Power Efficient Routing of Ad-Hoc Wireless Network Communications

By

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Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of
Master of Applied Science

Ottawa-Carleton Institute for Electrical and Computer Engineering
Faculty of Engineering
Department of Systems and Computer Engineering
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Power Efficient Routing of Ad-Hoc Wireless Network Communications

Submitted by
Hao Zhang, B. Eng.

In partial fulfillment of the requirements for
the degree of Master of Applied Science

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January 2003

Abstract

Energy and power limitation of mobiles is a major constraint on performance of ad-hoc wireless networks. To extend the lifetime of mobile devices, increase the capacity of network, and reduce the interference, power efficiency has to be one of the major parameters for the design and development of traffic routing scheme for ad-hoc wireless networks.

Most of the current researches focus on the model of ad-hoc networks with only isolated peer-to-peer connections. The study of this thesis presents a general model of ad-hoc networks with gateway access. This network model can be characterized by two functions of the mobile density and the base station density.

A new routing algorithm is proposed to optimize the mobile aggregate transmission power of the entire network. The critical part of this algorithm is the selection of mobile transmission power value, at which the mobile nodes maintain communications with their surrounding neighbors. This simulation study shows that the proposed algorithm has better performance on the mobile aggregate power efficiency in comparison with direct transmission method, especially when the mobiles function at an optimal value. This optimal power value can be closely estimated by the measurements of mobile density and the base station density in a given network area.

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Chapter 1

Introduction

1.1 General

There are two typical types of wireless network systems. One is the infrastructure wireless network, and the other is the ad-hoc wireless network. An infrastructure wireless network is divided into many smaller regions, each of which is covered by a base station, as shown in Figure 1-1 [Gol02]. In an infrastructure wireless network, a mobile terminal always directly communicates with a base station located in the same region. The base stations are typically connected to the fixed networks by a high speed wireline links.

An ad-hoc wireless network is a collection of mobile terminals that form a network without the aid of base stations. In an ad-hoc wireless network, the mobile terminals directly communicate with one another over the air, as shown in Figure 1-2. Each mobile node in the ad-hoc wireless network can perform necessary networking functions.

Figure 1-1 Infrastructure wireless network architecture

Figure 1-2 Ad-hoc wireless network structure

Ad-hoc wireless networks are highly appealing for many reasons. They can be quickly configured and deployed. They are also robust because the mobile nodes are distributed and redundant over the network area. The failure of one single node does not result in the crash of the whole network. These characteristics are particularly important

for the military applications, and so studies of such networks were originated by military research groups. For the last a few years, ad-hoc wireless networks have also become increasingly popular in civilian applications because of their flexibility of deployment and reduced cost on implementation and maintenance. To enable the packet data applications, such as IP-based application, in ad-hoc networks becomes a very hot topic of study.

To bring new applications into Ad-hoc wireless networks, there remains many technical challenges. Unlike wireline networks, ad-hoc wireless networks are constrained by scarce resources such as limited bandwidth, power constraints, severe propagation conditions, and dynamic network topology. The routing protocols, which were originally designed for packet data wireline networks, will not be suitable for the wireless applications. Designing ad-hoc wireless networks for packet data applications must overcome the stated challenges and the ad-hoc wireless characteristics.

1.2 Issue of ad-hoc network routing

Ad-hoc wireless networks have some characteristics that are not present in the wireline domain. A radio channel allows a node to broadcast signals directly to another node over the air. The link signal-to-noise ratio (SNR) determines the communication performance between the two nodes. The performance is measured by the data rate and the bit error rate (BER) that can be supported on the radio link. The SNR over radio link typically decreases as the transmission distance between two nodes increases.

Furthermore, the radio link SNR varies randomly due to the propagation, interference and node mobility. A successful transmission over the radio link requires a minimum SNR value. Generally, higher SNR results in higher data rate and lower BER. If the SNR is too low, the required data rate and BER can not be supported for certain applications, since the information cannot be successfully transmitted over this radio link.

In an ad-hoc wireless network, a mobile terminal can directly send packets to its final destination if the SNR on this radio link is high enough. In this case, the source and destination have direct connection. When the source and destination nodes are far apart, the SNR may not meet the minimum required value for successful transmission. In the case that the SNR is not high enough, the source and destination may be connected through their neighboring nodes. A communication between two widely separated nodes needs some intermediate nodes to forward the packets to the final destination. The routing via forwarding by intermediate nodes is called multi-hop routing.

In the study of multi-hop routing protocols in ad-hoc wireless networks, most of the proposed protocols can be organized into two categories: (1) proactive routing and (2) reactive routing.

1.2.1 Proactive routing

Proactive routing is also called hop-by-hop routing. In proactive routing, each node maintains a routing table. When a node forwards the packets, it looks up its routing table to determine the next hop towards the destination. The source node doesn't have to

know the entire route to the destination. The routing table keeps only the route to the next hop for a given destination node.

The proactive routing consists of three parts: route discovery, routing and route maintenance. During the route discovery, the mobile nodes broadcast a specific discovery packet to their neighboring nodes. When other nodes receive this packet, they send back an acknowledgement to the sender. After the exchange of the connection information, the routes are computed with this information and then kept in the routing table at each mobile node. When a mobile node starts to send packets to a given destination, it looks up its routing table to find the correct route and then transmits the packets to that next hop. Upon receipt of the packets, the node at the next hop will repeat the same operation until the packets reach the final destination. The routing table at each mobile node must be updated at regular intervals to keep up with the dynamics of the network. Each node transmits a maintenance packet to its neighbors to check the conditions of link connections and then update the routing table based on the feedback from its neighbors.

Proactive routing was originally designed for packet data routing in wireline networks whose topologies remain relatively stable such as the Internet. In the ad-hoc wireless network, the network topology dynamically changes. The periodic broadcast for route discovery and maintenance has to be done at very short intervals. It introduces overhead and interference to the entire network. To improve these shortcomings, Ad-hoc On Demand Distance Vector Routing (AODV) [Per99] was proposed, and it is now the prominent protocol in this category.

In AODV, the periodic broadcasts are eliminated. The mobile nodes broadcast discovery packets only when there is a demand. When a source node has data to transmit to another

node, and does not find the route in its routing table, this source will initiate the route discovery procedure.

Figure 1-3 AODV route discovery and setup procedure

This route discovery procedure is shown in Figure 1-3 [Fee]. Each route in the routing table has a sequence number and timeout setting to reflect the freshness of the network dynamics. The route with greater sequence number is more recent than that with

smaller sequence number. At the start, the source node 1 in Figure 1-3 has packets to to the destination node 14. There is no route to node 14 in the routing table of source node 1. Node 1 broadcasts a Route Request (RREQ) packet across the network. When other mobile nodes receive this RREQ packet, they update their information for the source node and set up backwards pointers to the source Node 1 in their route tables. In addition to the source node's address, they send current source sequence number, and broadcast ID. The RREQ also contains the most recent sequence number for the destination, of which the source node acknowledges. A mobile node receiving the RREQ may send a Route Reply (RREP) packet if it is either the destination Node 14 or if it has a route to Node 14 with corresponding sequence number greater than or equal to that contained in the RREQ. If this is the case, it unicasts a RREP back to the source Node 1. Otherwise, it rebroadcasts the RREQ. In the Figure 1-3, when node 2, 3 and 5 received the RREQ from node 1, they rebroadcast to other nodes until the packet reaches destination node 14. During this period, the mobile nodes keep track of the RREQ's source IP address and broadcast ID. If they receive a RREQ which they have already processed, they discard it. As the RREP propagates back to the source Node 1, the mobile nodes along the route set up forward pointers to the destination Node 14.

Once the source Node 1 receives the RREP, a route to the destination Node 14 is set up. The source may begin to send data packets to the destination. If the source Node 1 later receives a RREP containing a greater sequence number or contains the same sequence number with a smaller number of hops, it may update its routing information for that destination. Once the source stops sending data packets, the routes will time out and eventually be deleted from the intermediate node routing tables.

