Energy Consumption Analysis of the Stable Path and Minimum Hop Path Routing Strategies for Mobile Ad hoc Networks

Dr. Natarajan Meghanathan

Jackson State University, Jackson, MS 39217

Summary
The high-level contribution of this paper is in exploring the fundamental contradiction between the routing strategies based on optimum stability and minimum hop count and in setting up a framework to identify the routing strategy that will minimize the overall energy consumption for on-demand routing in mobile ad hoc networks (MANETs). We show that for a given node mobility, as the network density increases, aiming for a sequence of stable routes (called the stable mobile path) reduces the number of route transitions at the cost of an increased hop count. On the other hand, as the network density increases, aiming for a sequence of minimum hop routes (called the minimum hop mobile path) reduces the hop count per path but results in increased number of route transitions. Through extensive simulations, we further explore and elaborate this tradeoff and analyze its effect on the overall energy consumption of a source-destination session when using a stable mobile path vis-à-vis a minimum hop mobile path for on-demand routing in MANETs. We also show that as the energy consumed per hop is reduced, a stable mobile path brings significantly more energy savings in comparison to that obtained by using a minimum hop mobile path.

Key words:
Simulations, Stability, Minimum hop routing, Energy consumption, Overhearing, Mobile ad hoc networks.

1. Introduction

A mobile ad hoc network (MANET) is a dynamic distributed system of nodes that move freely and independently of one another. The transmission range of mobile nodes is often limited due to battery charge constraints, frequency reuse, channel fading, etc. Thus, routes between nodes are often multi-hop, necessitating the development of efficient routing protocols with an objective to optimize one or more routing qualities or metrics. Selecting the route with the minimum hop count (i.e., the smallest number of intermediate forwarding nodes) is one of the most commonly desired design objectives. Unfortunately, in the presence of node mobility, the lifetime of minimum hop paths is severely affected as they are likely to be comprised of long-distance (i.e., weakly connected) links that are highly vulnerable to failure. Well-known MANET routing protocols like Dynamic Source Routing (DSR) [9] and Ad Hoc Distance Vector (AODV) [15] routing are based on minimum-hop routing.

In [13], we present a simple but powerful polynomial-time greedy algorithm called *OptTrans* to determine the optimal (the minimum) number of route transitions for a source-destination (s-d) session. Given the complete information on the future topology changes, the algorithm operates on the simple greedy heuristic: Whenever an *s-d* path is required at a time instant *t*, choose the longest-living *s-d* path since *t*. The above strategy has to be repeated over the duration of the *s-d* session. The sequence of such longest living stable paths is called the stable mobile path. The complexity of *OptTrans* is $O(n^2T^2)$, where n is the number of nodes in the network and T is the duration of the *s-d* session. Simulation results in [13] suggest that the stability of paths could be considerably improved by looking at the near future itself. Signal Stability Adaptive (SSA) routing [4] and Route-lifetime Assessment Based Routing (RABR) [1] are some of the stability-based routing protocols for MANETs.

Energy consumption for an *s-d* session can be approximated as the sum of the energy consumed in discovering the *s-d* routes whenever required and the energy consumed due to data packet transfer along the discovered *s-d* route. It turns out that the energy consumed due to overhearing at the non-destination nodes in each of the hops contributes significantly to the overall energy consumption. On these lines, power-saving strategies [8][10] have been developed in the literature whose principle goal is to turn off a node that is neither the source nor the destination of the ongoing traffic in its neighborhood. Employing these power-saving strategies would significantly reduce the energy consumed per hop and the energy consumed due to route discoveries would start dominating the overall energy consumption, especially at high network densities. Note that the energy consumed per route discovery cannot be reduced significantly, especially in dense networks, as a node has

Manuscript received October 5, 2007
Manuscript revised October 20, 2007

to anyway receive the packet (and then discard it if already seen) broadcasted by a node in its wireless range. This is where the importance of path stability comes in. The larger is the life time of a path, lower is the number of route discoveries or route transitions. We use the terms path and route interchangeably.

