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1.1 INTRODUCTION

Wireless networks are increasingly deployed with the availability of inexpensive wireless network devices [blu, , Stemm et al., 1996]. These networks are power constrained since nodes operate with limited battery power. Therefore, there has been an increased interest in energy efficient communication protocols.

This chapter gives a background on current research for energy efficient media access control (MAC) and routing protocols. This chapter is divided into two sections: Section 1.3-Energy Efficient MAC Protocols and Section 1.4-Energy Efficient Routing Protocols.

Four MAC protocols are discussed in Section 1.3. Section 1.3.1 discusses the 802.11 protocol. Section 1.3.2 discusses the EC-MAC protocol. Section 1.3.3 discusses the PAMAS protocol. Finally, Section 1.3.4 discusses the Wave and Wait Protocol.

Six routing protocols are discussed in Section 1.4. Section 1.4.1 gives a an analysis of the energy consumption of routing protocols. Section 1.4.2 discusses power aware routing in mobile ad hoc networks. Section 1.4.3 discusses localized power, cost and power-cost efficient routing algorithms. Section 1.4.4 discusses routing techniques used in Personal Area Networks (PANs) based on power related optimization and device information. Section 1.4.5 discusses routing techniques based on balancing nodes' battery reserves in order to maximize the lifetime of the network. Section 1.4.6 discusses using topology control to maximize the lifetime of the network.

Finally, a summary concludes this chapter.

1.2 BACKGROUND

In order to understand the basis of the MAC and routing protocols, a brief background is given.

The MAC and routing protocols discussed in this chapter are used for different types of networks and topologies. These topologies can be static or dynamic. Some protocols are used for infra-structure based networks while others are used for ad hoc and sensor networks.

$Infra - structure\ based\ networks$: Infra-structure based networks extend wired networks. Wired networks are used as the backbone network which connect to base stations (special switching nodes).

$Ad\ hoc\ networks$: Ad hoc networks consist of radio-equipped nodes such as sensor nodes, laptops, and (Personal Digital Assistant) PDAs which communicate with each other without a central authority. All nodes are randomly deployed in the field and cooperate to maintain connectivity. These devices can be at a fixed location, or they can be mobile. These networks are typically used in military situations or for situation awareness.

$Sensor\ networks$: Sensor networks consist of inexpensive sensor nodes which are deployed for data collection from the field. Typical scenarios where sensor networks are useful are military surveillance, building security, and harsh physical environments [Estrin et al., 1999, Kulik et al., 1999, WIN,]. These sensor nodes collect audio, seismic, and other types of data and collaborate to perform a high level task in sensor web. These nodes are deployed in an ad hoc manner.

The path loss is considered when measuring energy consumption. The path loss represents signal attenuation which is measured in dB [Rappaport, 1996]. It is the difference between effective transmitted power and the received power. The protocols will consider freespace and/or urban scenarios. A freespace scenario occurs when there is little or no obstruction. An urban scenario occurs when there is some obstruction.

1.3 ENERGY EFFICIENT MAC PROTOCOLS

1.3.1 802.11

1.3.2 EC-MAC

1.3.3 PAMAS

1.3.4 Wave and Wait Protocol

[Tsaoussidis et al., 1999] provides an experimental transport-level protocol running on top of IP for small, mobile, wireless stations. The goal of this experimental protocol is conserve battery power for transmissions. The protocol does this by adjusting the amount of data transmitted, trying to keep it below perceived network congestion. Therefore, the need for duplicate data retransmissions is reduced. The outline for the protocol specification, mechanisms and implementation, and the preliminary evaluation results are presented which show the energy- savings capabilities of the protocol. No graphs or tables are presented in this paper.

1.4 ENERGY EFFICIENT ROUTING PROTOCOLS

1.4.1 Energy Analysis of AODV and DSR

[Feeney, 2001] presents a model for evaluating energy consumption behavior of mobile ad hoc networks. This model is used to examine two well known routing protocols: (Ad hoc On-Demand Distance Vector) AODV and (Dynamic Source Routing) DSR. A modified version of the CMU Monarch Project's mobility-enhanced ns-2 simulator was used along with the model to analyze the energy consumption of the routing protocols.

Specific observations were found about these protocols. Route discovery is expensive for both of these protocols (particularly for AODV). Source routing headers have some noticeable cost for DSR. When the network is operating in promiscuous -at zero bandwidth cost- mode, it is very costly. Also, in an ad hoc environment, link-layer costs can be extremely costly.

The two protocols have some similarities. They are both on-demand protocols which means they discover and maintain routes only when needed. All nodes participate equally in the routing process.

These two protocols differ in that AODV is destination-oriented based on the Bellman-Ford algorithm. It uses a distance vector routing information. DSR is a topology-oriented source routing protocol that uses aggressive caching of network wide topology information. More details on how these protocols work can be found in [Feeney, 2001, Broch et al., 1998].