When a link breakage occurs while the route is active, a Route Error (RERR) message is generated containing the list of unreachable destinations. The nodes upstream of the breakage propagate this message back to all active upstream nodes until it reaches the source node. This maintenance procedure is shown in Figure 1-4. The link between Node 8 and 10 is broken. RERR message is propagated back to upstream Node 5 and then to Source Node 1. After receiving the RERR, source Node 1 can reinitiate route discovery by issuing RREQ with higher destination sequence number across the network through Nodes 2, 3, and 5.

Figure 1-4 AODV route maintenance procedure

1.2.2 Reactive routing

Reactive routing is also called source routing. When a source node has packets to send to a given destination, it initializes a route discovery procedure, which is very similar to the previously described route discovery of proactive routing. When the route is found, the source node includes the routing information in the header of the packets, and then transmits the packets to the next forwarding node. The routing information contains the complete ordered list of nodes along the route to the destination. When the intermediate forwarding nodes receive the packets, they check the routing information in the packet header, and forward accordingly until the packets reach the destination. In reactive routing, the biggest difference from proactive routing is that reactive routing doesn't maintain the routing table at each mobile node. The packets themselves already contain all the required routing decisions. In reactive routing, the periodic broadcast is not necessary. On the other hand, every time when a source wants to start a session to send packets to a destination, the route discovery has to be initialized. Each packet contains more information in the header, so other overhead is introduced and the delay from the source to the destination.

To optimize the performance of reactive routing, Dynamic Source Routing (DSR) [Joh96] was proposed. It is currently the most widely used protocol in this category. DSR consists of route discovery, route maintenance and routing mechanisms. The route discovery and maintenance is the same as those of AODV. Its routing mechanism follows source routing procedure. One improvement on DSR is that each node in the network has a route cache. The routes are temporarily kept in the cache with timeout setting. When a

source can find a route to a destination in its cache, which has not expired yet, it does not have to initialize the route discovery procedure.

These proposed protocols focus on the problem of finding and maintaining the correct routes to the destination in the dynamic wireless networks. They attempt to provide a correct route to a destination with minimum number of intermediate forwarding nodes. When mobile nodes send packets along the route with minimum number-of-hops, they will transmit signals as far as possible. It requires higher transmission power. During the period of discovering routes, the mobile nodes broadcast the messages by transmitting at the highest power.

In many ad-hoc wireless networks, mobile devices are powered by batteries with limited energy. To extend the working time of device, power and energy constraints have to be considered in the development of routing protocols for ad-hoc wireless networks. Otherwise, the mobile devices will quickly lose battery charge and become unfunctional. The more mobiles drop out of the network, the more difficult the network maintains the communication. Furthermore, minimizing the power consumption can also reduce the interference to other nodes in the networks. Transmitting signals at higher power can cause excessive interference to surrounding nodes, which reduces the SNR on the connection link of neighboring nodes. It may result in a relatively low data rate or high BER. If the SNR on the link becomes lower than a given threshold, the ongoing transmission on the link will be broken. It introduces excessive delay and cost of energy. Therefore, in order to make the routing protocols work in practice, optimization of energy and power consumption has to be addressed as one of the most important technical issues in the development of ad-hoc wireless routing protocols.

1.3 Research on power efficient ad-hoc routing

Recently, the study of power and energy consumption in the context of ad-hoc wireless networks routing is beginning to gain more and more attention. Many research done in this field focuses on minimizing the transmission power because it is widely assumed that the power associated with the transmission phase dominates the total power consumption. In the power-aware routing protocols of ad-hoc wireless networks, the routing information additionally contains the transmission power value on each link connection from the source to the destination. Instead of the number of hops, the value of power consumption along the routes will be considered as the metric with priority in the selection of the optimum route to forward packets.

It is well known that the received signal power attenuates exponentially with transmitter-receiver separation distance. If the distance between the transmitter and receiver decreases, the required transmission power decreases significantly if the other condition on the connection remain same, such as modulation techniques, coding scheme. If an intermediate node is exploited to forward packets between the source and destination nodes, the aggregate transmission power from the source to the destination will be smaller than the transmission power directly from the source to the destination. A detailed analysis of this statement on this conclusion is presented in Section 2.3.

Many power-aware routing protocols of ad-hoc wireless networks are proposed [Gom99], [Gom01], [Gup00], [Rod99], [Dos02], [Xu01]. They all share the idea that including as many relaying nodes between source and destination nodes shortens the

distance between transmitting and receiving pairs, thereby reducing the aggregate transmission power to deliver packets.

Most of these algorithms still fall into the same two categories: proactive and reactive routings. In the proactive routing category, Power Aware Routing Optimization (PARO) [Gom99, Gom01] has the basic proactive routing characteristics. In the route discovery and update, it attempts to include the forwarding nodes between transmitter-receiver pairs by using the overhearing mechanism. It assumes that the mobile nodes are capable of adjusting the transmission power dynamically on a packet by packet basis, and the interference and fading condition in both directions between two nodes are similar in space and time. This overhearing procedure is shown in Figure 1-5.

Before transmitting a packet to a receiver, a transmitter node includes the required transmission power into its packet header. When another node overhears this transmission, it computes the minimum transmission power from the transmitter node to itself with the information in the received packets and the local measurements. Then the overhearing node generates the information about the current range of its neighboring nodes. When the overhearing node finds packet forwarding through itself can reduce the transmission power in comparison with the original direct communication between transmitting and receiving nodes, this overhearing node may elect to become a relay node by transmitting a *route-redirect* message to communicating pair to inform them about the new route. This node also creates appropriate entries in its routing table. In PARO routing protocol, when a node starts to transmit a packet, it searches the routing table to find a route toward the destination. If that route doesn't exist, PARO searches the overhear table to find the transmission power information regarding the destination. If the information

doesn't exist, this node transmits the packet using the highest power to reach the destination at best effort.

Figure 1-5 PARO overhearing operations

Another power aware routing protocol in proactive routing category of ad-hoc wireless networks is Common Power Protocols (COMPOW) [Nar02]. It is developed based on a theoretical study on the throughput and power consumption of mobile

networks in [Gup00]. This study indicates that if all identical mobile nodes, which are randomly located in an ad-hoc wireless network, transmit at a common power level of a specific value, a nearly optimal throughput per node can be reached. COMPOW shows that the power consumption of the whole network is also optimized if all mobile nodes transmit at this common power level, which results in the optimal throughput. The most important part of COMPOW protocol is to find the smallest common power level at which the entire network is connected. In the COMPOW, each mobile node may contain multiple routing tables, one for each of the transmission power levels available. The number of entries in one routing table gives the number of reachable nodes at this power level. For a mobile node, if a routing table with a smaller power level has the same number of entries as that of another routing table with a greater power level, the smaller power level is selected as the optimal power level for this mobile node to transmit packets. When the smallest power level is found, a mobile node can send packets to any one destination with optimal power consumption.

As a new proactive routing protocol of ad-hoc wireless networks, Minimum Power Topology protocol is proposed in [Rod99] to optimize the energy consumption of mobile devices. The main idea of this algorithm is that a mobile node does not need to search for all the possible forwarding nodes in the network to find the global minimum power path to a destination; thus, by a very much localized search, a node can eliminate any nodes beyond its immediate neighborhood. In this protocol, each node executes a local search to find the link connections in its enclosure, and then exchanges information containing the transmission power cost with every node it found. After computation and comparison of this information, the links corresponding to the minimum cost neighbor

are selected and the routing table is updated accordingly. Therefore, the nodes can only keep connections with these minimum power cost links to send and forward packets. This protocol assumes the nodes are equipped with GPS since it requires the precise information of the mobile node locations to search node's enclosure graph and compute the power cost.