In [14], we did an exhaustive literature survey and identified minimum hop based routing and stability-based routing as the two principal routing strategies in MANETs. A similar observation has also been made in [11]. In this paper, we first illustrate the tradeoff between minimum hop based routing and stability based routing strategies in terms of the average number of route transitions and the average hop count per route incurred during an *s-d* session. We show that for a given node mobility, as the network density is increased, aiming for a sequence of minimum hop paths (here after called the minimum hop mobile path) reduces the hop count per path at the cost of an increased number of route transitions for an *s-d* session. On the other hand, as the network density is increased, aiming for a stable mobile path reduces the number of route transitions at the cost of an increased average hop count per route. This motivated us to evaluate the overall energy consumption for an *s-d* session when using a stable mobile path and a minimum hop mobile path. Instead of comparing the energy consumption incurred by individual routing protocols, it would be worth evaluating the overall energy consumption for an *s-d* session incurred by the two routing strategies and get a general idea on their performance under different conditions of network densities, node mobility and offered traffic load. This idea was first introduced by us in [12] and is extended and elaborated here with detailed analysis on the impact of density and mobility on {number of route transitions, hop count) and extensive simulation results with different levels of overhearing at the intermediate nodes, network density, node mobility and offered traffic load. We show that as the energy consumed per hop is reduced, a stable mobile path brings significantly more energy savings in comparison to that obtained by using a minimum hop mobile path. The magnitude of the energy savings depends on the network density, node mobility and offered traffic load.

The rest of the paper is organized as follows. In Section 2, we briefly review the algorithm to find the optimal number of route transitions and give its proof of correctness. In Section 3, we motivate the importance of analyzing the tradeoff between stability and minimum hop based routing in MANETs. In Section 4, we present our simulation environment and the energy consumption models. In Section 5, we present the results of simulations conducted for different levels of overhearing, offered traffic load, node mobility and network density and discuss the energy savings obtained under the optimal stability and minimum hop based strategies. Section 6 presents our conclusions where we also discuss our future work.

2. Algorithm for the Optimal Number of Route Transitions

2.1 Mobile Graph

The algorithm uses the notion of mobile graph and mobile path to represent the history of network topology and path changes [6]. A *mobile graph* is defined as the sequence $G_M = G_1G_2 \dots G_T$ of static graphs that represents a history of the network topology changes over some time scale T. In the simplest case, the mobile graph $G_M = G_1G_2 \dots G_T$ can be extended by a new instantaneous graph G_{T+1} to a longer sequence $G_M = G_1G_2 \dots G_T G_{T+1}$, where G_{T+1} captures a link change (either a link comes up or goes down). But such an approach has very poor scalability. In this paper, we sample the network topology periodically which could, in reality, be the instants of data packet origination at the source. We assume that all graphs in G_M have the same vertex set (i.e., no node failures).

2.2 Mobile Path

A *mobile path*, defined for a source-destination (*s-d*) pair, in a mobile graph is the sequence of paths $P_M = P_1P_2 \dots P_T$, where P_i is a static path between the same *s-d* pair in $G_i = (V_i, E_i)$. That is, each static path P_i can be represented as the sequence of vertices $v_0v_1 \dots v_l$, such that $v_0 = s$ and $v_l = d$ and $(v_{j-1},v_j) \in E_i$ for $j = 1,2, \dots, l$. The timescale of T normally corresponds to the duration of a session between s and d. Let $w_i(P_i)$ denote the weight of a static path P_i in G_i. For additive path metrics, such as hop count and end-to-end delay, $w_i(P_i)$ is simply the sum of the link weights along the path. Thus, for a given *s-d* pair, if $P_i = v_0v_1 \dots v_l$ such that $v_0 = s$ and $v_l = d$,

$$w_i(P_i) = \sum_{j=1}^{l} w_i(v_{j-1}, v_j) \quad (1)$$

For a given mobile graph $G_M = G_1G_2 \dots G_T$ and *s-d* pair, the weight of a mobile path $P_M = P_1P_2 \dots P_T$ is

$$w(P_M) = \sum_{i=1}^{T} w_i(P_i) + \sum_{i=1}^{T-1} C_{trans}(P_i, P_{i+1}) \quad (2)$$

where $C_{trans}(P_i, P_{i+1})$ is the transition cost incurred to change from path P_i in G_i to path P_{i+1} in G_{i+1}. Note the transition cost $C_{trans}(P_i, P_{i+1})$ has to be represented in the same unit as that of the path metric used to compute $w_i(P_i)$.

2.3 Stable Mobile Path and Minimum Hop Mobile Path

The Stable-Mobile-Path for a given mobile graph and *s-d* pair is the sequence of static *s-d* paths such that the number of route transitions is as minimum as possible. A Minimum-Hop-Mobile-Path for a given mobile graph and *s-d* pair is the sequence of minimum hop static *s-d* paths. With respect to equation (2), a Stable-Mobile-Path minimizes only the transition cost $\sum_{i=1}^{T-1} C_{trans}(P_i, P_{i+1})$ and a Minimum-Hop-Mobile-Path minimizes only the term $\sum_{i=1}^{T} w_i(P_i)$, assuming unit edge weights. For additive path metrics and a constant transition cost, a dynamic programming approach to optimize the weight of a mobile path $w(P_M) = \sum_{i=1}^{T} w_i(P_i) + \sum_{i=1}^{T-1} C_{trans}(P_i, P_{i+1})$ has been proposed in [6].