Energy consumption can be divided into four possible state:

- transmitting data

- receiving data
- idle mode, where the interface can transmit or receive
- sleep mode, which uses the least power and can only transmit or receive when woken up

In an ad hoc network, the default state is idle since nodes do not know when they will receive messages. Several cost equations are presented in [Feeney, 2001]. In general the cost equation which represents the cost for send and receive is as follows:

$$cost = m * size + b \tag{1.1}$$

A fixed cost is assigned for channel acquisition and for incremental cost proportional to the size of the packet. Another cost equation is presented for broadcast traffic, where the sender listens briefly to the channel, and if it is clear sends data to all nodes. Otherwise, if it is not clear, the sender waits. Fixed channel access costs and incremental payload costs combined in the previous equation results in a new cost equation. For point-to-point traffic, the fixed cost includes channel access and the MAC negotiation. The incremental payloads are the same as the broadcast traffic. Nodes which discard traffic consume energy which is dependent on the MAC implementation. Two equations are provided: one for non-destination nodes and another for non-destination nodes operating at in promiscuous mode. The Lucent WaveLAN IEEE 802.11 PC card uses the strategy where based on the information size in the control message non-destination nodes in range of the sender enters a reduced energy consumption mode while data is being transmitted. Nodes in range of the destination node only just discard the destination side of the MAC protocol.

Some concerns of protocol designers are addressed. One is that receiving is a high cost. If a broadcast message is received by approximately four neighbors, then the total cost of receiving the message is more than the cost to send it. Second, the fixed cost of sending or receiving a packet is large compared to the incremental cost. The fixed cost is greater than the incremental cost of sending or receiving for small packets. Source router headers are quite inexpensive in terms of energy consumption. Third, discarding a packet usually consumes a lot less energy than receiving it. Finally, the cost of broadcast traffic is dominated at receiving while point-to-point traffic has higher send/receive costs than broadcast traffic, but it allows non-destination nodes to discard traffic. If discarding costs are high, then point-to-point traffic's advantage is collision avoidance and data acknowledgement. However, there are some substantial energy savings if discarding costs are low.

A table is provided in [Feeney, 2001] to show the send/receive costs for the Lucent IEEE 802.11 WaveLAN PC card.

For the simulations, transmit and receive characteristics were based on specifications for the Lucent WaveLAN 2.4 GHz DSSS IEEE 802.11 PC card. The transmission range is 400 meters, and 50 mobile nodes were used for a 2400m x 480m network for 900 seconds of simulation time. The node density used was 10.9 nodes per 400m radius.

Each node waits a certain amount of time and then moves to a random destination at a constant velocity in the range of 0m/s to 32m/s, then the node waits again. The networks used were in the range of mobile to static. 20 source- destination pairs were chosen. Four 64-byte IP packets/sec were sent to the destination.

DSR-np is also presented in the results. This is a variant of DSR that does not include eavesdropping.

[Feeney, 2001] shows that although DSR is usually the most efficient in terms of bandwidth utilization, it is less efficient than AODV and DSR-np due to eavesdropping.

Broadcast traffic is used in all three protocols for on-demand route discovery. DSR and DSR-np use this less often and more efficiently than AODV. For DSR and DSR-np, most routing traffic is sent point-to-point. The proportion of broadcast traffic is large enough to contribute to the energy costs. The amount of traffic received is so much larger than the amount of traffic sent that it accounts for 40-70% of the energy consumption.

DSR does not require the use of promiscuous mode. In DSR-np, only forwarding nodes take topology information from source routing headers. Nodes, therefore, must initiate the route discovery process more frequently causing higher energy costs for broadcast and point-to-point traffic. However, since overheard traffic can be discarded, energy savings occur outweighing these additional costs. It turns out that DSR-np reduces the cost of the route discovery process because rebroadcast messages are jittered in time to reduce the risk of collisions. An expanding ring search is also used where a sequency of hop-count-limited route discoveries are used to limit the route-request messages dispersed.

1.4.2 Routing in Mobile Ad Hoc Networks

1.4.3 Localized Power, Cost, and Power-cost Efficient Routing Algorithms

[Stojmenovic and Lin, 2000] defines a new power-cost metric based on the combination of a node's lifetime and distance based power metrics. [Stojmenovic and Lin, 2000] also proposes power, cost, and power-cost GPS-based localized routing algorithms. Routing decisions are made based on the location of a source node's neighbors and the destination. The goal of the power-aware algorithm is to minimize the total power needed to route a message from source to destination. The goal of the cost-aware algorithm is to extend a node's worst case lifetime. The goal of the combined power-cost algorithm is to minimize the total power needed and to avoid nodes with short battery lifetimes. The algorithms are also shown to be loop-free.