In reactive routing, a modified DSR is proposed in [Dos02] to optimize the power consumption of ad-hoc wireless networks. In this modified DSR, Route Request packet header includes the power at which the packet was transmitted. When a node receives the Route Request packet, it can compute the minimum required transmission power. This power value is included along with the node ID in the Route Request packet header, and then the packet is rebroadcast again if the node doesn't contain the route to the destination. When the Route Request reaches the destination node, the destination sends back in the reverse way the Route Reply packet, which includes not only the node ID but also the corresponding power information of each hop. Thus the source node can get the exact power values of each hop from this Route Reply packet to compute the total power required to reach the destination. This per-hop power information is stored in the source node cache with the route. For routing data packet, the minimum energy route is selected from the cache instead of the minimum hop routes. The source node simply includes this per-hop power information in the header of data packet and transmits it at controlled power level. The intermediate relay nodes just look up the next node and minimum power level at the header of packet, and transmit the packet at the controlled power.

1.4 Challenges of power efficient ad-hoc routing

Energy and power constraints significantly change the problems of routing protocols of ad-hoc wireless networks. A metric to assess the performance of proposed protocols should be the total energy (including that expended for any retransmissions necessary) spent in reliably delivering one packet to its final destination. A wireless terminal's state mode typically consists of three basic states: idle, transmitting or receiving. The energy for transmission dominates the total energy cost. So many protocols [Gom99], [Gom01], [Gup00], [Rod99], [Dos02] selected the total aggregate transmission power as a simplified energy metric for energy-efficient ad-hoc routing protocols. Some other algorithms [Bro01] proposed a different metric that is the mobile's active time to network partition; however they all have the same objective to extend the ad-hoc network effective working time.

First of all, the energy-efficient routing protocols should discover the minimum energy routes. Because the exchange of routing information between mobile nodes during the route discovery and update consumes energy, this energy consumption must be traded against the energy and power savings that result from the more efficient routings with this information. An energy efficient routing protocol must be simple for processing. If this protocol is too complex, it will consume more energy on processing routing information and introduce more overhead. That may make the performance even worse. Additionally, for the reliable delivery of packets, the energy consumption associated with any necessary retransmissions has to be considered, when error rate is very high on link connections.

As we know, the energy for transmission dominates the total energy cost. However, some research [Fee01] indicates that energy consumption associated with receiving and idle state is not negligible. Generally, optimization of energy for receiving data is more associated with hardware technology. The development of semiconductor will make a new mobile device that consumes less and less energy for receiving data and being idle. Therefore, optimizing the mobile transmission power will be the central issue in improving power and energy efficiency.

To minimize the transmission power, multi-hop routing is fully exploited in the most proposed protocols by including many intermediate forwarding nodes even when the source and destination are within a direct transmission range. This idea is based on the assumption that mobile can dynamically adjust transmission power.

Additionally, some other technical issues have to be addressed for ad-hoc wireless network routing. If a mobile device is often used for forwarding packets, the power consumption will quickly drain the battery of that node. If this node is gone, some other mobile nodes which rely on this node as a relaying node may lose the connection to the network. Thus, balancing the traffic distribution through the networks has to be considered in the development of energy-efficient ad-hoc routing protocols to maximize the mobile node's life-time in the network.

Therefore, a energy/power efficient routing protocol has to balance the energy consumption, routing efficiency, sophistication of processing and traffic balance to achieve the best performance.

1.5 Thesis Objective

Most of the current research in this field is based on peer-to-peer ad-hoc networks, in which the mobile terminals communicate with each other either directly, or through other relaying mobile nodes. In this network model, the communications are limited in the given network area because there is no gateway with the external networks such as the Internet. Thus, these kinds of networks have limited use. To extend the ad-hoc wireless network communication over a greater range of applications and, especially to bring Internet into the ad-hoc wireless networks, it is required to have the gateway access to fixed networks.

To describe this function of the network, a new ad-hoc wireless network model is established in this thesis study. In our model, we assume that each base station in such an ad-hoc network acts as a gateway to the high speed wireline networks. The base stations are also connected with each other through high speed wireline links.

If we assume that the service area has two dimensions, we define the two special functions: The first one is the mobile density function $m(x, y, t)$, and the other is the base station density function $b(x, y)$.

$$m(x, y, t) = \frac{M(x, y, t)}{\Delta S} \quad (1.1)$$

$$b(x, y) = \frac{B(x, y)}{\Delta S} \quad (1.2)$$

where ΔS is the service area which is centered at the coordinate (x, y) . $M(x, y, t)$ is the number of mobile nodes within the area ΔS at time t . $B(x, y)$ is the number of base

stations located within ΔS . $m(x, y, t)$ is a time-varying function representing the density of mobiles per unit area at time t . $b(x, y)$ is just a two-dimensioned space function representing the density of base stations per unit.

It is noted that the different size of area ΔS can result in the different mobile densities $m(x, y, t)$ and base densities $b(x, y)$, This is true even in the same network area. If the size of ΔS is too small, these density functions become meaningless; whereas, if the size of ΔS is too large, they can't describe the dynamic behavior of network area. Therefore, the size of ΔS should be carefully chosen and should be compatible with the mobile transmission range.

In a given network area, the behavior of mobile nodes can be characterized by the mobile density function, and the base station configuration can be described by base station density function. Thus, the ad-hoc wireless network can generally be characterized by these two density functions. In the conventional isolated peer-to-peer ad-hoc wireless networks, as opposed to the hybrid fixed/ad-hoc networks, there are only mobile nodes in the networks and no gateways exist, at least gateways do not affect the routing protocols. This conventional ad-hoc network can be considered as a special case of the presented network model, in which the base station density is zero everywhere in the service area. Therefore, this model can be used as a general model of ad-hoc wireless networks.

The main focus of this study is the mobile power efficiency characteristics as they apply to the network model described in this section. This thesis has three objectives:

1. Proposing a routing algorithm to optimize the mobile transmission power for a hybrid fixed/ad-hoc wireless network;
2. Designing and implementing simulation programs to evaluate the performance of the proposed algorithms;
3. Analyzing the simulation results to obtain valid conclusions regarding the proposed models

1.6 Organization

The remainder of this thesis is organized in four chapters.

Chapter 2 first provides the mathematical analysis of mobile transmission power characteristics over radio channel. From this theoretical analysis, a detailed routing algorithm of the ad-hoc networks is proposed to optimize the mobile transmission power.

Chapter 3 describes the simulation methodology. Scenario design and settings of simulation will be outlined. After that, the method of performance comparison in the simulation will be covered.

Chapter 4 provides the analysis on the results and statistics of the simulations of the proposed algorithms. This numerical study is categorized into many scenarios at different conditions such as traffic patterns, mobile densities and base densities, etc.

Chapter 5 contains the thesis conclusion and recommendations for future related research.

Chapter 2

Proposal of Selective Short Path Scheme

2.1 Introduction

This chapter first presents a theoretical analysis of transmission power over radio channels. Then a power cost model used in the following study is given. Based on this model, a mathematical analysis is presented to describe mobile transmission characteristics of ad-hoc wireless networks. Finally, a new algorithm is proposed to improve the mobile power efficiency.

2.2 The transmission power cost model

The transmission power is closely related to the radio channel conditions. Modeling the radio channel is one of the most challenging tasks of mobile radio system design. Unlike wireline channels, RF channels are extremely random and do not fit into

any static analysis. The transmission path between a transmitter and receiver can vary dramatically and quickly. Also, the speed, at which the mobile terminal travels, impacts the radio signal. Extensive studies on the channel indicate that radio channel variations are characterized statistically into two broad categories: *Large-scale variations* and *small-scale variations*. In practice, many channels have been found to fit this model quite well with appropriate parameters from field measurements [Rap96].

2.2.1 Large-scale variations

Large-scale variations are propagation models used to predict the mean signal power for an arbitrary transmitter-receiver separation distance. It is useful to estimate the radio coverage area of a transmitter. The average received signal power has been found to decrease logarithmically with transmitter-receiver separation distance. **Two-ray** model is one of the simplest models, which is commonly used in the literature. It is expressed as the following equation [Rap96]

$$P_r = P_t G_t G_r \frac{h_t^2 h_r^2}{d^4} \quad (2.1)$$

or

$$PL(dB) = 40 \log d - (10 \log G_t + 10 \log G_r + 20 \log h_t + 20 \log h_r) \quad (2.2)$$

where P_r is the received signal power, P_t is the transmitting signal power, $PL(dB)$ is the path loss in dB, G_t is the transmitter antenna gain, G_r is receiver antenna gain, h_t is the height of transmitter antenna, h_r is the height of receiver antenna, and d is the distance between transmitter and receiver.

