operation shown on end-to-end network layer route.

The neighbor nodes that can successfully overhear both the auction initiation messages (DATA packets) and associated acknowledgement frames will make a determination on whether or not participate in the auctions. In this example, node C and node B can overhear the DATA/ACK frame exchange between node A and node D. Similarly, node E can overhear the frame exchange between node D and node F; and node G can overhear the frame exchange between node F and node H.

Nodes C, B, E and G will make a decision on whether or not entering the auctions they have received (i.e. bidding), using the criteria explained above in detail. In this example, nodes C and B decide to bid on the auction placed by node A, and node E decides to bid on the auction placed by node D. Node G does not place any BID on the auction placed by node F, since it identifies that it can not reduce the cost node F sending packets to node H directly.

One important point here is that all these auctions placed (3 auctions in this example) are independent of each other, and there is no direct relationship between the phases of one and phases of another. For example, the bidding phase of the auction placed by node A can be completed even before the auction by node D is initiated. For simplicity, Figure 5.4 shows all auction setup phases and all bidding phases together, but there is no requirement for all auctions to be initiated (i.e. user data packet to be transmitted all the way to the application destination) before any of the bidding phases can start. As another example, the bidding phase of the auction placed by node D can be completed even before the auction by node F is initiated.

Using the parameters that bidder include in the BID frames, such as the required payment to the bidder, and the transmission power level used by the bidder to transmit the bid frame, the auctioneers can determine the best bid they receive based on the criteria discussed above in detail, which will minimize their cost.

In this example, node A receives bids from node B and node C for the auction it placed, and determines that node C is the winning bidder. Therefore, during the auctioned route phase, shown in part (c) of the figure, it will send its packets to node C with CARA destination address in the MAC frame header set as node D (i.e. network layer next hop), which will in turn be forwarded to node D by the CARA entity at node C. Since the auction that is placed is a sealed-bid second-price auction, the actual payment that node C receives depends on the amount of cost node A would have incurred if it selected node B as the winning bidder.

Similarly, node D determines that node E is the winning bidder of its auction, and since there is no other bid received for this auction, the actual payment that node E receives depends on the amount of cost node D would have incurred if it sent it packets to node F directly.

Node F does not receive any bid for the auction it placed; therefore will continue to send its packets to node H directly, during the auctioned route phase.

As indicated previously, the winning bidders (i.e. the redirectors) nodes C and node E initiates their own auctions as shown in part (c) of the figure, in order to reduce their cost of redirecting and further increase their profit. For simplicity, it is specified in this model that the auctioneers do not place other auctions for the same route during the auctioned route phase. In other words, the auctioneer does not auction the same route "twice". In this example, node A, node D, and node F do not place other auctions once they enter the auctioned route phase. However, as mentioned earlier, auctioned routes will expire after this configurable amount of time, due to the changes in the channel conditions (even if low mobility is assumed) and changes in the cost of energy of the nodes. After their auctioned routes expire, node A, node D, and node F can initiate new auctions for their transmissions.

5.3 Relationship Between the Node Density and Number of Auctions Placed

As discussed in the previous section, the auctioneer node is not allowed to place other auctions for an auctioned route until it expires. However, the winner of a particular auction can place its own auction (as an auctioneer), in order to reduce its cost of redirecting and further increase its profit.

Because of these rules, the total number of auctions placed on an end-to-end route only slightly increases compared to any increase in node density. Consider the simple case where there are $2^n - 1$ nodes, equally distributed and have the same cost of energy, on a single line between two nodes that are communicating directly on the network layer. When CARA is enabled, a number of auctions will take place and a number of intermediate nodes will be added, breaking the transmission into smaller hops and reducing the cost of transmissions. It can be argued in this scenario the maximum number of hops created will not exceed $n + 1$.

This is illustrated in Figure 5.5. In scenario (a), there are two nodes (nodes A&B) that are communicating directly on the network layer route determined by the routing protocol, and no other nodes that could participate in any MAC level forwarding,, and therefore the single auction placed results in no additional hops. In scenario (b), node C is introduced, which participates and wins the auction placed by node A, therefore adding another hops to the route, and at the same time placing its own auction. In scenario (c), two more nodes, node D and node E, are introduced. Node D can not be a winner of the initial auction placed by node A (the winner of that auction is node C), since the nodes are all equally distributed and cost of energy is assumed to be same at all nodes, and node A can only place a single auction. However, node E wins the auction of node C, and places its own auction. Eventually, in every step, the number of nodes along the line is eventually doubled, however the number of auctions placed and the number of hops added only increased by one in each scenario.

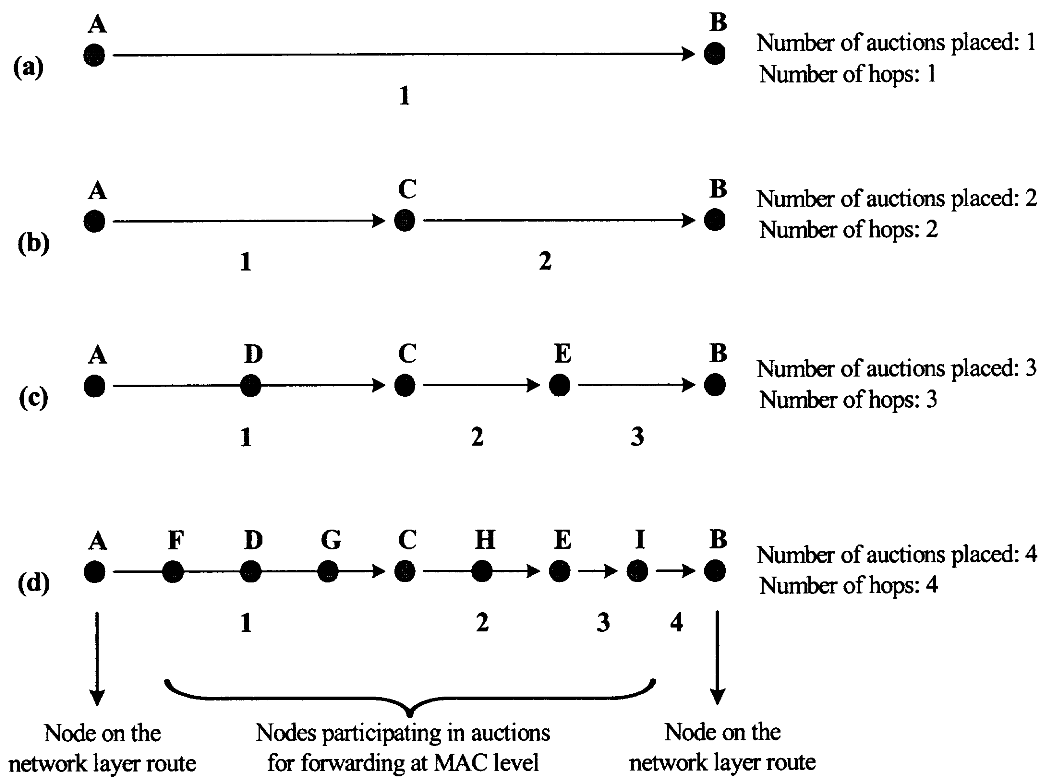


Figure 5.5 Node density and number of hops/auctions.

This observation could be generalized to have an estimate of the impact on the additional number auctions and number of hops created by CARA, as the node density increases. As the number of nodes in the network is increased exponentially (i.e. doubled at each step), the number of auctions placed and the number of hops will increase linearly. In other words, as the number of nodes in the network is increased linearly, the number of auctions placed and the number of hops will increase in the order of $\log n$. The relationship between the number of hops and node density is illustrated in Figure 5.6.

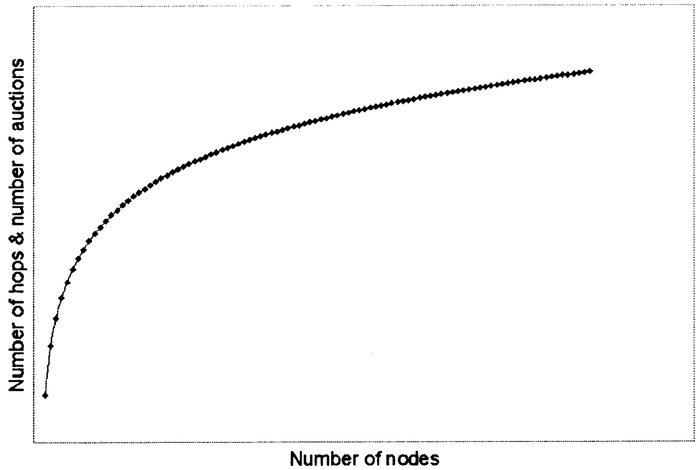


Figure 5.6 Relationship between the node density and the number of hops and auctions.

5.4 CARA Architecture

CARA operates below the wide-area routing protocols, as an extension of the MAC layer. Figure 5.7 illustrates this architecture.

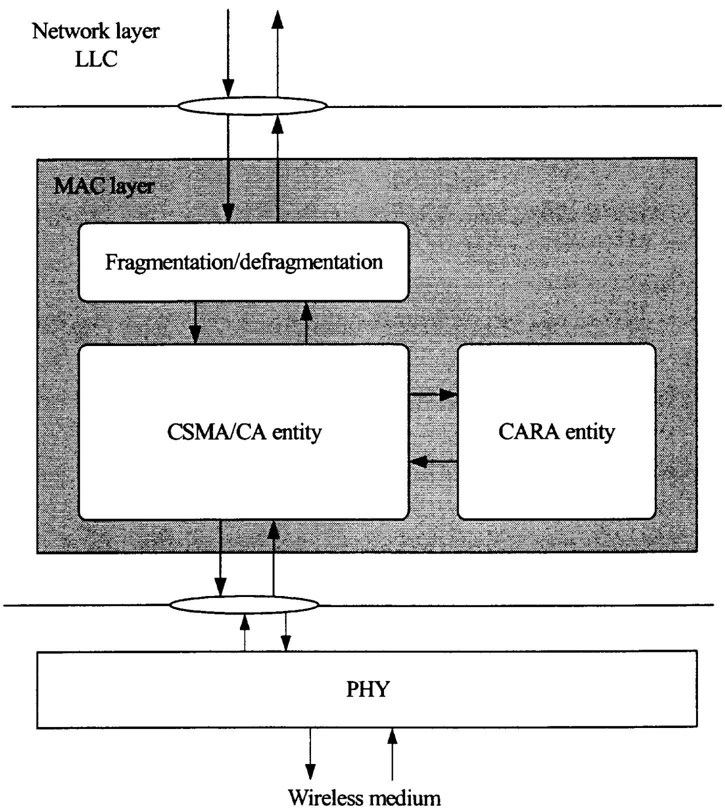


Figure 5.7 CARA architecture.

The functionality provided by the CSMA/CA entity includes the basic CSMA/CA access method (which was discussed in previous sections), directed or broadcast/multicast packet transfer, MAC-Level acknowledgments, recovery procedures and retransmissions, RTS/CTS usage, and duplicate detection and recovery.

The Fragmentation/defragmentation entity operates between the CSMA/CA entity and the higher layers, providing fragmentation/defragmentation service to the DATA packets that are received from the network layer or to be delivered to the network layer, as required. CARA entity operates on DATA packets that are already fragmented.

There is a continuous message exchange between the CSMA/CA entity and the CARA entity. The CSMA/CA entity forwards the pointer of every frame that will be transmitted, and every frame that has been successfully received from the physical layer, to the CARA entity. The CARA entity performs the required processing, if any, for each of these frames, based on the frame type (i.e. DATA, ACK, or BID) and direction (i.e. is about to be sent to the wireless medium or has just been received from the wireless medium). The CARA entity will than return the frames back to the CSMA/CA entity for further processing. Note that the CARA entity does not perform any processing for the RTS/CTS frames, which may optionally be used by the MAC layer as a method of virtual carrier sensing.

As presented in previous sections, the MAC header of the frames is modified to include the transmission power level used by the node to transmit the each frame. This power level is determined by the CARA entity, upon receipt of a frame (that is about to be sent out to the wireless medium) from the CSMA/CA entity. The MAC layer is responsible of setting the power level to the indicated value in the MAC header, during the actual transmission. The required processing for different frame types and directions are presented in Table 5.1.

Table 5.1 Processing Performed by the CARA Entity Based on Frame Type/Destination

Type and direction of the frame received by the CARA entity	**Processing performed by the CARA entity**
DATA frame about to be sent to the wireless medium	Determine whether or not the frame will be sent over an auctioned route or a new auction needs to be initiated. Modify frame header accordingly.
ACK frame about to be sent to the wireless medium	Modify frame header with the required minimum transmission power level.
DATA frame has been received from the wireless medium	Determine if the node is a redirector for the frame. In this case, determine whether or not an auction needs to be initiated, and modify frame header accordingly. Otherwise (i.e. the node is not a redirector for this frame), determine if the received data frame is the initiation of a new auction. In this case, store the auction parameters from the frame header.
ACK frame has been received from the wireless medium	Update auctioned route parameters, if this ACK frame is in response to a DATA frame that initiated an auction and this node is the auctioneer. Otherwise, if the node is simply overheard this ACK frame and auction setup is in place for this route, determine whether or not to enter the auction, and if required, prepare the BID frame and forward to the CSMA/CA entity.
BID frame has been received from the wireless medium	If this as a bid for an auction that this node initiated (i.e. this node is the auctioneer), determine whether or not this is the best bid received, and update the auctioned route parameters accordingly.

According to CARA architecture, each node typically takes one of the following two logical roles for every frame being processed: The *auctioneer* role and the *bidder* role. The main functionality of an auctioneer is initiating, maintaining and managing of the auctions being placed for the user data packets that need to be sent out. The main functionality of a bidder is processing of the auctions that are being placed, determining whether or not a bid will be placed, sending out of the bid frames, and performing redirecting operation (i.e. packet forwarding at the MAC level) for the auctions that are won.

The CARA entity maintains two tables for performing required actions as an auctioneer or as a bidder: *Auctioned Routes* table and *Bidding Information* table.

Table 5.2 Parameters Stored by the Auctioneer for Each Auctioned Route

Parameters	
CARA destination	The destination node on the auctioned route. The auctioneer's goal is to transmit packets to this node with lower cost, using redirectors.
Redirector	This is the node that will perform packet forwarding at the MAC level on this auctioned route. The redirector is selected from the set of bidders (i.e. the winner of the auction that was placed) for this route. It receives packets from the auctioneer and forwards them to the CARA destination. Note that this field will be empty if an auction was placed but there was no winning bid.
Transmit power	This is the required minimum transmission power level for sending messages to the redirector. If there is no redirector (i.e. no winning bid), this will indicate the transmission power level required for sending messages directly to the CARA destination. The minimum transmission power level can be calculated by the auctioneer using (4.3)
Payment	Payment to be made to the redirector for its packet forwarding service, calculated by the auctioneer using (5.6). Note that this field will be empty if an auction was placed but there was no winning bid.
Best bid	Best bid that has been received so far for this auction, which minimizes the cost that the auctioneer incurs, as shown in (5.5)
Second best bid	Second best bid that has been received so far for this auction. If there is only single bid received, this will be equal to the cost the auctioneer incurs for sending packets to CARA destination directly.
Auction timestamp	Identifies when this route's auction was initiated. Auctioned routes will expire after a configurable time period, upon which the auctioneers will initiate new auctions.

Auctioned Routes table, maintained by the auctioneers, has an entry for each auctioned route. As an auctioneer, the CARA entity at each node uses the Auctioned Routes table for initiating, managing and maintaining the auctions, and for using of the auctioned routes for cost reductions. In this table, the auctioneers store key parameters for each auctioned route. These parameters are given in Table 5.2.

Bidding Information table, maintained by the bidders, has an entry for each auctioned received. As a bidder, the CARA entity at each node uses the Bidding Information table for placing bids on the auctions that were placed by neighboring nodes. In this table, the bidders store the parameters are given in Table 5.3.

Table 5.3 Parameters Stored by the Bidder for Each Auction Received

Parameters	
Auctioneer	Address of the node that placed the auction.
CARA destination	The final destination node on the auctioned route. The auctioneer is looking for redirector (bidder) that will perform packet forwarding to this node.
Auctioneer's transmit power	This is the required minimum transmission power level of the auctioneer for sending messages to this node (i.e. bidder), calculated by the bidder using (4.3)
Bidder's transmit power	This is the required minimum transmission power level of the bidder for sending messages to CARA destination, calculated by the bidder using (4.3)
Auctioneer's cost of energy	Received by the bidder in the DATA frame that initiated the auction
Auctioneer's original cost	The amount of cost the auctioneer would incur for transmitting directly to the CARA destination for unit time. This can be calculated by the potential bidder using (5.1)

CHAPTER 6

CARA PROCESS FLOW

6.1 Main Process Flow

Now, the process flows that need to be implemented by the CARA entity at each node for required operation will be presented in detail.