2.4 Algorithm Description

The algorithm *OptTrans* operates on the following simple greedy strategy: Whenever a path is required, select a path that will exist for the longest time. Let $G_M = G_1G_2 \ldots G_T$ be the mobile graph generated by sampling the network topology at regular instants $t_1, t_2, \ldots, t_T$ of an *s-d* session. When an *s-d* path is required at sampling time instant t_i, the strategy is to find a mobile sub graph $G(i, j) = G_i \cap G_{i+1} \cap \ldots \cap G_j$ such that there exists at least one *s-d* path in $G(i, j)$ and no *s-d* path exists in $G(i, j+1)$. A minimum hop *s-d* path in $G(i, j)$ is selected. Such a path exists in each of the static graphs $G_i, G_{i+1}, \ldots, G_j$. If sampling instant $t_{j+1} \le t_T$, the above procedure is repeated by finding the *s-d* path that can survive for the maximum amount of time since t_{j+1}. A sequence of such maximum lifetime static *s-d* paths over the timescale of a mobile graph G_M forms the stabile mobile *s-d* path in G_M. The pseudo code of the algorithm is given in Figure 1. In a mobile graph $G_M = G_1G_2 \ldots G_T$, the number of route transitions can be at most T. The minimum hop Dijkstra algorithm will have to be run at most T times, each time on a graph of n nodes. If we use $O(n^2)$ Dijkstra algorithm, the complexity of *OptTrans* is $O(n^2T)$. For proof of correctness, interested readers are referred to [13].

Input: $G_M = G_1G_2 \ldots G_T$, source s, destination d
Output: P_S // stable mobile path
Auxiliary Variables: i, j
Initialization: i=1; j=1

Begin *OptTrans*

while ($i \le T$) do

Find a mobile graph $G(i, j) = G_i \cap G_{i+1} \cap \ldots \cap G_j$ such that there exists at least one *s-d* path in $G(i, j)$ and {no *s-d* path exists in $G(i, j+1)$ or $j = T$}

$P_S = P_S$ U {minimum hop path in $G(i, j)$ }

$i = j + 1$

end while

return P_S

End *OptTrans*

Figure 1: Pseudo code for algorithm *OptTrans*

3 Stability Vs Minimum Hop Path Routing

Maximum path stability (i.e. minimum route transitions) and minimum hop count are not likely to be easily achieved at the same time. Aiming for minimum hop count (or for that matter any particular path metric) paths can lead to unnecessary route transitions. Frequent route transitions can lead to congestion, packet losses, wastage of battery charge, out-of-order packet delivery, jitter, etc. On the other hand, by staying with stable paths that are sub-optimal in terms of the hop count, we may incur a larger end-to-end delay, which is not good for time-critical applications. In this section, we show a simple motivating example to illustrate the importance of analyzing the potential tradeoff between stability and minimum hop based routing with respect to the overall energy consumption of an *s-d* session.

Let the sequence of network topology changes be represented by the graph sequence $G_1G_2G_3G_4G_5$ as shown in Figure 2. The source-destination pair is 1 – 6. The sequence of graphs is constructed at the instants when the minimum hop path breaks. The minimum hop mobile path is the sequence of minimum hop static paths. Running Dijkstra's shortest path algorithm on G_1, G_2, G_3, G_4 and G_5 would yield the minimum hop mobile path [(1–3–6), (1–4–6), (1–2–6), (1–3–6), (1–2–6)]. On the other hand, path 1–4–5–6 is available in graphs G_1, G_2 and G_3 and path 1–2–5–6 is available in graphs G_4 and G_5. Thus, the stable mobile path, the sequence of static paths representing the minimum required number of route transitions, is [(1–4–5–6), (1–4–5–6), (1–4–5–6), (1–2–5–6), (1–2–5–6)].