In two-ray model, the signal power falloff is proportional to d^{-4} . Researches and measurements have found that, in different environments, the signal power falls off with distance to the power of different values. Generally, the average large-scale path loss is expressed as below:

$$\overline{PL}(d) \propto \left(\frac{d}{d_0}\right)^n \quad (2.3)$$

or

$$\overline{PL}(dB) = \overline{PL}(d_0) + 10 \cdot n \cdot \log\left(\frac{d}{d_0}\right) \quad (2.4)$$

where $\overline{PL}(d_0)$ is the free space path loss at reference distance d_0 , d_0 is the close-in reference distance, and d is the transmitter-receiver separation distance, n is the path loss exponent determined from the field measurements. Path loss exponent values for different environment are listed in the Table 3-1 [Rap96].

Environment	Path Loss Exponent n
Free Space	2
Urban area cellular radio	2.7 to 3.5
Shadowed urban cellular radio	3 to 5
In building line-of-sight	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factories	2 to 3

Table 2-1 Path loss exponents for different environments

In reality, surrounding environmental clutter may be vastly different over two different locations with the same distance separation. The variable number of obstructions and type of obstructions between transmitter and receiver generate a shadowing effect on the signal power. Empirical research finds that the shadowing effect typically follows a lognormal random process. By combining the path loss and shadowing effect together, we can get the following **Log-normal shadowing** path loss model:

$$PL(dB) = \overline{PL}(d_0) + 10 \cdot n \cdot \log\left(\frac{d}{d_0}\right) + N(0, \sigma) \quad (2.5)$$

where $N(0, \sigma)$ is a zero-mean Gaussian distributed random variable (in dB) with standard deviation σ (also in dB). The value of σ is determined by the environment.

2.2.2 Small-scale variation

Small-scale variation or fading model characterizes the rapid fluctuations of radio signal amplitude over very short travel distance or short time durations. Fading is caused by the interference between two or more versions of the transmitted signal which arrive at the receiver at slightly different times. These waves, called *multipath waves*, combine at the receiver antenna to give a resultant signal varying widely in amplitude and phase. The received signal over this fading channel is commonly modeled by a Rayleigh distribution, in which the received signal is a wide-sense stationary stochastic process whose envelope is Gaussian random variable and phase is uniform random variable at each point in time.

A wireless communication receiver is typically designed with diversity reception to reduce the performance degradation caused by small-scale variations. Diversity reception is the technique with which the receiver can collect streams of the same data through the independent paths. A solution called Maximum Ratio Combining (MRC) is used to optimally combine these independent streams. In a CDMA system, for example, a widely used diversity reception solution is the Rake receiver, in which the multipath components are collected at the intervals of chip period and combined optimally.

In well-designed wireless communication systems, diversity techniques and MRC handle the small-scale variations at physical layer; however they cannot completely get rid of that variation. We assume that the only parameter of consequence when designing power efficient transmission schemes at the upper layers is the power of received signal after MRC, which is mainly determined by the large-scale variations, but not small-scale variations [Rod99].

2.3 Mathematical Analysis

To present a mathematical analysis of transmission power over wireless channel, we define some parameters. The transmission power over a transmitter-receiver separation distance of d is defined as P_{T-R} . To make sure the signal is received and demodulated correctly, the received power of the signal at the receiving node has to be above some threshold, which is defined as minimum required received power $P_{R \min}$. Then, P_{T-R} is given by the following:

$$P_{T-R}(dBm) = \overline{PL}(dB) + P_{R\min}(dBm) \quad (2.6)$$

where $\overline{PL}(dB)$ is the average path loss of signal power over wireless channel of transmitter-receiver separation due to the large-scale variations.

$P_{R\min}$ is a function of data rate Eb/N_0 . If all the nodes communicate at same constant data rate with same coding and modulation techniques, $P_{R\min}$ should be same for all of the receiving nodes. If it is assumed that the data rate is constant for all the nodes all the time, $P_{R\min}$ will be constant. Thus, P_{T-R} will be only determined by path loss $\overline{PL}$, which is a function of distance d if the path loss exponent n is given. Therefore, P_{S-R} is determined by d at the same conditions. If lognormal shadowing is not considered, the following equation can be obtained by setting $P_{R\min} = C$.

$$P_{T-R}(dBm) = \overline{PL}(d_0) + 10 \cdot n \cdot \log\left(\frac{d}{d_0}\right) + C \quad (2.7)$$

Since $\overline{PL}(d_0)$ is constant, we get the following

$$P_{T-R}(d) = k \cdot d^n \quad (2.8)$$

First a simple scenario is given for the transmission power cost analysis. A source node S sends traffic to the destination node D. There are a number of mobile nodes $R_i (i = 1, 2, \dots, m)$ lined up straight between S and D shown as Figure 2-1, these mobiles will be relaying nodes to forward the traffic.

Figure 2-1 Transmission power scenario

For direct transmission from S to D, the transmission power

$$P_{S-D} = k \cdot d^n \quad (2.9)$$

If the separation distance from S to relay mobile R_1 is d_1 , the transmission power from S to R_1 is following.

$$P_{S-R_1} = f(d_1) = k \cdot d_1^n \quad (2.10)$$

Therefore, if traffic is transmitted to the closest relay mobile one by one along the line until reaching the destination, the aggregate transmission power is obtain as below:

$$P_{aggregate} = \sum_{i=1}^{m+1} f(d_i) = \sum_{i=1}^{m+1} k \cdot d_i^n \quad (2.11)$$

To evaluate the power efficiency of this relaying method, we define a power saving ratio “ pe ” as power comparison between aggregate power of relaying and direct transmission power, power saving ratio pe can be express as following equations:

$$pe = \frac{P_{aggregate}}{P_{S-D}} = \frac{\sum_{i=1}^{m+1} k \cdot d_i^n}{k \cdot d^n} = \frac{\sum_{i=1}^{m+1} d_i^n}{d^n} \quad (2.12)$$

$$\sum_{i=1}^{m+1} d_i = d$$

First we focus on the simplest case. Suppose there is one relaying node ($m=1$) in the middle, since $d = d_1 + d_2$, we get following.

$$pe = \frac{d_1^n + d_2^n}{d^n} = \frac{d_1^n + (d - d_1)^n}{d^n} = \left(\frac{d_1}{d}\right)^n + \left(1 - \frac{d_1}{d}\right)^n \quad (2.13)$$

$(0 \leq \frac{d_1}{d} \leq 1)$

When environment exponent $n = 3, 4, 5$, the values of pe are shown in Figure 2-2.

Figure 2-2 pe values in the case of one relaying node

It can be concluded from the above figure that, by using relaying node in the middle of source and destination instead of direct transmission, the efficiency of aggregate transmission power can be greatly improved at a cost of more delay and more load.

When the mobile nodes are not lined up on a straight line, but randomly located in this area, the situation is getting much more complex. A general mathematical theory is provided in [Rod99], which is summarized in the following.

First a relay region of the transmit-relay node pair (i, r) is defined to be

$$R_{i \rightarrow r} \equiv \{j | P_{i \rightarrow r \rightarrow j} < P_{i \rightarrow j}\} \quad (2.14)$$

where $P_{i \rightarrow r \rightarrow j}$ denotes the aggregate power to transmit traffic from node i through node r to node j , and $P_{i \rightarrow j}$ denotes the power to transmit traffic from i to j directly.

For this transmit-relay node pair (i, r) , it can reduce the total aggregate power to use node R for relaying traffic of Source node only when the destination node j is located in the relay region, shown in the Figure 2-3. For the destinations outside of Relay region, the Relay node is not power efficient for relaying traffic of Source node. This Relay node in the figure is called power efficient relay node for the source-destination pair (Source, Destination), in which the Destination is located within the Relay region.