As presented in Figure 5.5, there is a continuous message exchange between the CSMA/CA entity and the CARA entity. The CSMA/CA entity forwards the pointer of every frame that will be transmitted, and every frame that has been successfully received from the physical layer, to the CARA entity. The CARA entity will return the pointer back to the CSMA/CA after performing the required processing.

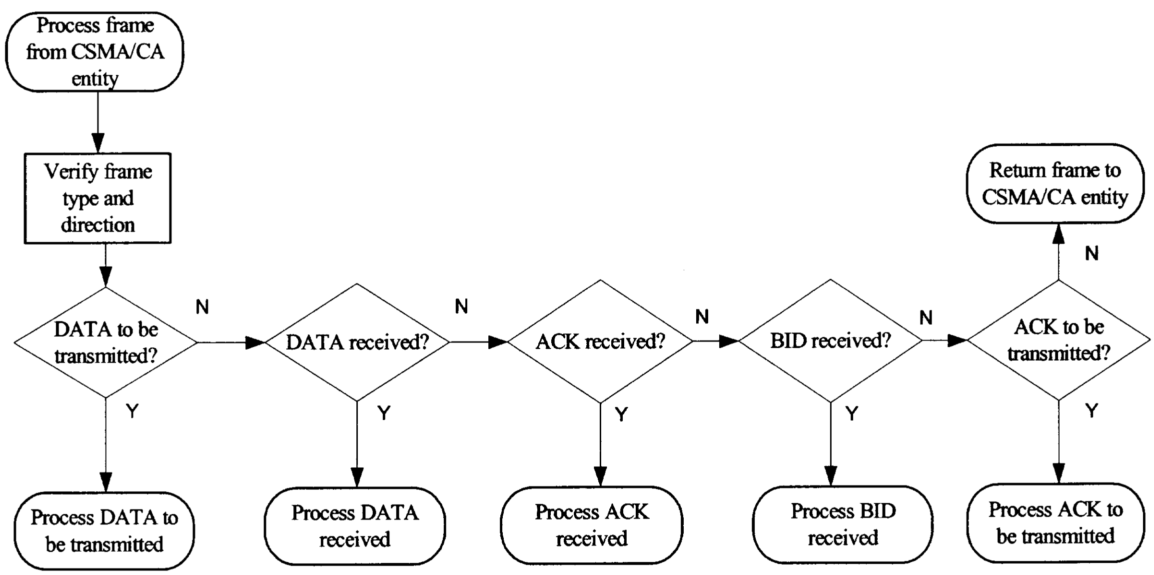


Figure 6.1 CARA main process flow diagram.

Figure 6.1 illustrates the flow of the main process followed by each CARA entity. Upon receiving a frame from the CSMA/CA entity, the CARA entity verifies the MAC frame type and direction.

The potential MAC frame types in this model are:

- DATA frame, used to carry messages to other nodes from network layer and above.
- ACK frame, which is a MAC level control message used to acknowledge successful receipt of a DATA frame
- BID frame, a new MAC level control frame defined for CARA, used by the nodes to place bids on auctions for redirecting packets at the MAC level.
- RTS/CTS frames, which are MAC level control messages used by the nodes to implement a method of virtual carrier sensing.

The direction of the MAC frame forwarded by the CSMA/CA entity will be one of the following:

- A frame that has just been successfully received by the MAC layer from the wireless medium (i.e. received from the physical layer)
- A frame that is just about to be transmitted (i.e. about to be sent to the physical layer)

The CARA entity will perform further processing if the frame type and direction matches the ones listed in Table 5.1; which is a DATA or ACK frame to be transmitted, or a DATA, ACK or BID frame that has been received from the wireless medium.

6.2 Process DATA to be Transmitted

If the node is about to transmit a DATA frame, the CARA entity follows the process flow given in Figure 6.2. In this case, the CARA entity first checks whether or not the frame is carrying network layer control data and not user data. An example of this type of packet is the HELLO packets used in most of the traditional routing protocols. For network layer control packets, the CARA entity does not perform any processing and returns the frame back to the CSMA/CA entity directly. Network layer control data is transmitted using normal MAC operation (no auctions and no redirection at the MAC level), to ensure proper operation of the routing protocol. Note that for most traditional minimum-hop routing protocols, network layer control packets are sent to the broadcast MAC address; therefore this could be used as a criteria by the CARA entity for determining these packets.

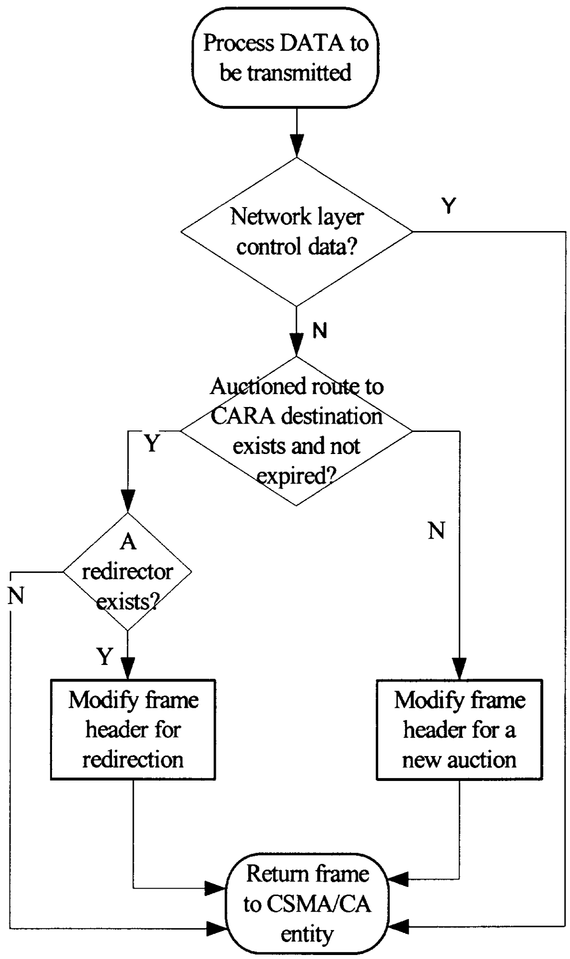


Figure 6.2 Process DATA to be transmitted.

If the DATA frame to be transmitted is not carrying network layer control data, the CARA entity tries to apply the auction based scheme for reducing the cost of this transmission. First, using its Auctioned Routes table, it checks if there has been an auction already initiated, and not expired, for transmissions to this CARA destination. If this is not the case, a new auction will be initiated, and therefore the frame header needs to be updated to include the key parameters required to initiate the auction:

- The node's (i.e. auctioneer's) cost of energy, known by the CARA entity at each node
- The transmission power level used to transmit the packet. In this case, this will be set to the maximum/common power level used in normal minimum-hop routing operation with no CARA redirection scheme.

After updating the frame header, the CARA entity returns the frame back to the CSMA/CA entity, which will in turn send the frame to physical layer for transmission. The MAC layer ensures the frame is transmitted at the power level indicated by the CARA entity in the frame header.

If there has been an auction already initiated, and not expired, for transmissions to this CARA destination, the CARA entity determines whether or not there is a redirector (i.e. winning bidder) selected for this route. The CARA entity once again uses the Auctioned Routes table to determine this condition. If there is a redirector already selected (for example, in the user data transmission by node D at part (c) of Figure 5.4, the redirector selected by node D in this example is node E), the CARA entity prepares the frame for redirection by the following updates on the frame header:

- Set the CARA destination address field to the MAC destination address indicated by the network layer.
- Set the MAC destination address field as the MAC address of the selected redirector.

These modifications will ensure the frame first to be transmitted to the redirector, which will in turn forward it at the MAC level to CARA destination.

If there has been no redirector selected (for example, in the user data transmission by node F at part (c) of Figure 5.4), the CARA entity will not need to perform any updates on the frame header, and returns the frame back to the CSMA/CA entity directly.

6.3 Process ACK to be Transmitted

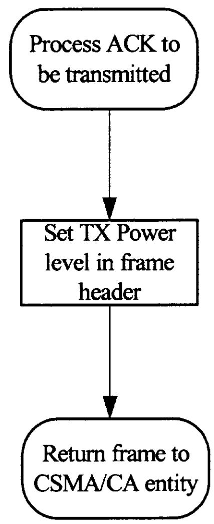


Figure 6.3 Process ACK to be transmitted.

If the node is about to transmit an ACK frame, the CARA entity follows the process flow given in Figure 6.3.

In this case, the CARA entity's responsibility is to update the frame header with the minimum required transmission power level. The CARA entity will then return the frame back to the CSMA/CA entity, which will ensure the transmission of the frame at this power level.

Setting of the ACK transmission power level to the minimum value is critical for proper CARA operation, because in cases where this ACK frame is part of an auction setup, the bidder nodes use this information to estimate the amount of cost the auctioneer would incur for transmitting to the CARA destination directly, as shown in (5.1). The CARA entity can calculate this minimum transmission power level using (4.3).

6.4 Process DATA Received

If the node has received a DATA frame, the CARA entity follows the process flow given in Figure 6.4.

The CARA entity first checks if the frame is carrying a network layer control packet, or the CARA destination set in the frame header is this node (i.e. frame contains a packet whose network layer destination is this node). If this is the case, the CARA entity does not perform any processing and returns the frame back to the CSMA/CA entity directly, which will in turn forward the packet to higher layers via the fragmentation/defragmentation entity.

Otherwise (the frame does not need to be forwarded to higher layers), the CARA entity checks whether or not the node is a redirector for this transmission, i.e. winning bidder of this auctioned route and will perform forwarding of the frame at the MAC level. If redirection is to be performed, this is indicated by the sender node by setting the MAC address of the frame header to the redirector's MAC address, and the CARA destination address of the frame header to the MAC address of the node whose network layer is intended to receive the packet carried by this MAC frame.

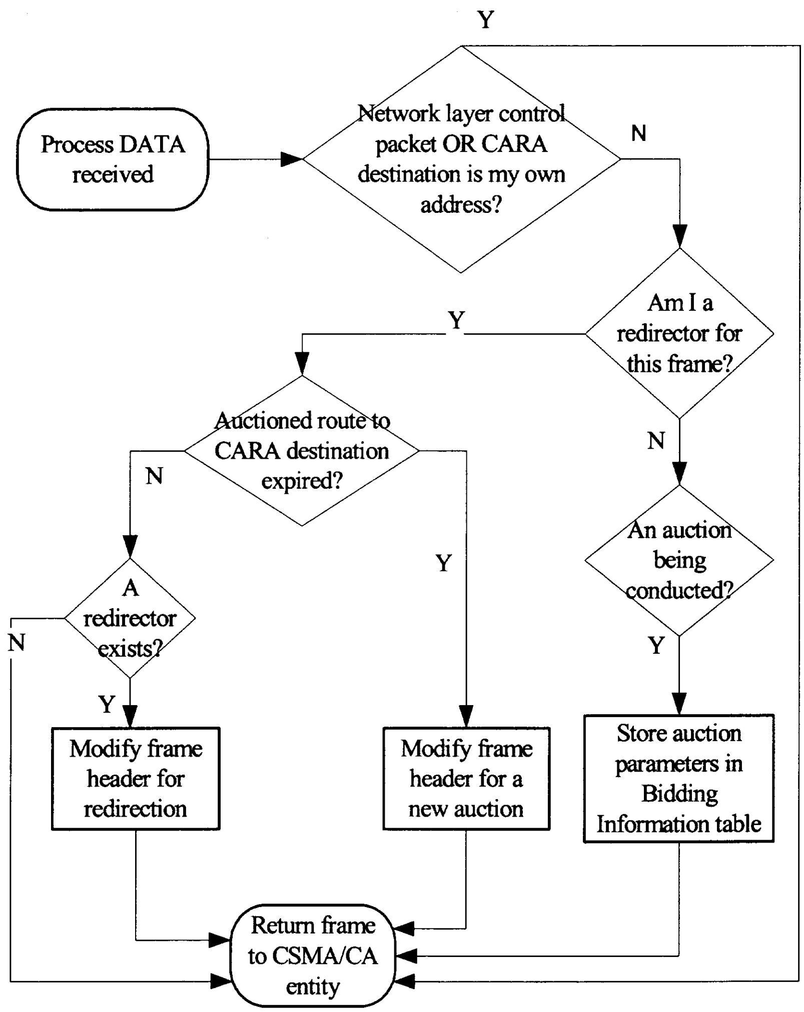


Figure 6.4 Process DATA received.

If the node is a redirector for this transmission, the CARA entity is responsible of making the necessary changes in the frame header, and returns it to the CSMA/CA entity to be forwarded to the CARA destination. In this case, the CARA entity may initiate its own auction to reduce its cost of forwarding packets to this CARA destination, and to further increase its profit. The process followed in this case is very similar to the process already given in detail above with Figure 6.2, and therefore will not be repeated. If the node is not a redirector for this transmission, and simply overhearing this DATA packet, the CARA entity checks whether or not an auction is being initiated through this DATA frame. If an auction is being initiated, the frame header will contain key parameters of the auction, such as the auctioneer's cost of energy and the transmission power level used to transmit the packet. In this case, the CARA entity stores this information into its Bidding Information table, to be used later to make a determination for bidding when the associated ACK frame from CARA destination is also received. The CARA entity then returns the frame back to the CSMA/CA entity.

6.5 Process ACK Received

If the node has received an ACK frame, the CARA entity follows the process flow given in Figure 6.5. In this case, the CARA entity checks if the frame is destined to this station. If the frame is destined to this station, using the Auction Routes table, the CARA entity checks if there has been an auction previously initiated by this station using the associated DATA frame. If this is the case, the CARA entity will update its Auctioned Routes table based on the transmission power level from the MAC header and the measured received power level, and then return the frame back to the CSMA/CA entity.

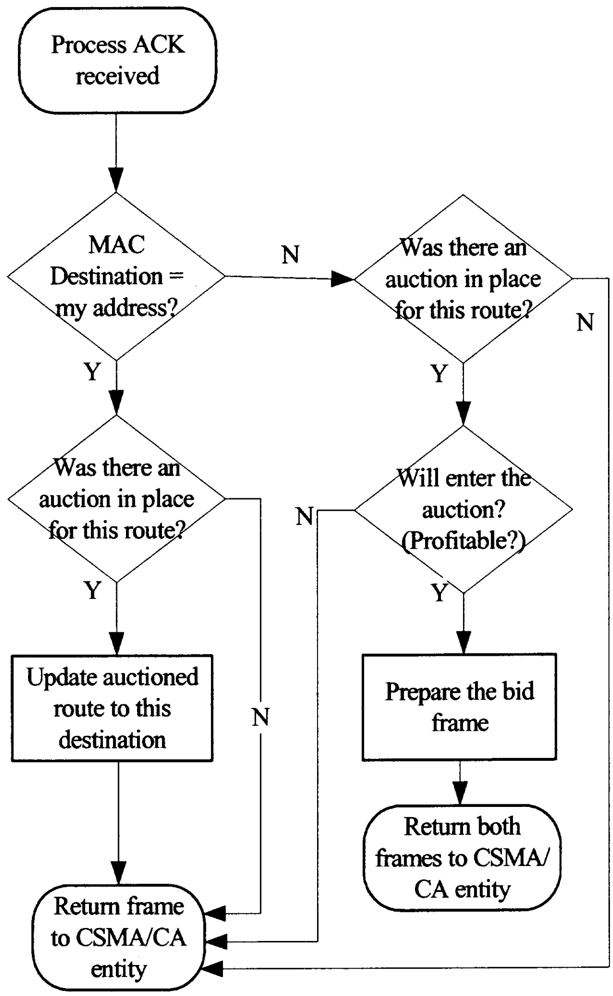


Figure 6.5 Process ACK received.

If the frame is not destined to this station, using its Bidding Information table, the CARA entity again checks if there has been an auction previously initiated by some other station using the associated DATA frame. If there was no auction initiated, the CARA entity simply returns the frame back to the CSMA/CA entity. Otherwise, it will make a decision on whether or not entering the auction (i.e. bidding) using the criteria explained above with (5.1), (5.2) and (5.3). If the CARA entity determines that a bid has to be placed, it will prepare the BID frame and forward it to the CSMA/CA entity to be transmitted to the auctioneer. In this case, CARA entity will include the following parameters in the BID frame header:

- Required payment to the bidder, calculated using Equation (5.4)
- The transmission power level used by the bidder to transmit the bid frame
- The CARA destination address

The CARA entity also returns the received ACK frame back to the CSMA/CA entity.

6.6 Process BID Received

If the node has received an ACK frame, the CARA entity follows the process flow given in Figure 6.6.

Upon receipt of a BID frame, the CARA entity checks if this as a bid for an auction that this node initiated (i.e. this node is the auctioneer). If this is the case, the CARA entity determines whether or not this is the best bid received, and updates the auctioned route parameters accordingly. The best bid should minimize the cost of auctioneer's transmission on this auctioned route, based on (5.5).