One can notice that all the constituent static paths in the stable mobile path have a larger hop count compared to that in the minimum hop mobile path. On the other hand, the minimum hop mobile path requires 5 route discoveries, while the stable mobile path requires only 2 route discoveries. We now show how the energy consumed per route discovery, energy consumed per hop for a data

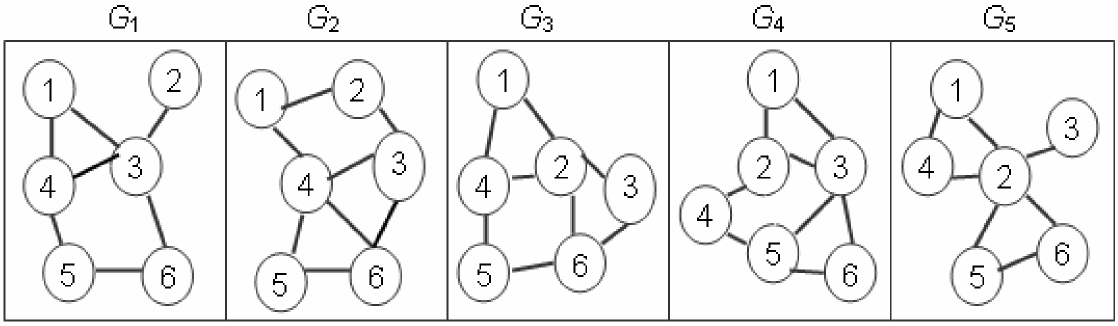

Figure 2: A graph sequence (Motivating Example: Stability Vs Minimum Hop Routing)

packet transfer and the number of data packets transferred in each of the constituent paths can impact the overall energy consumption. Under these conditions, the total energy consumption of a mobile path, explored in detail in Section 4, can be simplified as (Energy consumed per hop)*{Number of hops traversed per packet* Number of packets per static path * Number of static paths} + (Energy consumed per route discovery) * {Number of route discoveries}.

Case 1: Let the energy consumed per route discovery be 2J and the energy spent per hop be 0.5J. Let one packet be transferred from node 1 to node 6 in each of the graphs G_1 ... G_5. The total energy consumption of the minimum hop mobile path is 0.5 *{2*1*5} + 2 *{5} = 15 J; where as the total energy consumption of the stable mobile path is 0.5 * {3*1*5} + 2 *{2} = 11.5 J.

Case 2: Let the energy consumed per route discovery and the energy consumed per hop be the same as in Case 1. Now, let four packets be transferred from node 1 to node 6 in each of the graphs G_1 ... G_5. The total energy consumption of the minimum hop mobile path is 0.5 * {2*4*5} + 2 *{5} = 30 J; the total energy consumption of the stable mobile path is 0.5 * {3*4*5} + 2 *{2} = 34 J.

We thus see that even though the energy consumed per route discovery and the energy consumed per hop are fixed, the packet sending rate or the offered traffic load alone can decide whether a minimum hop mobile path or a stable mobile path is better in terms of the overall energy consumption. Similar cases can be developed by fixing the offered traffic load and varying the energy per hop and / or the energy consumed per route discovery.

4. Energy Consumption Models

The energy consumption at a node in ad hoc wireless networks can be divided into three categories: (1) energy utilized for transmitting a message, (2) energy utilized while receiving a message and (3) energy utilized in idle state. In this paper, we do not consider the energy lost in the idle state and focus only on minimizing the energy consumed for transmitting and receiving a message and energy consumed due to route discoveries. Irrespective of the length of a hop (physical distance), we use the same fixed transmission power per hop. We model the energy consumption due to broadcast traffic and point-to-point traffic as linear functions of packet transmission time, network density, and transmission and reception power per hop. A similar linear modeling for energy consumption has been used in [9]. Table 1, explains the notations used in the energy consumption calculations. The values for the sizes of the headers for the data and control packets coincide with the default values used in ns-2 [5] for the IEEE 802.11 MAC model [8] and the AODV [15] routing protocol. We use the least overhead routing approach (LORA) [3] of staying with the chosen route as long as exists. This is the strategy used by the on-demand routing protocols for networks with node mobility.

For broadcast traffic, we assume the sender can send the packet any time and it will be received by all the nodes in its wireless transmission range. For point-to-point traffic, we consider the IEEE 802.11 basic MAC negotiation without any retransmissions. In other words, the source is charged (in terms of energy consumption) for sending an RTS (request-to-send) packet and DATA packet to the destination and receiving the CTS (clear-to-send) and ACK packets from the destination. Similarly, the destination is charged for sending CTS and ACK packets to the source and receiving the RTS packet and DATA packet from the source. In the case of point-to-point traffic with overhearing considered, nodes in the range of the sender are charged for receiving an RTS packet and the DATA packet, while the nodes in the range of the receiver are charged for receiving the CTS and ACK packets. No retransmission costs are considered in the simulation. A similar MAC layer model is considered in [7] for evaluating the energy consumption of the routing protocols.