The networks used can be static, static most of the time, or moving. These algorithms apply to ad hoc or sensor networks. [Stojmenovic and Lin, 2000] uses GPS to provide location information to nodes, which allows the nodes to use the least transmission power needed for reception.

A localized algorithm is defined as each node being able to make the decision which neighbor(s) to forward packets to based on the location of itself, its neighboring nodes, and a constant amount of additional information. Each node can process information locally. Each node will decide how to route a packet depending on the task performed and the algorithm used, which is part of the incoming message. Additionally, destination locations are needed in case of routing. The sender uses the latest location information and attaches it to the message. Intermediate nodes may use their most recent location information and replace the location information in the header and can also update their own. All nodes should update locations of all other nodes in the network. Path adjustments can be made as the message travels closer to the destination.

It is assumed that every node contains geographic location of all other nodes in the network in its routing table. This includes the time when the location of the node is established. The routing table is only used to provide approximate location information of the destination node and provide accurate information about the location of neighboring nodes.

[Stojmenovic and Lin, 2000] generalizes the model of [Rodoplu and Meng, 1999] and assumes the power needed for transmission and reception of a signal is $u(d) = ad^{\alpha} + bd + c$ in order to include models that attenuate signal power of various exponents. This model includes all three power aware metrics discussed which are [Rodoplu and Meng, 1999, Heinzelman et al., 2000] and a third one that [Stojmenovic and Lin, 2000] describes. The variables are described in the following way:

- c : Constant factor c stands for total energy consumption. The energy consumption may include energy consumed in computer processing and encoding/decoding.

- a : Coefficient a can be adjusted according to the physical environment, unit of length considered, unit size of a signal, and so on.

- d : The distance between any two nodes is represented as d.

- α : α is adjusted depending on the model used. Here α is equal to two or four, but results of different values of α can be achieved.

The optimality of power adjusted transmissions in mobile ad hoc networks (MANETs) are discussed in more detail in [Stojmenovic and Lin, 2000].

If nodes have information about position and activity of all other nodes in the network, then Dijkstra's single source shortest weighted path algorithm can be applied as the optimal power savings algorithm. Each edge has a weight of $u(d) = ad^{\alpha} + bd + c$. This is referred to as the SP-power algorithm.

[Stojmenovic and Lin, 2000] describes a corresponding localized routing algorithm. A source node or intermediate node, S, selects one of its neighbors, A, to forward a packet towards its destination node which will minimize the transmission power from S to A. If the destination node, D, is a neighbor of A, then the packet is sent directly to D if it reduces energy. D can be treated as any other neighbor, and the algorithm proceeds until the destination is reached, if possible. If looping is detected, then the algorithm stops. The equation, $p(B, A) = u(r) + tv(s)$ is attempted to be minimized by the power-efficient routing algorithm, where t is a network parameter.

In the experiments reported in [Stojmenovic and Lin, 2000], t is set to one. The power-routing algorithm is as follows.

```
Power-routing(S,D) {
    A:=S;
    Repeat
      B:=A;
      Let A be neighbor of B that minimizes p(B,A)=u(r)+tv(s);
      Send message to A
    Until A=D (destination reached) or A=B (delivery failed);
}
```

Another metric measuring nodes' lifetimes is studied in [Singh et al., 1998]. The cost of each node is represented as $f(A) = 1/g(A)$, where $g(A)$ stands for the remaining lifetime. A shortest weighted path algorithm based on node cost was proposed in [Singh et al., 1998]. The algorithm uses cost to select a path, however, the actual power is charged to nodes.

[Stojmenovic and Lin, 2000] describes a localized version of this algorithm. Constant power for each transmission is assumed. The cost, $c(a)$, of a route from B to D using a neighboring node A is the sum of the cost $f(A) = 1/g(A)$ of node A and the estimated cost of the route from A to D. Node B has knowledge of the cost of $f(A)$ of each neighbor A of node B currently holding the packet.

It is assumed that the cost of other nodes on the remaining path are proportional to the number of hops between A and D. The number of hops is proportional to the distance between A and D and is inversely proportional to radius R. The cost can be represented as ts/R, where different factors of t have been investigated. The cost definition, $c(A) = f(A)ts/R$ is suggested for investigation as well as $c(A) = f(A) + ts/R$ since it is not clear which will give the best results.

The cost-routing algorithm is described as follows.

```
Cost-routing(S,D) {
    A:=S;
    Repeat
      B:=A;
      Let A be neighbor of B that minimizes c(A);
      If D is a neighbor of B
          then send to D else send to A
    Until D is reached or A=B;
}
```

Power and cost are migrated into a single routing algorithm. Two different ways to combine power and cost metrics into a single power-cost metric, based on the product and sum of the two metrics are proposed. For product, the power- cost of sending a message from B to a neighbor A is represented as $powercost(B, A) = f(A)u(r)$, where r is equal to the distance between A and B. The power-cost algorithm can find the optimal power-cost by applying single source shortest weighted path Dijkstra's algorithm. For sum, the new metric can be represented as $powercost(A, B) = \alpha u(r) + \beta f(A)$, where values for α and β are suitable.

