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Lifetime-extended, Power-aware, Non-position Based Localized Routing in Hybrid Ad-Hoc/Infrastructure Network

By

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the Faculty of Graduate Studies and Research

in partial fulfillment of

the requirements for the degree of

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Abstract

This thesis presents a localized routing protocol for both hybrid ad-hoc/infrastructure networks and conventional ad-hoc networks. The work is focused on small ad-hoc networks, or small clusters of terminals falling between gateways. The purpose of the proposed strategy is to extend the lifetime of the network. The main idea of the proposed strategy is to restrict the size of the neighborhood by controlling the transmitted power. When mobile terminals refrain from searching for routes and transmitting packets with full power, the overall interference in the network would be less and the total required power will also be small. The work presented in this thesis illustrates that, there is a benefit of controlling the power and reducing the neighborhood of terminals. The thesis shows that, the lifetime of small ad-hoc networks (either on their own or as a hybrid ad-hoc/infra-structure network) can be extended by choosing the right size of the neighborhood. The work illustrates that there is an optimal neighborhood size which is a function of the terminal density as well as the density of the gateways.

Several performance cost metrics are proposed considering node's transmission power and/or remaining battery capacity. To balance the impact of node's transmission power and remaining battery capacity on the route selection, normalized cost metrics are introduced to normalize contribution parts.

Comparing the performance of the proposed strategy with that of more classical approaches such as the minimum energy protocol, we illustrate by simulation that the

proposed strategy discovers the optimal (i.e. minimum energy) route with high probability without flooding the network. We did not evaluate the impact of reduced interference on the protocol performance; however, it is self evident that controlling the transmitted power and restricting the terminal neighborhood would have benefits in terms of total network throughput and extending the lifetime of the network.

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Motivations, Objectives and Contributions

(A) Motivation

Over the next few years, it is expected that a wide range of wireless applications will be introduced. Terminals for these applications will vary in size and capabilities and many applications will require small terminals with limited power and resources.

Examples of these applications are sensor networks, machine-machine intelligent control, location and tracking applications and others. We further expect, that the existing cellular networks will evolve and will be able to support the heterogeneous traffic generated by such terminals and applications. In this thesis, we take the view that, the integrated wireless networks of the near future will support two modes: (1) the infrastructure mode and (2) the Ad-hoc mode. In other words, hybrid ad-hoc/infrastructure networks will play major role in future developments in wireless applications. Such networks have the capabilities and flexibility needed to the unpredictable evolution of wireless networks.

Under this scenario, it is reasonable to assume that the existing cellular infrastructure will be integrated with ad-hoc access. This is the basic vision of this thesis. We assume that the cell size of existing base stations will remain too big for some applications and some terminals, and in such cases, ad-hoc sub-networks will be formed to fill in the gaps among sparsely deployed base stations. Therefore, it is inherent in our vision, that ad-hoc networks are relatively small in sizes and that communications over several kilometers will involve a base station with high probability.

(B) Objectives

Small terminals communicating in the environment described above need to conserve energy as much as possible. The main objective would be to extend the lifetime of the ad-hoc sub-networks, such that small terminals (including sensors) that cannot reach a base station directly and are powered by batteries can remain active as long as possible. Our objective is to develop an algorithm that maximizes the average terminal lifetime for the scenario described in section (A). We assume that the major source of power consumption is the transmitted power and communication overhead. We acknowledge that there are other sources for power loss, such as periodical wake ups in paging cycles, power wasted in signal processing and other management and control signaling. The exact impact of such factors depends on the details of communication protocols and the applications. In this thesis we neglect these secondary sources of power loss.

We also assume that the data packet size is usually small. Therefore, the route discovery and maintenance scheme with less communication overhead is very important to improve the power efficiency of the network in this scenario.

Note that the simulation study only simulates and evaluates the function of the proposed network layer routing protocol. It doesn't include the issues of other layers. Overheads, which include the route discovery and maintenance overhead, are not considered in the simulation for both proposed protocol and other protocols for comparison. In addition, location update and destination search overhead for position-based localized protocols that are implemented in the simulation to provide comparison, are not considered.

We also assume that the density of gateways in the infrastructure network (e.g., GSM/GPRS network), to which a multi-hop wireless ad-hoc network has access, is in an appropriate range so that a wireless node can often reach a gateway in a few hops and each wireless node is at least in the coverage of one gateway in the hybrid network. Thus, in the majority of the cases, packet can be delivered to the destination in very high probability. Proposed protocol also fits well for the small-scale conventional ad-hoc networks without gateways (e.g., a rectangle network service area with 100 meter side length). Therefore, the scenarios chosen for the simulation is in accordance to the above assumptions.

(C) Contributions

The contributions of this thesis are:

1. The thesis argues that the lifetime of the ad-hoc sub-network depends on the size of the terminal neighborhood, and that the size of the neighborhood that maximizes the network lifetime depends on the density of terminals and the density of the base station. The neighborhood size is determined by the level of transmitted power, which is controlled by the terminal and can be optimized for the densities of terminals and base stations. The simulation result shows clearly, that there is an optimum size of such neighborhood, and that limiting the transmitted power can significantly increase the network lifetime.
2. The small size neighborhood results in a small neighbor information list, and reduces the traffic used to update these lists and reduces the overall interference in the network. Moreover, due to the low power transmission over small range, it

would be possible to have con-current transmissions within the overall network over the same radio channel in the case where the high power transmission does not often occur. This is similar to channel reuse in cellular networks.

3. The proposed algorithm is a localized routing algorithm. It does not require knowledge of the position of terminals or base stations. It only needs to know the power needed to reach different terminals (or base station) and terminals' remaining battery reserve. These parameters can be easily determined by sending test packets during the neighbor information list updates.
4. The thesis introduces eight power and/or battery cost metrics. Four metrics are normalized power and battery cost metrics. They solve the problem of unevenly weight the impact of the power and battery cost on the route decision in the existing combined metrics.

Chapter 1

INTRODUCTION

1.1 Highlight of The Study

In the study of this thesis, we present a localized routing protocol. It applies to both small conventional ad-hoc networks and the hybrid ad-hoc/infrastructure networks, in which each wireless terminal is in the coverage of at least one gateway and in uplink, it often can reach a gateway in a few hops.

The main objective of this study is to propose a strategy that can maximize the network lifetime. The major contribution of the study is: it demonstrates that the size of neighborhood has significant impact on the network lifetime. Restricting the size of the neighborhood to an optimal size can maximize the network lifetime. The size of the neighborhood is adjusted by controlling the transmitted power. In this study, we illustrates by simulation that choosing an optimal size of neighborhood can extend the network lifetime to the most and this optimal neighborhood size depends on the density of both wireless terminals and gateways.

This study also presents other benefits of the proposed strategy: 1) The localized search within small neighborhood can avoid flooding and reduce the traffic within the neighborhood, therefore lowers the overall interference in the network and reduce power consumption. This advantage is especially evident when the communication sessions are

short. 2) This strategy does not require the knowledge of positions of the terminals and gateways.

In the study, we also introduce normalized cost metrics. They are applied to assist sending terminal to make a route decision. Normalized cost metrics address the problem of unevenly weight the impact of the power and battery cost on the route decision in the existing combined metrics.

A computer simulation study is carried out to evaluate the performance of the proposed protocol and show the relation between network lifetime and the size of neighborhood. In the simulation, we also compare the strategy with some well-known schemes, such as the classical minimum-energy scheme. Simulation results show that without flooding the network, the proposed strategy can discover a near optimal route.

1.2 Conventional Ad-Hoc Network

A conventional wireless ad-hoc network is a group of wireless terminals with little or no fixed infrastructure. These wireless terminals are battery-operated devices and have limited transmission range, for example, laptop computers, PDAs, mobile phones and sensors. As shown in Figure 1.1, such terminals can communicate with each other within their transmission range or by relaying the packet through one or more intermediate nodes in multi-hop fashion.

In contrast with infrastructure wireless networks, such as GSM, an ad-hoc network can be reformed “on the fly” without any centralized administration. It is autonomous and highly flexible. A traditional ad-hoc wireless network is isolated since it

does not provide access to any fixed network entities. Therefore such networks have limited applications.

In recent years, wireless ad-hoc network have become more popular due to the flexibility of deployment and low maintenance cost. It is well suited to applications where temporary network connectivity is needed. Some examples of applications include disaster relief, communication in the battlefield, conferences with a network of laptops and sensor networks. A sensor network is a dense wireless network of heterogeneous nodes collecting and disseminating data. The collected data are forwarded back to a central node for further processing. Applications include, for example, environment

Figure 1.1 Conventional Ad-Hoc Network

control, space exploration.

Since a wireless ad-hoc network is composed of battery-operated mobile nodes, node mobility, node failure due to battery depletion and the dynamic propagation condition could result in frequent network topology change. Therefore, the unpredictable

and random nature of wireless ad-hoc networks makes the design of efficient, highly adaptive routing protocol a big challenge. In addition, a wireless ad-hoc network is constrained by scarce bandwidth and power resource. Effectively utilizing the limited resource is a critical issue in wireless ad-hoc networks.

1.3 Hybrid Ad-Hoc/Infrastructure Network

A hybrid ad-hoc/infrastructure network integrates conventional ad-hoc networks with infrastructure access points. In such a network, wireless terminals communicate with each other in ad-hoc fashion. However, some terminals can have access to fixed gateways (access points) as shown in Figure 1.2. These terminals can communicate with one or more than one type of external networks. Gateways can be interconnected through wired links. They all have RF modules to communicate with wireless terminals in the network. The example of the fixed gateways can be the base stations in the existing GSM/GPRS or CDMA networks. Hybrid network model is a more general ad-hoc network model. The density of gateways is assumed to be small. If the density is reduced to zero, then the hybrid network becomes a conventional (pure) ad-hoc network.

The gateways (access points) provide the wireless terminals with connections to external networks or services, such as the Internet or a database. Thus, the hybrid networks expand the narrow application domain of pure ad-hoc networks into a wide domain. The hybrid networks enhance scalability. The service area of a hybrid network

Figure 1.2 Hybrid Ad-Hoc/Infrastructure Network

could be much larger than that of a conventional network as the gateways can join a set of conventional ad-hoc networks to form a large hybrid network. What's more, the fixed gateways have no power constraint. They are the ideal relay nodes in the internal traffic, which is the traffic from one wireless terminal to another one.

Hybrid ad-hoc networks inherit most characteristics of conventional ad-hoc networks, such as dynamic, unpredictable topology change, multi-hopping and resource constraint. In addition to the conventional characteristics, fixed gateways play an

important role in hybrid networks. Most of the current research in ad-hoc networks ignores the role of gateways and tends to focus on the pure forms in ad-hoc networking.

1.4 Issue of Ad-Hoc Network Routing

The dynamic, indeterministic topology change in ad-hoc networks has prompted much research into highly adaptive, stable multi-hop routing protocol. A desirable ad-hoc network routing protocol has the following properties:

- Detects the frequent network topology changes, which are caused by node mobility, node failure, propagation environment changes etc.
- Discovers resource efficient routes and maintains the connectivity with low signalling overhead and interference.
- Maintains high communication throughput and minimizes end-to-end delay.
- Independent of any centralized administration.
- Fast route convergence.
- Loop-free.

Most of the routing protocols, which are currently widely applied on ad-hoc networks such as DSR and AODV, typically find a route with minimized hop count. In order to reduce the number of relaying nodes, wireless nodes transmit at high power. This mechanism yields high interference and is not power efficient.