If the received bid was indeed the best bid, the CARA entity will have to update the following fields in it's auctioned routes table:

- Redirector
- Best bid
- Second best bid

Note that since the auction that is placed is a sealed-bid second-price auction, the actual payment that winner receives will depend on the amount of cost the auctioneer would have incurred if it selected the second best bid as the winner.

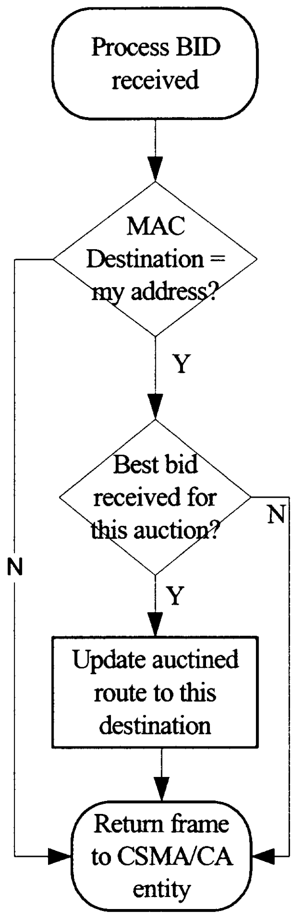


Figure 6.6 Process BID received.

CHAPTER 7

SIMULATION MODEL

The modeling and simulation tool OPNET Modeler^{TM} was used for developing the simulations and measuring the performance of CARA. OPNET provides a library of models for implementing wireless simulation scenarios and is among the leading discrete event network simulators. In the following sections, first a brief overview of OPNET's modeling and simulation tool will be given. Then, the simulation model used for measuring the performance of CARA will be presented in detail.

7.1 Modeling with OPNET

Optimized Network Engineering Tool (OPNET) is a discrete event simulation tool used very commonly for network simulation, specification, and performance analysis, both by the commercial and research communities. It provides a comprehensive development environment and a tool set suitable for different network environments. It can simulate different types of wired and wireless networks, and also provides a 802.11 compliant MAC layer implementation, which was used in this thesis.

Modeling environment of OPNET uses a hierarchical structure, with each level of the hierarchy used to model a different aspect of the simulation. These hierarchical levels are Network, Node, and Process modeling levels, which are sometimes called *modeling domains* of OPNET. Models developed at one layer can be used by another model at a higher layer. For example, one or more node models, which are connected in a certain way, will be used when defining a network model. Similarly, multiple process models, which are arranged in a certain manner, can be used for developing a process model. For each of these modeling domains, OPNET provides tools called *editors* for develop a representation of the system being modeled at the associated level.

Table 7.1 OPNET Modeling Domains

Domain	Editor	Modeling Focus
Network	Project	Network topology described in terms of subnetworks, nodes, links, and geographical context.
Node	Node	Node internal architecture described in terms of functional elements and data flow between them.
Process	Process	Behavior of processes (protocols, algorithms, applications), specified using finite state machines and extended high-level language.

The issues addressed by each domain are summarized in the above table. More detailed descriptions of each of the modeling domains can be found in (Xinjie C. 1999), a good reference for the interested readers.

7.2 Network Model

A number of wireless nodes are randomly distributed in a circle-shaped area of diameter D, according to a uniform distribution model. An example ad-hoc network consisting of 20 nodes is shown in Figure 7.1. During the simulations, the diameter of the circle-shaped area, D, and the number of nodes, N, were varied for different scenarios. The following combinations were used:

- D = 1000m, N = 20, 40, 80
- D = 800m, N = 10, 20, 40, 60

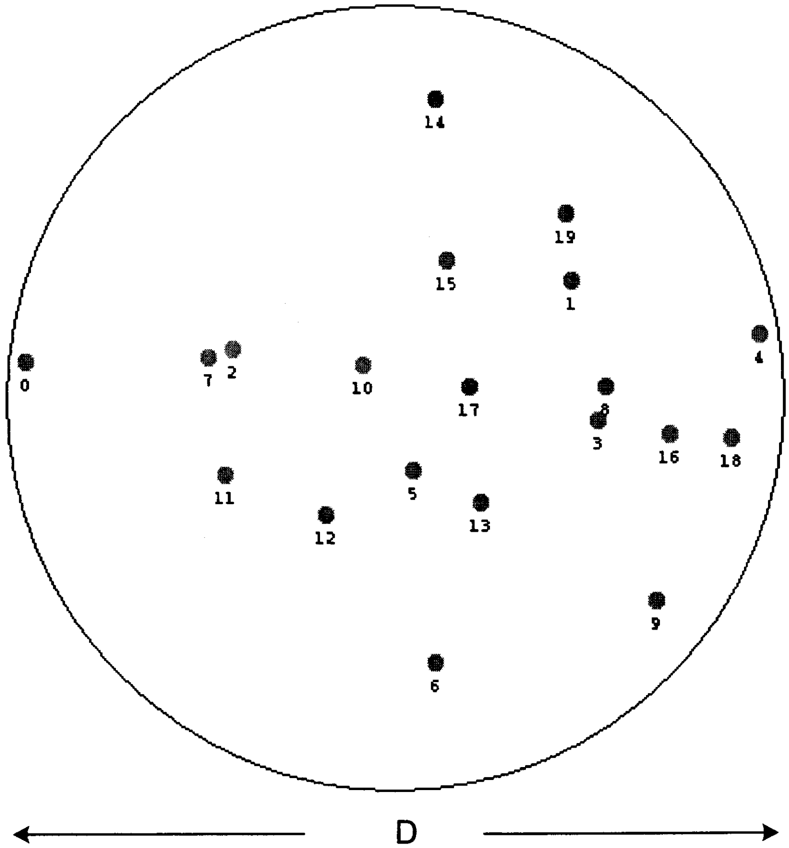


Figure 7.1 Example ad-hoc network with 20 nodes.

Mobility

As discussed in the previous chapters, at this stage of this work, the performance of CARA is being measured with no mobility, although the design should successfully support networks with nodes having relatively low mobility (comparing to the vehicular speeds), either at fixed positions or moving at walking speeds. Performance study of CARA under various mobility models is being left as a future work.

7.3 Node Model

Each wireless node in the network is modeled with a combination of multiple processes, with each layer in its protocol stack a separate process. The node model is shown in Figure 7.2

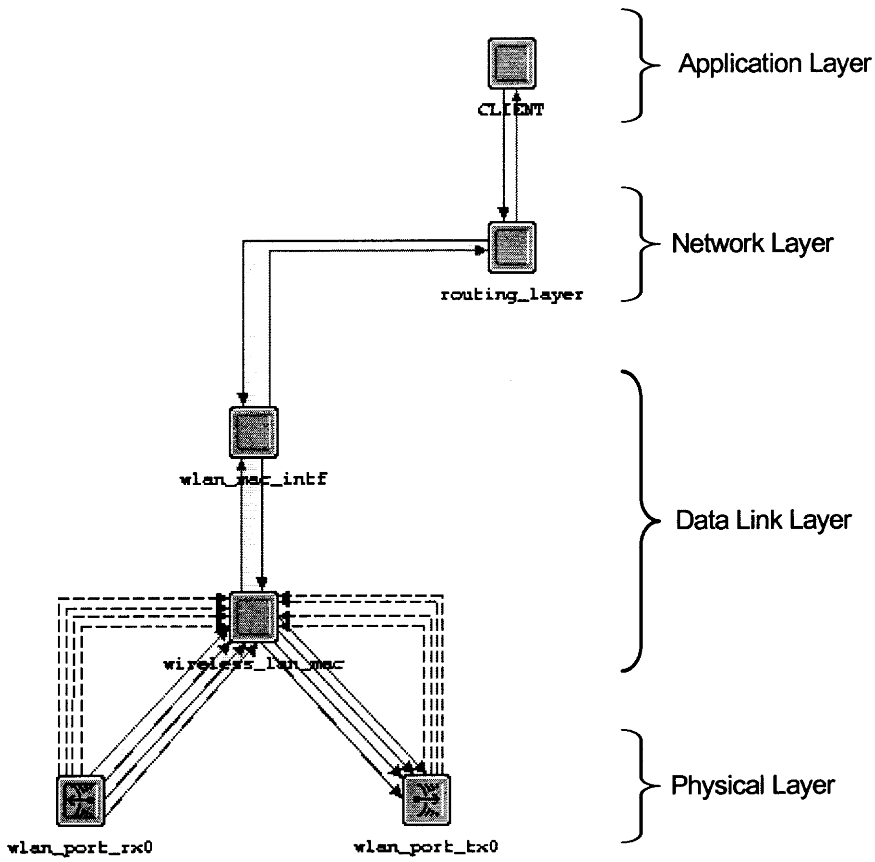


Figure 7.2 Node model.

Application Layer and Traffic Generation Model

The application layer sits on top of the protocol stack. This is simply a traffic generation layer simulating the application layer traffic. An interactive traffic model was assumed and implemented, considering the generation of activity periods (i.e. pages for www browsing), where several information packets are generated, and a certain thinking time between them, reflecting the service interactivity. The following parameters are of specific interest:

- **Start time**: The application layer at each node waits for a certain amount of time before any traffic is generated, to allow the underlying routing protocol to fully complete its neighbor lists and any initial network layer control operations. The default value of this parameter is 20 seconds.

- **Average user data packet size**: The size of each application layer user packet generated is set to a constant value. The default value of this parameter is 512 bytes. Multiple packets together form a single page.

- **Average time between packets**: The average time between two packets within a page was randomly selected according to an exponential distribution, with an average set by this parameter. The default value of this parameter is 0.5 seconds. Multiple pages together form a single session.

- **Average page size**: The average number of packets contained within a single page was randomly selected according to an exponential distribution, with an average set by this parameter. The default value of this parameter is 8 packets.

- **Average time between pages**: The average time between two pages within a session was randomly selected according to an exponential distribution, with an average set by this parameter. The default value of this parameter is 15 seconds.

- **Average session size**: The average number of pages contained within a single session was randomly selected according to an exponential distribution, with an average set by this parameter. The default value of this parameter is 8 pages

- **Average time between sessions**: The average time between two sessions was randomly selected according to an exponential distribution, with an average set by this parameter. The default value of this parameter is 150 seconds

Network Layer

The network layer, implemented between the traffic generation layer and the MAC layer, provides end-to-end routing capability. The routing protocol used in the simulations is a position-based technique, utilizing Terminode local routing (TLR) (Blazevic et al. 2001) and geographic packet forwarding (GPF) (Karp and Kung, 2000). This technique requires transmission of HELLO packets by all nodes at regular intervals, and generates a routes based on the geographic destination metric to the destination.

Terminode routing is developed at the EPFL in Switzerland, with the goal of developing a system that is capable of wide area Ad Hoc Routing. Terminode routing is structured in two layers: long-distance routing and short-distance routing. Different rules are applied for both of these layers, in a hierarchical methodology. Typical approach is that position-based routing (GPF) is used for routing on long distances, while when a packet arrives close to the destination (one or two hops distance) a proactive distance vector scheme (TLR) is followed. The following parameters are of specific interest:

- **HELLO period**: The amount of time between two HELLO messages sent by the routing layer from a particular node is randomly distributed, according to a uniformly distribution model, between 0.5 seconds and 1.5 seconds.

- **Update Threshold**: The routing protocol periodically goes through the neighbor tables to clear any aged out entries. This parameter determines if whether or not a particular should be removed from the table. The default value of this parameter is set to 4.5 seconds.

- **Update Frequency**: The routing protocol periodically goes through the neighbor tables to clear any aged out entries. This parameter determines the period of this operation. The default value of this parameter is set to 1 second.

Data Link Layer

The significant portion of the functionality in Data link layer is OPNET's 802.11 medium access control layer (MAC) implementation. This layer has been modified to implement the CARA entity, as described in detail in earlier chapters.

There is a thin layer (wlan_mac_intf module) between the MAC layer and Network Layer. This layer maps the network layer address to a medium access control layer address and passes this information, along with the packet, to/from the MAC layer for transmission/reception.

The CARA entity for each node was implemented within OPNET's WLAN MAC process model, inline with the architecture described above. OPNET's WLAN model is based on the IEEE 802.11 standard using CSMA/CA as the fundamental access mechanism, which is inline with the detailed requirements and process flows described earlier. The physical layer dependent parameters are also modeled in the WLAN MAC. The following MAC layer and physical layer simulation parameters are of interest.

- **RTS threshold**: This parameter determines whether or not the RTS/CTS exchange should be used for transmitting a DATA packet. The default value for this parameter is set to 256 bytes.

- **Fragmentation threshold**: This parameter determines whether or fragmentation should be applied to the DATA packet that is being transmitted. The default value for this parameter is set to 512 bytes.

- **Data rate**: The available data rates in OPNET's WLAN module are 1, 2, 5.5 and 11 Mbps.

- **Bandwidth**: The default value for this parameter is set to 1000 kHz

- **Minimum frequency**: The default value for this parameter is set to 2400 MHz

- **Maximum WLAN radio range**: This is the maximum range of transmission, when transmission power is set to the maximum level. The default value is set to 300 meters. OPNET, as by default, does not support variable power control and variable transmission ranges. The pipeline stages were modified for the purpose of implementing CARA, in order to allow varying of the power levels and transmission ranges.

- **Maximum TX power level**: The default value of this parameter is set to 100 mW. As mentioned above, the pipeline stages were modified to allow variable power levels.
- **Propagation model**: Free space propagation model has been used, inline with the requirements and assumptions described earlier.
- **Maximum battery level**: This is a parameter introduced specifically for measuring the impact of CARA on cost efficiency and lifetime of the network. The battery level of each node has been reduced as the node participated in packet forwarding/transmissions. The value of this parameter has been changed between 0.1 joules and 0.5 joules.

Physical Layer

OPNET uses computational pipeline stages in the WLAN model for simulating the effects of the physical layer. Each pipeline stage computes the value of some physical layer parameters and updates any associated fields in the packet for use in subsequent stages of the pipeline. The baseline wireless pipeline stage "*wlan_propdel*" uses a predefined range (which is the maximum WLAN radio range) as a criterion to determine whether the packet being received is valid or noise. If the distance between the transmitter and receiver is less than this range, packet is considered as valid; otherwise the packet is considered to be noise. This pipeline stage was modified so that the transmission range of a node dynamically varies, based on the transmission power level used, and according to the propagation model described previously.

Physical layer simulation parameters were reviewed in the previous section. As mentioned above, free space propagation model has been used, inline with the requirements and assumptions described earlier. The path loss exponent used is 2. The transmission range of a particular transmission is calculated as follows:

$$d = d_{max} * \sqrt{\frac{p_{tx}}{p_{tx,max}}} \tag{7.1}$$

where d is the transmission range, d_{max} is the maximum transmission range when the power level is set to maximum, p_{tx} is the transmission power level, and $p_{tx,max}$ is the maximum transmission power level.

The code shown in Figure 7.3 is an extract from the Received Power Model of OPNET's pipeline stages, and implements the free space propagation model.

```
/* Get power allotted to transmitter channel. */
tx_power = op_td_get_dbl (pkptr, OPC_TDA_RA_TX_POWER);

/* Get transmission frequency in Hz. */
tx_base_freq = op_td_get_dbl (pkptr, OPC_TDA_RA_TX_FREQ);
tx_bandwidth = op_td_get_dbl (pkptr, OPC_TDA_RA_TX_BW);
tx_center_freq = tx_base_freq + (tx_bandwidth / 2.0);

/* Caclculate wavelength (in meters). */
lambda = C / tx_center_freq;
/* Get distance between transmitter and receiver (in meters). */
prop_distance = op_td_get_dbl (pkptr, OPC_TDA_RA_START_DIST);

path_loss = (lambda * lambda) /
    (SIXTEEN_PI_SQ * prop_distance * prop_distance);

/* Determine the receiver bandwidth and base frequency. */
rx_base_freq = op_td_get_dbl (pkptr, OPC_TDA_RA_RX_FREQ);
rx_bandwidth = op_td_get_dbl (pkptr, OPC_TDA_RA_RX_BW);
/* The base of the overlap band is the highest base frequency. */
if (rx_base_freq > tx_base_freq)
    band_min = rx_base_freq;
else b
    and_min = tx_base_freq;

/* The top of the overlap band is the lowest end frequency. */
if (rx_base_freq + rx_bandwidth > tx_base_freq + tx_bandwidth)
    band_max = tx_base_freq + tx_bandwidth;
else band_max = rx_base_freq + rx_bandwidth;

/* Compute the amount of in-band transmitter power. */
in_band_tx_power = tx_power * (band_max - band_min) / tx_bandwidth;

/* Get antenna gains (raw form, not in dB). */
tx_ant_gain = pow (10.0, op_td_get_dbl (pkptr, OPC_TDA_RA_TX_GAIN) / 10.0);
rx_ant_gain = pow (10.0, op_td_get_dbl (pkptr, OPC_TDA_RA_RX_GAIN) / 10.0);

/* Calculate received power level. */
rcvd_power = in_band_tx_power * tx_ant_gain * path_loss * rx_ant_gain;

/* Assign the received power level (in Watts) */
/* to the packet transmission data attribute. */
op_td_set_dbl (pkptr, OPC_TDA_RA_RCVD_POWER, rcvd_power);
```

Figure 7.3 OPNET's received power model.