Table 1: Notations used in energy consumption models

Notation	Meaning	Value in the simulation
Tx_energy	Energy consumed for transmitting a packet	1.4 W
Rx_energy	Energy consumed for receiving a packet	1 W
BW	Channel bandwidth	$2 * 10^6$ bits/sec
Br_size	Size of a broadcast route search packet including the headers	800 bits
RTS_size	Size of an *RTS* (request-to-send) packet, including the *PLCP* (Physical Layer Convergence Protocol) header	352 bits
CTS_size	Size of a *CTS* (clear-to-send) packet, including the *PLCP* header	304 bits
ACK_size	Size of the *ACK* packet, including the *PLCP* header	304 bits
DATA_size	Size of the data packet, including the headers of all the other layers in the protocol stack	4672, 1088 bits
DATA_HDR_size	The header size of a data packet	576 bits
Neighb(*n*, *t*)	Set of neighbors of node *n* at sampling time instant *t*	varying with time
| *Neighb* (*n*, *t*) |	Number of neighbors of node *n* at sampling time instant *t*	varying with time
N	Number of nodes in the network	25, 50, 75
$B_{init}(n)$	Initial battery charge of a node $n \in N$	1000 Joules
Ptop_Tx(*n*)	Energy consumed for successfully transmitting the data packet at node *n*	varying with data packet size
Ptop_Rx(*n*)	Energy consumed for successfully receiving the data packet at node *n*	varying with data packet size
Ovh_sender(*n*, *a*, *b*, *t*)	Energy consumed for overhearing the *RTS* and *DATA* packets at time *t*. $n \in Neighb(a, t)$	varying with data packet size
Ovh_receiver(*n*, *a*, *b*, *t*)	Energy consumed for overhearing the *CTS* and *ACK* packets at time *t*. $n \in Neighb(b, t)$	depends whether over hearing is considered or not
Energy_hop(*a*, *b*, *t*)	Energy consumed for transfer of a *DATA* packet across hop (*a*, *b*) @ *t*	varying with time, network density and packet size
Energy_path(*P*, *t*)	Energy consumed for transfer of a *DATA* packet across path *P* @ *t*	varying with time, network density and packet size

4.1 Energy Consumption Model for Point to Point Traffic

All the discussions in this section and the following sections correspond to a mobile graph $G_M = G_1G_2 \ldots G_T$ generated for an *s-d* session by sampling the network topology at instants of packet origination $t_1, t_2, \ldots, t_T$. Let $P_i = v_0v_1 \ldots v_l$ be the static *s-d* path in $G_i=(V_i, E_i)$ at time t_i. Here, $v_0 = s$ and $v_l = d$ and $(v_{j-1}, v_j) \in E_i$ for $j = 1,2, \ldots, l$ are the hops of the *s-d* path. All the energy consumption calculations for the *s-d* path at time t_i are strictly based on the snapshot of the network topology G_i at t_i. We neglect the queuing delays and propagation delays and assume infinite channels. We thus model the packets being instantaneously transmitted from source *s* to destination *d*. In practice, there would be non-negligible delay in transferring packets.

The energy consumed for a point-to-point traffic on the *s-d* path P_i is modeled as the sum of the energy consumed along each hop. We model the energy consumption per hop considering complete overhearing (non-destination nodes receive the entire data packet), a reduced overhearing case where the non-destination nodes discard the data packet after scanning its header and when there is no overhearing.

$$\forall \text{ hop } (v_{j-1}, v_j) \in P_i,$$
$$Energy(v_{j-1}, v_j, t_i) = Ptop\_Tx(v_{j-1}) + Ptop\_Rx(v_j) + \sum_m OvhE(m, v_{j-1}.v_j, t_i) + \sum_n ovhE(n, v_{j-1}, v_j, t_i)$$
$$\text{where, } m \in Neighb(v_{j-1}, t_i),\ n \in Neighb(v_j, t_i). \tag{3}$$

$$Ptop\_Tx(v_{j-1}) = TxEnergy * \left(\frac{RTS\_Size + DATA\_Size}{BW}\right) + RcvEnergy * \left(\frac{CTS\_Size + ACK\_Size}{BW}\right) \tag{4}$$

Manuscript received October 5, 2007
Manuscript revised October 20, 2007

$$Ptop\_Rx(v_j) = TxEnergy * \left(\frac{CTS\_Size + ACK\_Size}{BW} \right) + RcvEnergy * \left(\frac{RTS\_Size + DATA\_Size}{BW} \right) \quad (5)$$

We present the over hearing costs at the non-destination nodes for each of the three following cases:

4.1.1 Complete overhearing

This is the case of the nodes operating in promiscuous mode. The non-destination nodes at the neighborhood of the sender v_{j-1} are charged for receiving the entire data packet. In addition, these nodes are charged for receiving the RTS packet. Similarly, the non-destination nodes at the neighborhood of the receiver v_j are charged for receiving the ACK and CTS packets.