Recent research focuses more on the power-aware routing protocol. Since battery imposes power, weight and size constraints, portability may be the most critical issue in

those battery-operated wireless terminals. Moreover, battery technology hasn't experienced significant advancement in the past years compared with other areas. In order to improve portability, besides using low power components, it is essential to design energy-efficient protocols. Power consumption of a wireless terminal can be divided into computation related and communication related. The latter one refers to the power spent on transmitting and receiving packets and it is the target that most power-aware protocols are designed to reduce. Numerous studies have been devoted to power efficient design for conventional ad-hoc networks. A survey of entire network protocol stack design to enhance power efficiency is given in [2]. In [3], a modification on existing ad-hoc routing and 802.11 MAC layer protocol is proposed to reduce power consumption. In this thesis, we mainly discuss the power-aware routing protocols. A power-aware routing protocol should select an optimal path, which can minimize the total power to route a packet and can maximize the lifetime of the nodes. It accommodates the scenarios where the nodes can dynamically adjust their transmission power.

Network lifetime is an important performance evaluation of ad-hoc networks. It is also a measure of power efficiency. Network lifetime is a statistical parameter indicating the period elapsed until certain percentages of wireless terminals are dead. Some previous work often used the time until the first terminal dies as the lifetime. Extending lifetime prevents early network re-partitioning and service interruption. A routing protocol, which is designed to reduce overall transmission power, cannot prevent uneven use of wireless nodes. It may result in overusing of energy resources of a small set of nodes, routing packets around a congestion area. This will cause early death of some nodes and decrease network lifetime. Therefore, in order to maximize the lifetime

of the network, overall transmission power and remaining battery capacity of nodes should be taken into account simultaneously in the route selection.

1.5 Review of Related Work

Existing routing protocols for conventional ad-hoc network can be classified into two main categories: Non-localized and Localized. In a non-localized routing protocol, the complete route from the source node to the destination node is determined by the route discovery procedure before data packets are sent. Non-localized protocols require global knowledge of nodes and/or links in the network by flooding the entire network before a route decision is made. In a localized routing protocol, each node makes a route decision of which node will be the next hop node in the neighborhood solely based on its local knowledge of its neighbors. Therefore, the route decision is made hop by hop until the data packet reaches the destination. It is not necessary for a sender node to hold data packets until a complete route is discovered. Routing overhead is reduced in a localized routing protocol. Prior works on these two categories of routing protocols are reviewed in this section.

1.5.1 Non-localized Ad-Hoc Routing

In general, all existing non-localized routing protocols are variations of shortest weighted path algorithm using a variety of broadcast flooding methods. There are two types of routing protocols in the category of non-localized ad-hoc routing protocol: *proactive* and *reactive* ([23], [1]).

A proactive protocol is a table-driven algorithm. Each node has one or more tables containing the latest routing information to any nodes in the network. Responding to changes of network topology, this type of routing protocol periodically updates, stores and maintains routing information, regardless of whether the source node requires a route or not. A notable example of proactive protocols is DSDV (Destination Sequenced Distance Vector). Serious problems of proactive protocols are that they generate a large amount of signaling overhead; the bandwidth and power resource consumed by the excessive overheads can't be neglected.

A reactive protocol initiates route discovery only on-demand when a node requires a route. An optimal route has to be discovered by flooding the entire network and after all the possible routes are evaluated. Different from proactive routing protocols, only the route between source and destination nodes is discovered and maintained until the route is no longer desired. In [23], two well-known reactive routing protocols AODV (Ad-hoc On-demand Distance Vector Routing) and DSR (Dynamic Source Routing) are discussed. Figure 1.3 is the route discovery procedure in AODV. The source node broadcasts a route request message to the entire network. (Figure 1.3a). Once the route

Figure 1.3 AODV route discovery

request message reaches the destination node, it sends back a route reply message along the reverse path. At the same time, nodes along this path set up the forward route in their route tables. In large network, we should not ignore the delay caused by route discovery procedure in reactive protocols since source node must wait until an optimal complete route is established to send packets. A performance comparison of some prominent proactive and reactive routing protocols is provided in [1].

A non-localized protocol tries to evaluate all possible routes between source and destination by flooding the entire network. The route being chosen is the route with minimum cost. The scheme using hop-count as the cost metric is called Minimum-Hop. DSR, AODV, DSDV are all famous Minimum-Hop scheme protocols. The difference among them is the method of entire network flooding. The method reflects the amount of route discovery/maintenance

overhead. However, as we indicated in the previous section, this approach is not power-efficient and can reduce network lifetime.

A power-aware DSR is the scheme derived from DSR. However, instead of using hop counts as the cost metrics, a power-aware DSR protocol use the link power cost as the cost metric. One of the examples of power-aware DSR schemes is to find the route with minimum energy consumption, so called Minimum-Energy scheme ([6], [7]).

If the goal of the routing protocol is only to discover a minimum total power (energy) route, the nodes in the network may tend to have widely different energy consumption profiles resulting in early death of some nodes [6]. Figure 1.4 illustrates the

Figure 1.4 Shortcoming of minimum power routing

shortcoming of minimum power routing. We suppose node 6 will be selected as the relay node for the packets from 0-3, 1-4, 2-5. As a result, node 6 will exhaust its battery faster than the other nodes and will be the first to die. Therefore, it cannot prevent uneven use of the devices. Note that since transmission power dominates the communication related power consumption, most of the power-aware routing protocols only consider node transmission power. To maximize the lifetime of an ad-hoc network, the power

consumption rate of each node must be evenly distributed and overall consumed power for each route must be minimized. However, these two objectives cannot be satisfied at the same time by metrics considering power or battery reserve only. There is a tradeoff between the two.

In [4]~[14], many cost metrics for non-localized shortest weighted path protocols are proposed, which respectively aim to minimize the total energy consumption of a route, extend network lifetime (considering battery reserve), or try to satisfy two or more goals simultaneously. Paper [7] proposes two metrics: Minimum Battery Cost and Min-Max Battery Cost. The goal is to maximize node lifetime and reduce variation in node battery level. In Minimum Battery Cost routing, the route with minimum battery cost is selected. Battery cost of a route is defined as the summation of the battery cost of the nodes on a route. Battery cost of a node is a function of its remaining battery capacity. One choice of node battery cost function is the reciprocal of its remaining battery capacity. Therefore this metric actually is to find the route with maximum battery capacity to prevent nodes from being overused. However, a route containing nodes with little battery reserve may still be chosen by this scheme. To address this problem, Min-Max Battery Cost routing is proposed to minimize the maximum node's battery cost in the route. In other words, it tries to avoid the route with nodes having the least battery capacity. However, since there is no guarantee that the selected route consumes less power, it may not always be effective to extend lifetime of all nodes.

A conditional max-min battery capacity routing (CMMBCR) is proposed in [7] to simultaneously satisfy the goals of reducing overall transmission power and maximizing network lifetime. The basic idea is that when all nodes in the possible routes have

sufficient remaining battery capacity (above a threshold), a route with minimum total transmission power among these routes is chosen. Otherwise if all routes have nodes with low battery capacity (below a threshold), routes including nodes with the lowest battery capacity should be avoided. The latter case is exactly like Min-Max Battery Cost routing.

A new power-aware routing protocol called Maximum Residual Packet Capacity (MRPC) is presented in [8]. It is conceptually similar to the Min-Max Battery Cost algorithm. It tries to pick the route that maximizes the residual capacity at the most critical node (the one with least residual capacity). However, MRPC identifies the capacity of a node not only by its residual battery capacity, but also by the expected energy spent in reliably forwarding a packet over a specific link, in which the cost of retransmission is considered. The node-link capacity metrics is defined as:

$$C_{ij} = B_r(i) / E_{i \rightarrow j} \quad (1.1)$$

$$E_{i \rightarrow j} = T_{i \rightarrow j} / (1 - p_{ij})^L \quad (1.2)$$

where $B_r(i)$ is node i 's remaining battery capacity, $E_{i \rightarrow j}$ is the transmission energy from node i to node j considering retransmission. $T_{i \rightarrow j}$ is the single packet transmission energy. p_{ij} is the link's packet error probability. $L = 1$ if hop by hop retransmission exists, otherwise $L > 1$. Paper [8] also presents a Conditional MRPC (CMRPC). It switches from minimum energy routing to MRPC when the capacity of nodes falls below a threshold. MRPC and CMRPC are simulated to compare with the performance of Minimum-Hop, Minimum-Energy, Min-Max Battery Cost (MMBCR) and CMMBCR algorithms in [8]. Figure 1.5 shows the node's expiration (dead) sequence of these

algorithms, in which protection threshold was set to 50% of the total battery capacity for CMMBCR and 50% of the initial node capacity for CMRPC.

A general link cost metric is suggested in [10] as in equation (1.3): where $e_{i \rightarrow j}$ is the transmission energy over link (i, j). E_i is node i's initial energy (battery capacity)

Figure 1.5 Expiration sequence of different algorithms

and $\underline{E}_i$ is node i's residual energy (residual battery capacity). The path cost is computed

$$C_{ij} = e_{i \rightarrow j}^{x_1} \underline{E}_i^{-x_2} E_i^{x_3} \quad (1.3)$$

by summation of the link cost on the path. Any existing shortest path algorithm such as Bellman-Ford, Dijkstra algorithm can implement this algorithm. Note that if $\{x_1, x_2, x_3\} = \{0, 0, 0\}$, the algorithm becomes the minimum hop algorithm, and if it is $\{1, 0, 0\}$, then it is minimum transmission energy algorithm. If $x_1=0, x_2=x_3$, it is minimum residual energy (battery cost) algorithm using normalized residual energy. Simulation result shows that network lifetime obtained at $\{1, 50, 50\}$ is close to the optimal.

Equation (1.4) presents a link cost metric proposed in [12] summing up the impact of transmission power and residual battery capacity. It attempts to introduce fairness consideration in node usage.

$$C_{ij} = W_p \frac{P_{i \rightarrow j}}{P_{\max}} + W_e \frac{E_j^o}{E_j^R} \quad (1.4)$$

W_p, W_e are weights on the two terms. $P_{i \rightarrow j}$ is the transmission power over a link. $P_{\max}$ is the maximum transmission power of a node. E_j^o is node j's initial battery capacity. E_j^R is node's residual battery capacity. In the beginning, the second term is equal for all nodes, therefore transmission power is the main measure of the link cost. However, as the battery reserve begins to drop, the second term will dominate.

Besides designing power, battery reserve aware cost metrics, a routing protocol proposed in [14] tries to extend network lifetime by avoiding overusing single optimal path. It keeps a set of good path. Each path is assigned a probability of being chosen, depending on the cost metric.

In summary, non-localized routing protocols can offer optimal routes by obtaining global knowledge of the network. However, they have following drawbacks:

- Excessive overhead: It is critical in proactive routing.
- Delay in large networks: In reactive routing, delay (time to block sender) during the route establishment is intolerable especially in large networks.
- No scalability: Node mobility and topology change is quadratic in network size. Overhead for discovering and maintaining a route in a large network is much greater than that in a small network.

- Route is unstable and hard to maintain: It becomes serious when many relay nodes are involved. Each change in link or node may trigger route update in a large portion of the network.
- High interference level.

In order to solve some of the above problems, some research has been done to improve the performance of non-localized protocols. In [15]~[17], 3 non-centralized routing protocols are proposed, which combine local decisions within route discovery procedure. [16], [17] introduce two non-blocking protocols, in which first arrived route will be selected by the destination as the optimal route.