CHAPTER 8

SIMULATION RESULTS

8.1 Performance Metrics

The following performance metrics are collected from several different simulation scenarios, which will be presented in detail in the following sections.

- Network lifetime
- Average cost of delivering a user packet at the application layer
- Average cost of delivering a user data bit at the MAC layer
- Average energy required to deliver a user packet at the application layer
- Average energy to deliver user data bit at the MAC layer
- Average end-to-end delay for packet delivery at the application layer
- Average number of hops for packet delivery at the application layer
- RTS frame retransmit rate
- DATA frame retransmit rate
- Packet delivery rate at the application layer
- Percentage of lost bid messages
- Ratio of energy spent for bidding to energy spent for user data transmission
- Distribution of the average energy spent for delivering an application layer user packet.
- Auction, bid, and data packet averages
- Ratio of MAC level redirections to all user packet transmissions
- Payment and profit ratios

8.2 Simulation Scenarios

The following four different simulation scenarios have been implemented for evaluating and measuring the performance of CARA. Throughout these different scenarios, the number of nodes in the network, and the diameter of the network, and the maximum battery level of the nodes area have also been changed. Then, the performance of the network from these scenarios is compared.

Scenario 1

CARA enabled, cost = f (battery level, energy). This scenario implements a CARA Enabled Network, with cost of energy at each node is calculated as a function of remaining battery level. Therefore, the cost of a particular transmission of each node depends on the battery level of the node, and the amount of energy spent for the transmission. The amount cost for a given packet transmission can be calculated using Equation (4.1).

Note that one of the simulation parameters (as described previously) is the maximum battery level of the nodes. This is a parameter introduced specifically for measuring the impact of CARA on cost efficiency and lifetime of the network. At simulation startup, the battery level of each node is set to the maximum. As simulation progresses, the battery level of each node is being reduced as the node participates in packet forwarding/transmissions.

The cost of energy of each node is defined as $\frac{1}{{b_r}^3}$, where b_r is the remaining battery level on each node. Note that formulation of the cost of energy is not the purpose of this study. The cost of energy will naturally be different at different nodes depending on many variables, such as the current battery level of the node, cost of recharging the battery, or cost of potential processing delay to node's own message transmission or reception. Because of the complexity involved, this study does not attempt to formulate the cost of energy based on these variables, but simply assumes that each node is able to determine its cost of energy at any given time. In the simulations, however, the above relationship between the cost of energy and current battery level of the node is defined, in order to allow testing and performance analysis of CARA.

Scenario 2

CARA enabled, cost = f (energy). This scenario also implements a CARA Enabled Network, however the cost of energy at each node is set to a constant. Therefore, the cost of a particular transmission of each node depends only on the amount of energy spent for the transmission. The amount cost for a given packet transmission can be calculated using Equation (4.1).

This scenario is expected to result in improved energy efficiency, but not true cost efficiency, since cost is only a function of the energy used in the transmissions. Therefore, the lifetime of the network in this scenario is expected to be shorter, when compared to Scenario 1.

Scenario 3

Power control only, with no auctions. This scenario disables the auctioning scheme of CARA, however leaves the variable transmission power capability of CARA on. Therefore, nodes do not place any auctions, and the original end-to-end network layer routes determined by the routing protocol is followed for all transmissions (i.e. no MAC level forwarding). However, nodes do not always transmit at maximum power levels for DATA packet transmissions, and apply the dynamic power control scheme of CARA.

This scenario is expected to perform worse than Scenario 1 and Scenario 2 in terms of cost and energy efficiency, however perform better in terms of end-to-end delay and number of hops.

Scenario 4

CARA disabled. CARA is totally disabled in this scenario. MAC layer operates as in its original form. The nodes always transmit at maximum power levels, and do not place any auctions, i.e. the original end-to-end network layer routes determined by the routing protocol is followed without any MAC level forwarding.

This scenario is expected to perform worst in terms of cost and energy efficiency, however will perform better than Scenario 1 and Scenario 2 in terms of end-to-end delay and number of hops.

List of Simulation Parameters

The specific parameters used in the simulations are given in Table 8.1. Refer to Chapter 7 for a review and description of each of these parameters. The following parameters were changed to measure the performance of the system for each simulation scenario described in the previous section:

- Number of nodes in the network: 10, 20, 40, 60 and 80 nodes.
- Diameter of the network area: 800 meters and 1000 meters.
- Maximum Battery level: 0.1, 0.3 and 0.5 joules

Please refer to Table 8.1 for a full list of simulation parameters.

Table 8.1 List of Simulation Parameters

Parameter	**Value**
Number of nodes in the network	10, 20, 40, 60, 80
D (diameter of the network area)	800m, 1000 m
Routing Layer Parameters	
Routing Protocol	TLR/GPF
HELLO period (Uniform)	0.5 – 1.5 sec
Update Threshold	4.5 sec
Update Frequency	1 sec
Traffic Generation Parameters	
Traffic Model	Interactive
Average user data packet size	512 bytes
Average time between packets	0.5 secs
Average page size	8 packets
Average time between pages	15 seconds
Average session size	8 pages
Average time between sessions	150 secs
Start time	20 secs
Wireless LAN & Physical Layer Parameters	
RTS Threshold	256 bytes
Fragmentation Threshold	512 bytes
Data rate	1 Mbps
Bandwidth	1000 kHz
Min frequency	2400 MHz
Maximum WLAN radio range	300 m
Maximum TX power level	100 mW
Propagation model	Free space
Maximum Battery Level	0.1 joules – 0.5 joules

8.3 Network Lifetime

There are various definitions or formulations in the literature used for specifying network lifetime. Some define network lifetime as the time the first node in the network dies. Some others require a certain percentage of the network to be lost for specifying the network lifetime.

This study does not attempt to formulate the network lifetime, however presents the times where 25% of the network is lost for the following three scenarios, which were reviewed in detail earlier, with varying number of nodes in the network:

- CARA is enabled in the network, with cost = f (battery level, energy)
- CARA is enabled in the network, with cost = f (energy)
- CARA is disabled in the network

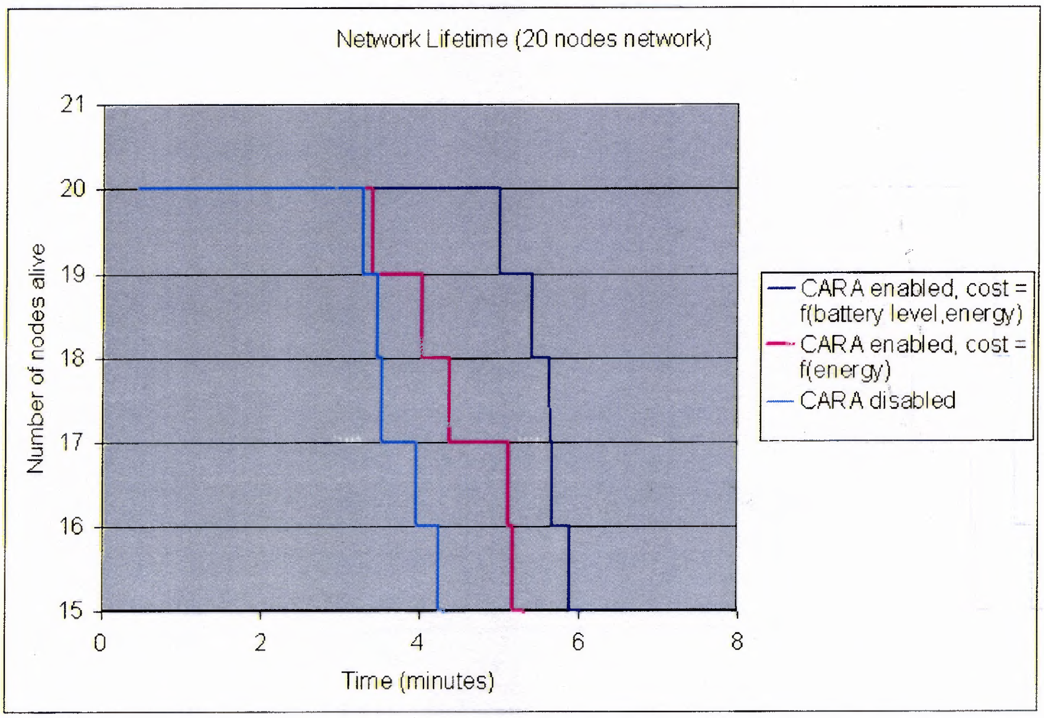


Figure 8.1 Network lifetime (20 nodes network).

Figure 8.1, Figure 8.2, and Figure 8.3 presents the results for these scenarios for networks with 20, 40, and 80 nodes. In all cases, the diameter of the network area was set to 100 meters, and initial battery level of the nodes was set to 0.1 joules. Results show that CARA significantly improves network lifetime, specifically when cost of transmission is defined as a function of battery level and energy spent. This is because the nodes with reduced battery levels have their cost of energy significantly increased, and therefore will be more reluctant in entering any auctions, or will have less chance of winning any auctions they enter (compared to other nodes with higher battery levels), even if they are in the most energy efficient route.

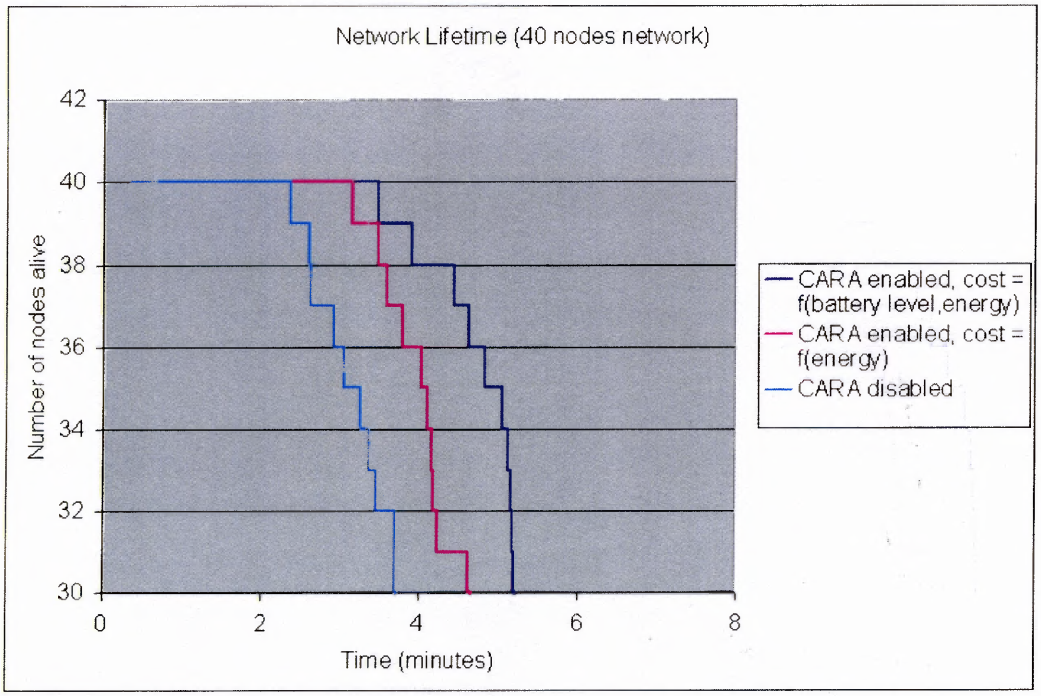


Figure 8.2 Network lifetime (40 nodes network).

In the simulations, a given node stops any transmissions/receptions when its battery level reaches %10 of its maximum battery level (in this case, when it reaches 0.01 joules), a technique used in similar network lifetime studies. This is the time the node is considered "dead", and from then on, none of the protocol layers in the node's protocol stack will function, i.e. no application layer user packets or routing layer control packets are received. In addition, the node does not receive any packets from physical layer, and therefore does not send any acknowledgements or responses to other nodes.

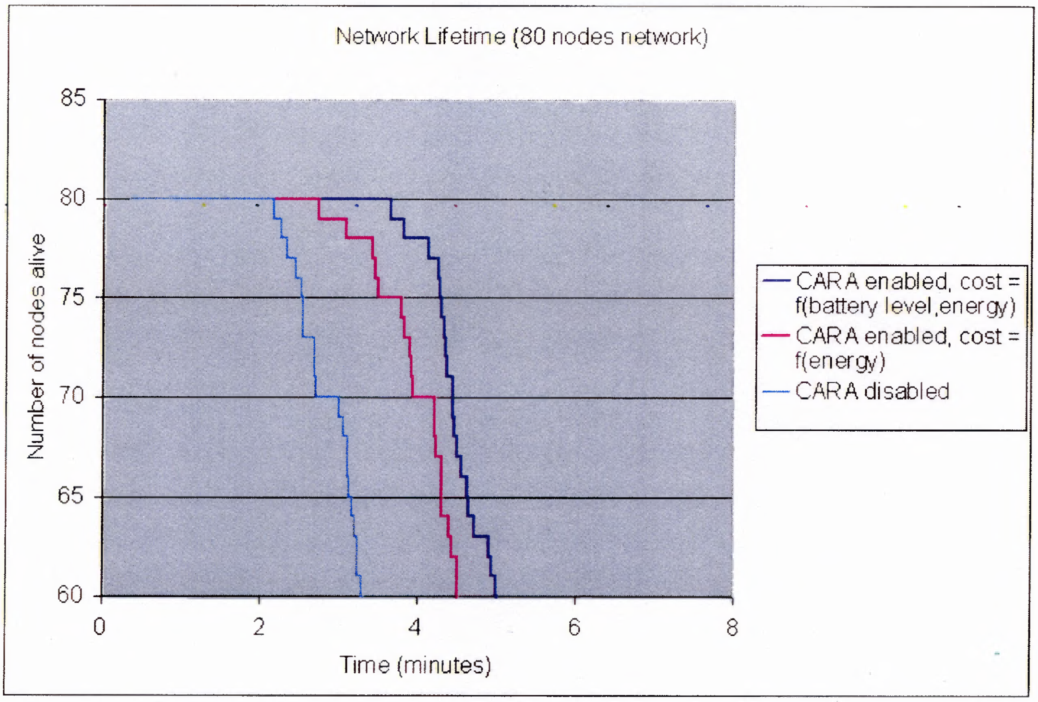


Figure 8.3 Network lifetime (80 nodes network).

8.4 Cost Efficiency

Each node in an ad-hoc network incurs a variable amount of cost for forwarding other nodes' packets, which depends on several variables, such as the current battery level of the node, cost of recharging the battery, or cost of potential processing delay to node's own message transmission or reception. This study does not attempt to formulate this cost, and assumes each node in the network can come up with its own cost. In the simulations, however, this cost has been formulated as a function of the remaining battery level and/or energy being spent, as described earlier in this chapter. The following four scenarios have been considered for measuring the cost performance of CARA:

- CARA is enabled in the network, with cost = f (battery level, energy)
- CARA is enabled in the network, with cost = f (energy)
- Power control only (no auctions)
- CARA is disabled in the network

In each of these scenarios, the number of nodes in the network was set to 20, and the diameter of the network area was 800. In addition, the initial battery level of the nodes was set to 0.3 joules.

The following metrics have been collected for measuring the cost performance:

- Average cost of delivering a user packet at the application layer
- Average cost of delivering a user data bit at the MAC layer

Average Cost of Delivering a User Packet at the Application Layer

This is the average cost spent in the network for delivering a single application layer user packet from application source to application destination. Overhead of the routing protocol is not considered in this metrics, since CARA is designed to work with any routing protocol and the improvements in cost and energy efficiency comes from the user data transmissions and not related to the routing protocol overhead. Note that delivering of a single application layer packet may involve several hops being involved at the network layer. Several additional hops may be introduced by the auctioning scheme of CARA, which forward packets only at the MAC layer, without involving the network layer.

At each hop along the end-to-end route from application source to application destination, RTS/CTS and DATA/ACK frame exchanges occur, potentially with some retransmissions, and possibly a number of BID frames. Note that auction initiations are also DATA transmissions. For each of these transmissions the cost incurred by the transmitting node (dollars) could be calculated using Equation (4.1), which uses the cost of energy (dollars/joule), the transmission power level (watts), the data transmission rate (bits/sec), and packet length is (bits).