Figure 2-3 Relay Region of transmit-relay node pair when $n=4$

The above analysis is for an isolated ad-hoc mobile network without gateway access. Generally, it can be concluded that the aggregate transmission power can be reduced by relaying traffic with appropriately located nodes until reaching the destination.

The network model in our study is an ad-hoc mobile network of a certain area with access gateways located on a number of base stations. With the availability of base stations which do not have power constraints, they should be utilized as relaying nodes to optimize the mobile power efficiency. This network can be modeled as a direct graph $G(M, B, P)$, where M is the set of mobile nodes $\{m_i, i = 1, 2, \dots, N\}$, B is the set of

base stations $\{b_i, i = 1, 2, \dots, L\}$, P is the direct link power cost $\{p_{t \rightarrow r}, t \in M, r \in M \cup B\}$.

In the link power cost, $p_{i \rightarrow j}$ is the transmission power from sender i to receiver j .

When a mobile node S sends traffic to an external destination, any one of base station will be the destination. This is reasonable because we assume that any base station can access any external destination without cost. The optimal mobile aggregate transmission power P_o is as below:

$$P_o = \begin{cases} \text{Min}(P_{S \rightarrow b_i} (i = 1, 2, \dots, L)) & (1) \\ P_{S \rightarrow r_1} + \sum_{i=1}^K P_{r_i \rightarrow r_{i+1}} + P_{r_{K+1} \rightarrow b} & (2) \end{cases} \quad (2.15)$$

- (1) If the transmission power from source mobile to one of base stations is the minimum, and no one mobile node can act as power efficient relay nodes between source and any one of base stations.
- (2) If there are some mobile nodes which can act as power efficient relay nodes between source mobile and one of base stations.

where $b \in B$ and $\{r_i, i = 1, 2, \dots, K + 1\}$ is the set of relaying nodes in the optimal route, along which the packets can be sent to one of base stations at the minimum aggregate mobile transmission power.

When the mobile S sends traffic to another mobile D , the destination node can be either the destination mobile or a base station. We assume that power cost from the base station to the destination D is negligible because the base stations do not have power limitation. The optimal mobile aggregate transmission power P_o can be express as the following equation, in which N is either D or $b(b \in B)$:

$$P_o = \begin{cases} \text{Min}(P_{S \rightarrow D}, P_{S \rightarrow b_i} \ (i = 1, 2, \dots, L)) & (1) \\ P_{S \rightarrow r_1} + \sum_{i=1}^K P_{r_i \rightarrow r_{i+1}} + P_{r_{K+1} \rightarrow N} & (2) \end{cases} \quad (2.16)$$

- (1) If no any other mobile nodes can act as power efficient relay node between source S and destination D or any one of base stations.
- (2) If there are some mobile nodes which can act as power efficient relay nodes.

When the mobiles are missing precise location information of other nodes, it becomes extremely complicated to discover and maintain the optimal routes. Furthermore, the mobility of mobile nodes and the variations of radio channels make it more challenging. Thus there is a tradeoff between optimization of mobile power efficiency and the simplification of discovering and maintaining the optimal routes.

2.4 Selective Short Path Scheme

In this part, a new routing algorithm is proposed to optimize the aggregate transmission power efficiency of mobile nodes in ad-hoc mobile networks. In the ad-hoc mobile network with gateway accesses of base stations, there are four types of traffic scenarios:

1. *External downlink*: the traffic from outside of this area arrives at one base station, and will go to a mobile destination.
2. *Internal downlink*: the traffic is generated internally, and will go from one base station to the mobile destination.

3. *External uplink*: the traffic is generated by one internal mobile, and it will reach one base station with the gateway.
4. *Peer-to-peer*: traffic is generated by one mobile, and will go to another mobile in the same network.

The proposed algorithm consists of two parts: downlink model and uplink model. Downlink model is for the traffic starting from base stations, and uplink model is for traffic starting from mobile.

2.4.1 Downlink model

Downlink solution focuses on the traffic transmissions starting from the base station. Because the base stations have infinite energy supply, power cost is not an issue of performance for the base stations. We assume that a mobile can be reached by at least one of base stations in the service area. Thus the use of relay node is not necessary in order to optimize the power efficiency. Downlink model is simply like the cellular routing algorithm. For the internal traffic scenario, downlink solution routes traffic to the base station which is the closest to the destination mobile, and then transmit directly to the destination over RF channel. The external traffic is just forwarded through wireline to gateway. The flowchart is given in the following.

Figure 2-4 Flowchart of downlink model of Selective Short Path Scheme

2.4.2 Uplink model

Since the base stations don't have the power limitation, the base station can be exploited as relaying nodes to optimize the power consumption of mobile devices. Let the mobile transmission power be P_S . At this P_S , a mobile's transmission can cover a certain

range, and communicate with any nodes within this range. We define these nodes as this mobile's *Neighbor List*.

Suppose the value of P_s is set up for a mobile. After information exchange by broadcasting at this P_s , a mobile gets its Neighbor List. When the mobile wants to transmit traffic, it will look up its Neighbor List to see if the destination or any base station is in its Neighbor List. If so, this source mobile just directly transmits the traffic to either the destination or the base station, whichever costs less power.

If neither the destination nor a base station is in the source mobile's Neighbor List, the source mobile will send an *INQ* message to each one of the mobiles in its Neighbor List. If any one of those mobiles finds the destination or base station in its own Neighbor List, it will send back a "Yes" confirming message to notify the source of the power cost. Otherwise, a "No" message is sent back to the source. Based on all the received "Yes" confirming messages, the source will select an optimal route with the minimum power cost, to send traffic to another mobile for relaying.

If no "Yes" message is received, the source can use source routing to discover the route to the destination or base station.

In the external traffic scenario, the destination for uplink solution is any one of base stations. After reaching a base station, the traffic will be routed to outside through gateway. The flowchart of external traffic is shown in the following Figure 2-5.

Unlike the external traffic case, the destination in the case of internal traffic can be either a mobile node or a base station. After reaching the base station, the traffic will be forwarded with downlink solution. The flowchart is shown in Figure 2-6.

Figure 2-5 Flowchart of uplink solution for external traffic

Figure 2-6 Flowchart of uplink solution for internal traffic

At beginning, the source node broadcasts initial message at its highest transmission power. After the routing information is exchanged with its neighbors, a Neighbor List can be initialized. Based on the exchanged information, the source node can determine a transmission power value P_s . Afterwards, the Neighbor List can be updated periodically by broadcasting an “Update” message at the transmission power value of P_s . When another node receives this message, it can compute the power cost between the sender and receiver, based on the received signal power and the transmission signal power noted in the message. If the power cost is beyond the sender’s P_s , this packet will be ignored; otherwise, an “acknowledge” is sent back for updating the Neighbor List.

We call this routing algorithm *Selective Short Path Scheme* since it attempts to reach the destination through a short path based on selections from Neighbor List. Thus, P_s is defined as *Selective Transmission Power*.

2.4.3 Characteristics of Selective Short Path Scheme

Generally, the Selective Short Path scheme can be thought as a combination of proactive routing and source routing. The Neighbor List is equivalent to a routing table of one-hop. Meanwhile, the route discovery acts like a source routing.

One of the objectives of this scheme is to optimize the mobile power efficiency. This is accomplished mainly by limiting the direct RF connections to the nearest neighbors. Other proposed algorithms attempt to minimize the power consumption at the

expense of other performance, such as making route maintenance complicated, increasing the long delay from the source to the destination. This scheme also attempts to simplify the route discovery and maintenance to reduce the overhead. The node's Neighbor List only contains the link connections with its immediate neighbors. Compared with other hop-by-hop algorithms, the Selective Short Path scheme is much simpler in terms of routing table maintenance, and that greatly reduces overhead. In the case of route inquiry, the source node starts transmitting the discovery message among the nodes in its Neighbor List, instead of broadcasting at maximum possible range.