The power-cost efficient routing algorithm can be described as follows. Let A be the neighbor of B that minimizes $pc(B, A) = powercost(B, A) + v(s)f'(A)$, where s=0 for D, if D is a neighbor of B. This algorithm is referred to as power-cost0 when $powercost(B, A) = f(A)u(r)$. Power-cost1 refers to $powercost(B, A) = f'(S)u(r) + u(r')f(A)$. The packet is delivered to neighbor A. The packet does not have to be delivered to D when D is B's neighbor. The algorithm keeps running until the destination node is reached, if possible.

```
Power-cost-routing(S,D) {
    A:=S;
    Repeat
      B:=A;
      Let A be neighbor of B that minimizes pc(B,A)=power-cost(B,A) + v(s)f'(A);
      Send message to A
    Until A=D (destination reached) or A=B (delivery failed);
}
```

The algorithm can be modified for different network conditions. [Stojmenovic and Lin, 2000] provides proofs that these three routing algorithms are loop-free.

Experiments are conducted using 100-node random unit graphs. The average node degree, $k = 10$, is controlled, and the radius R which corresponds to k is equal to the length of $nk/2 - th$ edge in the sorted order. Disconnected graphs were ignored.

The proposed distributed power efficient routing algorithm outperforms all GPS based algorithms for all sizes of the network. The larger the network, the more significant the results become. Also the proposed power efficient algorithm produces paths close to the optimal ones (obtained by SP). More results can be found in [Stojmenovic and Lin, 2000]. In these results, all batteries are refreshed.

For the evaluation of cost and power-cost efficient routing algorithms, it is assumed that nodes have different remaining powers. Random unit graphs are generated. An iteration is defined as a routing task specified by a random choice of source and destination nodes. If a current node does not have enough power to transmit the message to the next node or the node is a concave node for that task (method failure), then the node will stop the routing process. Experiments are run to determine the number of iterations until the first node dies. The simulations are run for 20 graphs for different network sizes and for HCB-models [Heinzelman et al., 2000]. A table of results can be found in [Stojmenovic and Lin, 2000].

Both cost functions and all four power-cost methods gave close simulation results. All proposed cost and power-cost methods, which are localized, performed equally well as the corresponding non-localized shortest path cost and power-cost algorithms. The cost and power-cost algorithms last significantly longer in terms of iterations than the power algorithm.

The average remaining power at each node after the network dies for the most competitive methods were analyzed. Cost methods have more remaining power only for when $m = 10$ (smallest network). Two better power-cost methods leave about 15% more power at nodes than the cost method for larger values of m. Therefore, since networks will continue to operate after the first node dies, the power-cost method may outperform cost methods.

1.4.4 Routing in Personal Area Networks

Personal Area Networks are communication networks consisting of devices that are in a short range of each other such as cellular phones, pagers, and PDAs. Bluetooth and IEEE 802.15 are two emerging short-range wireless standards which allow devices to communicate with each other over wireless links.

While other work related to power consumption has focussed on reducing the overall device usage and energy consumption, [Gomez et al., 1999] considers maximizing nodes' lifetimes in order to maintain performance and usage of the network. [Gomez et al., 1999] proposes a power-aware routing protocol that minimizes power transmission among nodes by using a tradeoff between power control and allowing intermediate nodes to relay packet transmissions. Choosing a minimum energy cost path without considering node information about the intermediate nodes could cause intermediate nodes to die quickly. However, only choosing paths which use nodes with plenty of battery power could mean that a minimized energy cost path is not being used. [Gomez et al., 1999] notes that a tradeoff between the two methods should be used.

[Gomez et al., 1999] uses device behaviors to describe the actions that nodes can take when forwarding packets. Nodes have two modes: social mode and greedy mode. Social mode is where a node with generous battery reserves should be able to forward a packet if another node requests it. Greedy mode is where a node may refuse to forward a packet if its battery level is below a certain threshold. Source nodes also have different behaviors. If a source node has a lower battery level, then it will forward a packet to the nearest node without considering that node's power level. The threshold used which divides social and greedy modes depends on the device and radio attached to it.