The average cost of delivering a single application layer user packet at any given time is then calculated as follows:

$$c_{app}^{pkt} = \frac{c_{total}^{RTS} + c_{total}^{CTS} + c_{total}^{DATA} + c_{total}^{ACK} + c_{total}^{BID}}{n} \tag{8.1}$$

where

c_{app}^{pkt} is the average cost of delivering a single application layer user packet

n is the total number of application layer user packets delivered

c_{total}^{RTS} is the total cost of all RTS frame transmissions

c_{total}^{CTS} is the total cost of all CTS frame transmissions

c_{total}^{DATA} is the total cost of all DATA frame transmissions

c_{total}^{ACK} is the total cost of all ACK frame transmissions

c_{total}^{BID} is the total cost of all BID frame transmissions

As can be seen from Figure 8.4, a CARA enabled network with cost defined as a function of both battery level and energy, outperforms all other scenarios, keeping the cost of delivering application layer user packets low for longer periods. The scenario where CARA is disabled performs worst in terms of cost efficiency.

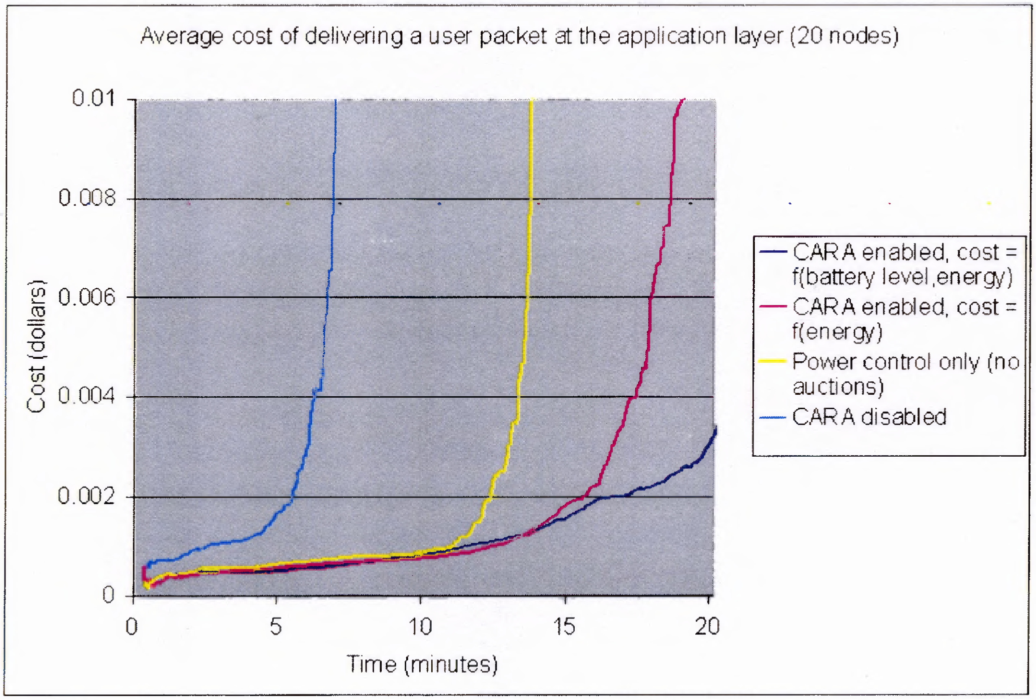


Figure 8.4 Average cost of delivering a user packet at the application layer.

Average Cost of Delivering a User Data Bit at the MAC Layer

For measuring this metrics, the total amount of cost spent in the system for user data transmissions (i.e. total cost of all RTS, CTS, DATA, ACK and BID transmissions) is divided by the total number of DATA frame bits transmitted. Overhead of the routing protocol is not considered in this metrics, since CARA is designed to work with any routing protocol and the improvements in cost and energy efficiency comes from the user data transmissions and not related to the routing protocol overhead. At a given time, this metrics is calculated as follows. Note that for each of these transmissions, the cost incurred by the transmitting node (dollars) could be calculated using Equation (4.1), which uses the cost of energy (dollars/joule), the transmission power level (watts), the data transmission rate (bits/sec), and packet length is (bits).

$$c_{MAC}^{bit} = \frac{c_{total}^{RTS} + c_{total}^{CTS} + c_{total}^{DATA} + c_{total}^{ACK} + c_{total}^{BID}}{b} \tag{8.2}$$

where

c_{MAC}^{bit} is the average cost of delivering a single user data bit at the MAC layer

b is the total number of all bits in all DATA frames transmitted

c_{total}^{RTS} is the total cost of all RTS frame transmissions

c_{total}^{CTS} is the total cost of all CTS frame transmissions

c_{total}^{DATA} is the total cost of all DATA frame transmissions

c_{total}^{ACK} is the total cost of all ACK frame transmissions

c_{total}^{BID} is the total cost of all BID frame transmissions

As can be seen from Figure 8.5, a CARA enabled network with cost defined as a function of both battery level and energy, outperforms all other scenarios, keeping the cost low for longer periods. The scenario where CARA is disabled performs worst in terms of cost efficiency.

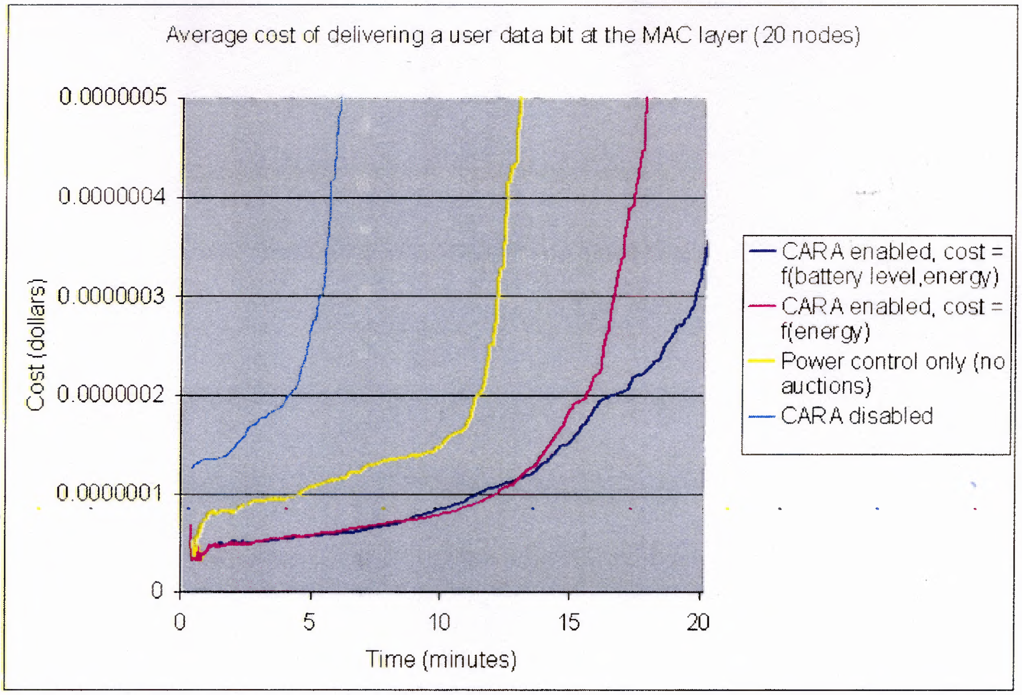


Figure 8.5 Average cost of delivering a user data bit at the MAC layer.

8.5 Energy Efficiency

The following four scenarios have been considered for measuring the energy performance of CARA, with varying number of nodes (10, 20, 40 and 60 nodes) in the network in each scenario. In each of these scenarios, the diameter of the network area was 800 meters. In addition, the initial battery level of the nodes was set to 0.5 joules.

- CARA is enabled in the network, with cost = f (battery level, energy)
- CARA is enabled in the network, with cost = f (energy)
- Power control only (no auctions)
- CARA is disabled in the network

The following metrics have been collected for measuring the cost performance:

- Average energy required to deliver a user packet at the application layer
- Average energy to deliver user data bit at the MAC layer

Average Energy Required to Deliver a User Packet at the Application Layer

This is the average energy spent in the network for delivering a single application layer user packet from application source to application destination. Overhead of the routing protocol is not considered in this metrics, since CARA is designed to work with any routing protocol and the improvements in cost and energy efficiency comes from the user data transmissions and not related to the routing protocol overhead.

At each hop along the end-to-end route from application source to application destination, RTS/CTS and DATA/ACK frame exchanges occur, potentially with some retransmissions, and possibly a number of BID frames. Note that auction initiations are also DATA transmissions. For each of these transmissions the energy spent (joules) could be calculated using the transmission power level p^{tx} (watts), the data transmission rate R (bits/sec), and packet length L (bits):

$$e = \frac{L}{R} p^{tx} \tag{8.3}$$

The average energy spent for delivering a single application layer user packet at any given time is then calculated as follows:

$$e_{app}^{pkt} = \frac{e_{total}^{RTS} + e_{total}^{CTS} + e_{total}^{DATA} + e_{total}^{ACK} + e_{total}^{BID}}{n} \tag{8.4}$$

where

e_{app}^{pkt} is the average energy spent for delivering a single application layer user packet

n is the total number of application layer user packets delivered

e_{total}^{RTS} is the total energy spent for of all RTS frame transmissions

e_{total}^{CTS} is the total energy spent for all CTS frame transmissions

e_{total}^{DATA} is the total energy spent for all DATA frame transmissions

e_{total}^{ACK} is the total energy spent for all ACK frame transmissions

e_{total}^{BID} is the total energy spent for all BID frame transmissions

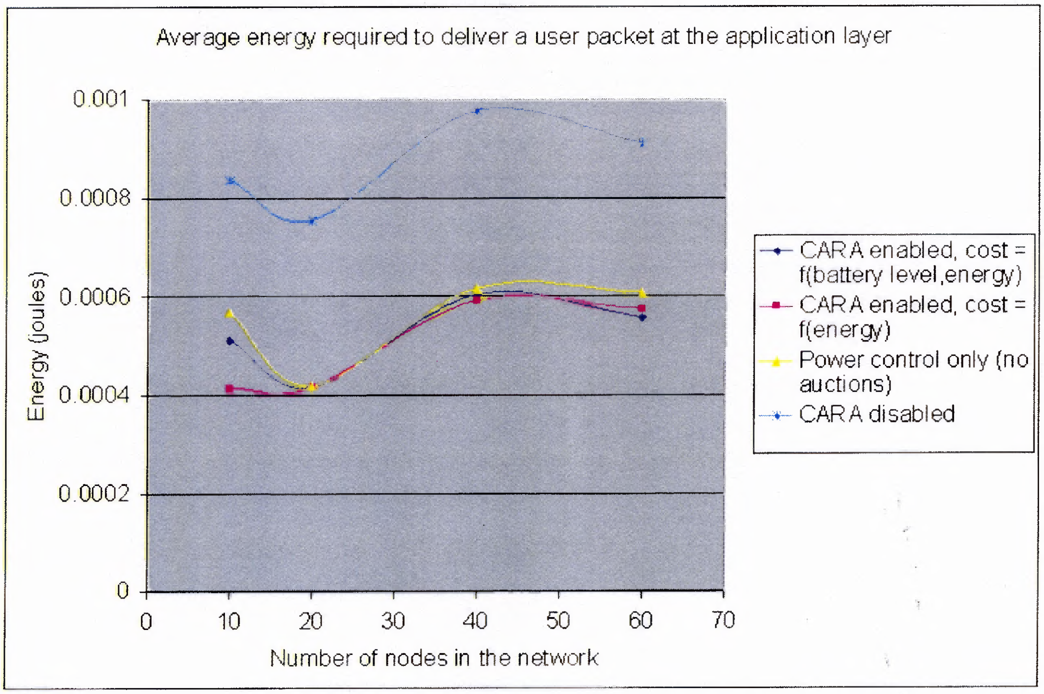


Figure 8.7 Average energy required to deliver a user packet at the application layer.

As can be seen from Figure 8.7, CARA enabled networks with auctioning (Scenario 1 and Scenario 2) outperforms all other scenarios, keeping the energy of delivering application layer user packets low in networks with varying number of nodes. The scenario where CARA is disabled performs worst in terms of energy efficiency.

An interesting note in the above figure is that the routing protocol performs more inefficiently when number of nodes in the network is increased from 20 nodes to 40 nodes. This also causes the scenarios where CARA is enabled to perform inefficiently with 40 nodes, when compared to 20 nodes. This is because CARA runs below the routing protocol and uses the same network layer route, potentially introducing additional intermediate nodes forwarding packets at the MAC layer. This observation (inefficiency of the routing protocol) does not change the fact that CARA always significantly increases the energy efficiency when compared to the scenario where CARA is disabled in the network.

Average Energy Required to Deliver a User Data Bit at the MAC Layer

For measuring this metrics, the total amount of energy spent in the system for user data transmissions (i.e. total energy for all RTS, CTS, DATA, ACK and BID transmissions) is divided by the total number of DATA frame bits transmitted. Overhead of the routing protocol is not considered in this metrics, since CARA is designed to work with any routing protocol and the improvements in cost and energy efficiency comes from the user data transmissions and not related to the routing protocol overhead. At a given time, this metrics is calculated as follows. Note that for each of these transmissions, the energy spent could be calculated using Equation (8.3).

$$e_{MAC}^{bit} = \frac{e_{total}^{RTS} + e_{total}^{CTS} + e_{total}^{DATA} + e_{total}^{ACK} + e_{total}^{BID}}{b} \quad (8.4)$$

where

e_{app}^{pkt} is the average energy spent for delivering a single user data bit at the MAC layer

b is the total number of all bits in all DATA frames transmitted

e_{total}^{RTS} is the total energy spent for of all RTS frame transmissions

e_{total}^{CTS} is the total energy spent for all CTS frame transmissions

e_{total}^{DATA} is the total energy spent for all DATA frame transmissions

e_{total}^{ACK} is the total energy spent for all ACK frame transmissions

e_{total}^{BID} is the total energy spent for all BID frame transmissions

As can be seen from Figure 8.8, CARA enabled networks with auctioning (Scenario 1 and Scenario 2) outperforms all other scenarios, keeping the energy of delivering application layer user packets low in networks with varying number of nodes. The scenario where CARA is disabled performs worst in terms of energy efficiency.

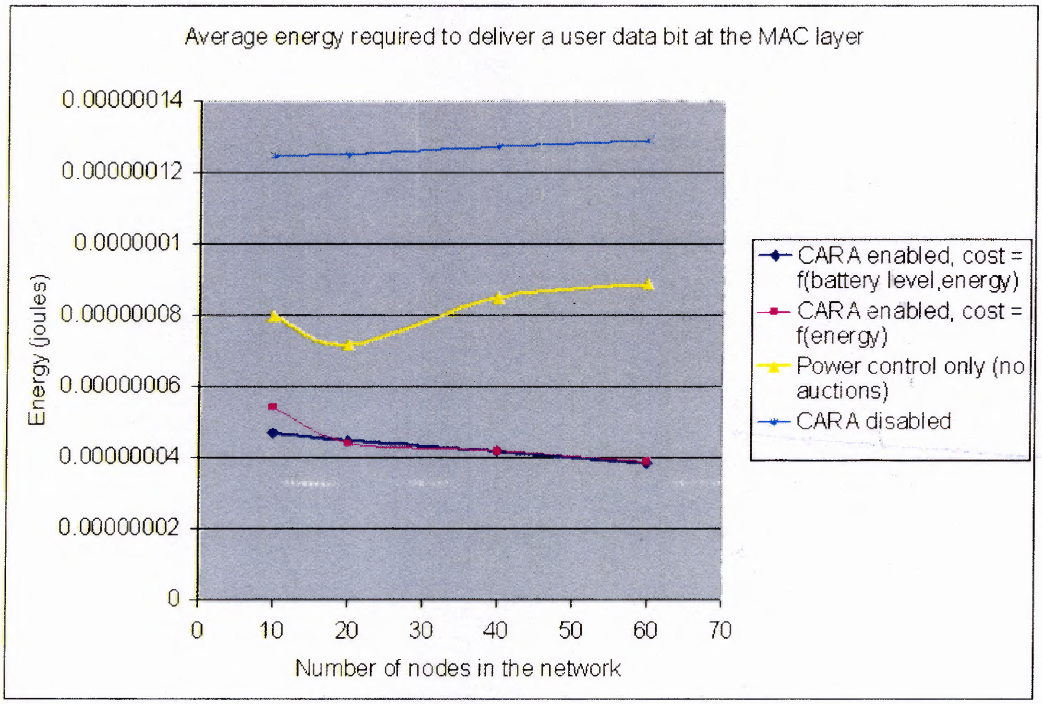


Figure 8.8 Average energy spent to deliver user data bit at the MAC layer.

8.6 Average End-to-end Latency and Average Number of Hops

The following two scenarios have been considered for measuring the end-to-end latency performance and the average number of hops in end-to-end transmissions, with varying number of nodes (10, 20, 40 and 60 nodes) in the network in each scenario. In each of these scenarios, the diameter of the network area was 800 meters. In addition, the initial battery level of the nodes was set to 0.5 joules.

- CARA is enabled in the network, with cost = f (battery level, energy)
- CARA is disabled in the network

While having this significant performance improvement in terms of cost and energy efficiency, CARA will negatively affect the end-to-end latency and the number of hops required for transmitting user data packets between the application source and application destination, as shown in Figure 8.9 and Figure 8.10.