1.5.2 Localized Ad-Hoc Routing

In a localized ad-hoc routing protocol, the sender need only find the most appropriate next hop terminal within a limited search radius. In contrast with non-localized routing protocols, localized routing protocols are scalable, overhead reducible. Routes discovered by localized routing protocols are easy to maintain even in a high mobility network.

Almost all the existing localized routing protocols are position-based. Most of them require nodes to be equipped with GPS. Route decision is made based on the location of sender, its neighbors, destination and some additional information. Paper [18] provides a survey on some well-known position-based routing protocols – MFR, NFP, Random Progress Method, GEDIR, DIR etc. MFR (Most Forward within Radius), NFP

(Nearest Forward Progress) and Random Progress Method are progress-based schemes. Progress of a neighbor is defined as the projection onto the line from source to destination. It can be calculated by the positions of sender, destination and neighbor. A neighbor has positive progress if it is in forward direction to destination,

Figure 1.6 Position-based localized routing. (S: sender, D: destination)

otherwise it has negative progress. In MFR scheme, a packet is forwarded to a neighbor with maximal progress (node M in Figure 1.6). In NFP scheme, the sender selects the nearest neighbor with positive progress (node N in Figure 1.6) to forward the packet. In Random Progress Method, the sender chooses at random one of its neighbors with positive progress. GEDIR (Geographic Distance Routing) is a routing scheme based on geographic distance. The sender selects the neighbor that is closest to the destination (node G in Figure 1.6), but if the best choice of forwarding node is the node where the packet came from, the packet is dropped. Compass routing (DIR) is proposed in [20]. The main idea of this scheme is to forward the data packet from node S to its neighbor A

such that the direction of line SA is closest to the direction of line SD, where D is the destination node. For example, in Figure 1.6, S chooses node A to be the next hop node. However, DIR scheme is not loop-free. None of the methods discussed above are power-aware localized routing protocols. Moreover, they have high delivery rates in dense networks, but low delivery rates in sparse networks.

Paper [19] proposes power, cost and power-cost GPS based localized routing protocols. The power-aware localized protocol attempts to minimize the total power consumption for a route. A sender node S will forward packet to its neighbor B for which the sum of power for transmitting from S to B and ideal power from B to D (destination) is minimized. The exact power for transmitting from B to D is unknown. It is assumed to be equal to the optimal. The objective of cost-aware localized routing is to extend network lifetime. The cost of a node is the reciprocal of the node's remaining battery capacity. The cost $C(A)$ of a route from S to D via S's neighbor A is the sum of cost of node A, $f(A)$ and the cost of the rest of the route from A to D. The scheme of the protocol is to select a neighbor A which can minimize $C(A)$. $f(A)$ can be obtained by S. The cost of the rest of the path is assumed to be proportional to the number of hops between A and D. The number of hops is proportional to the distance $s = |AD|$, and inversely proportional to the transmission radius R. The cost function $C(A)$ is presented in equation (1.5), where t is a network parameter that has several choices. Three of these choices are: i) t is a constant depending on network condition, ii) $t = f(A)$, iii) $t = \bar{f}(A)$, where $\bar{f}(A)$ is the average values of $f(X)$ for A and all neighbors X of A. The localized cost-aware routing protocol with t defined by choice ii) is called COSTII. It is simulated and compared with the proposed routing protocol as shown in Chapter 4.

$$C(A) = f(A) + ts / R \quad (1.5)$$

The power-cost localized routing protocol incorporates both power and battery cost considerations into the route decision. It aims to minimize total power consumption and to avoid nodes with little battery reserve. Sender S will pick neighbor A that minimizes $C(S,A) = \text{power-cost}(S,A) + v(s)f(A)$, where $s = /AD/$, $v(s)$ is estimated transmission power from A to D. There are two different ways to define power-cost metric: Product and Sum.

$$\text{Product:} \quad \text{power-cost}(S,A) = f(A)u(r) \quad (1.6)$$

$$\text{Sum:} \quad \text{power-cost}(S,A) = f'(S)u(r) + u(r')f(A) \quad (1.7)$$

where $r = /SA/$, r' is the average length of all links going out of S, $u(x)$ is the power to transmit on from S to A.

In all the above reviewed localized routing protocols proposed in [19], the transmission stops if the destination is reached or the message is to be returned to the neighbor it came from.

Non-localized ad-hoc routing protocols have some attractive properties that the non-localized protocols don't have, such as low overhead and scalability. However, most of the existing localized protocols are position-based. Position-based localized protocols have the following drawbacks:

- Most of the position-based protocols require each node to be equipped with a GPS device. However, an ad-hoc network should support heterogeneous wireless nodes. GPS devices may not be available to some nodes.

- GPS positioning may not be accurate enough, especially in environment with poor coverage or reception such as indoor and under water. It is not economical and not good for energy preservation.
- A GPS-free positioning technique is proposed in [21]. The algorithm uses the distance between nodes to build a relative coordinate system to compute node positions. This technique brings a lot of overhead and it is only suitable for small networks with low mobility.
- The accuracy of destination node location is a serious problem. Proper location update schemes handling node mobility and destination search are more complex than routing [22].
- Low delivery rate for sparse networks.

1.6 Organization

The rest of thesis is organized as below:

- Chapter 2 provides a detailed description of the proposed routing protocol for the discussed network scenario.
- Chapter 3 describes cost metrics for the proposed protocol. New normalized cost metrics are introduced in this chapter.
- Chapter 4 explains the simulation model, assumptions and provides simulation result analysis and performance comparison. Limitations of the proposed protocol are discussed in this chapter as well.
- Chapter 5 presents conclusions and provides some suggestions for future work.

Chapter 2

PROPOSED NON-POSITION BASED, LOCALIZED ROUTING PROTOCOL

2.1 Overview

The proposed routing protocol is designed for both hybrid and conventional ad-hoc network. The work is focused on small ad-hoc networks, or small clusters of terminals falling between gateways. It aims at extending network lifetime, minimizing power consumption with a localized approach. The main idea of our proposed algorithm is to determine the optimal next hop node by the messages exchanged between the sender and its one hop and two hops neighbors. We introduce two level neighborhoods: small ring and large ring, the size of which depends on the route request packet transmission power. Our study illustrates that there exists an optimal small ring search radius (small ring neighborhood size) that can most extend the network lifetime. The protocol does not need to know node positions. Moreover, the localized approach and small size neighborhood result in less overall interference and the communication overhead and interference is further diminished by temporarily memorizing neighbor's information in the node's cache. Several cost metrics are proposed considering power and/or battery reserve, some of which normalize the contribution components to balance their impacts.

2.2 Network Model

The hybrid ad-hoc/infrastructure network model can be described as putting fixed gateways, such as base stations, into the conventional ad-hoc network service area. Gateways provide connections to external networks and services. Gateways can be interconnected through wired links. They all have RF modules. They are fixed nodes with continuous, stable power supply. We assume that the density of gateways is of appropriate value such that the majority of terminals can reach one gateway within two hops at maximum transmission power. We also assume that every wireless node can be reached by at least one gateway on the downlink.

In hybrid networks, traffic is categorized into internal and external traffic.

2.2.1 Internal Traffic

Internal traffic is a data flow from a wireless node to another wireless node within the network service area. The service area of a hybrid network can be much larger than that of a conventional network, as the gateways join a set of conventional ad-hoc networks to form a large hybrid network. Gateways are the ideal zero cost nodes (without power constraint) to relay internal traffic. Therefore a sender node can route packets to a destination node via several wireless relay nodes or by reaching a gateway in multi-hop fashion first, then forwarding to the destination node directly by the gateway, whichever costs less.

2.2.2 External Traffic

External traffic is a data flow from a wireless node to a gateway (uplink traffic to external network), or from a gateway to a wireless node (downlink traffic from external network). In an uplink case, the destination is one of the gateways, and a sender node routes the traffic through the most cost efficient route to a gateway in multi-hop fashion. The downlink case will not be further discussed in this thesis, since it is simply the forwarding of traffic directly from a gateway to the destination. Therefore, in the rest of this thesis, external traffic means only the uplink external traffic.

2.3 Routing Algorithm

2.3.1 Small Ring and Large Ring Neighborhood

We introduce two level neighborhoods as shown in Figure 2.1: small ring and large ring. A small ring is a route request packet transmission range of a sender node using small transmission power which we call *reference power* P_{ref} . A large ring is a sender's transmission range using its maximum transmission power. In Figure 2.1, S, D, GW is respectively the wireless sender/source, destination, and gateway node. The shaded area is the small ring two-hop neighborhood, where A, B are S's small ring one hop neighbors and C is S's small ring two hops neighbor. The white area including the shaded area is the large ring two-hop neighborhood, where A, B, C, E, F are S's large

Figure 2.1 Small ring and large ring neighborhood

ring one hop neighbors and rest nodes G, H, I, J, K are S's large ring two hops neighbors. A sender node starts to search for the destination within the small ring two-hop neighborhood first. If it is found, an optimal complete route is selected. If not, a new search within the sender node's large ring two-hop neighborhood will be initiated and an optimal next hop node that has the high potential to reach the destination is chosen. Then data packet will be forwarded to this node, and the procedure will be repeated again using a small ring search until the destination is reached, if possible.

The route decision is made after applying the cost metric, which is based on the messages exchanged within the sender's two-hop neighborhood. Cost metrics will be further discussed in Chapter 3. Messages include source, destination node ID, packet transmission power, estimated exact transmission power needed and battery reserve. Data packets are sent by actual power needed (power-controlled).

2.3.2 Route Discovery

The route discovery procedure of proposed routing protocols is illustrated in the flowcharts in Figure 2.2 and Figure 2.3. They respectively show the cases of small ring search and large ring search. Note that a gateway is the destination in uplink external case. In internal traffic case, a wireless node or a gateway is the destination, whichever costs less.

1. *In cases where the destination is within the sender node's small ring two-hop neighborhood.*

The source/sender sends a route request RREQ to its neighbors, and the neighbors further forward RREQ to their neighbors (sender's small ring two hops neighbors) to look up the destination. As shown in Figure 2.2, if the destination is found in the sender's small ring one hop neighbor list (NLs), the data packet will be sent to the destination directly. Otherwise, any nodes in the sender's small ring one hop neighbor list can send back a "Reply" message to the sender if the destination is in their own small ring one-hop neighborhood. The sender picks the optimal relay node among the nodes that send back "Reply" message (Nodes in list X in Figure 2.2). Then the data packet is forwarded to the optimal one hop neighbor, which is determined by the sender according to the cost metric and further forwarded to the destination. In case there aren't any nodes in sender's small ring one hop neighbor

S: sender/source wireless node

D: destination wireless node

GW: gateway

NL_a: node a's small ring one hop neighbor list

Figure 2.2 Route discovery -- small ring

S: sender/source wireless node   D: destination wireless node   GW: gateway
NL_MAXa: node a's large ring one hop neighbor list
Pa->b: transmission power from node a to node b

Figure 2.3 Route discovery -- large ring

list (NLs) or the destination is not within sender's small ring two-hop neighborhood, the route discovery procedure with large ring search is initiated.

2. In cases where the destination is NOT within the sender node's small ring two-hop neighborhood.

Figure 2.3 illustrates the routing algorithm when a large ring search is necessary. NL_MAX in Figure 2.3 stands for a node's large ring one hop neighbor list, which is obtained by sending RREQ in the node's maximum transmission power. The optimal next hop relay node is determined by the cost metric, which is based on the messages exchanged by RREQ and "Reply" from inquired neighbors. Unlike case 1, "Reply" messages are sent by the sender's large ring one hop neighbors whether or not D and/or GW are in their own large ring one-hop neighborhood. Four branches of the flowchart in Figure 2.3 represent four circumstances:

- a) *D and/or GW are found in both the sender's large ring one hop and large ring two hops neighbor lists.*

As shown in Figure 2.3, in this case, even if D and/or GW are located in the sender node's large ring one-hop neighborhood, it is not always necessary to send the packet to the destination directly since it may not be an optimal choice.