[Gomez et al., 1999] uses a cost function to assign a cost to each possible route. The cost function captures the transmission cost for each node in the route and how much each node "prices" its battery power while forwarding packets. For a packet traveling along route k which needs N transmissions to reach its destination, the cost of each alternative route is defined as:

$$R_k = \sum_{i=0}^{N} P_i f(B_i), \tag{1.2}$$

where P_i is the transmission power for node i, and $f(B_i)$ models the price of node i's battery power. The transmission power should take into account the path loss. The path loss is usually described as $1/d^{\alpha}$, where d is the distance between the source node and the destination node, and α is a function of the distance and type of environment. For a freespace scenario, where there is little obstruction, α would be two. For an urban scenario, where there is a lot more obstruction, and therefore a lot more power is needed to transmit, α would be four. Different parameters are used such as current battery level, total storage capacity, and type of battery. Price of batter power can vary depending on parameters such as non-rechargable batteries.

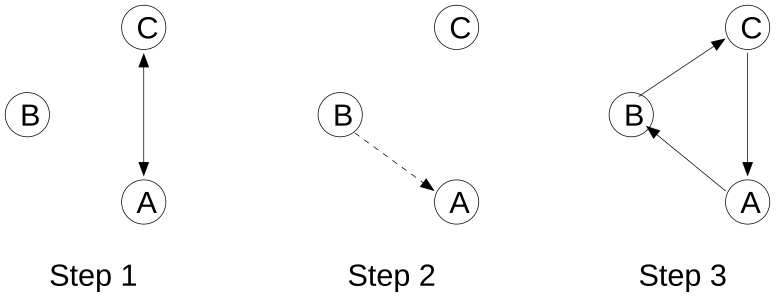

Fig. 1.1 The working of route-redirect

[Gomez et al., 1999] uses route-redirect so that nodes with generous battery power can do more work. The idea of route-redirect is that nodes can redirect other nodes to transmit through them if it is a more intelligent route. The headers of the packets contain nodes' transmitted powers battery cost parameters, and the total cost of the route. An example of how route-redirect works is explained in the following 3 steps as depicted in Figure 1.1, where nodes A and C want to transmit packets to each other. It is assumed that all nodes can overhear other transmissions, are within transmission range, and operate in a social mode in this example.

1. Assume that nodes A and C are unaware of the presence of a third node, B. Node A can only transmit directly to node C at this point. If node A is not aware of its attenuation distance from node C, then node A may transmit at full power to locate node C and then adjust its transmission power after node C replies.
2. Since node B can overhear transmissions from node A and node B, node B can estimate the power attenuation with respect to both nodes. If node B computes that the route from A->B->C is lower cost than A->C, then node B sends a route- redirect message to node A. In this particular example, route C->B->A costs more than C->A.
3. After node A receives the route-redirect message from node B, node A transmits the packets to node C through node B.

However, if there are multiple route-redirect messages received by a node, there needs to be some method to handle this condition. [Gomez et al., 1999] proposes how to address this issue. Two methods are being considered:

- Let the transmitting node collect all route-redirect messages and then choose which route is the minimal cost.
- Let potential forwarding nodes advertise lower cost routes first. A potential forwarding node overhearing a route-redirect message will not transmit its own route-redirect message if it overhears a lower cost route.

This route-redirect approach helps to minimize signaling overhead which is ideal for dynamic mobile scenarios. Another factor to consider is when nodes die or move out of the route. [Gomez et al., 1999] explains that when this happens, the previous node in the route must re-establish a route. The node can do this by transmitting with full power in order to find the destination node. This allows intermediate nodes to optimize the route again.

In [Gomez et al., 1999], authors have considered extending the protocol to work for WANs (Wide Area Networks). Currently, a node in greedy mode wanting to transmit a packet to a node in social mode will not work for WANs. [Gomez et al., 1999] proposed to separate the wide area routing with the local power optimization. However, [Gomez et al., 1999] uses a wide area routing protocol to find unknown routes at high power. Then [Gomez et al., 1999] uses the route-redirect protocol to optimize routes locally which keeps the signaling overhead for searching low while reducing the transmission power to find the route with minimal power.

1.4.5 Routing Based on Balanced Energy Consumption of Nodes

[Chang and Tassiulas, 2000] studies the problem of information being generated in certain nodes and needing to route this information to a set of designated nodes for wireless static networks. Each node can adjust its power within a certain range that determines the set of possible one hop neighbors. If a neighbor is not located within one hop, then a multihop path is used. [Chang and Tassiulas, 2000] proposes algorithms which select routes based on remaining battery power levels and shortest cost paths instead of just selecting a minimum cost path in order to maximize nodes' lifetimes. These localized algorithms are applicable to a distributed implementation.

[Chang and Tassiulas, 2000] assumes that with enough power, nodes can transmit data correctly to a receiver, given that the receiver is within an appropriate range. Every node has the ability to forward a packet to one of its neighbors.

An example network that can be used for this type of implementation is a wireless sensor network, where sensor nodes gather different types of data such as acoustic, magnetic, and seismic information and transmit this to some type of designated node such as a gateway node. This gateway node will have more processing power for further processing of the information or can have a larger transmission range to transmit to possibly a larger network.