$$\forall\ m \in Neighb(v_{j-1}, t_i),\ OvhE(m, v_{j-1}, v_j, t_i) = RcvEnergy * \left(\frac{RTS\_Size + DATA\_Size}{BW} \right) \quad (6)$$

$$\forall\ n \in Neighb(v_j, t_i),\ OvhE(n, v_{j-1}, v_j, t_i) = RcvEnergy * \left(\frac{CTS\_Size + ACK\_Size}{BW} \right) \quad (7)$$

4.1.2 Reduced overhearing

Instead of receiving the entire data packet, a node could scan only the header of the data packet and discard the rest of the packet if the packet is not addressed to the node. Thus, the non-destination nodes at the neighborhood of the sender v_{j-1} are charged for only receiving the data packet header and the RTS packet. On the contrary, the non-destination nodes at the neighborhood of the receiver v_j are charged for receiving the ACK and CTS packets as before (ref. equation 7). This simple strategy can bring significant power savings when the data size is considerably larger than the size of the header preceding the actual data in the data packet.

$$\forall\ m \in Neighb(v_{j-1}, t_i),\ OvhE(m, v_{j-1}, v_j, t_i) = RcvEnergy * \left(\frac{RTS\_Size + DATA\_HDR\_Size}{BW} \right) \quad (8)$$

4.1.3 No overhearing

We assume a node enters the doze or sleep state when there is an ongoing transmission in its neighborhood in which the node is neither a transmitter nor a receiver. We assume an intended receiver of the data packet is notified by the sender through energy-efficient IEEE 802.11 ATIM frame mechanism [11]. We also assume nodes identify their neighbors through the beacon frames exchanged as part of the power saving mechanism. The energy consumed for the transmission and reception of the ATIM and beacon frames is assumed negligible. Such an assumption may not be completely true because when the topology changes more frequently, power saving strategies require nodes to be awake at least half of the beacon interval. Nevertheless, we wanted to evaluate the maximum energy savings that could be obtained in stability and shortest-hop based routing strategies when the cost of overhearing is totally discarded.

$$\forall\ m \in Neighb(v_{j-1}, t_i),\ OvhE(m, v_{j-1}, v_j, t_i) = 0 \quad (9)$$

$$\forall\ n \in Neighb(v_j, t_i),\ OvhE(n, v_{j-1}, v_j, t_i) = 0 \quad (10)$$

4.2 Energy Consumption Model for Broadcast Traffic

The source is assumed to initiate a network-wide broadcast route search whenever there is a route transition. At each node n, the cost incurred for an s-d route discovery at t_{i+1} is $Br\_cost(n,t_{i+1}) = \{Tx\_energy + Rx\_energy * |Neighb(n,t_{i+1})|\} * \frac{Br\_size}{BW}$ (11)

In addition, energy is lost due to the forwarding of the route reply packet from the destination to the source. When links are assumed bi-directional, the route reply packet is usually sent on the reverse direction of the discovered route. Let P_{i+1} be the discovered s-d path at time t_{i+1}. The energy consumed for the transfer of a route reply packet across the reverse of this path $rev(P_{i+1})$ could be found by using the point-to-point traffic energy consumption models by assuming d as the source and s as the destination of the packet and using Br_size in the place of $DATA\_size$. Thus, the energy consumed for a required transition from at t_{i+1} is

$$\sum_{n \varepsilon N} Br\_cost(n, t_{i+1}) + Energy\_path(rev(P_{i+1}, t_{i+1})) \quad (12)$$

4.3 Energy Consumption per Static Path and Mobile Path

Once the energy consumed at each hop is determined using equations (3 – 12), the energy consumed for transmitting a data packet from the source s to destination d can be easily determined as it is basically the sum of the energies consumed at the hops.

$$Energy\_path(P_i, t_i) = \sum_{j=1}^{l} Energy\_hop(v_{j-1}, v_j, t_i) \quad (13)$$

If $P_M = P_1 P_2 \ldots P_T$ is a mobile path between source s and destination d over the time scale T, the energy consumed for the mobile path can be computed using equations (12) and (13) as $Energy\_path(P_M) = \sum_{i=1}^{T} Energy\_path(P_i, t_i) +$

$$\sum_{i=1}^{T-1} C_{trans}(P_i, P_{i+1}) \quad (14)$$

5 Simulations

The node mobility model used in all of our simulations is the Random waypoint model [2], a widely used mobility model in MANET studies. According to this model, each node starts moving from an arbitrary location to a randomly selected destination with a randomly chosen speed in the range [0 .. v_{max}]. Once the destination is reached, the node selects another destination and then continues to move with a different speed.