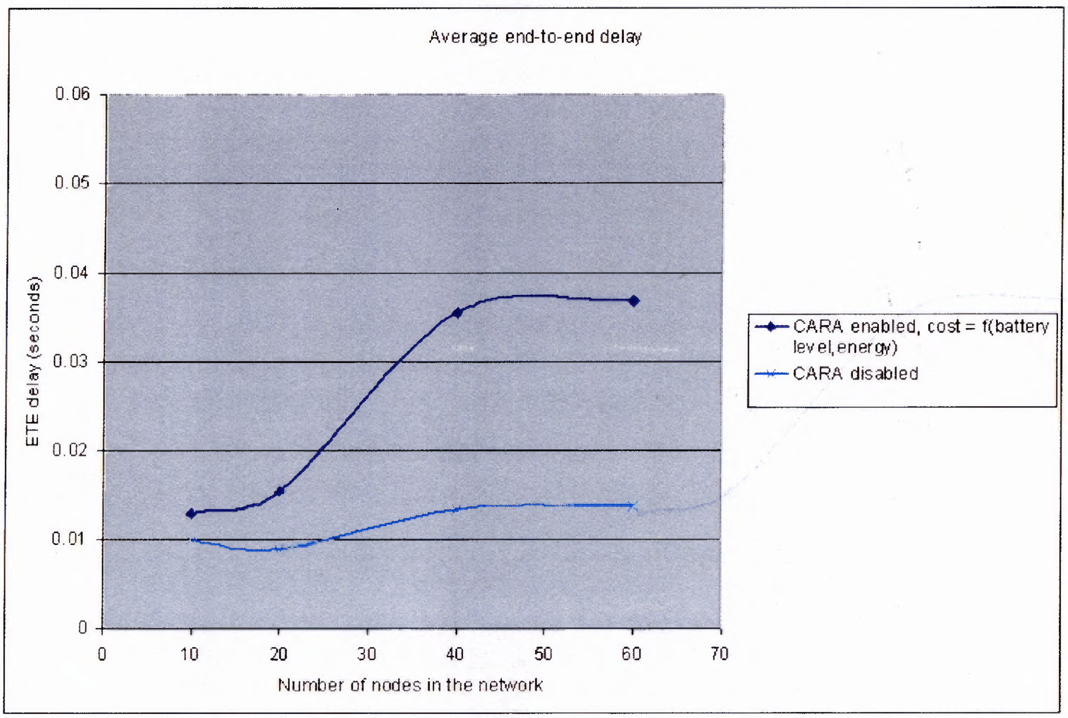


Figure 8.9 Average ETE latency for delivering a user data.

This is an expected result, since CARA adds more nodes to the end-to-end route that perform MAC-level packet forwarding. Because of these reasons, CARA is more suitable for applications where latency is not critical, such as www browsing or email.

An interesting observation in these figures is that the increase in the end-to-end delay slows down significantly as the number of nodes in the network is increased. The main reason contributing to this is the relationship between the number of hops and node density, as explained previously in Chapter 5. As the number of nodes increased linearly, the increase in number of hops is only logarithmic, in other words, the number of hops only slightly increases when compared to the increase in node density, because of the auctioning scheme used.

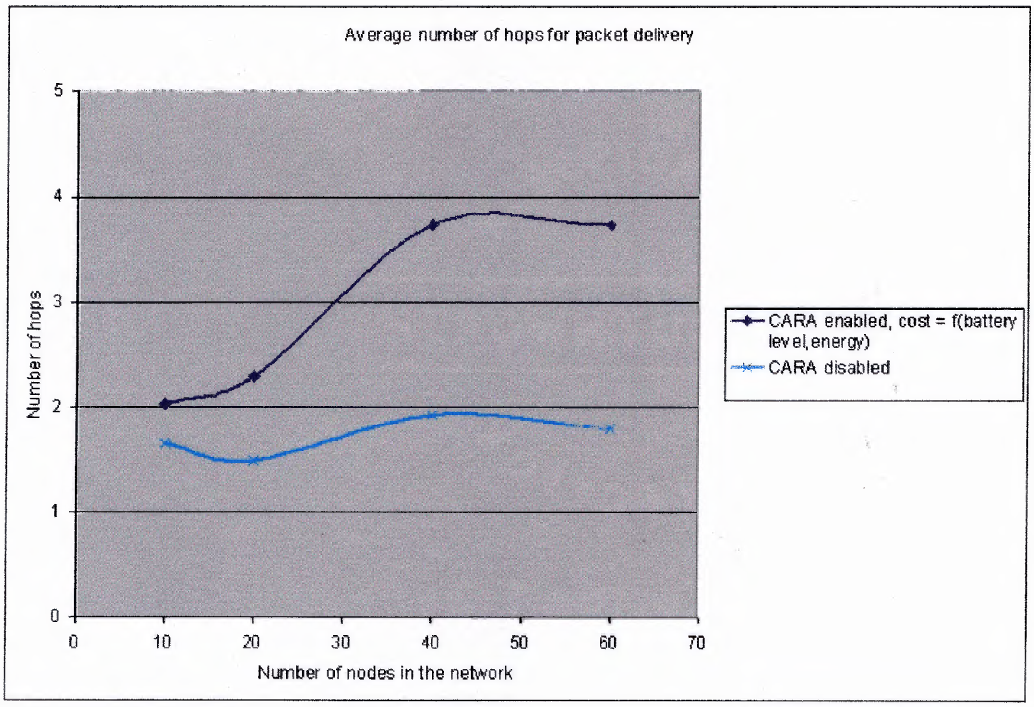


Figure 8.10 Average packet number of hops for delivering a user data packet.

8.7 Retransmission Rates and Application Layer Packet Delivery Rate

The following two scenarios have been considered for measuring the retransmission rates and application layer packet delivery rates, with varying number of nodes (10, 20, 40 and 60 nodes) in the network in each scenario. In each of these scenarios, the diameter of the network area was 800 meters. In addition, the initial battery level of the nodes was set to 0.5 joules.

- CARA is enabled in the network, with cost = f (battery level, energy)
- CARA is disabled in the network

The following metrics have been collected:

- RTS frame retransmit rate
- DATA frame retransmit rate
- Packet delivery rate at the application layer

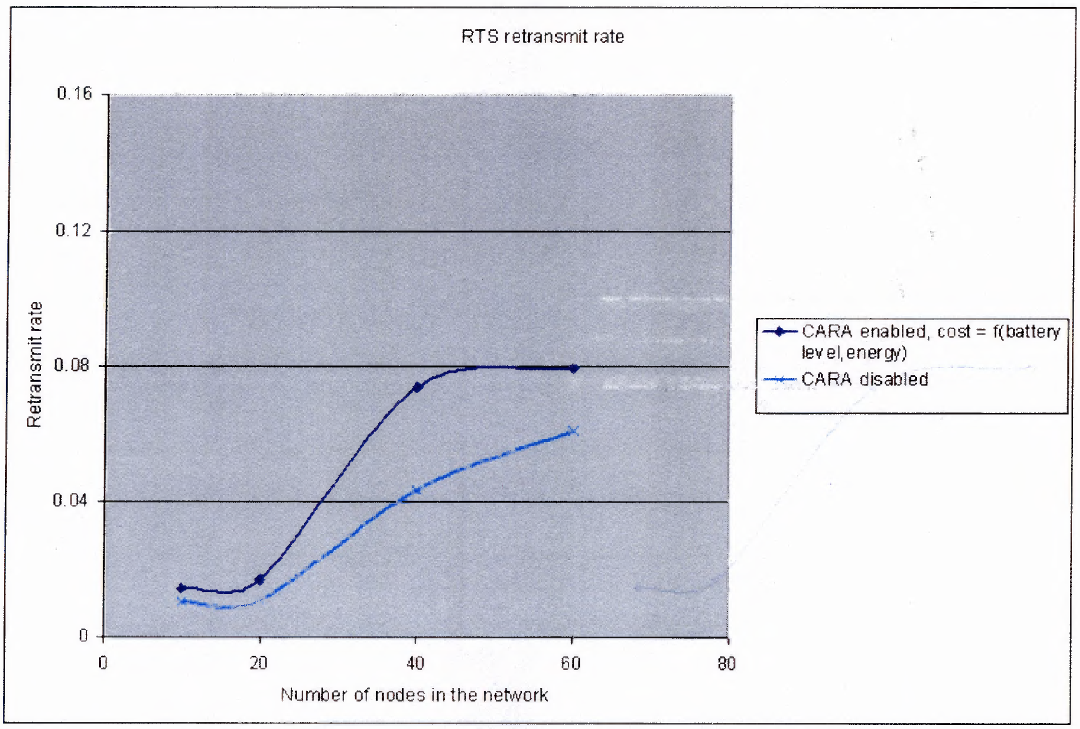


Figure 8.11 RTS frame retransmit rate.

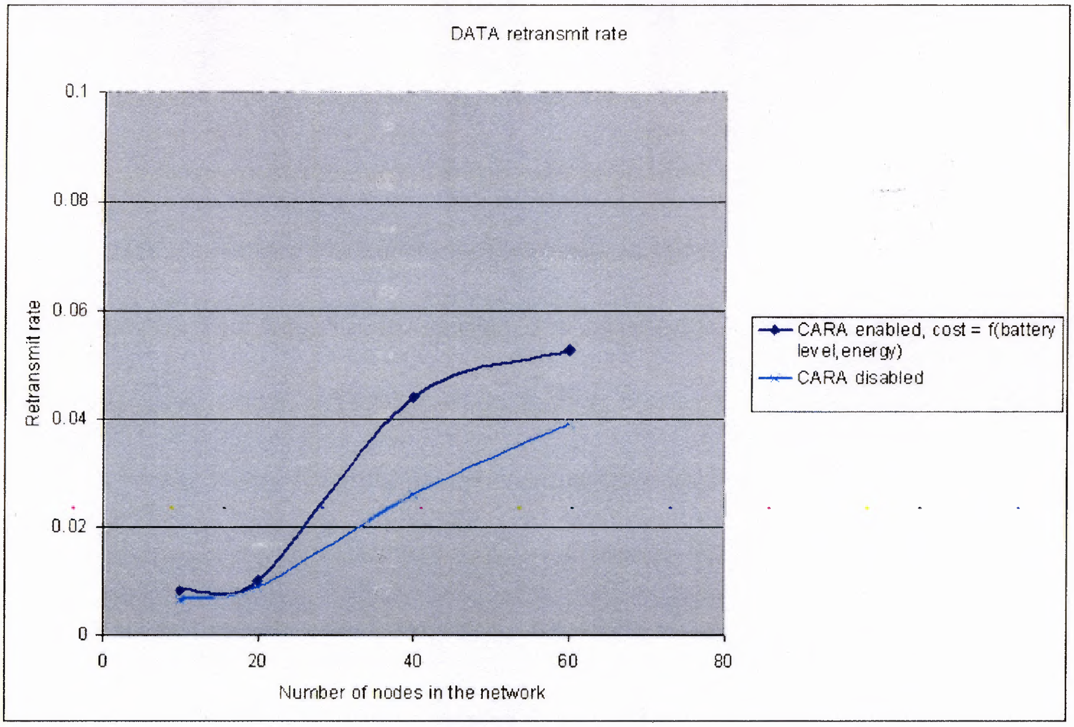


Figure 8.12 DATA frame retransmit rate.

The simulation results show that both RTS and DATA retransmission rates increase in a CARA enabled network. This is not a favorable result, even though CARA was able to make significant cost and energy improvements despite these increased retransmission rates, shown in Figure 8.11 and Figure 8.12. Increased retransmission rates also caused a slight decrease in application layer packet delivery rate, about %0.5, as shown in Figure 8.13.

These results underline the need for future work to study the reasons behind these retransmissions, and make any potential improvements to the method. One possible cause of these retransmissions could be the increased risk in the "hidden node" problem, caused by having reduced transmission power levels for the DATA/ACK frames (Jung and Vaidya, 2002). One possible solution is periodically increasing the transmit power for very short durations, during data transmissions (Jung and Vaidya, 2002).

Another observation from these figures, similar to earlier sections, is that the increase in the retransmissions and the slight decrease in packet delivery rate slow down significantly as the number of nodes in the network is increased. The main reason contributing to this is the relationship between the number of hops and node density, as explained previously in Chapter 5.

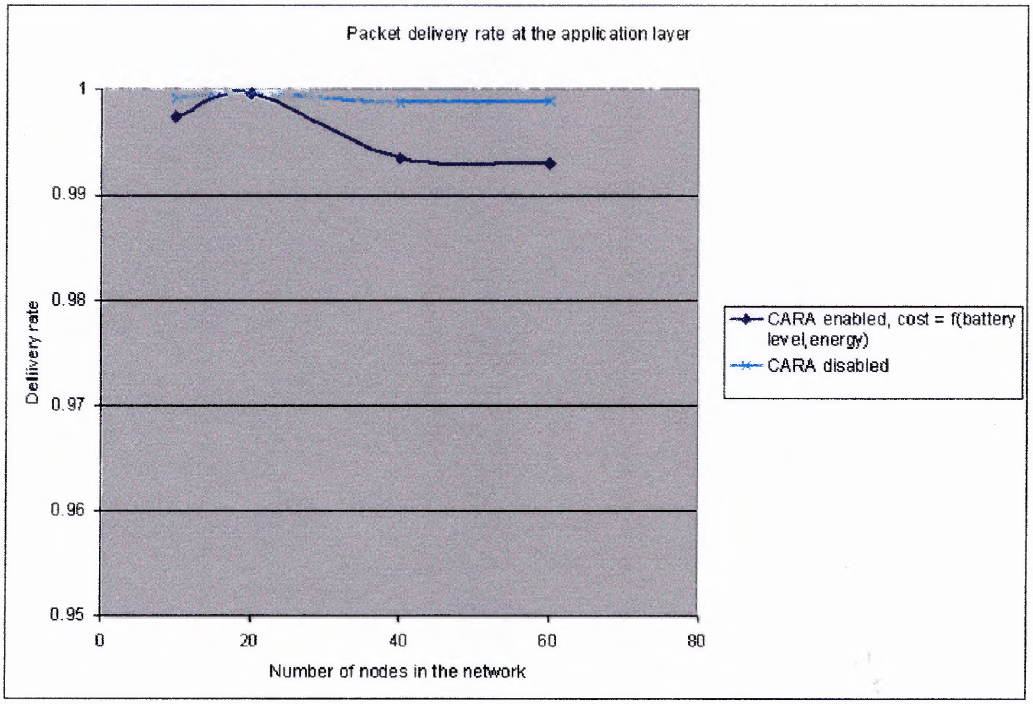


Figure 8.13 Application layer packet delivery rate.

8.8 Overhead

CARA provides significant improvements in cost and energy efficiency of the network, however is expected to introduce slightly increased overhead, in terms of increased number of RTS/CTS/ACK frames, and use of the BID frames. In spite of this additional overhead, CARA provided the efficiency improvements that were reviewed in earlier sections.

The following two scenarios have been considered for measuring the overhead, with varying number of nodes (10, 20, 40 and 60 nodes) in the network in each scenario. In each of these scenarios, the diameter of the network area was 800 meters. In addition, the initial battery level of the nodes was set to 0.5 joules.

- CARA is enabled in the network, with cost = f (battery level, energy)
- CARA is disabled in the network

The following metrics have been collected:

- Ratio of energy spent for bidding to energy spent for user data transmission
- Percentage of lost bid messages
- Distribution of the average energy spent for delivering an application layer user packet.

Figure 8.14 presents the percentage of the energy spent for bidding. This ratio (i.e. the ratio of energy spent for bidding to energy spent for user data transmission) is calculated as follows:

$$\frac{e_{total}^{BID}}{e_{total}^{RTS} + e_{total}^{CTS} + e_{total}^{DATA} + e_{total}^{ACK} + e_{total}^{BID}} \tag{8.5}$$

where

e_{total}^{RTS} is the total energy spent for of all RTS frame transmissions

e_{total}^{CTS} is the total energy spent for all CTS frame transmissions

e_{total}^{DATA} is the total energy spent for all DATA frame transmissions

e_{total}^{ACK} is the total energy spent for all ACK frame transmissions

e_{total}^{BID} is the total energy spent for all BID frame transmissions

As shown in the figure, the energy spent for bidding is minimal, and does not cause any significant degradation in CARA's performance. As in previous sections, it is observed in these figures that the increase in the bidding energy ratio slows down significantly as the number of nodes in the network is increased. The main reason contributing to this is the relationship between the number of auctions and node density, as explained previously in Chapter 5.