The problem [Chang and Tassiulas, 2000] mentions about using only a minimum cost path to route data, is that certain nodes may be used more often than others causing them to drain their battery more quickly. [Chang and Tassiulas, 2000] extends the problem from a single destination to the multicommodity case, where each commodity has its own set of destinations.

[Chang and Tassiulas, 2000] focuses on trying to balance the energy consumption among nodes. This applies to static networks or networks which topologies change slowly enough so that there is enough time for optimally balancing the traffic between changes.

[Chang and Tassiulas, 2000] proposes a class of flow augmentation (FA) algorithms which use the shortest cost path. A linear programming model of this problem was also presented. [Cormen et al., 1990] shows that this linear programming problem is a variation of the well known maximum flow problem. These algorithms should choose paths which consume less energy and should avoid nodes with small amount of battery power. A link cost function is proposed which uses three parameters:

- energy cost to transmit over a link from the source node to the destination node, e_{ij}
- initial energy of the source node, E_i
- remaining battery power of the source node, $\underline{E}_i$

The link cost function is developed so that when nodes have a lot of of battery power, the shortest cost path is emphasized, but after nodes' batteries have drained, the remaining battery power levels are emphasized. The link cost function is as follows:

$$c_{ij} = e_{ij}^{x_1} \underline{E}_i^{-x_2} E_i^{x_3}, \tag{1.3}$$

where x_1, x_2, x_3 are nonnegative weighting factors. If $\{x_1, x_2, x_3\}$ = {0,0,0} then the shortest cost path is the minimum hop path. If it is {1,0,0}, then the shortest cost path is the minimum transmitted energy path. If $x_2 = x_3$, then normalized remaining battery power is used, and if $x_3 = 0$ then the absoluted remaning battery power is used.

By summation of the link cost paths, the path cost can be calculated. The algorithm can be implemented with any shortest path algorithms. [Chang and Tassiulas, 2000] used the Bellman-Ford algorithm for their experiments.

[Chang and Tassiulas, 2000] also extended the flow direction algorithm to the multicommodity case. In this algorithm, [Chang and Tassiulas, 2000] redirects a portion of each commodity flow at every node so that the minimum lifetime of every path with positive flow from the source node to the destination node will increase or at least stay the same. The algorithm works as follows:

1. Determine the two paths to the destination which are to be involved in the redirection.
2. Calculate the amount of redirection.
3. Redirect the flow - increment and decrement the flows of the two paths determined in Step 1 by the amount of redirection.

More detail involving these three steps can be found in [Chang and Tassiulas, 2000].

A total of 200 random graphs were generated to evaluate the performances of the propsed algorithms. The performances were compared to the minimum transmitted energy (MTE) routing algorithm and the maximum residual energy path (MREP) routing algorithm proposed in [Chang and Tassiulas, 1999].

Algorithm X	avg R_x	min R_x	Pr$\{R_x$ > 0.9$\}$
MTE	0.7310	0.1837	33%
FR	0.9596	0.6878	88%
MREP	0.9572	0.8110	89%
FA(1,1,1)	0.9744	0.7347	94%
FA(1,50,50)	0.9985	0.9911	100%

Table 1.1 Performance comparison of the algorithms in the single commodity case

Table 1.1 shows the performance comparison of the algorithms in the single commodity case. R represents the ratio of Algorithm X to the optimal performance. [Chang and Tassiulas, 2000] explains $R_{FA(1,50,50)}$ is always over 0.99 of the optimal. FA(1,1,1)'s performance is comparable to MREP's performance. The system lifetime of FR, MREP, and FA(1,x,x) where x>=1 are greater than 0.95 of the optimal while MTE is only 0.7310. R_{FR} and R_{MREP} are over 0.9 about 90% of the time while MTE is over 0.9 only 33% of the case. The algorithm gained a system lifetime of between 49% and 55% compared to MTE.

Algorithm X	avg R_x	min R_x	Pr$\{R_x$ > 0.9$\}$
MTE	0.6982	0.2201	25%
FR	0.8862	0.4297	54%
MREP	0.9349	0.7298	69%
FA(1,1,1)	0.9565	0.7178	86%
FA(1,50,50)	0.9974	0.9906	100%

Table 1.2 Performance comparison of the algorithms in the multicommodity case

Table 1.2 reflects the results of the algorithms in the multicommodity case. $R_{FA(1,50,50)}$ is always over 0.99 of the optimal. FA(1,1,1)'s performance is comparable to MREP's performance as in the single commodity case. R_{FR} and R_{MREP} are 0.8862 and 0.9349, respectively while the average R_{MTE} is only 0.6982. R_{FR} and R_{MREP} are over 0.9 in 54% and 69% of the case. However, MTE is only 25% of the case. The performance of FA(1,50,50) is still very close to the optimal while MTE, FR, and MREP does not perform well compared to the single commodity case.