Meanwhile, the interferences to the networks are also reduced because each node limits its transmission power to its neighbors. As each mobile node using Selective Short Path scheme only keeps connections with its neighbors. The transmission only covers a limited range. Compared with the transmission at the highest power, the number of mobile nodes under the transmission cover is much fewer than that of the highest power. If we assume each node has the same probability to send, the probability that collision happens for Selective Short Path scheme is much lower than that of highest power transmission. Even multiple-hop routing is used in Selective Short Path, the probability, which packet is damaged over the air is not higher than that of highest transmission power, especially when the number of nodes in the service area is very large. This is very similar to the mobile cellular network. By reducing the size of cells, the number of mobiles in each cell is reduced, and the interference is reduced. Finally the error rate is reduced.

Furthermore, the precise information of node location is not needed in this scheme, whereas some other protocols need GPS availability for precise location of nodes.

The Selective Short Path Scheme is proposed for hybrid fixed/ad-hoc wireless networks with access gateways to external networks. However, this algorithm can be deployed in the conventional peer-to-peer ad-hoc wireless networks. The scheme has some advantages compared to other ad-hoc routing algorithms. The simulation studies by comparison with other pure ad-hoc routing algorithms are given in the following chapters.

The critical part of this algorithm is the selection of P_s value that results in the best power efficiency. Obviously, if P_s is too large, all destinations will be within the range covered by the source. Thus, Selective Short Path becomes equivalent to “*Direct Transmission*”, and there is no power efficiency improvement. On the other hand, if P_s is too small, there will be no node in the source’s Neighbor List or there will be too many hops between the source and the destination, with corresponding increase in delay and overhead. An important study is the power efficiency of this algorithm at different values of P_s .

Chapter 3

Design of Simulation Study

3.1 Introduction

The purpose of simulations is to numerically study the power efficiency performance of the Selective Short Path scheme under different conditions. Because the power cost is not a performance issue for downlink model. The simulation studies focus only on the uplink model. The design and implementation of the simulations are the critical part of this study work. This chapter provides the numerical method used in the simulation for the performance computation. The settings of network parameters and the assumptions are also listed at the end of this chapter.

3.2 Method of simulation study

The power efficiency is evaluated by the value of power saving which is the average aggregate transmission power of the Selective Short Path relative to average transmission power of the direct transmission under the same conditions.

With direct transmission scheme, the mobile source directly transmits over RF channel to either the destination node or the nearest base station, whichever is closer to the source. The transmission power of mobile source is defined as P_{DT} .

With the Selective Short Path Scheme, the aggregate transmission power from source to the destination is

$$P_{ST} = \sum_{i=1}^M P_{ST}(i) \quad (3.1)$$

where M is the number of mobiles which the packet traverses from source to destination along the forwarding route. $P_{ST}(i)$ is the transmission power at which the mobile i sends traffic to the next relaying node $i+1$ with *Selective Short Path* scheme.

For a given traffic pattern, a pair of source and destination nodes are selected randomly for each run of simulations. After repeating the simulation runs enough large times, the average of these power values is taken for statistics. The average transmission power of direct transmission is expressed in equation 3.2, and the average aggregate transmission power of Selective Short Scheme is expressed in equation 3.3.

$$\overline{P_{DT}} = \lim_{N \rightarrow \infty} \frac{1}{N} \cdot \sum_{i=1}^N P_{DT}(i) \quad (3.2)$$

$$\overline{P_{ST}} = \lim_{N \rightarrow \infty} \frac{1}{N} \cdot \sum_{i=1}^N \sum_{j=1}^{M(i)} P_{ST}(j)_i \quad (3.3)$$

In the equations, N is the number of repetition times of simulation runs, and $M(i)$ is the number of mobile nodes the traffic traverses from source to destination in the number i simulation run:

The power saving ratio $pe(dB)$ is computed as below to evaluate the power efficiency of Selective Short Path:

$$pe(dB) = \overline{P_{ST}}(dBm) - \overline{P_{DT}}(dBm) \quad (3.4)$$

3.3 Simulation design and settings

We simulate a network with 20 kilometers by 20 kilometers service area. Two kinds of path loss models are used in the simulation: one is two two-ray model and the other is lognormal shadowing model. To focus on the main issues that are critical to the performance of the proposed scheme, some parameters are set with constant values in Table 3-1 in the simulation study.

Network Area		20 km by 20 km square
Mobile	Antenna Gain	6 dB
	Antenna Height	2 m
Base Station	Antenna Gain	6 dB
	Antenna Height	15 m
RF channel carrier		1.9 GHz
required E_b / N_0 at receiving end		10 dB
Lognormal shadowing standard deviation σ		6
Interference		constant and same for all the nodes
Data rate		constant value

Table 3-1 Simulation assumptions

In the course of simulation, the mobile nodes are generated randomly with the locations in the defined service area. The base stations are generated with symmetrical location in a defined grid. For instance, the scenarios with 4 and 9 bases are shown in the following Figure 3-1 and Figure 3-2 respectively.

Figure 3-1 Simulations scenario with 4 base stations

Figure 3-2 Simulation scenario with 9 base stations

Each source node is selected randomly out of the generated mobile nodes. Based on the traffic pattern which is the percentage of external traffic, the destination is either one of the base stations for external traffic, or another mobile for internal traffic. In the case of internal traffic, the mobile destination is also randomly selected from the generated mobiles. After that, the transmission power will be computed with both direct transmission and Selective Short Path scheme.

After repeating the above procedure enough times, the average power value will be convergent, which is the value of amount of total transmission power divided by repetition times. Then the power efficiency is obtained by comparing the average power values of Selective Short Path scheme to that of the direct transmission with Equation 3.4.

Chapter 4

Performance Results and Analysis

4.1 General

This chapter presents the numerical results collected in the simulation study on the performance of uplink solution of Selective Short Path scheme. The mobile power efficiency of the Selective Short Path scheme is the main focus in all the simulation cases. The first section is about mobile power efficiency with different traffic patterns. Next, the mobile power efficiency with different mobile densities and base station densities are presented respectively. The following section is the results with different data rates. In each section, the results are categorized into two groups of two-ray and log-normal path loss models respectively. Finally, a summarizing analysis of the simulation results is provided.

4.2 Simulation Results

4.2.1 Mobile power efficiency with different traffic patterns

In this section, the simulations are designed and implemented to study how the traffic patterns impact power efficiency performance of uplink solution of Selective Short Path scheme. The traffic patterns are characterized by the percentage of external traffic, which are the data mobile nodes send to the outside of this certain network through the gateways. Selective transmission power P_s is the transmission power value at which a mobile node keeps the direct connections with its neighboring nodes. Obviously, the higher P_s , the more neighbors the mobile can directly communicate with. In the simulations of this section, the data rate is a constant value of 200 Kbps both mobile and base densities are given in each case. The values of power saving are computed by varying value of P_s .

For the two-ray model, Figure 4-1 shows the simulation results of four different mobile densities and one same base density; meanwhile, the results of four different base densities for the same mobile density are shown in Figure 4-2. For log-normal shadowing model, the results of four different mobile densities with one same base density are presented in Figure 4-3, and the following Figure 4-4 shows the results of four different base densities with one mobile density. In each simulation case, five different values of external traffic percentage are taken for comparison.