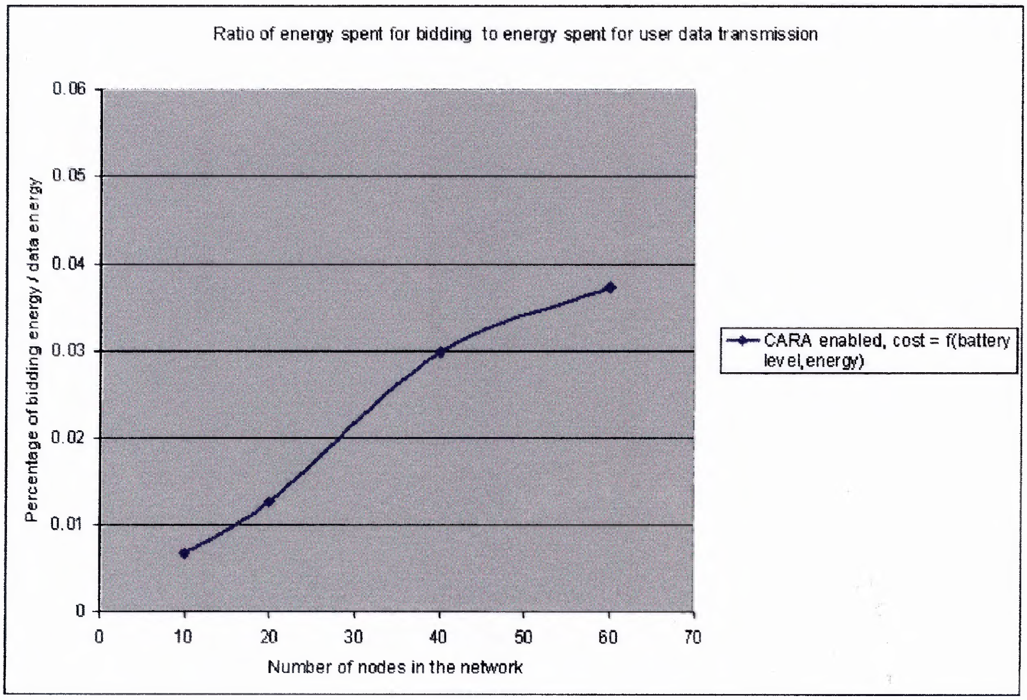


Figure 8.14 Ratio of energy spent for bidding to energy spent for user data transmission.

Another interesting metrics collected is the percentage of "lost" bids during the simulations. BID frames are unacknowledged, and are never retransmitted. Therefore there is a risk in having a bid successfully transmitted to the auctioneer. The main reason for not having to require guaranteed delivery of BID frames in this study is the simplicity. Furthermore, auctions are expired/renewed periodically (every few seconds) to allow for any channel changes and the changes in cost of energy of the nodes, the owner of a lost bid will (in most cases) will have other chances to bid for the same route. As it can be seen in Figure 8.15, the percentage of lost bids stays between 1% and 10%. Again, the increase in the percentage of lost bids slows down significantly as the number of nodes in the network is increased.

One potential enhancement to CARA for reducing the chance of collisions in BID frame transmissions for a particular auction is to require a random waiting interval at any node before sending any BID frame, similar to the waiting scheme used in (Gomez et al. 2003). This enhancement is proposed for future work.

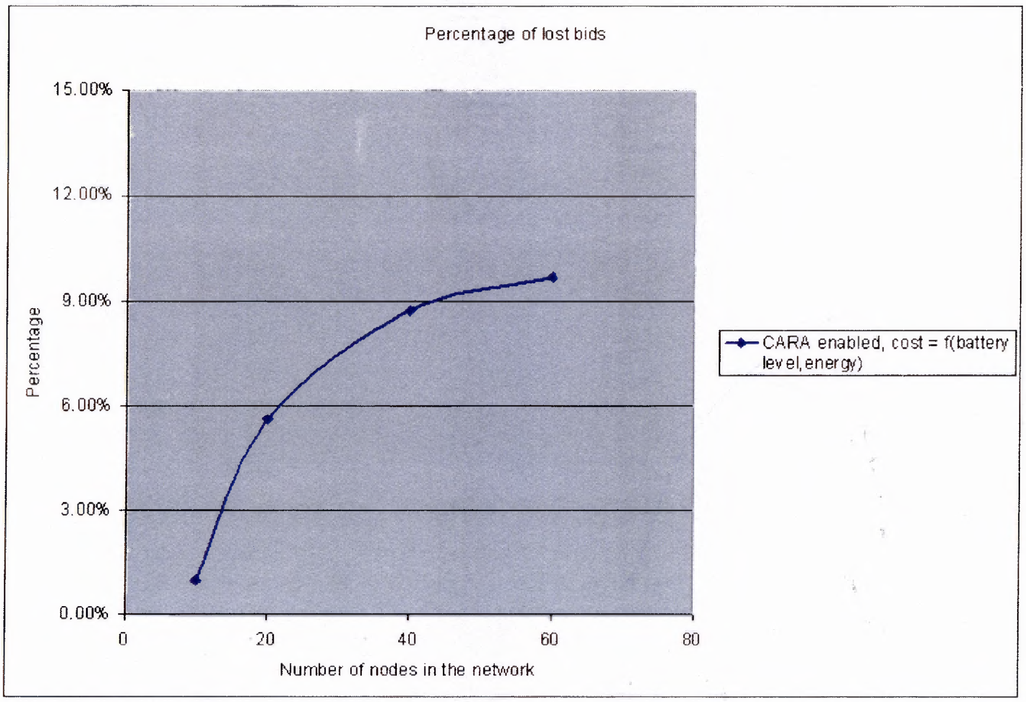


Figure 8.15 Percentage of lost bids.

Figure 8.16 presents the detailed distribution of the average energy spent for delivering an application layer user packet. As it can be seen in the figure, CARA is able to improve the energy efficiency, despite the fact that overhead is slightly increased. This figure is from network with 40 nodes in a network area with 800 meters diameter.

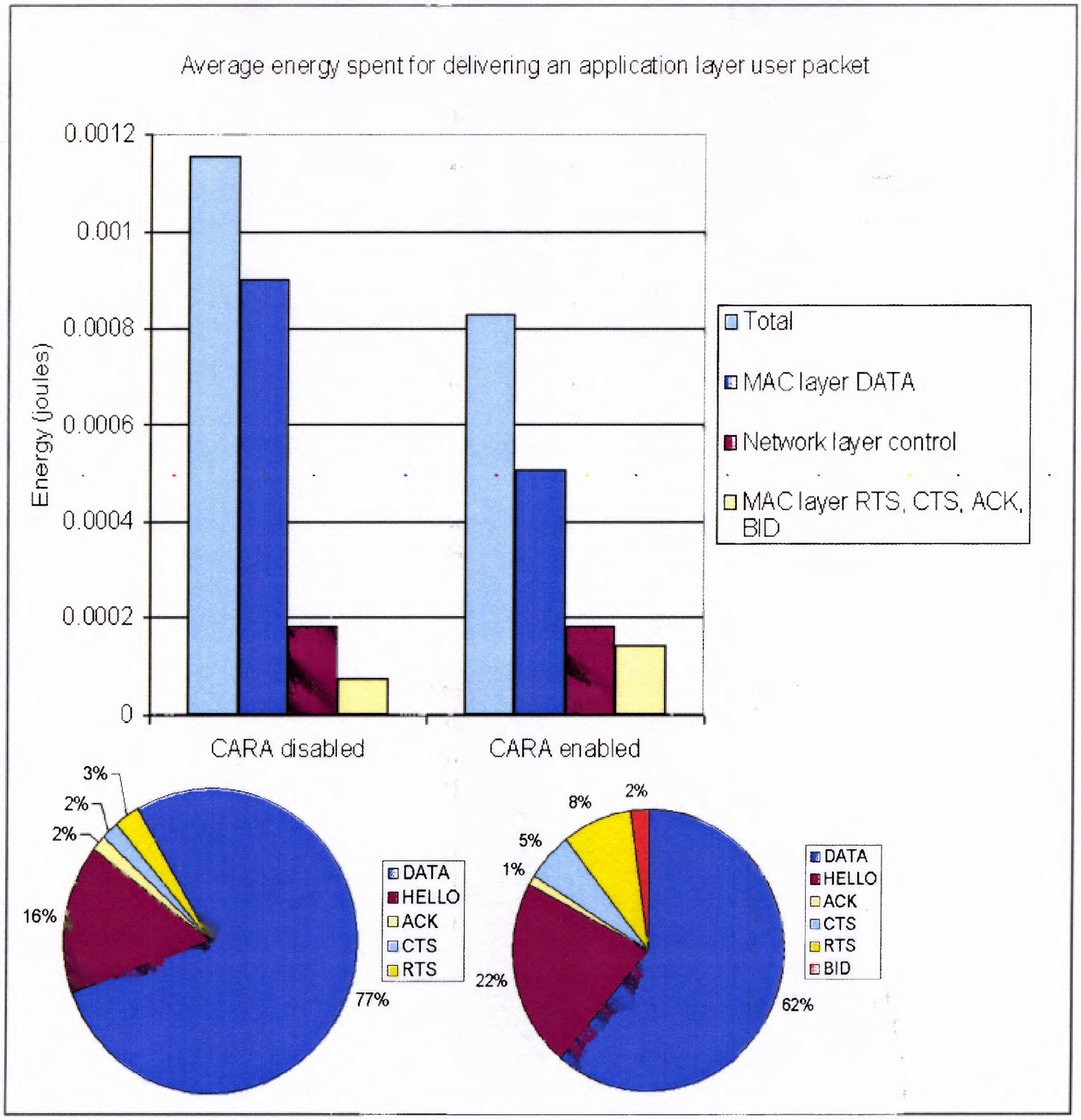


Figure 8.16 Distribution of the average energy spent for an application layer packet.

8.9 Other Metrics

Some additional metrics that may be of interest to the reader is presented in this section. These figures were collected from a network with varying number nodes and network area with 800 meters diameter.

- Auction, bid, and data packet averages
- Ratio of MAC level redirections to all user packet transmissions

- Payment and profit ratios

As it can be seen from Figure 8.17, an average of 7-8 user packets has been carried per auction. Note that auctions are expired/renewed periodically (every few seconds) to allow for any channel changes and the changes in cost of energy of the nodes. The average number of bids received for a single auction increased from about 0.5 nodes (10 nodes network) to 2 nodes (40-60 nodes network). The average number of application layer packets per auction decreased as the node density was increased. This also means that the average number of auctions placed over an end-to-end application layer transmission increases, as the node density increases (along with the number of hops), which is an expected result. As in previous sections, it is observed that this increase slows down significantly as the number of nodes is increased from 40 to 60 (see Chapter 5, relationship between the number of auctions and node density).

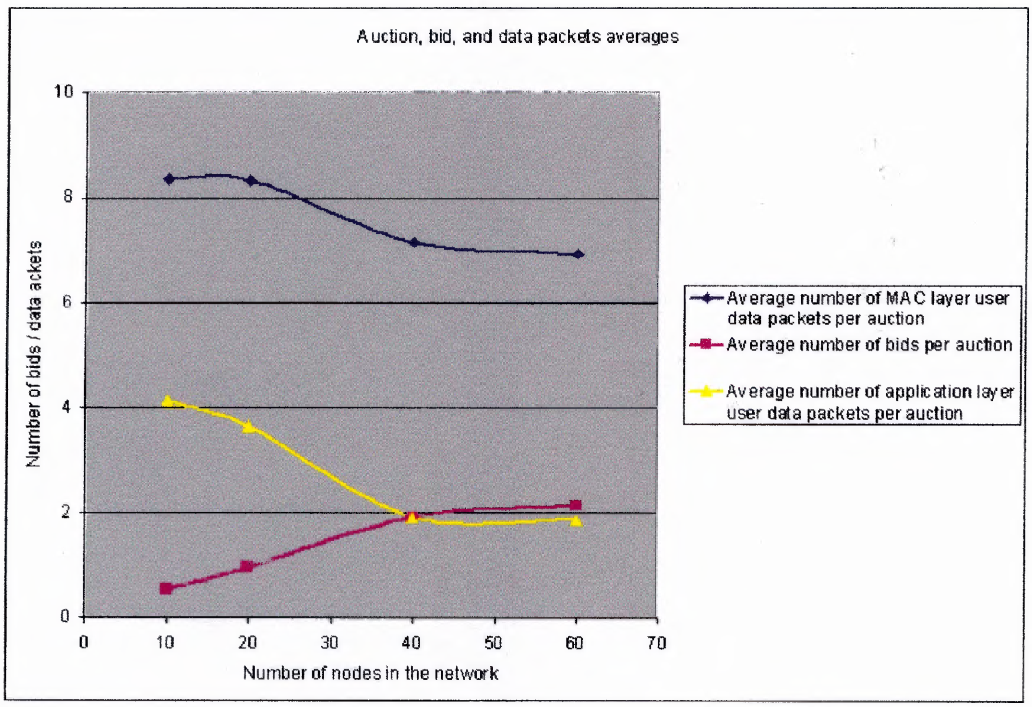


Figure 8.17 Auction, bid, and data packet averages.

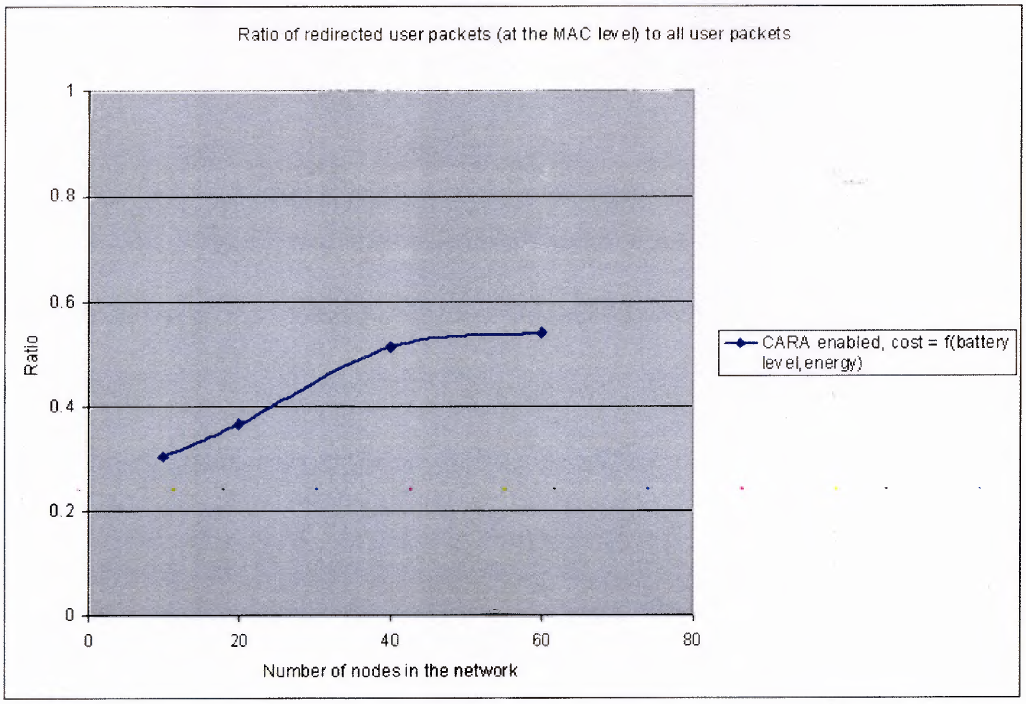


Figure 8.18 Ratio of MAC level redirections to all user packet transmissions.

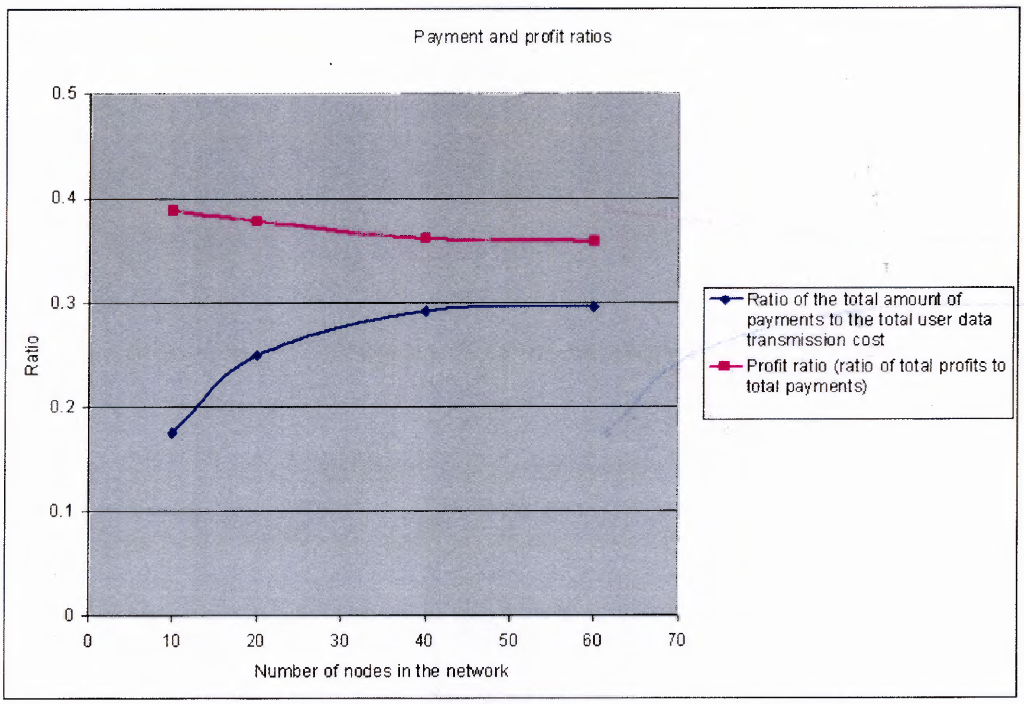


Figure 8.19 Payment and profit ratios.