The system lifetime's average gain obtained by the algorithms is between 40% and 62% compared to MTE.

1.4.6 Topology Control using Transmit Power Adjustment

While the previous sections focussed on routing techniques to minimize energy consumption, [Ramanathan and Rosales-Hain, 2000] approaches the problem by controlling the topology of the network. Little has been done in the area of adjusting the controllable parameters in order to create the desired topology. [Ramanathan and Rosales-Hain, 2000] proposes two centralized algorithms for static networks which are shown to be optimal and two distributed heristics that adjust node transmit powers in response to topological changes and attempts to maintain a connected topology using minimum power.

The topology needs to be controlled because the wrong topology can considerably reduce the capactiy, increase the end-to-end packet delay, and decrease the robustness to node failures. Sparse networks can cause network partitioning and high end-to-end delays. While dense networks can cause the limited spatial reuse to reduce network capacity. The battery life of nodes can be extended by using transmit power control. No research has considered the assignment of different transmit powers to different nodes to meet a global topological property, such as a connected network and studied the implementation in the context of a typical ad hoc network.

A new representation for ad hoc networks is presented. Since the conventional representation hides the radio parameters and propegation properties that are critcial to a realistic analysis, a new framework is developed. The conventional representation of ad hoc networks contain edges between nodes which can communicate with one another. In the representation of [Ramanathan and Rosales-Hain, 2000], the geographical locations, the propegation characteristics, and the node transmission parameters are kept separate.

[Ramanathan and Rosales-Hain, 2000] looks at maintaining a biconnected network because the loss of a single node will not partition the network, and it provides multiple-path redundancy between every pair of nodes enabling fault-tolerance, load balancing, or both. The goal of minimizing the maximum transmit power is looked at rather than the total over all nodes because battery life is a local reserve and so collective minimization has little practical value is also looked at. The effect that is studied is the throughput metric. Per-node minimality is also looked at (if it is not possible to lower the assigned power of any single node and still keep the graph connected or binconnected) because it ensures a certain "tightness" of the power assignments is also examined.

[Ramanathan and Rosales-Hain, 2000] presents two polynomial time algorithms: one that results in a connected network and the other in a biconnected network. The node locations and the least-power function are inputs to the algorithms.

[Ramanathan and Rosales-Hain, 2000] claims that algorithm CONNECT is an optimum solution to the CMP problem, algorithm BICONN-AUGMENT produces an optimum solution to the BAMP problem, and the worst case running time of these algorithms is O($n^2 log(n)$), where n is the number of nodes.

In a mobile ad hoc network, the topology is constantly changing. Therefore, the transmit powers of nodes must continually readjust to maintain the desired topology. Since global information requires prohibitive control overhead, local or already available information needs to be used. Two distributed heuristics for topology control are presented: Local Information No Topology (LINT) and Local Information Link-State Topology (LILT). These protocols differ in the nature of the feedback information used and the network property needed to be maintained. LINT uses locally available neighbor information collected by some routing protocol and attempts to bound the number of each node's neighbors. It is assumed that the neighbor discovery protocol returns only bidrectional neighbors. LILT also uses locally available neighbor information, but also makes use of some global topology information that is available with some routing protocols. These protocols do not use any special control messages to operate.

Adjusting the transmit power can cause link up/downs. In many routing protocols, this causes routing updates. With a large number of updates, network bandwidth may be largely consumed and the effective throughput will be decreased as a result. To minimize this problem, LINT and LILT are incremental, meaning they calculate the new transmit powers based on the currently used values.

In order to evaluate the performance of these algorithms, the following methods were used.

- Each node in the testbed consists of a radio modem and a router module connected using a serial interface.
- A psuedo-random mobility model was used.
- The performance metrics studied are throughput, delay, maximum transmit power, and average transmit power.

All experiments were based on a 40 node network run for 3 minutes of simulation time. CONNECT and BICONN-AUGMENT were compared to no topology control, which is labeled "NONE" in the graphs. With no topology employed, the throughput is acceptable for a small range of density values. For a more sparse network, the network is poorly connected, and for a more dense network, interference reduces spatial reuse and therefore capacity. Algorithm BICONN perfroms the best in terms of throuhput and adapts well to changing densities. It improves the throughput by about 227% for densities above one node/sq mile.

Algorithm BICONN uses a lot more power than CONNECT at lower densities. At lower densities, BICONN increses powers of some isolated nodes so that there are articulation points. Only a few nodes have close to maximum powers.