Figure 4 -1 Power savings with different traffic patterns, two-ray model, same base density and different mobile densities

Figure 4-2 Power savings with different traffic patterns, two-ray model, same mobile density and different base densities

Figure 4-3 Power savings with different traffic patterns, log-normal shadowing model, same base density and different mobile densities

Figure 4 -4 Power savings with different traffic patterns, log-normal shadowing model, same mobile density and different base densities

The following observations can be made on the above figures, in which every curve represents a case of a certain different traffic pattern:

- The simulation results of two path loss models show that the value of power saving ratio of each traffic pattern curve varies with the change of P_s value. At a certain value of P_s , the power saving ratio reaches the minimum value. It means the Selective Short Path scheme has the best performance on power efficiency at that value of P_s , compared with direct transmission. The value of P_s which accomplishes the best performance of the mobile power efficiency is called *Optimal Selective transmission power* P_{os} . Furthermore, it is noted that the difference of traffic does not affect the value of P_{os} . All the curves with different traffic patterns have almost the same P_{os} value when the mobile density and the base density are given.
- For the simulation results of two-ray model, the traffic patterns do not have great impact on the performance of power efficiency. The power saving ratio curves of different traffic patterns are almost identical when the mobile and base densities are certain. For the simulation results of log-normal shadowing model, the difference of the traffic does not change the pattern of power saving ratio curves, but higher percentage of external traffic results in a up-shift of the curve. As we know, for the Uplink model, the destination of external traffic is just one base station; whereas the destination of internal traffic is either one base station or the destination mobile. In the case of log-normal shadowing model, the power attenuation between transmitter and receiver varies randomly because of fading

and shadowing affects. When it requires a higher transmission power between the transmitting mobile and base station because of the shadowing affect, the transmitting mobile node may send traffic to the mobile destination if it requires less power. For external traffic, the transmitting mobile can only transmit the packets to the nearest base station. The higher external traffic percentage, the more often this scenario happens. That is why the difference of traffic patterns results in a shift of power efficiency curves of log-normal shadowing simulation results.

- Theoretically, Selective Short Path scheme is supposed to become equivalent to direct transmission when the value of P_s is large enough to reach the destination at any location. However, each power saving ratio curve of log-normal shadowing model does not converge to the value of 0 dB with the increase of P_s . It still fluctuates within a small value range. That is due to the log-normal shadowing effects.

4.2.2 Performance with different mobile densities

In this part, the simulations are designed to study the performance of Selective Short Path scheme with different mobile densities, and the relation between P_{os} and mobile density under given circumstances. At the same time, the statistics study is also conducted on the average number-of-hops of the route using Selective Short Path scheme in each scenario. The results are also categorized into two different path loss models.

Figure 4-5 shows the mobile power efficiency of Selective Short Path with different mobile densities in the case of two-ray model. Figure 4-6 gives the number-of-hops for the same scenario. Figure 4-7 describes the power efficiency with different mobile densities for lognormal shadowing model, and Figure 4-8 presents the average number-of-hops in that case.

Some observations and explanations on Figure 4-5 and Figure 4-7 are given as below:

- For each curve representing a mobile density, the value of power saving ratio reaches the minimum at the value of P_{OS} . Moreover, the greater mobile density is, the better (lower) the power saving ratio at P_{OS} . It is because more relaying node can be included in the case of higher mobile density. Therefore the power saving is better than that of fewer mobile nodes.
- The P_{OS} value of each curve decreases with the increasing of the mobile density. The mobile nodes using Selective Short Path keep connections with a number of neighboring nodes at a P_S value. If there are too many, the destination is covered and no power saving. If there are too few, the mobile node becomes “blind” and only relies on the source routing through the nearest neighbor node. The P_{OS} is the value at which mobile node keeps connections with the number of neighbors, which gives the best performance on power saving. When the mobile density is lower, it requires higher transmission power for a node even to keep direct connection with its nearest neighbor node. That is why P_{OS} value decreases with the increasing of mobile density.

- In the case of two-ray model, the power saving ratio curve of mobile number of 400 is over 0 dB when P_s is very small, such as less than 0 dBm. That means power saving performance of this scheme is worse than direct transmission at the small value of P_s . When P_s is very small, the Neighbor List of the mobile node does not include any neighboring node. Thus, a mobile source node only relies on its nearest node to find a route to the destination, which is also out of the source node range covered by P_s . When that nearest node of the source receives a packet, it cannot find a node in its Neighbor-List, but explore a route using its nearest node as a forwarding node (the source node is excluded at this time, so there is no loop). This discovery procedure will continue until the destination is reached. The Figure 4-6 of average number-of-hop of each route shows that the average number-of-hops for each route is very large at small values of P_s . As we discussed in section 2.3, the route through a relaying node is power efficient only when the relaying node is located in some specific areas between source and destination nodes. The route always through the nearest node of transmitter may not be efficient on total transmission power. To check whether a mobile node is a power efficient relaying node between the source and the destination, it requires the precious location information of that node. Selective Short Path scheme does not have other equipment for precious location information; therefore, the value of P_s has to be large enough to cover a certain number of neighboring nodes so that this scheme can work effectively.

Figure 4-5 power saving with different mobile densities, two-ray model

Figure 4-6 Number of hops with different mobile densities, two-ray model

Figure 4-7 power saving with different mobile densities, log-normal shadowing model

Figure 4-8 Number of hops with different mobile density, log-normal shadowing model

4.2.3 Performance in pure peer-to-peer ad-hoc networks

The Selective Short Path scheme is originally designed for the use in the hybrid fixed/ad-hoc wireless networks with gateway access. This algorithm can also be deployed in the conventional ad-hoc wireless networks, in which there are only mobile terminals. As a special case of different mobile densities, the simulations in this part are designed to evaluate the performance of this scheme in a pure ad-hoc wireless network area. The simulation settings are same as other cases, except there is no base station containing the gateway in the network. Therefore, all the traffic is peer-to-peer constrained in this network. With different mobile densities, the power efficiency value is calculated by comparison with the direct transmission power value. The relation between P_{OS} and mobile density is also studied.

The results are also categorized into two different path loss models. Figure 4-15 shows the simulation results of two-ray model, and Figure 4-16 describes the power efficiency with lognormal shadowing model. The figures demonstrate that the simulation results are consistent with those of scenarios of hybrid fixed/ad-hoc network. The value of power saving ratio reaches the minimum at the value of P_{OS} for each curve representing a mobile density. That means the Selective Short Path scheme has the best performance of mobile power saving at P_{OS} .

Furthermore, the greater mobile density is, the better the power efficiency at P_{OS} . Also, the value of P_{OS} is decreased with the increasing of mobile density. The P_{OS} values with different mobile densities are listed in the following Table 4-1

Figure 4-9 Power saving with different mobile densities in isolated ad-hoc network, two-ray model

Figure 4-10 Power saving with different mobile densities in isolated ad-hoc network, lognormal shadowing model

Number of Mobiles	Optimal Selective Tx Power Pos (dBm)
50	20
100	16
200	14
400	8

Table 4-1 Path loss exponents for different environments

To further evaluate the performance of Selective Short Path in the pure peer-to-peer ad-hoc networks, some more simulations are implemented by comparing the performance of Selective Short Path (SSP) with DSR and PARO. As we introduced in chapter 1, DSR is routing algorithm that forward packets to the destination with the route of minimum number of hops. The mobile nodes using DSR routing protocol always transmits packets at highest possible power to the furthest reachable node until the packet arrives the destination. PARO is a power aware routing algorithm that includes the relay node between transmitter and receiver pair to reduce the transmission power by shortening the transmission distance.

In the scenarios of the simulations, we assume that the transmission power can be adjusted by mobile node based on the transmitter receiver distance. The maximum transmission power of mobile node is 30 dBm. In the case of different mobile densities,

the Selective Short Path keeps connections with neighbors at P_{os} values, which are listed in the above table.

Figure 4-11 shows that the performances of DSR and PARO are consistent with different mobile densities, but the performance of Selective Short Path (SSP) varies with the change of mobile density. The higher mobile density is, the better performance of SSP at P_{os} . When mobile number is 400, the power saving performance of SSP at P_{os} is better than those of both DSR and PARO; whereas, when mobile number is 50, the performance of SSP is still better than DSR, but worse than PARO.

Figure 4-12 gives the statistics of average number-of-hop for each route of three different routing algorithms. PARO has a larger value of number-of-hops than DSR because PARO tries to include relaying nodes between a transmitter-receiver pair. The value of SSP increases with the increase of mobile density. When mobile number is 400, the average number-of-hops for SSP is over 70.