The sender first generates a node list X, which contains its large ring one hop neighbors that can reach the destination in their own large ring one-hop neighborhood. X does not include destination nodes (D and/or GW). Instead of forwarding the packet directly to the destination from the sender, an optimal relay

node r in X is selected to forward the traffic if the conditions expressed in equation (2.1) are met.

$$\begin{cases} P_{s \rightarrow r} < P_{\min} \\ \min (P_{r \rightarrow D}, P_{r \rightarrow GW}) < P_{\min} \end{cases} \quad (2.1)$$

$$P_{\min} = \min (P_{s \rightarrow D}, P_{s \rightarrow GW}), \quad r \in X$$

where $P_{a \rightarrow b}$ denotes the power to transmit a packet from node a to node b . For example, $P_{s \rightarrow r}$ is the transmission power from sender/source node S to relay node r . A small ring search is initiated to continue route discovery after the sender forwards the packet to relay node r .

Only in the situation that no nodes in X satisfy the conditions in equation (2.1), the packet is sent directly from the sender to the destination.

b) *D and/or GW are found in the sender's large ring one hop neighbor list only.*

In this case, the sender forwards packet to D or GW directly, whichever costs less.

c) *D and/or GW are found in the sender's large ring two hops neighbor list only.*

A node list X is generated by the sender, which includes all its large ring one hop neighbors where the destination is in those neighbors' large ring one hop neighbor list. An optimal relay node r is chosen from X according to the cost metric. After the sender routes the packet to r , route discovery is repeated from small ring search (See Figure 2.2).

d) *D and/or GW can't be found within the sender's large ring two-hop neighborhood.*

In this case, the sender avoids sending to a relay node that cannot reach any nodes within its large ring one-hop neighborhood. If all the nodes in NL_MAXs cannot reach any nodes in their large ring one-hop neighborhood, the route discovery fails at this stage. As discussed previously, since the majority of terminals can access a gateway within few hops, then this case rarely happens.

Please note that GW in Figure 2.2 and Figure 2.3 is the closest gateway to the node sending RREQ, in the case where there is more than one gateway in a node's one-hop neighborhood.

2.4 Reduce Overhead

Reducing routing overhead is a common goal of all the routing algorithms. A routing protocol with less control overhead can reduce power and bandwidth consumption, lower interference level, and decrease packet collision. The proposed routing protocol uses localized approach to avoid entire network flooding, thus diminishing control overhead for route discovery and maintenance.

It can be derived from the above proposed routing protocol description that each wireless node needs to maintain two lists: both a small ring and a large ring one hop

neighbor's information list. A list contains several entries, where each entry records a neighbor's ID, this neighbor's remaining battery capacity (Br), and the power required to transmit to this neighbor (Pt) (See Table 2.1 below).

Small ring one hop neighbor list NL			Large ring one hop neighbor list NL_MAX		
Neighbor ID	Br	Pt	Neighbor ID	Br	Pt
..	..	..	..	..	..
..	..	..	..	..	..
⋮	⋮	⋮	⋮	⋮	⋮

Table 2.1 Small ring and large ring one hop neighbor list

The information in the list is used by cost metrics to make a route decision. In order to further reduce route discovery overhead, periodically updating these two lists or establishing new lists each time a route is required by a source node should be avoided. We introduce two timers for each node: T_s , T_l , which are respectively set for small ring and large ring list. Each fresh list is temporarily stored in a node's cache until the timer expires, then it is moved to the backup cache. There are two cases:

- 1) Route request arrives before the timer expires: use the list in the node's cache directly.
- 2) Route request arrives after the timer expires: discover new list by RREQ and "Reply" messages, store it into the node's cache and compare the new list with

the expired list in the node's backup cache. If they are the same, adjust the timer initial setting to $T = T + \Delta T_1$, otherwise adjust to $T = T - \Delta T_2$. T is T_s or T_l depending on which list is requested.

ΔT_2 is proportional to the difference between the fresh list and the expired list. The difference between two lists can be evaluated by matching number of entries, neighbour ID and neighbour's information (Br, Pt). They can be assigned different weight. For example, number of entries and neighbour ID in the list can be assigned more weight than Br, Pt since they show the mobility level of the network. This scheme can be further investigated by future research. ΔT_1 can be designed to be a fixed amount. A small step is conservative, but will bring extra route discovery overhead if there is little traffic and network topology is relatively stable.

Although the overhead reducing mechanism described above needs extra small storage cache, it can reduce routing overhead effectively especially in low traffic, low mobility networks. Moreover, present chip technology can integrate a lot of memory into a tiny chip. What's more, dynamically timer setting is highly flexible and reducing overhead in turn preserves power and extends network lifetime.

In the proposed protocol, we assume that each wireless node is within the coverage area of at least one gateway in the hybrid network. One of the gateways in the hybrid network is responsible for forwarding the traffic to a destination wireless node in external downlink traffic case, or when a gateway is selected as the relay node to forward internal traffic to the destination. How gateways forward packets to a destination in a cost-effective way is the problem that is worth discussing. The ideal scheme is to

forward the packet from a gateway that is closest to the destination to the destination directly. The procedure to find the closest gateway should not involve too much overhead. Here we provide a candidate scheme:

All the gateways in a hybrid network periodically transmit a short beacon. A beacon message contains the gateway ID the beacon's transmission power from a gateway. Each wireless node estimates its distance from a certain gateway by the received power level of beacon message and the beacon's transmission power. Each wireless node only stores the ID of its nearest gateways into its cache. The gateways share a common table and duplicate the table at each gateway. This table records the nearest gateway ID of each wireless node in the network. Each wireless node can update this table by sending the ID of its closest gateway and its own ID to a gateway as an external uplink traffic case. However, the update is only necessary when a wireless node finds the ID of recently discovered nearest gateway is different than the old one stored in its cache. The relay nodes along the route to update the table can attach their closest gateway ID to the packet if necessary. The period of transmitting beacon is not fixed. It is adjustable according to the mobility of the nodes. The interval is increased if few updates are reported from wireless nodes. The attractive property of this scheme is at any time, the closest gateway to a given destination is known to all gateways. The gateway currently holding the data packet can look up the table first, then directly forward the packet to the nearest gateway of the destination, and then the packet is further routed to the destination by that gateway. This scheme costs extra control overhead. However, proper adjustment of the transmission interval of beacons can reduce such overhead.

2.5 Loop-free

Our proposed localized routing algorithm is loop-free. Once an intermediate node has relayed a data packet, this node then rejects further copies of the same packet within a period of time that is long enough for the packet to reach the destination. A packet can be uniquely identified by source, destination node ID, and packet ID.

Chapter 3

COST METRICS

3.1 Existing Cost Metrics Review

Cost metrics design is crucial for a routing protocol with the goal of extending network lifetime and reducing power consumption. High power consumption links and low battery reserve nodes are assigned high cost. They should be avoided in route selection. As proposed in papers [4]~[14], the most popular existing cost metrics in this category consider transmission power between two nodes or node remaining battery capacity, or both. A brief summary is provided below:

- 1) Equation (3.1) expresses a cost metric that assigns Tx power to the link and aims to minimize the total power consumption in a route:

$$C_{ij}^P = P_{i \rightarrow j} \quad (3.1)$$

where the cost of link between node i and node j is denoted by C_{ij}^P . Note that node j is node i's neighbor. $P_{i \rightarrow j}$ is the power needed to transmit from node i to node j. We assume that transmission power is the dominant part in power consumption.

- 2) Equation (3.2) expresses a cost metric which considers remaining battery capacity and aims to balance battery reserves of the nodes in the network, thereby extending network lifetime:

$$C_i^B = 1 / B_r(i) \quad (3.2)$$

C_i^B in equation (3.2) denotes the battery cost of node i. $B_r(i)$ is node i's remaining battery capacity. C_i^B is inversely proportional to a node's remaining battery capacity.

- 3) Cost metrics that combine Tx power and battery reserve can be mainly classified into two groups, Add and Product:

$$C_{ij}^{Add} = W_B C_j^B + W_P C_{ij}^P \quad (3.3)$$

$$C_{ij}^{Product} = (C_i^B)^{W_B} (C_{ij}^P)^{W_P} \quad (3.4)$$

W_B, W_P are weights applying on the two terms. A variation of equation (3.3) and (3.4) is to replace battery cost term to $B_o(i) / B_r(i)$, where $B_o(i)$ is node i's original full battery capacity. They are shown in equations (3.5) and (3.6).

$$C_{ij}^{Add} = W_B \frac{B_o(j)}{B_r(j)} + W_P C_{ij}^P \quad (3.5)$$

$$C_{ij}^{Product} = \left(\frac{B_o(i)}{B_r(i)} \right)^{W_B} (C_{ij}^P)^{W_P} \quad (3.6)$$

3.2 Normalized Cost Metrics

As shown in equations (3.3) to (3.6), a combined cost metric is composed of two contributing parts. It is possible that one part substantially outweighs the other part. In order to balance the influence of $P_{i \rightarrow j}$ and $B_r(i)$ on a route decision, several normalized cost metrics are introduced in this thesis to normalize cost of these two factors to let both in interval $[0,1]$. In this thesis, we also analyze and investigate through simulation how applying normalized cost metrics can increase network lifetime.

1) Normalize cost of transmission power

$$(C_{ij}^P)_N = P_{i \rightarrow j} / P_{\max}(i), \quad (C_{ij}^P)_N \in [0,1] \quad (3.7)$$

Where $P_{\max}(i)$ is node i 's maximum transmission power. $(C_{ij}^P)_N$ is normalized power cost and it is a linear function of $P_{i \rightarrow j}$.

2) Normalize cost of battery capacity

Battery cost of a node rises when the node's remaining battery capacity drops. We are looking for a non-linear normalized cost curve, the slope of which varies according to the change of B_r . The curves with smaller slope when B_r is low are preferred. Since the cost stays high when a node has low battery reserve, it can further protect the nodes with little battery reserve. We introduce two normalized cost functions: *cosine* and *sigmoid*' as below:

- *Cosine*

Equation (3.8) presents the cosine normalized cost function as below.

$$(C_i^B)_{N\_cos} = \cos \left((B_r(i) / B_o(i)) \times \pi / 2 \right) \quad (3.8)$$

$$(C_i^B)_{N\_cos} \in [0,1], \quad B_r(i) / B_o(i) \in [0,1]$$

- *Sigmoid'*

Sigmoid' is a modified sigmoid function. Equation (3.9) presents the original sigmoid function, in which y_{sig} asymptotically approaches 0 and 1 respectively as x approaches negative and positive infinity. Figure 3.1 shows the curve of original sigmoid function.

$$y_{sig} = 1/(1 + e^{-x}), \quad x \in (-\infty, +\infty), \quad y_{sig} \in (0,1) \quad (3.9)$$

$$y_{sig'} = 1/(1 + e^{(coeff * (x-0.5))}), \quad x \in [0,1], \quad y_{sig'} \in (0,1) \quad (3.10)$$

Figure 3.1 Sigmoid function

To apply sigmoid to the battery cost function, a modified version sigmoid' is proposed in equation (3.10), where x is in the range of $[0,1]$ and y_{sig} decreases while x increases. $Coeff$ is the coefficient to compress x to the interval $[0,1]$. Sigmoid' battery cost function is defined in equation (3.11):

$$(C_i^B)_{N\_sig'} = 1 / (1 + e^{(coeff * (B_r(i) / B_o(i) - 0.5))}) \quad (3.11)$$

$$coeff = 15, \quad B_r(i) / B_o(i) \in [0,1], \quad y_{sig'} \in (0,1)$$

Figure 3.2 cosine, sigmoid' cost function

Figure 3.2 illustrates the curves of cosine and sigmoid' normalized cost function. It can be observed from Figure 3.2 that when the remaining battery capacity is in the low range, the slope of cost curves is small which means the cost is relatively stable and remains high. The rate of cost drop is slower when the battery reserve is low than the rate when it is high. It is a beneficial feature that further prevents overusing the node with little battery reserve

3.3 Cost Metrics for Proposed Routing Protocol

Eight cost metrics are designed for the proposed routing protocol. Their performance comparison is provided in Chapter 4. They can be classified into three groups:

- a) consider Tx power cost only.
- b) consider node's battery cost only.
- c) consider both. It includes two subcategories: Add & Product. Normalized cost functions belong to this group.