Table 2: Simulation Parameters

Simulator	*ns*-2 version 2.26 [5]	
	Network Size	1500 m x 300 m
	Number of Nodes	25 and 75
	Simulation Time	1000 Seconds
	Transmission Range	250 m
MAC Layer	IEEE 802.11 [8]	
Routing Strategies	Minimum Hop and Optimal Path Stability	
Mobility Model	Random-way point model [2]	
	Maximum Node Speed	10, 15, 20, 30, 40 and 50 m/s
	Pause Time	0 Second
Traffic Model	Constant bit rate (CBR), UDP	
	Number of Source-Destination (*s*-*d*) Pairs	15
	Data Packet Size	64 and 512 Bytes
	Packet Sending Rate per s-d Pair	(Low) 1, (High) 4 Packets / sec

We obtain a centralized view of the network topology by generating mobility trace files for a certain simulation time period in the *ns*-2 network simulator [5]. Note that, two nodes *a*, *b* are assumed to have a bidirectional link at time *t* if the Euclidean distance between them at time *t* (derived using the locations of the nodes from the mobility trace file) is less than or equal to the wireless transmission range of the nodes. The simulation time is 1000 seconds. The network topology is sampled depending upon the packet rate (for example, if the packet rate is 4 packets / sec, the network topology is sampled for every 0.25 seconds). The offered traffic load is 1 and 4 packets / sec, with 64 and 512 bytes / data packet. The simulations were conducted for all the three levels of overhearing. Table 2 presents the simulation parameters, not directly related with the energy consumption models.

We measure the average hop count per mobile path (time averaged over the static paths), the number of route transitions (= number of route discoveries – 1) and the overall energy consumption (computed using equation 14) per mobile path for a source-destination (*s*-*d*) session. The tradeoff between the stable mobile path and minimum hop mobile path with respect to number of route transitions and hop count) is explained in the next section. Detailed plots of the energy consumption per *s*-*d* session for both the minimum hop mobile path and stable mobile path under all the different conditions stated above are presented in Figures 3 – 8. Each value in these figures is an average of 15 source-destination pairs in five different mobility trace files run for each of the two strategies under each of the different simulation conditions.

5.1 Path Stability Vs. Hop Count

Under fixed node mobility and network density, the number of route transitions of a stable mobile path is not very sensitive to the varying traffic load; while the number of route transitions of a minimum hop mobile path increases as the number of data packets sent per second by the source increases. Larger is the offered traffic load, the larger should be the lifetime of a path as more packets have to be transmitted. The average hop count of both a stable mobile path and minimum hop mobile path are not very sensitive to the varying traffic load under fixed node mobility and network density. This may be partly because we assume instantaneous packet transfers from the source to the destination and the selection of routes is independent of the load at a node.

For a fixed velocity, the number of route transitions in a stable mobile path decreases as the network density increases; while in the case of a minimum hop mobile path, the number of route transitions increases as the network density increases. On the other hand, the average hop count of a stable mobile path increases as the network density increases; while in the case of a minimum hop mobile path, the average count hop of a minimum hop mobile path decreases as the network density increases. This contradictory trend in the two routing strategies could be reasoned as follows:

As the network density increases, the algorithm for the optimal number of route transitions tries to make use of the increasing neighborhood size and selects the sequence of nodes (the stable path) that would live for the longest time from the time of route discovery. Such a stable node sequence is chosen independent of the number of hops that would constitute the path. On the contrary, the minimum hop path algorithm makes use of the increasing neighborhood size and chooses the sequence of nodes that would have the smallest hop count. At the time of route discovery, the link length (physical distance between the two end nodes of a link) is at most 150 – 160 m for a stable path at low density and reduces further as the density increases; while for the minimum hop path, at low density, the length of a link is mostly between 170 – 200 m, and as