Generally, the performance of Selective Short Path in the conventional peer-to-peer ad-hoc wireless network has a drawback. When mobile density is low, the power of this scheme may not be better than other power aware routing protocol. When mobile density is higher, this scheme has better performance on power saving at the cost of large number-of-hops of the route.

Figure 4-11 Power saving comparisons of SSP, DSR and PARO

Figure 4-12 Number-of-hops of SSP, DSR and PARO

4.2.4 Performance with different base densities

The simulations are also implemented to study the performance of power saving with different base densities. Figure 4-13 presents the results of power saving of two-ray model, followed by the number-of-hops in Figure 4-14. For lognormal shadowing model, the power saving performance for different base densities are shown in Figure 4-15, and Figure 4-16 gives the number-of-hops study.

The following are some observation and analysis for Figure 4-13 and Figure 4-15 about the power saving performance:

- First, we can see that the value of P_{OS} is smaller when the base density gets greater. Meanwhile, the power saving ratio value at P_{OS} is smaller when base density is greater. Obviously, when the base density increases, it is easier for mobile node to directly access the base station than when base density is smaller. Thus it becomes easier for Selective Short Path to become equivalent to direct transmission.
- When P_S value is much smaller than P_{OS} , the power saving ratio of 9-base case is over 0 dB. The reason is similar to that described in Section 4.2.2. Because P_S is very small, there is no neighboring node in the mobile's Neighbor-List. The source node just starts source routing through the nearest neighboring node. That route may not be the power efficient because of the missing precious location information. Figure 4-14 and 4-16 show that the number-of-hops at smaller P_S range is much greater than that at greater P_S values.

Figure 4-13 power efficiency with different base density, two-ray model

Figure 4-14 Number of hops with different base density, two-ray model

Figure 4-15 power saving with different base densities, log-normal shadowing model

Figure 4-16 probability of destination within the source range with different base density, log-normal shadowing model

4.2.5 Power efficiency with different data rates

This section describes the results of simulation study on the power efficiency of Selective Short Path with different data rates, when other conditions remain constant in the course of simulation. Figure 4-17 shows the results of two-ray path model, and results of lognormal shadowing is shown in Figure 4-18. The observations on those figures are given in the following:

- First, different data rate results in different P_{os} value. The higher data rate, the greater value of P_{os} . As we know that higher data rate requires higher transmission power. Therefore, the value of P_{os} goes higher with the increase of data rate.
- The values of power saving ratio at P_{os} are almost same with the different data rates, however different data rates have different P_{os} . Generally, the power saving curves of different data rates have almost same pattern, but are right-shifted with the increase of data rate.

Figure 4-17 Power saving with different data rates, two-ray model

Figure 4-18 Power saving with different data rates, log-normal shadowing model

4.3 Numerical Analysis

It is shown in the above simulation results that the mobile number and base number are related to the P_{OS} value. Since the network area is constant, the change of number of mobiles and number of bases result in the change of the densities of mobiles and bases. The mobile density and base density can be characterized by following two defined parameter. One is average mobile distance D_m and the other is average base distance D_b , defined in the following:

$$D_m = \sqrt{\frac{Area}{Number_of_Mobiles}} \quad (4.1)$$

$$D_b = \sqrt{\frac{Area}{Number_of_Bases}} \quad (4.2)$$

By extracting some numerical value from the simulation results, the following tables 4-1 and 4-2 are obtained to study the relation between P_{OS} and value of D_m and D_b .

It is obvious that increase of mobile density results in the decrease of D_m value, and increase of base density results in the decrease of D_b value. With the increase of D_m and D_b , the value of P_{OS} also increases. By taking the value of $10 \cdot \log(\sqrt{D_b \cdot D_m})$, the tables give the numerical relation between P_{OS} and value of $10 \cdot \log(\sqrt{D_b \cdot D_m})$, which characterizes the mobile and base density in a certain area. They are shown in the Figure 4-17 and Figure 4-18.

Base = 4	Mobile = 50	Mobile = 100	Mobile = 200	Mobile = 400
D_m (km)	2.83	2.00	1.41	1.00
D_b (km)	10	10	10	10
$\sqrt{D_b \cdot D_m}$ (km)	5.32	4.47	3.76	3.16
P_{OS} (dBm) Lognormal	8.00	7.00	6.00	4.00
P_{OS} (dBm) Two-ray	30.00	28.00	27.00	25.00

Table 4-1 D_m , D_b and P_{OS} for lognormal case with variable mobile density

Mobile = 200	Base = 9	Base = 25	Base = 49	Base = 81
D_m (km)	1.41	1.41	1.41	1.41
D_b (km)	6.67	4.00	2.86	2.22
$\sqrt{D_b \cdot D_m}$ (km)	3.07	2.38	2.01	1.77
P_{OS} (dBm) Lognormal	0.00	-7.00	-12.00	-17.00
P_{OS} (dBm) Two-ray	27.00	14.00	7.00	0.00

Table 4-2 D_m , D_b and P_{OS} for lognormal case with variable base density

Figure 4-19 P_{OS} vs. $10 \cdot \log(\sqrt{D_b \cdot D_m})$ with variable mobile density

Figure 4-20 P_{OS} vs. $10 \cdot \log(\sqrt{D_b \cdot D_m})$ with variable base density

It can be concluded that P_{OS} decreases with the increasing of mobile or base density, however, the curves do not show the strictly linear relationship between P_{OS} and mobile and base density, which is characterized by $10 \cdot \log(\sqrt{D_b \cdot D_m})$; With the values of D_m and D_b , the P_{OS} value can be initially estimated by the mobile for the use of optimal transmission. Furthermore, P_{OS} is adaptive to the change in the densities. The values of D_m and D_b can be measured by the mobile based on the covered number of nodes at a certain value of transmission power. The value of D_m and D_b can also be exchanged between mobile nodes for the more accurate estimation of density values.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

This thesis starts by reviewing the current published research on the power efficient routing of conventional peer-to-peer ad-hoc wireless networks. After an analysis of the characteristics of mobile transmission power, a new routing algorithm of mobile nodes, Selective Short Path scheme, was proposed for the hybrid fixed/ad-hoc wireless networks with gateway access. The detailed explanation on the proposed scheme is provided.

This new algorithm suggests that the mobile nodes should utilize the relaying nodes to forward traffic, which are located in a certain region covered by an adaptive transmission power instead of highest power value. At this value, a mobile only keeps the direct connections with a certain number of neighbors surrounding it.

To evaluate the performance of this new algorithm, a simulation study was designed and implemented for different scenarios. The overall results of simulations show that there is an optimal value of the adaptive transmission power, at which the new

algorithm has the best performance on transmission power efficiency when compared with direct transmission. This optimal value P_{os} was not affected by the traffic patterns, but merely determined by the mobile density and base density of network area when other conditions such as data rate, modulation and coding techniques are fixed. The value of P_{os} decreases approximately logarithmically with the increase of average node distance, which characterizes mobile and base densities.

5.2 Contribution

This thesis aims to propose a power efficient routing algorithm for the general model of ad-hoc wireless network with gateway access since it is believed that the gateway access is necessary to bring Internet into ad-hoc networks. The proposed algorithm demonstrates improved performance on mobile power efficiency. Meanwhile, it also reduces the overhead of mobile nodes in the service area by simplifying route maintenance compared with current approaches.

5.3 Recommendations for future research

Most of the work in this thesis has concentrated on the performance of transmission power efficiency of hybrid fixed/ad-hoc wireless network with gateway access. The power efficiency performance study is also given by comparison with PARO

and DSR. It will be interesting to investigate the power efficiency performance by comparing to other power aware routing algorithms.

The performance study in this work is conducted only on the power efficiency. It would be interesting to investigate the performance of throughput, whole network capacity and delay with this proposed scheme. A comprehensive wireless link cost metric study can be conducted for the performance evaluation.

Finally, a simple method to estimate P_{os} value by means of mobile density and base density is given in this study. Some other methods can be developed to estimate the P_{os} more accurately.

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