CHAPTER 9

CONCLUSIONS AND FUTURE WORK

9.1 Conclusions

A novel method of reducing costs associated with routing in an ad hoc network is introduced, where on each individual link in an end-to-end route, the source node can auction the packets to neighboring nodes and thus reduce overall cost and energy spent on data transmissions. The method improves the lifetime of the network, and supports networks with selfish nodes. An added benefit in this method is that it creates a "wireless market" whereby willing nodes have the opportunity to take advantage of their geographic positions (with respect to the end nodes of the link in question) and of their spare battery energy in extracting economical benefits from the system.

One important aspect of the proposed scheme is that it makes use of existing routing schemes on the way to achieving cost efficient routing, rather than attempting to design "the" most efficient routing protocol. CARA is designed to improve the cost performance of any routing protocol available in the literature or in practice. The novelty of CARA lies in the fact that it brings the game theoretic notion of auctioning into the world of wireless communications in a way that results in reduction of costs associated with routing and also opening up a market of packet exchange. This study presents a case where the energy and cost savings with CARA, along with the improvements in network lifetime, make it a very attractive tool. Simulation results from various different network scenarios show that CARA significantly improves the cost efficiency, energy efficiency and lifetime of the network, while introducing only minimal additional overhead, and not overwhelming the network.

On the down side, CARA results in increased end-to-end packet delay. Although the increase in delay may be unacceptable for delay sensitive applications, the same increase might be irrelevant for a set of applications, such as web browsing, email, etc., which can afford the added latency and yet still add great value to the portfolio of services available to the ad hoc network node. Nevertheless, an inventive method is introduced and established, offering a very attractive cost reduction to the way packets are routed in ad hoc networks. CARA may be extremely useful in the context of the ad hoc networks of the future that are provisioned to operate with selfish users in an independent and distributed fashion.

9.2 Future Work

There is a need to analyze the performance of CARA under a credible mobility model. Some potential enhancements may need to be introduced to improve the performance, specifically for high mobility conditions. CARA is seen to slightly increase the rate of retransmissions, and this could increase further under high mobility. Potential improvements could be applied to the method to avoid these transmissions and further reduce the risk of "hidden node" problem, for example, periodically increasing the transmit power for very short durations during long data transmissions (Jung and Vaidya, 2002). In addition, in this study it is assumed that the channel between the transmitter and the receiver is symmetrical. Having unidirectional links may require additional measures in CARA, possibly use of a security threshold as a power margin, to make the transmissions more reliable. These measures may improve the performance under high mobility.

In this thesis, the issue of reducing power consumption while the radio is in transmission state has been considered. In the future studies, the energy consumed during receive and idle states may need to be considered. Recent studies have shown that additional significant improvements could be achieved by intelligently powering off the radios (or switching nodes into sleep state) that are not actively transmitting or receiving packets, such as PAMAS (Singh and Raghavendra, 1998) or BECA (Xu et al. 2000). Similar enhancements could be incorporated into CARA for resource saving during receive and idle states.

Another potential enhancement to CARA, for reducing the chance of collisions in BID frame transmissions for a particular auction, is to require a random waiting interval at any node before sending any BID frame, similar to the scheme used in (Gomez et al. 2003).

CARA is designed to work with existing network layer routing protocols. In this thesis, the performance analysis was has been performed using a position-based technique, utilizing Terminode local routing (TLR) (Blazevic et al. 2001) and geographic packet forwarding (GPF) (Karp and Kung, 2000). In future studies, the results could be confirmed by also using a topology-based popular MANET routing protocols. In addition, this study assumed that a payment based incentive scheme was provided by the network layer, such as Nuglets (Buttyan and Hubaux, 2003). A similar scheme could be implemented within the network layer, and this would allow further testing of the microeconomics aspect of CARA and the resulting payments.

REFERENCES

1. Adya A., Bahl P., Padhye J., Wolman A. & Zhou L. (2003). A multi-radio unification protocol for IEEE 802.11 wireless networks. Technical Report MSR-TR-2003-41, Microsoft.

2. Aguayo D., Bicket J., Biswas S., De Couto D. S. J. & Morris R. (2003). MIT roofnet implementation. Retrieved April 1, 2005, Web site: http://www.pdos.lcs.mit.edu/roofnet/design/

3. Akyildiz I.F., Su W., Sankarasubramaniam Y. & Cayirci E. (2002). Wireless sensor networks: a survey. Computer Networks, (38), 393-422.

4. Anderegg L. & Eidenbenz S. (2003). Ad hoc VCG: A Truthful and Cost-Efficient Routing Protocol for Mobile Ad hoc Networks with Selfish Agents, Proceedings of the Ninth Annual ACM/IEEE International Conference on Mobile computing and Networking (Mobicom), 245-259.

5. Basagni S., Chlamtac I., Syrotiuk V. & Woodward B. (1998). A distance routing effect algorithm for mobility (DREAM). Proceedings of the Fourth Annual ACM/IEEE International Conference on Mobile Computing and Networking (Mobicom), 76-84.

6. Bellur B. & Ogier R. G. (1999). A reliable, efficient topology broadcast protocol for dynamic networks. Proceedings of the Eighteenth Annual Joint Conference of the IEEE Computer and Communications Societies (Infocom), 178-186.

7. Bergamo P., Maniezzo D., Travasoni A., Giovanardi A., Mazzini G., & Zorzi M. (2004). Distributed power control for energy efficient routing in ad hoc networks. Wireless Networks, 10(1), 29-42.

8. Beyer D. (1990). Accomplishments of the DARPA SURAN Program. Proc. IEEE MILCOM'90, 855-862.

9. Bhagwat P., Raman B. & Sanghi D. (2004). Turning 802.11 Inside-Out. ACM SIGCOMM Computer Communication Review, 34(1), 33-38.

10. Blazevic L., Buttyan L., Capkun S., Giordano S., Hubaux J.-P. & Le Boudec J.-Y. (2001). Self-organization in mobile ad hoc networks: the approach of terminodes, IEEE Communication Magazine, 39(6), 166-175.

11. Buttyan L. & Hubaux J. (2003). Stimulating Cooperation in Self-Organizing Mobile Ad Hoc Networks. ACM/Kluwer Mobile Networks and Applications, 8(5), 579-592.

12. Chakeres I. D., Royer E. M., and Perkins C. E. (2005). Dynamic MANET On-demand Routing Protocol. IETF Internet Draft, http://www.ietf.org/internet-drafts/draft-ietf-manet-dymo-00.txt, work in progress.

13. Chen B., Jamieson K., Balakrishnan H. & Morris R. (2002). Span: an Energy-Efficient Coordination Algorithm for Topology Maintenance in Ad Hoc Wireless Networks. ACM Wireless Networks Journal, 8(5), 85-96.

14. Chen Chi-Tung, Tekinay Ş., Saraydar C. U. (2004). Minimum-power & energy-balancing cellular ad hoc augmented networks. WCNC 2004 - IEEE Wireless Communications and Networking Conference, 5(1), 1094-1099.

15. Chlamtac I., Conti M. & Liu J. (2003). Mobile Ad Hoc Networking: Imperatives and Challenges. Elsevier Ad Hoc Networks Journal, July 2003, 1(1), 13-64.

16. Doshi S., Bhandare S. & Brown T. (2002). An On-demand minimum energy routing protocol for a wireless ad hoc network. ACM Mobile Computing and Communications Review, 6(3), 50-66.

17. Jung E.-S. & Vaidya N. H. (2002). A Power Control MAC Protocol forAd Hoc Networks. Proceedings of the Eighth Annual ACM/IEEE International Conference on Mobile Computing and Networking (Mobicom), 36-47.

18. Freebersyser J. A., Leiner B. (2001). A DoD perspective on mobile ad hoc networks. Ad Hoc Networking, Addison Wesley, 29-51.

19. Goldsmith A. J. & Wicker S. B. (2002) Design challenges for energy-constrained ad hoc wireless networks. IEEE Wireless Communications Magazine, 9(4), 8-27.

20. Gomez, J., Campbell, A.T., Naghshineh, M. & Bisdikian C. (2003). PARO: Supporting Dynamic Power Controlled Routing in Wireless Ad Hoc Networks. ACM/Kluwer Journal on Wireless Networks (WINET), 9(5), 443-460.

21. Gomez, J. & Campbell, A.T. (2004). A Case for Variable-Range Transmission Power Control in Wireless Multihop Networks. IEEE Infocom.

22. Hoebeke J., Moerman I., Dhoedt B. & Demeester P. (2004). An overview of mobile ad hoc networks: applications and challenges. Proceedings of the 43rd European Telecommunications Congress, FITCE2004, 60-66.

23. International Standard ISO/IEC 8802-11; ANSI/IEEE Std 802.11, 1999 Edn. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications.

24. Jacquet P. (Ed.) & Clausen T. (Ed.) (2003). Optimized Link State Routing Protocol (OLSR). IETF Request for Comments 3626.

25. Jain S. (2003). Energy Aware Communication in Ad-hoc networks. Technical Report UW-CSE 03-06-03.

26. Johnson D. B. (1994). Routing in Ad Hoc Networks of Mobile Hosts. ACM Mobicom '94, 158-163

27. Johnson D. B., Maltz D. A. (1996). Dynamic Source Routing in Ad Hoc Wireless Networks. Mobile Computing, Kluwer Academic Publishers, Chapter 5, 153-181.

28. Johnson D. B., Maltz D. A., & Yih-Chun Hu. T. (2004). The Dynamic Source Routing Protocol for Mobile Ad Hoc Networks (DSR). http://www.ietf.org/internet-drafts/draft-ietf-manet-dsr-10.txt, work in progress.

29. Jones C.E., Sivalingam K.M., Agrawal P. & Chen J.C. (2001). A survey of energy efficient network protocols for wireless networks. ACM Wireless Networks, 7(4), 343-358.

30. Jubin J. & Tornow Janet D. (1987). The DARPA packet radio network protocols. Proceedings of the IEEE, 75(1), 21-32.

31. Jurdak R., Lopes C. & Baldi P. (2004). A Survey, Classification and Comparative Analysis of Medium Access Control Protocols for Ad Hoc Networks. IEEE Communications Surveys, 6(1), 2-16.

32. Karp B., & Kung H. T. (2000). GPSR: Greedy Perimeter Stateless Routing for Wireless Networks. ACM/IEEE MobiCom'00, 243-254.

33. Ko Y.B. & Vaidya N.H. (2000). Location-aided routing (LAR) in mobile ad hoc networks. ACM/Kluwer Wireless Networks, 6(4), 307-321.

34. Kumar K. Kalyan and Chockalingam A. (2002). Energy Efficient Routing in Wireless Ad-hoc Networks. Proceedings of the NCC'2002.

35. Leiner B. M., Neilson D. L. & Tobagi F. A. (1987). Proceedings of the IEEE, 75(1), Special Issue on Packet Radio Networks.

36. Liao W.H., Tseng Y.C. & Sheu J.P. (2001). GRID: a fully location-aware routing protocols for mobile ad hoc networks. Telecommunication Systems 18 (1-3), 37-60.

37. Luo H. et al. (2003). UCAN: A unified cellular and ad-hoc network architecture. 9th Mobicom, 353-367.

38. Mahajan R., Rodrig M., Wetherall D. & Zahorjan J. (2004). Encouraging Cooperation in Multi-Hop Wireless Networks. Technical Report CSE-04-06-01, University of Washington.

39. MANET. IETF Mobile Ad-hoc Network Working Group, MANET. Accessed April 15, 2005, Web site: http://www.ietf.org/html.charters/manet-charter.html.

40. Mauve M., Widmer J. & Hartenstein H. (2001). A survey on position-based routing in mobile ad-hoc networks. IEEE Network Magazine, 15(6), 30-39.

41. Min R. (2003). Energy and Quality Scalable Wireless Communication. PhD Thesis, Massachusetts Institute of Technology.

42. Muqattash A., & Krunz M. (2004). A Distributed Transmission Power Control Protocol for Mobile Ad Hoc Networks. IEEE Transactions on Mobile Computing, 3(2), 113-128.

43. Murthy S. & Garcia-Luna-Aceves J. J. (1996). An efficient routing protocol for wireless networks. ACM Mobile Networks and Application, 183-197.

44. Obreiter, P., K¨onig-Ries, B., Klein, M. (2003). Stimulating cooperative behavior of autonomous devices: An analysis of requirements and existing approaches. Proceedings of the 2nd Int'l Workshop on Wireless Information Systems.

45. Ogier R., Templin F. & Lewis M. (2004). Topology Dissemination Based on Reverse-Path Forwarding (TBRPF). IETF Request for Comments 3684.

46. OPNET Modeler. Accessed April 15, 2005, Web site: http://www.opnet.com/products/modeler/home.html.

47. Park V. & Corson S. (2001). Temporally-Ordered Routing Algorithm (TORA). Retrieved April 1, 2005, Web site: http://www.ietf.org/proceedings/02mar/I-D/draft-ietf-manet-tora-spec-04.txt, work in progress.

48. Perkins C., Royer E., & Das S. (2003). Ad-hoc On-Demand Distance Vector (AODV) Routing. IETF Request for Comments 3561.

49. Perkins C., Bhagwat P. (1994). Highly dynamic Destination-Sequenced Distance-Vector routing (DSDV) for mobile computers. Proceedings of ACM SIGCOMM '94.

50. Ramanathan R. & Redi J. (2002). A Brief Overview of Ad Hoc Networks: Challenges and Directions. IEEE Communications Magazine, 40(5), 20-22.

51. Rappaport T. (2002). Wireless Communications: Principles and Practice. Prentice Hall.

52. Rodoplu V. & Meng Teresa H. (1999). Minimum Energy Mobile Wireless Networks. IEEE Journal On Selected Areas In Communications, 17(8), 1333-1344.

53. Royer E. M. & Toh. C.-K. (1999). A Review of Current Routing Protocols for Ad-Hoc Mobile Wireless Networks. IEEE Personal Communications Magazine, 6(2), 46-55.

54. Sinha P., Krishnamurthy S., & Dao S., Scalable. (2000). Scalable Unidirectional Routing with Zone Routing Protocol (ZRP). Proceedings of the WCNC.

55. Singh S. & Raghavendra C. S. (1998). PAMAS - Power Aware Multi-Access Protocol with Signalling for Ad Hoc Networks. ACM Computer Communications Review, 28(3), 5-26.

56. Singh S., Woo M. & Raghavendra C.S. (1998). Power-aware routing in mo-bile ad hoc networks. Proceedings of Fourth Annual ACM/IEEE Conference on Mobile Computing and Networking, 181-190.

57. Stojmenovic I. & Lin X. (1999). GEDIR: Loop-free location based routing in wireless networks. Proceedings of the IASTED International Conference on Parallel and Distributed Computing and Systems.

58. Tacconi D., Saraydar C.U. & Tekinay Ş. (2004). Ad hoc enhanced routing in UMTS for increased packet delivery rates. Proceedings of IEEE WCNC 2004.

59. Takagi H. & Kleinrock L. (1984). Optimal transmission ranges for randomly distributed packet radio terminals. IEEE Transactions on Communications, 32 (3), 246-257.

60. Tobagi F. A. (1987). Modeling and Performance Analysis of Multihop Packet Radio Networks. Proceedings of EEE, 135-55.

61. Toh C. K. (2001). Maximum battery life routing to support ubiquitous mobile computing in wireless ad hoc networks. IEEE Communications Magazine, 39(6), 138-147.

62. Xinjie C. (1999). Network simulations with OPNET. Proceedings of the 31st conference on Winter simulation.

63. Xu Y., Heidemann J. & Estrin D. (2000). Adaptive energy-conserving routing for multihop ad hoc networks. Research Report 527, USC/Information Sciences Institute.

64. Zhong S., Yang Richard Yang, & Chen J. (2003). Sprite: A Simple, Cheat-Proof, Credit-Based System for Mobile Ad-hoc Networks. Proceedings of INFOCOM 2003, 1987-1997.

65. Zou, X., Ramamurthy, B. & Magliveras, S. (2002). Routing Techniques in Wireless Ad Hoc Networks -Classification and Comparison. Proceedings of the Sixth World Multiconference on Systemics, Cybernetics and Informatics.

66. Hou T.C. & Li V.O.K. (1986). Transmission range control in multihop packet radio networks, IEEE Transactions on Communications, 34 (1), 38-44.