[Ramanathan and Rosales-Hain, 2000] concludes that for even a simple topology control algorithm on throughput is significant. It is also concluded that at high densities, it is better to use BICONNECT instead of CONNECT. However, at low densities, the choice of which algorithm to use depends on if battery power or throughput is more important.

Both LILT and LINT are reactive schemes. This means that there are periods in which the topology may be undesirable. Also, the repeated changes in transmit powers introduce link-state updates and increase the routing overhead.

The increased density causes a decrease in throughput in all cases. LILT and LINT cause nodes to decrease their powers in order to reduce interference and increase throughput. The throughput gain is about 53% for a density of two. LINT also performs better than LILT. One reason is that the radios used use CSMA which performs poorly at high loads and suffers from the hidden terminal problem. So the database is often not up-to-date causing false alarms and an increase in transmit power. Work with such mobility models is currently being worked on.

There are slight gains in delay performance in the middle ranges in densities. It appears that not having topology control performs about the same as topology control because [Ramanathan and Rosales-Hain, 2000] takes into account only the delay for successful packets. If a packet has transmitted successfully, it has typically gone through a less number of hops when there is no topology control. LILT generally operates at a higher power than LINT, so the delay is less for LILT. Also, these delays are quite less than 200 msec, which is usually tolerable for realtime communications.

1.5 SUMMARY

REFERENCES

blu, .

WIN, .

Broch et al., 1998. Broch, J., Maltz, D. A., Johnson, D. B., Hu, Y., and Jetcheva, J. (1998). A Performance Comparison of Multi-Hop Wireless Ad Hoc NetworkRouting Protocols. In *Proceedings of Mobicom '98*.

Chang and Tassiulas, 1999. Chang, J. and Tassiulas, L. (1999). Routing for maximum system lifetime in wireless ad-hoc networks. In *Proceedings of 37-th Annual Allerton Conference on Communcation, Control, and Computing*.

Chang and Tassiulas, 2000. Chang, J. and Tassiulas, L. (2000). Energy Conserving Routing in Wireless Ad-hoc Networks. In *IEEE Proceedings of Infocom 2000*.

Cormen et al., 1990. Cormen, T., Leiserson, C., and Rivest, R. (1990). *Introduction to Algorithms*. McGraw-Hill and MIT Press.

Estrin et al., 1999. Estrin, D., Gobindan, R., Heidemann, J., and Kumar, S. (1999). Next Century Challenges: Scalable Coordination in Sensor Networks. In *Proceedings of ACM/IEEE Mobicom' 99*.

Feeney, 2001. Feeney, L. M. (2001). An Energy-consumption Model for Performance Analysis of Routing Protcols for Mobile Ad Hoc Networks.

Gomez et al., 1999. Gomez, J., Campbell, A. T., Naghshineh, M., and Bisdikian, C. (1999). Power-Aware Routing in Wireless Packet Networks. In *Mobile Multimedia Communications '99*.

Heinzelman et al., 2000. Heinzelman, W., Kulik, J., and Balakrishnan, H. (2000). Energy-efficient Routing Protocols for Wireless Microsensor Networks. In *Proceedings of Hawaii International Conference on System Sciences*.

Kulik et al., 1999. Kulik, J., Rabiner, W., and Balakrishnan, H. (1999). Adaptive Protocols for Information Dissemination in Wireless S ensor Networks. In *Proceedings of ACM/IEEE Mobicom' 99*.

Ramanathan and Rosales-Hain, 2000. Ramanathan, R. and Rosales-Hain, R. (2000). Topology Control of Multihop Wireless Networks using Transmit Power Adjustment. In *IEEE Proceedings of Infocom 2000*.

Rappaport, 1996. Rappaport, T. S. (1996). *Wireless Communications*. Prentice-Hall.

Rodoplu and Meng, 1999. Rodoplu, V. and Meng, T. (1999). Minimum Energy Mobile Wireless Networks. In *IEEE Journal on Selected Areas in Communications*.

Singh et al., 1998. Singh, S., Woo, M., and Raghavendra, C. (1998). Power-aware Routing in Mobile Ad Hoc Networks. In *Proceedings of Mobicom '98*.

Stemm et al., 1996. Stemm, M., Gauthier, P., Harada, D., and Katz, R. (1996). Reducing Power Consumption of Network Interfaces in Hand-Held Devices. In *Proceedings of 3rd International Workshop on Mobile Multimedia Communications*.

Stojmenovic and Lin, 2000. Stojmenovic, I. and Lin, X. (2000). Power-aware localized routing in wireless networks. In *IEEE International Parallel and Distributed Processing Symposium*.

Tsaoussidis et al., 1999. Tsaoussidis, V., Badr, H., and Verma, R. (1999). Wave Wait Protocol (WWP) An Energy-Saving Transport Protocol for Mobile IP-Devices. In *7th IEEE Conference on Network Protocols, ICNP'99*.