Each proposed cost metric has a set of two cost functions, which respectively apply to the two cases in the routing algorithm: small ring search and large ring search. Our proposed routing protocol uses the cost metric to pick the optimal (lowest cost) next relay node r or R respectively for these two cases. Below is the detail of the eight cost

metrics. Note that r denotes a small ring one hop neighbor of sender S and R denotes a large ring one hop neighbor of S . d is the destination node.

1) LPE: consider Tx power only

$$\text{small ring: } C_{lpe}^s = P_{s \rightarrow r} + P_{r \rightarrow d} \quad (3.12)$$

$$\text{large ring: } C_{lpe}^l = P_{s \rightarrow R} \quad (3.13)$$

2) LBLN: consider node's battery cost only

$$\text{small ring: } C_{lbn}^s = B_o(r) / B_r(r) \quad (3.14)$$

$$\text{large ring: } C_{lbn}^l = B_o(R) / B_r(R) \quad (3.15)$$

Cost metrics 3) to 6) are the normalized cost metrics considering Tx power and Br:

3) COSA

$$\text{small ring: } C_{cosa}^s = (C_s^B)_N \_ \cos * (C_{sr}^P)_N + (C_r^B)_N \_ \cos * (C_{rd}^P)_N \quad (3.16)$$

$$\text{large ring: } C_{cosa}^l = (C_R^B)_N \_ \cos + (C_{sR}^P)_N \quad (3.17)$$

4) COSP

$$\text{small ring: } C_{cosp}^s = (C_s^B)_N \_ \cos * (C_{sr}^P)_N + (C_r^B)_N \_ \cos * (C_{rd}^P)_N \quad (3.18)$$

$$\text{large ring: } C_{cosp}^l = (C_R^B)_N \_ \cos * (C_{sR}^P)_N \quad (3.19)$$

5) SIGA

$$\text{small ring: } C_{siga}^s = (C_s^B)_N \_ sig' * (C_{sr}^P)_N + (C_r^B)_N \_ sig' * (C_{rd}^P)_N \quad (3.20)$$

$$\text{large ring: } C_{siga}^l = (C_R^B)_N \_ sig' + (C_{sR}^P)_N \quad (3.21)$$

6) SIGP

$$\text{small ring: } C_{sigp}^s = (C_s^B)_N \text{\_sig}^l * (C_{sr}^P)_N + (C_r^B)_N \text{\_sig}^l * (C_{rd}^P)_N \quad (3.22)$$

$$\text{large ring: } C_{sigp}^l = (C_R^B)_N \text{\_sig}^l * (C_{sR}^P)_N \quad (3.23)$$

Cost metrics 7) and 8) are non-normalized cost metrics considering Tx power and Br:

7) INVA

$$\text{small ring: } C_{inva}^s = (B_o(s) / B_r(s)) * P_{s \rightarrow r} + (B_o(r) / B_r(r)) * P_{r \rightarrow d} \quad (3.24)$$

$$\text{large ring: } C_{inva}^l = B_o(R) / B_r(R) + P_{s \rightarrow R} \quad (3.25)$$

8) INVP

$$\text{small ring: } C_{invp}^s = (B_o(s) / B_r(s)) * P_{s \rightarrow r} + (B_o(r) / B_r(r)) * P_{r \rightarrow d} \quad (3.26)$$

$$\text{large ring: } C_{invp}^l = B_o(R) / B_r(R) * P_{s \rightarrow R} \quad (3.27)$$

Chapter 4

SIMULATION AND RESULTS ANALYSIS

4.1 Simulation Objectives:

In this chapter we describe a computer simulation study that determines the performance and limitations of the proposed routing strategy. The objectives of the simulation are:

- (1) Determine the expected lifetime of the hybrid Ad-Hoc/Infrastructure networks that comply with the assumptions stated in the next section. The lifetime of the network is defined as the time elapsed until a certain percentage of the mobile terminals die due to battery drainage.
- (2) Determine the relation between the network lifetime and the selection of the reference power, P_{ref} . The reference power is defined as a level of transmitted power $0 < P_{ref} < P_{max}$ that determines the initial search area around the mobile as described in chapter 2.
- (3) A third objective of the simulation study is to compare the performance of our proposed system to other known search strategies. The comparison leads to a conclusion as to under what traffic and system scenarios our proposed system will be a useful technique.

4.2 Simulation Assumptions:

The simulation study presented in this chapter has limited and focused objectives. It does not represent a comprehensive study of the full communication protocols that are normally involved in ad-hoc and/or infrastructure-based communication. The simulation is based on the following assumptions:

- (1) The mobile terminals are identical and each has the same maximum transmission power of 50 mw
- (2) The mobile terminals generate statistically identical traffic. Since we are only interested in the internal and external uplink traffic (i.e. we are interested in the traffic generated by the terminals and not by a fixed network), the traffic is expected to be biased towards few short packets rather than long files.
- (3) Each terminal has two co-center coverage regions: a small circle when the mobile transmits at P_{ref} and a large circle, when the mobile transmits at P_{max} . Either way, we assume that the power received at the edge of the circle is large enough such that the probability of transmission failure is very small.
- (4) In the case of hybrid Ad-Hoc/Infrastructure simulations, we assume that the area is 2 km x 2 km. In the case of ad-hoc only simulations we assume that the area size is 100 m x 100 m
- (5) Mobile terminals dissipate power only while transmitting. Power used for digital signal processing and for route discovery and maintenance functions is neglected.
- (6) Mobile terminals are uniformly distributed in the service (simulation) area. Gateways in a hybrid network are evenly distributed in a network service area.

- (7) We further assume that the probability of not finding either a gateway or the destination within 2 km to be very small.

There are also some implicit assumptions implied by the scenarios represented in this thesis. These assumptions are:

- Since we view the Ad-Hoc sub-network as a relaying mechanism for small terminals located in overlapped areas of powerful base stations, then most of the connections will occur locally and terminals within the small search circle will likely have access to a base station or have access to other terminals that have access to a base station. Packet delivery will then be realized with high probability within few small circle hops. This kind of local transmission (either for route discovery or packet delivery) will result in lower interference throughout the network and some other benefits such as:
  - Implicit frequencies re-use. Two or more terminals could be using the same frequency to communicate over their own small circles without interference if they are sufficiently separated in distance.
  - Probability of transmission failure and re-transmission is very small, when the distance is small and the overall interference is low
  - Low re-transmission probability lowers the overhead traffic as well (e.g. smaller number of acknowledgement packets)

4.3 Basis for Comparison with Other Schemes:

Our proposed scheme introduces a novel concept that does not exist in other competing algorithms; namely, “optimizing the size of local neighborhood based on the mobile and base station densities”. The size is controlled by transmitting at an optimal power level, P_o , where $0 < P_o < P_{\max}$. Our simulation indicates that the choice of P_o has a considerable impact on the network lifetime.

In comparing the performance of our system to others, we first find P_o for the case under consideration, and then proceed to compute how many packets would be transmitted until the network lifetime expires. Then we conduct a simulation for the other scheme and count the number of packets under identical traffic and network conditions.

We define the following parameters:

Average transmission energy per packet: average transmission energy spent by transmitting a packet on the route from source to destination.

Average hops per route: Average number of hop-counts in a route of successful delivery.

To the best of our knowledge, there is little non-position based, localized routing protocol for hybrid network. Therefore in the simulation, we compare our proposed protocol with two well-known non-localized routing schemes: Minimum-Hop and Minimum-Energy. Also, in conventional ad-hoc network model, we compared our

scheme with two more existing GPS based localized protocols; namely: DIR and COSTII.

As we stated in Chapter 1, the Minimum-Hop scheme is a non-localized routing scheme, which aims to choose a route with minimum hop counts by evaluating all the possible routes through flooding the entire network. DSR, AODV (reactive) and DSDV (proactive) are the most famous Minimum-Hop schemes protocols. The difference among them is the method of network flooding which is reflected as the amount of route discovery/maintenance overhead. In the simulation study, we implement Minimum-Hop scheme by applying Dijkstra algorithm. We don't simulate the procedure of how the route discovery messages are communicated through the network. Thus, we don't consider the route discovery/maintenance overhead in the simulation. Therefore, in the simulation, we don't specify a specific protocol of Minimum-Hop scheme. It represents the classical, traditional ad-hoc network routing scheme, which has been widely applied on the ad-hoc networks, and it is interesting and worthwhile to compare it with our scheme.

A power-aware DSR scheme is the scheme derived from DSR. The route discovery procedure of it could be very similar to that of DSR. However, instead of using hop counts as the cost metrics, a power-aware DSR protocol use the link power cost as the cost metric. Therefore, it aims at reducing power consumption of a route and extending node's lifetime. One of the examples of power-aware DSR scheme is to find the route with minimum energy consumption. In this case, it is a Minimum-Energy scheme protocol. In the simulation, we choose Minimum-Energy as a power-aware DSR scheme to compare with our scheme, because they both are power-aware schemes.

Minimum-Energy is also a non-localized scheme. Similar to the way we simulate Minimum-Hop scheme, we implement it by applying Dijkstra algorithm and don't consider the route discovery/maintenance overhead.

The difference between a power-aware DSR scheme and our scheme are:

- A power-aware DSR scheme is a non-localized scheme. By flooding the entire network, it is guaranteed to find the minimum power/energy route, however, that is obtained at the expense of large route discovery/maintenance overhead. In the case of short transmission sessions (such as the scenarios envisaged in this thesis), a large overhead can have a considerable impact on the lifetime of small terminals and disposable sensors. We did not account for overhead in our simulation, so this advantage is not pointed out in our simulation. We do argue, however, that by selecting the right neighborhood size (small circle), we can obtain a power efficient route with high probability and with low overhead. Therefore, for short communication sessions, our scheme has an advantage over the brute force approach supported by the classical minimum energy flooding approach.
- Our scheme is a localized scheme. Route is established based on the local decision within small search radius, therefore no large-scale flooding. Our scheme cannot guarantee to find the minimum cost route, but it saves the energy spent on the flooding and reduces the interference.

The simulation could be conservative since we don't calculate the flooding power consumption of all the schemes simulated. The simulation results show that, network

lifetime of our schemes is close to that of Minimum-Energy (80%) for the selected simulation scenarios. We should also realize that the mechanism of our routing scheme implies high efficiency of reducing interference, which is the problems of non-localized protocol, such as a power-aware DSR protocol.

In the simulation study, we also compare our scheme with two GPS based localized protocols: DIR and COSTII in conventional network models. DIR and COSTII are both reviewed in Chapter 1. Simulation results show that without position assistance, how the proposed scheme performs. Note that, location update and destination search overhead are not considered in the simulation of GPS based protocols.

4.4 Simulation Model and Strategy

In the simulation model, wireless nodes are randomly allocated according to uniform distribution in a network service area. Gateways in a hybrid network are evenly distributed in a network service area. Static model is assumed in the simulation.

4.4.1 Propagation Models and Simulation Parameters Setting

Radio channels are random and extremely unpredictable. This brings fundamental limitations to the performance of wireless communication systems. Therefore a good simulation must take into account the propagation path loss between transmitter and receiver. In the simulation, we consider the large-scale path loss. We assume that small-scale fading can be addressed by diversity technology and other advanced technologies. The large-scale path loss models used in the simulation are two popular models: free space propagation model and lognormal shadowing propagation model [25].

- Free space propagation model

Free space propagation model is used to predict received signal strength when the transmitter and receiver have a clear line-of-sight path between them. The received power in free space model is:

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \quad (4.1)$$

where P_t is the transmission power, $P_r(d)$ is the received power which is the function of transmitter-receiver (T-R) separation distance d , G_t and G_r are respectively the transmitter and receiver antenna gain, L is the system loss factor not

related to propagation ($L \geq 1$), and λ is the wavelength in meters. The path loss for the free space model is given in equation (4.2)

$$PL(d)_{free-space} [dB] = -10 \log \left[\frac{G_t G_r \lambda^2}{(4\pi)^2 d^2} \right] \quad (4.2)$$

- Lognormal shadowing propagation model

Lognormal shadowing propagation model is a statistical model that considers shadowing effect on a radio channel. The random shadowing effect is the fact that the surrounding environment clutter may be vastly different at two different locations having the same T-R distance. Measurements have discovered that the measured signal levels at a specific T-R separation have a Gaussian distribution. The path loss $PL(d)$ at a particular location with T-R distance d is random.

$$PL(d) [dB] = \overline{PL}(d) + X_\sigma \quad (4.3)$$

where $\overline{PL}(d)$ is the mean path loss at T-R distance d , X_σ is a zero-mean Gaussian distributed random variable in dB and the standard deviation σ that describes the shadowing also has unit dB. Both theoretical and measurement-based propagation models shows that average received signal strength decreases logarithmically with distance. The average large-scale path loss $\overline{PL}(d)$ is expressed as:

$$\overline{PL}(d) [dB] = \overline{PL}(d_0) + 10n \log \left(\frac{d}{d_0} \right) \quad (4.4)$$

where n is the path loss exponent, d_0 is the close in reference distance and d is T-R separation distance. In our simulation model, we use two-ray ground reflection model to predict the mean path loss $\overline{PL}(d)$. The two-ray model considers both the direct path and a ground reflection path between transmitter and receiver. This model is found to be more accurate for predicting the large-scale path loss over a long distance (several km) than the free space model. The received power at distance d from the transmitter is given in equation (4.5) and the path loss for two-ray model is expressed in equation (4.6).

$$P_r = P_t G_t G_r \frac{h_t^2 h_r^2}{d^4} \quad (4.5)$$

$$\overline{PL}(d)_{two-ray} [dB] = 40 \log d - (10 \log G_t + 10 \log G_r + 20 \log h_t + 20 \log h_r) \quad (4.6)$$

where P_t is the transmission power, G_t, G_r are the antenna gains of transmitter and receiver respectively and h_t, h_r are respectively the antenna heights of transmitter and receiver. The total path loss using two-ray model to predict the mean path loss and considering shadowing is presented in equation (4.7). In our simulation, we call it **“Two-ray shadowing propagation model”**.

$$PL(d) [dB] = \overline{PL}(d)_{two-ray} [dB] + X_\sigma \quad (4.7)$$

The proposed protocol is simulated in both hybrid ad-hoc/infrastructure networks and conventional ad-hoc networks. Table 4.1 lists the network service area size and propagation models used in the simulation model for hybrid and conventional ad-hoc networks. Other simulation parameters settings are shown in Table 4.2.

	Service area size	Propagation model
Hybrid ad-hoc network	2Km * 2Km	Two-ray shadowing model
Conventional ad-hoc network	100m * 100m	Free space model

Table 4.1 Service area size and propagation models

Wireless node antenna gain	6dB
Wireless node antenna height	2m
Gateway antenna gain	6dB
Gateway antenna height	30m
RF channel carrier frequency	1.9GHz
Required E_b / N_0	10dB
Standard deviation σ of shadowing Gaussian random variable X_σ	$\sqrt{6}$ dB

Table 4.2 Simulation parameters

4.4.2 Simulation Strategy

The simulation code is written in C++. The simulation is run individually for each different network graph (model). A simulation run contains several simulation cycles. In each simulation cycle, a reference power level P_{ref} for small ring search is set. Traffic is sent from a randomly selected wireless source to the destination. In the internal traffic case, the destination is also a randomly selected wireless node, while in the external traffic case, the destination is one of the gateways. Packets are routed one by one from a randomly selected living source to a destination until 50% of the wireless nodes are dead. A node is said to be dead when its battery is depleted. Data are collected from the average of 100 repetitions of the simulation cycle.

In each simulation run, reference power P_{ref} is set as a simulation parameter from -40dBm to 10dBm in a conventional network simulation, and from -24dBm to 16dBm in a hybrid network case. The purpose of setting different reference power levels is to evaluate the impact of reference power on the proposed routing protocol performance.

4.5 Results and Performance Evaluation

Each of the eight proposed cost metrics is applied to the proposed routing protocol individually. Their performances are evaluated to provide comparison. It is also compared with the two existing non-localized shortest weighted path schemes: Minimum hop count (Min-Hop), Minimum transmission energy (Min-Eng), and two GPS-based localized routing protocols: DIR, COSTII.

Min-Hop and Min-Eng are implemented by applying Dijkstra algorithm. When they are applied to the hybrid network, the cost from gateways to any node is 1 in Min-Hop and 0 in Min-Eng. That is because the gateways are assumed to have a stable, infinite power supply. Unlike battery-operated devices, the gateways have no cost to relay a packet in Min-Eng algorithm. Also as described in Chapter 2, we have assumed that each wireless node can be reached by at least one gateway in the hybrid network directly in downlink, therefore, in Min-Hop algorithm, the cost from gateways to any nodes is 1 (one hop). Min-Eng algorithm requires that Tx power of each node is NOT the same and fixed, it is adjustable. Otherwise it is not different from Min-Hop.

DIR and COSTII are discussed in Chapter 1. DIR and COSTII are only simulated to compare with the proposed routing protocol in conventional ad-hoc networks. Compass routing DIR is a localized protocol based on direction [20]. DIR doesn't require nodes to memorize the passing traffic/nodes unless they can be carried in its small local memory. In the DIR simulation, we assume a node knows only the previous node ID where the packet comes from, to therefore prevent the node from sending the packet

back to the previous node. COSTII is proposed in [19]. The main idea of COSTII is to find the lowest cost route. The cost of a route from S to D via neighbor A is the sum of the battery cost of node A and the estimated cost of the route from A to D. The second term in equation (4.8) is the estimated cost part.

$$Cost(A) = f(A) + f(A) * d / r \quad (4.8)$$

$$f(A) = B_o(A) / B_r(A), \quad d = |AD|, \quad r : Tx \text{ radius}$$

where $f(A)$ is the battery cost of node A, $B_o(A)$ and $B_r(A)$ are the initial and remaining battery capacity of node A, d is the distance from node A to destination and r is the node's transmission radius. Note that in DIR, COSTII simulation, nodes are supposed to transmit data packets by using the exactly required transmission power.

4.5.1 Network Lifetime of Hybrid Ad-Hoc Networks

We simulated the hybrid networks with 70 wireless nodes and with one, two, and four gateways respectively. The simulation sets the percentage of external network traffic to zero. The impact of external traffic rate on the network lifetime will be shown and discussed in the next section. Figure 4.1, Figure 4.2, and Figure 4.3 show respectively the network lifetime of the hybrid network with 70 wireless nodes and with one, two, and four gateways. The network lifetime is shown in each of the figures as the function of reference power P_{ref} . Network lifetime is evaluated by the first node dead time and 20% nodes dead time separately. They are shown in the two diagrams (a) & (b) in Figure 4.1 ~ 4.3.

Reference power P_{ref} is the small ring search transmission power in the proposed routing protocol. Performances of Min-Hop and Min-Eng are not related to the reference power P_{ref} , therefore they are the fixed values as shown in the box in each of the figures. The eight curves in each of the figures represent the performance of eight cost metrics – LPE, LBLN, INVA, INVP, COSA, COSP, SIGA, and SIGP. They show the same pattern that there exists an optimal reference power P_o at which the network lifetime can be extended the most. Too small P_{ref} causes low node degree in the small ring neighborhood, which leads to frequent large ring searches. Degree of a node is the number of neighbors of a node. Detoured, less cost-effective routes may be discovered with small P_{ref} , which shorten the network lifetime. Routes discovered by large P_{ref} tend to a direct transmission. Thus the performances of eight curves are close when P_{ref} is large. Apparently the network lifetime is shortened with large P_{ref} .

(a) First node dead time

(b) 20% nodes dead time

Figure 4.1 Network lifetime: 70 wireless nodes, 1 gateway, 0% external traffic

(a) First node dead time

(b) 20% nodes dead time

Figure 4.2 Network lifetime: 70 wireless nodes, 2 gateways, 0% external traffic

(a) first node dead time

(c) 20% nodes dead time

Figure 4.3 Network lifetime: 70 wireless nodes, 4 gateways, 0% external traffic

(a) first node dead time: 40 wireless nodes, 2 gateways

(b) first node dead time: 100 wireless nodes, 2 gateways

Figure 4.4 Network lifetime: 2 gateways and different number of wireless nodes

As shown in Figure 4.1, Figure 4.2 and Figure 4.3, optimal reference power P_o is smaller in a gateway dense network. For example, in Figure 4.1 (b), Figure 4.2 (b) and Figure 4.3 (b), when the network lifetime is evaluated as 20% nodes dead time, P_o is -6dBm when there is one gateway in the network, -8dBm when there are two gateways and -14dBm when there are four gateways. Because in both the internal and external traffic case, gateways can be the destination of the traffic, it implies that in gateway-dense networks, the destination can be found with higher probability in the sender's small ring search radius than it can be in a gateway sparse network. Therefore P_o is smaller in gateway dense networks. Also, in the same hybrid network model, optimal reference power P_o is different when the network lifetime definition is different. We can see the difference by comparing diagram (a) and (b) in Figure 4.1 ~ 4.3.

If we take a look at Figure 4.2 (a), Figure 4.4 (a) & (b), the three simulated hybrid networks each have 2 gateways, but different number of wireless nodes. The optimal reference power P_o is almost the same in these three cases, which indicates that P_o is less sensitive to the number of wireless nodes in the hybrid networks.

Since gateways can relay packets without cost, hybrid networks with more gateways consume less cost to send a packet. Therefore, for all the algorithms except Min-Hop, the network lifetime of a gateway-dense network is longer than that of a gateway-sparse network. It can be obviously observed from the above figures.

If we observe the network lifetime at P_o , cost metrics that consider both Tx power and remaining battery capacity -- SIGA, SIGP, COSA, COSP, INVA, INVP-- present competitive performance in comparison to the others. LBLN is shown to provide

the worst performance, as it only considers node battery reserves. Simulation results show that SIGP provides the longest lifetime in a gateway-dense network where the network lifetime is defined as 20% of nodes dead time (See Figure 4.2, Figure 4.3).

Compared with Min-Hop in a hybrid network model, our proposed protocol shows dramatic performance improvement in terms of network lifetime. Min-Hop algorithm tries to find the minimum hop route, therefore it is less sensitive to the gateway density in the network (we suppose there are far fewer gateways than the wireless nodes in the hybrid network). However, gateway density has great impact on the performance of the proposed protocol. The performance improvement to Min-Hop is more prominent in gateway-dense network. Also, the network lifetime at optimal reference power P_o of each curve reaches approximately 80% of that of Min-Eng.

4.5.2 Network Lifetime vs External Traffic Rate in Hybrid Ad-Hoc Networks

External traffic rate is the percentage of external traffic of the total traffic. Figure 4.5 (a) shows how the network lifetime is impacted by the external traffic rate for a gateway-sparse network with 70 wireless nodes and 1 gateway. Figure 4.5 (b) shows the case for a gateway-dense network with 70 wireless nodes and 4 gateways. Network lifetime in Figure 4.5 is 50% of nodes dead time.

It can be observed from Figure 4.5 (a) that in the network with low gateway density, network lifetime is reduced when the external traffic rate increases. Unlike external traffic, internal traffic can be routed through several wireless nodes or through a gateway to the destination, whichever involves less cost. It is more flexible and cost effective to find an optimal route than it is in the external traffic case. The increase of internal traffic rate (decrease of external traffic rate) increases the routing flexibility, therefore prolongs the network lifetime. However, it is only apparent in gateway-sparse networks. As we observe from Figure 4.5 (b), the impact of the external traffic rate on the network lifetime in a gateway-dense network is small. This is because, in a gateway-dense network with N gateways, internal traffic is considered as a sender sending packets to one of the $N+1$ destinations, whichever costs less. More gateways (larger N) result in a large possibility that the optimal route finally reaches a gateway as in external traffic case. Therefore, the network lifetime is not sensitive to the external traffic rate in a gateway-dense network.

Figure 4.5 Network lifetime vs external traffic rate

4.5.3 Network Lifetime of Conventional Ad-Hoc Networks

Figure 4.6, Figure 4.7, and Figure 4.8 show the network lifetime versus reference power P_{ref} of the conventional ad-hoc network with 20, 30, and 50 wireless nodes respectively. Diagram (a) and (b) in each figure respectively shows the first node dead time and 20% nodes dead time.

The pattern of the curves is similar to that of hybrid networks, which is shown in Figure 4.1 ~ 4.3. There exists an optimal reference power P_o at each curve in each figure. The network lifetime of Min-Hop and Min-Eng algorithms is not related to P_{ref} , therefore they are the fixed value as shown in the box in each of the figures.

Optimal reference power P_o is smaller in a dense network. As we can observe from Figure 4.6 (b), 4.7 (b), and 4.8 (b), P_o is -20dBm when there are 50 nodes in the network and it is -18dBm when there are 20 and 30 nodes in the network. Optimal performance happens when the optimal reference power P_o is used as the small ring search power. It can be further interpreted as the maximal network lifetime is achieved when the average node degree in a small ring neighborhood reaches an optimal level. Degree of a node (the number of neighbors of a node) is determined by the P_{ref} . Large P_{ref} results in large node degree and vice versa. To keep the optimal node degree level in different network models, optimal reference power P_o must be adjusted to be large when the node density is low and to be small when the node density is high.

(a) first node dead time

(b) 20% nodes dead time

Figure 4.6 Conventional Ad-Hoc network lifetime: 20 wireless nodes

(a) first node dead time

(b) 20% nodes dead time

Figure 4.7 Conventional Ad-Hoc network lifetime: 30 wireless nodes

(a) first node dead time

(b) 20% nodes dead time

Figure 4.8 Conventional Ad-Hoc network lifetime: 50 wireless nodes

Figure 4.6, Figure 4.7, and Figure 4.8 also show that dense networks have longer network lifetime. This is because in dense networks, there are more candidate routes for a specific source-destination pair. The route picked is more optimal and may involve more relay nodes than in sparse networks.

If we observe the network lifetime at P_o , except SIGP, other cost metrics combining transmission power and remaining battery reserve --COSA, COSP, SIGA, INVA, and INVP-- typically outperform LPE and LBLN at the most of time. What's more, SIGA, INVA, and INVP present better performance than the other cost metrics in sparse networks (Figure 4.6, 4.7). COSP shows competitive performance in dense networks (Figure 4.8).

All the proposed cost metrics present much better performance than Min-Hop at optimal reference power P_o . Except LPE and SIGP, network lifetime of other curves at P_o reaches approximately 80% of lifetime of Min-Eng.

4.5.4 Network Lifetime Comparison with Two GPS-based Localized Routing Protocols in Conventional Ad-Hoc Networks

Our proposed protocol is compared with two existing GPS-based localized routing protocols: DIR and COSTII. DIR and COSTII have low probability of packet delivery in sparse networks or in the case when the average node degree is low, which results from a small transmission radius [18 ~20]. However, in the proposed protocol, the probability of packet drop is small and we assume that all packets are received by the destination.

In order to compare them on a fair basis, P_{ref} of the proposed protocol is set to the level that when it applies to DIR, COSTII as the route discovery transmission power, the probability of packet delivery of DIR and COSTII should exceed 85%. The route discovery transmission power of DIR and COSTII is the node transmission power that is used by a node to discover its neighbors. The optimal relay node is selected from the neighbors, and packets are transmitted using the actual transmission power required. Figure 4.9 ~ 4.11 show DIR, COSTII's probability of packet delivery versus route discovery transmission power. It can be observed from Figure 4.9 ~ 4.11 that in order to have the probability of packet delivery of DIR and COSTII exceed 85%, the routing discovery transmission power should be equal to or greater than -14dBm when there are 20 wireless nodes in the network and -16dBm when there are 30, 50 wireless nodes in the network. Therefore P_{ref} of the proposed protocol is set to -14dBm , -16dBm and

probability of packet delivery vs reference power (100m, 20, 0 GW, $B_0=0.5$)

Figure 4.9 Probability of packet delivery of DIR and COSTII – 20 wireless nodes

probability of packet delivery vs reference power (100m,30, 0 GW, $B_0=0.5$)

Figure 4.10 Probability of packet delivery of DIR and COSTII – 30 wireless nodes

probability of packet delivery vs reference power (100m, 50, 0 GW, Bo=0.5)

Figure 4.11 Probability of packet delivery of DIR and COSTII – 50 wireless nodes

nodes / GWs / Pref (dBm)	first node dead time			20% of nodes dead time		
	20/0/-14	30/0/-16	50/0/-16	20/0/-14	30/0/-16	50/0/-16
LPE	207.32	292.68	453.46	324.96	518.14	897.44
LBLN	256.76	420.5	744.88	349.46	589.48	1057.80
INVA	287.98	438.34	799.02	375.12	611.02	1121.80
INVP	286.84	445.25	817.42	373.7	605.72	1112.40
COSA	272.58	421.82	763.84	359.36	599.5	1074.10
COSP	271.68	424.2	760.28	360.14	592.16	1063.20
SIGA	261.34	487.8	786.3	359.34	629.27	1068.10
SIGP	215.04	330.75	470.82	332.22	563.06	923.80
COSTII	225.44	494.36	871.4	336.06	710.44	1212.80
DIR	225.3	305.78	525.22	323.14	506.18	929.32

Table 4.3 Lifetime comparison with DIR and COSTII

-16dBm for the case when there are 20, 30 and 50 wireless nodes respectively in the network. This is the base of the comparison. The network lifetime comparison result is summarized in Table 4.3. Except LPE and SIGP, cost metrics of the proposed routing protocols have longer network lifetime than DIR. The performance of INVA, INVP, COSA, COSP, and SIGA approach that of COSTII. INVA, INVP and SIGA are the best of the proposed cost metrics for our protocol in the scenario set for the comparison.

We can infer from the above observation and discussion that without the requirement of GPS devices and other positioning techniques, our proposed localized routing protocol is better than the GPS based localized protocol DIR in terms of network lifetime, and the network lifetime is close to that of COSTII. Note that we do not consider the control overhead on the location update and destination search in DIR, COSTII simulation.

4.5.5 Other Performances

In this section, performance measures other than network lifetime are presented. They are the total transmission power per packet (P_T) and the average number of hops per route. A route with more intermediate relay nodes (more hops) is likely to result in longer end-to-end delay. However, since in our study, we mainly focus on small networks, delay is not an important issue. The simulation results of average transmission energy per packet P_T and average number of hops per route are shown in Table 4.4 for hybrid networks.

	Average Transmission energy per packet (P_T)			Average hops per route		
	70/4/-14	70/2/-8	70/1/-6	70/4/-14	70/2/-8	70/1/-6
nodes / GWs / Po						
LPE	1.8457E-05	9.6548E-05	3.0101E-04	2.02	2.06	2.17
LBLN	1.6673E-05	8.6778E-05	2.5834E-04	2.02	2.06	2.16
INVA	1.6690E-05	8.5105E-05	2.4561E-04	2.02	2.06	2.17
INVP	1.6651E-05	8.3181E-05	2.3633E-04	2.02	2.06	2.17
COSA	1.6758E-05	8.5492E-05	2.4785E-04	2.02	2.06	2.17
COSP	1.6614E-05	8.3858E-05	2.4539E-04	2.02	2.06	2.17
SIGA	1.6755E-05	7.8650E-05	2.3715E-04	2.02	2.05	2.17
SIGP	1.6632E-05	7.6732E-05	2.3446E-04	2.02	2.06	2.17
Min-Eng	1.6126E-05	7.4728E-05	2.1312E-04	2.14	2.34	2.65
Min-Hop	1.8300E-02	1.8700E-02	1.7800E-02	1.58	1.57	1.58

Table 4.4 Hybrid network: Total transmission power per route, total hops per route

Table 4.5 shows the simulation results for conventional ad-hoc networks. For the proposed protocol, data in Table 4.4 and 4.5 are the simulation results when optimal reference power P_o is applied to each network simulated.

In both the hybrid Ad-Hoc/Infrastructure and pure Ad-Hoc networks, Min-Eng is shown to be the most power efficient protocol with smallest P_T , but average hops per route of Min-Eng is the largest among all the simulated protocols. The performance of Min-Hop is the worst in terms of power efficiency. The P_T of the Min-Hop protocol is much larger than P_T of other protocols. The difference is extremely dramatic in hybrid network. However, the average number of hops per route are minimized in Min-Hop.

Performance of the proposed protocol, which is displayed by eight variations representing eight cost metrics, is promising and competitive comparing with Min-Eng. As we can observe from Table 4.4 and 4.5, P_T of the proposed protocol with each cost metric is close to the P_T of Min-Eng. Moreover, the average number of hops per route of the proposed protocol is less than that of the Min-Eng method, which implies shorter end-to-end delay. It should be stressed, however, that since we are focusing on relatively small networks, the issue of delay is not very important.

	Average Transmission energy per packet (P_T)			Average hops per route		
	nodes / GWs / Po	20/0/-18	30/0/-18	50/0/-20	20/0/-18	30/0/-18
LPE	3.3322E-05	3.3637E-05	3.0484E-05	1.82	1.96	2.61
LBLN	1.9549E-05	1.9432E-05	1.4846E-05	1.65	1.71	2.01
INVA	1.9313E-05	1.8710E-05	1.4995E-05	1.65	1.72	2.03
INVP	1.7227E-05	1.4658E-05	1.3440E-05	1.80	1.90	2.59
COSA	1.9538E-05	1.8964E-05	1.5205E-05	1.66	1.71	2.03
COSP	1.7559E-05	1.5022E-05	1.3340E-05	1.80	1.91	2.57
SIGA	1.9524E-05	1.8267E-05	2.3334E-05	1.69	1.72	2.07
SIGP	1.7648E-05	1.4696E-05	1.5706E-05	1.81	1.93	2.59
Min-Eng	1.7094E-05	1.3779E-05	1.2115E-05	3.44	4.28	5.76
Min-Hop	4.3516E-05	4.5385E-05	4.6098E-05	1.00	1.00	1.00

Table 4.5 Conventional network: Total transmission power per route, total hops per route

Among the eight cost metrics, in hybrid networks, SIGP exhibits to be the best to reduce packet transmission energy (See Table 4.4). Table 4.4 and 4.5 also show that cost metrics LPE and LBLN which only consider transmission energy or remaining battery capacity of a node, are less competitive.

In the proposed scheme, packet drop happens when destination and/or gateway cannot be found within the sender's large ring two-hop neighborhood and all the nodes in senders large ring one hop neighbor list cannot reach any nodes in their large ring one-

hop neighborhood. (See case d in page 34). Since we have assumed that the majority of terminals can reach one gateway within two big hops at maximum transmission power, packet drop is rarely happen under this assumption. However, packet drop is more likely to happen in lower density networks with fewer gateways and wireless nodes, where a wireless node may be more than two big hops away from the closest gateway.

Here, we investigate the probability of packet delivery. In the following hybrid network simulation, we report the results as a function of the ratio D/d , where D is the interval between two adjacent gateways and d is the maximum transmission radius of a wireless node. In the case where there is only one base station, we assume that the service area of interest ($'m' \times 'm'$ sq. km) is served by a single base station, located in the middle, and that that base station reaches every mobile terminal (in the downlink direction). We further assume that the next service area is identical to the area of interest, such that the station to station distance equal " m ". We have assumed that gateways are evenly distributed in network service area. (See Figure 4.12a). D/d reflects the density of gateways in the network. A large D/d ratio corresponds to the scenario with lower gateway density and a small D/d ratio corresponds to the scenario with higher gateway density. A is the maximal distance between a wireless node and the closest gateway to it. A/d is the maximal number of big hops between a wireless nodes and the closest gateway to it. Therefore, in such a network, all the wireless nodes can reach a gateway within A/d big hops. We can deduct from Figure 4.12a that $A/d = (\sqrt{2}/2)(D/d)$.

In the simulation scenarios in the previous sections, the service area of hybrid networks is a square area $2\text{Km} \times 2\text{Km}$ with 70 wireless nodes and respectively 1, 2 and 4

Figure 4.12 D/d, A/d definition in hybrid networks

gateways.

Packet drop is more likely to happen in the networks with higher D/d ratio and lower wireless node density. In order to compare with the results of previous simulation scenarios, we keep the wireless nodes density as 70 nodes per $2\text{Km} \times 2\text{Km}$ area and investigate the probability of packet delivery with larger D/d ratios. We choose the case where $D/d = 2.8$ ($A/d = 2$) and $D/d = 8.5$ ($A/d = 6$), in which the wireless nodes can reach a gateway within respectively 2 and 6 big hops. Figure 4.13 shows that the probability of packet delivery is 1 when $D/d = 2.8$ ($A/d = 2$) and Figure 4.14 shows that probability of packet delivery drops when D/d increases.

Probability of packet delivery vs reference power ($D/d=2.8, A/d=2, 70/2\text{Km} \times 2\text{Km}$)

Figure 4.13 Probability of packet delivery: $D/d=2.8, A/d=2, 70/2\text{Km} \times 2\text{Km}$

Probability of packet delivery vs reference power ($D/d=8.5, A/d=6, 70/2\text{Km} \times 2\text{Km}$)

Figure 4.14 Probability of packet delivery: $D/d=8.5, A/d=6, 70/2\text{Km} \times 2\text{Km}$

Probability of packet delivery vs reference power ($D/d=2.8, A/d=2, 10/2\text{km} \times 2\text{km}$)

Figure 4.15 Probability of packet delivery: $D/d=2.8, A/d=2, 10/2\text{Km} \times 2\text{Km}$

Probability of packet delivery vs reference power ($D/d=8.5, A/d=6, 10/2\text{km} \times 2\text{km}$)

Figure 4.16 Probability of packet delivery: $D/d=8.5, A/d=6, 10/2\text{Km} \times 2\text{Km}$

Probability of packet delivery is also related to the wireless node density. Figure 4.15 and 4.16 show the probability of packet delivery of the hybrid network with the same D/d ratios: 2.8 and 8.5, but the with lower wireless node density of 10 nodes per $2\text{Km} \times 2\text{Km}$ area. Simulation results show that when $D/d = 2.8$ ($A/d = 2$), the probability is still as high as 1. However, the probability of packet delivery drops in the networks with lower wireless node density when D/d ratio is 8.5 ($A/d = 6$).

In the simulation study of this thesis, the service area of a conventional ad-hoc network is a square as shown in Figure 4.17. Diag represents the length of the diagonal of the square and it is the maximal distance between two nodes. Diag/d is the maximal number of big hops between a source and destination node in the service area. Therefore, in such a network, a source can reach a destination within Diag/d big hops.

Figure 4.17 Conventional network service area

As we declared in the beginning of this thesis, proposed scheme fits well for the small size conventional ad-hoc networks without gateways. In the simulation scenarios in section 4.5.3, we respectively simulate the scenarios of 20, 30 and 50 nodes in a

network service area $100\text{m} \times 100\text{m}$. In these scenarios, $\text{Diag}/d < 1$ and simulation results show that the probabilities of packet delivery are 1.

Here we further investigate the probability of packet delivery of larger conventional networks with larger Diag/d ratio. We report the results as the function of ratio Diag/d . We choose the cases where $\text{Diag}/d = 2$ and $\text{Diag}/d = 6$, in which a source node can reach a destination node within respectively 2 and 6 big hops. We set the node density to 70 nodes per $2\text{Km} \times 2\text{Km}$ area (same wireless node density as we set in hybrid network simulation). The results are shown in Figure 4.18 and 4.19. We can observe that when $\text{Diag}/d = 2$, the probability is almost 1 and the probability decreases when Diag/d ratio increases to 6.

Figure 4.18 Probability of packet delivery: $\text{Diag}/d = 2$

Figure 4.19 Probability of packet delivery: Diag/d = 6

4.6 Summary and Discussion

Chapter 4 explains the simulation model, assumptions and the simulation strategy. Simulation results of the proposed routing protocol and comparison with other existing routing protocols are presented. The evaluated performances include network lifetime,

average transmission energy per packet and average hops per route. The major points are summarized as below:

- There exists an optimal reference power P_o for small ring searches in each hybrid or conventional ad-hoc network. The network lifetime is extended the most at P_o . P_o is inversely proportional to the density of gateways and wireless nodes in the network. The density of wireless nodes has less impact on P_o in hybrid networks.
- The network with more gateways and/or more wireless nodes has longer network lifetime.
- In hybrid gateway-sparse networks, network lifetime is reduced when the external traffic rate increases.
- Compared with non-localized routing schemes Min-Hop and Min-Eng, the proposed routing protocol exhibits huge performance improvement to Min-Hop and its performance is close to that of Min-Eng.
- The proposed localized routing protocol is better than the GPS based localized protocol DIR in terms of network lifetime, and its network lifetime is close to that of COSTII.
- Among all the cost metrics introduced to the proposed routing protocol, cost metrics INVA, INVP, COSA, COSP, SIGA, and SIGP, which combine the transmission power and remaining battery capacity, typically outperform cost metrics LPE and LBLN, which only consider one of them.

- In gateway-dense hybrid networks, normalized combined cost metric SIGP is shown to be the one with longest network lifetime (20% nodes dead time).

Since optimal reference power P_o is a crucial parameter to achieve optimal performance, properly setting node's small ring transmission power to P_o is very important to prolong the network lifetime. As we already deduced from simulation results analysis, P_o is related to density of both gateway and wireless node. Therefore a good estimation of the gateway and node densities of the network and accurate P_o setting according to the estimations are critical to the network performance. It could be a limitation of the proposed non-position based localized routing protocol. In addition, optimal performance may not be seen in extremely sparse networks since P_o might be too large to be within a node's maximum transmission range.

Chapter 5

CONCLUSION AND FUTURE WORK

5.1 Conclusion

This section summarizes the work presented in this study, which proposes a non-position based loop-free, localized routing protocol for hybrid and conventional ad-hoc networks. It can minimize the route discovery/maintenance overhead greatly in comparison with other non-localized and position-based localized protocols, and can effectively prolong the network lifetime.

This thesis begins with a brief introduction of traditional isolated ad-hoc networks and hybrid ad-hoc/infrastructure networks in chapter 1. Also, in this chapter, the issues of ad-hoc network routing are discussed. The existing non-localized and position-based localized ad-hoc network routing protocols are reviewed and their advantages and disadvantages are summarized.

Chapter 2 provides the detailed description of the proposed routing algorithm. This includes the explanation of the traffic model and route discovery mechanisms of the proposed routing protocol.

In chapter 3, we propose eight cost metrics for the proposed routing protocol. They respectively consider node transmission power, node remaining battery capacity, or combine both of those factors into consideration. Among combined cost metrics,

normalized cost metrics that balance the influences of transmission power and battery reserve on route selection are proposed.

Computer simulation is done to evaluate the performance of the proposed routing protocol and to compare it with some existing ad-hoc routing protocols. The simulation does not consider the route discovery/maintenance overhead for all the protocols simulated. In chapter 4, the simulation assumptions, model and how the simulation works are explained. The obtained simulation results are presented and discussed in this chapter.

The proposed protocol demonstrates excellent performance in comparison with some existing schemes and protocols in the scenarios this thesis discuss. The evaluated performances include network lifetime, average total transmission power per packet, and average hops per route. Cost metrics, especially normalized ones that consider both transmission power and battery reserve, are proven to present better performance than the ones that only rely on one of those two factors. An optimal reference power P_o exists for each network model. To adjust a node's small ring transmission power to the optimal level is the key to achieve optimal performance.

5.2 Future Work

The proposed scheme has many inherent advantages that could not be fully demonstrated in this thesis. It is a replacement to total flooding algorithms. While network flooding and examining every possible combination of hops would obviously discover the optimal route, yet, the cost could be very high for small sensors and very low power devices. This is particularly true in networks where sensors are required to transmit short bursts of data and need to relay such data to a gateway through other devices. The proposed scheme can discover a near optimum route without flooding. The self-imposed limitation of the transmitted power, would emulate micro-cellular radio coverage. The full benefits of such scheme can be displayed by conducting more in depth study that accounts for interference, packet error rate, re-transmission overhead and any all sources of power loss. A detailed study of the physical layer of the proposed scheme compared to other schemes such as Min-Eng DSR is highly recommended. Such a study will further illustrate the benefits of the proposed scheme. It is also recommended that any future continuation of this work should be conducted on a wide range of data traffic in order to identify the type of traffic where the proposed scheme is most beneficial.

Other recommendations for future work include:

- The optimization of the simulation to involve control overhead. A More accurate and real-life simulator is required to further evaluate the performance and efficiency of the proposed routing protocol.

- Accurate estimation of optimal reference power P_o .
- More work is required to search for high performance non-position based, localized routing protocols. The research in this area is far from over.

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