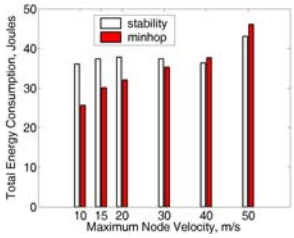

Figure 3.1
64 Bytes / Packet

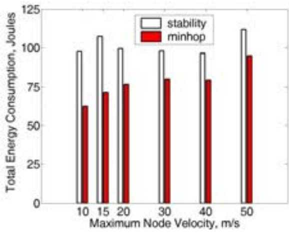

Figure 3.2
512 Bytes / Packet

Figures 3.1 – 3.2: 1 Packet / Second

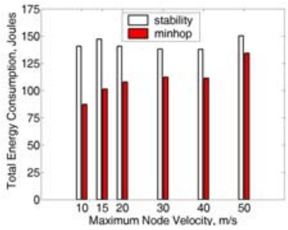

Figure 3.3
64 Bytes / Packet

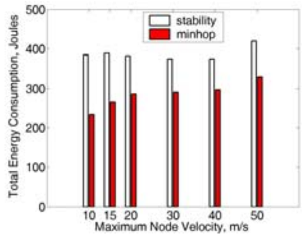

Figure 3.4
512 Bytes / Packet

Figures 3.3 – 3.4: 4 Packets / Second

Figure 3: 25 Nodes

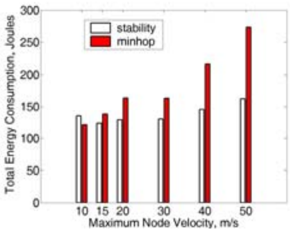

Figure 4.1
64 Bytes / Packet

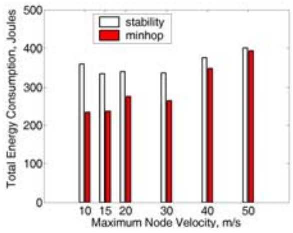

Figure 4.2
512 Bytes / Packet

Figures 4.1 – 4.2: 1 Packet / Second

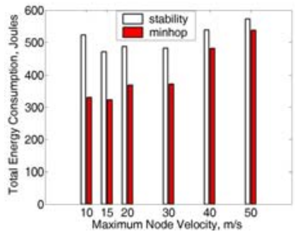

Figure 4.3
64 Bytes / Packet

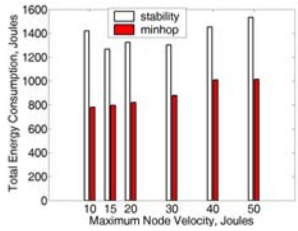

Figure 4.4
512 Bytes / Packet

Figures 4.3 – 4.4: 4 Packets / Second

Figure 4: 75 Nodes

Figures 3 – 4: Stable Mobile Path Vs Minimum Hop Mobile Path (Complete Overhearing)

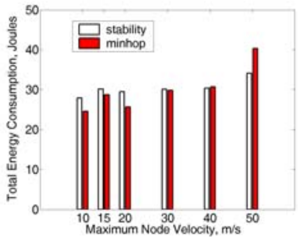

Figure 5.1
64 Bytes / Packet

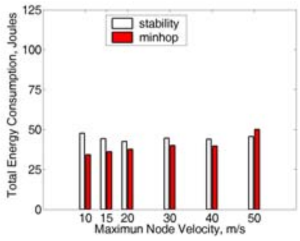

Figure 5.2
512 Bytes / Packet

Figures 5.1 – 5.2: 1 Packet / Second

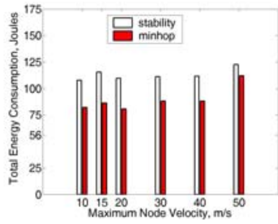

Figure 5.3
64 Bytes / Packet

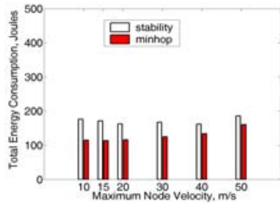

Figure 5.4
512 Bytes / Packet

Figures 5.3 – 5.4: 4 Packets / Second

Figure 5: 25 Nodes

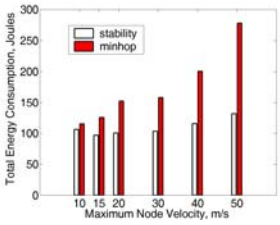

Figure 6.1
64 Bytes / Packet

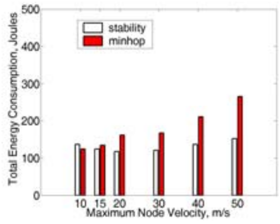

Figure 6.2
512 Bytes / Packet

Figures 6.1 – 6.2: 1 Packet / Second

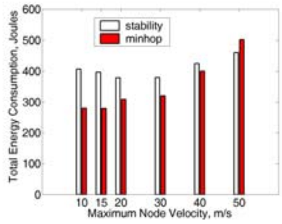

Figure 6.3
64 Bytes / Packet

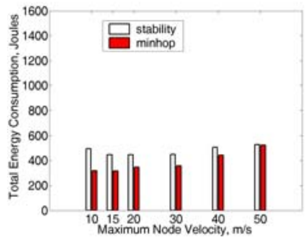

Figure 6.4
512 Bytes / Packet

Figures 6.3 – 6.4: 4 Packets / Second

Figure 6: 75 Nodes

Figures 5 – 6: Stable Mobile Path Vs Minimum Hop Mobile Path (Reduced Overhearing)

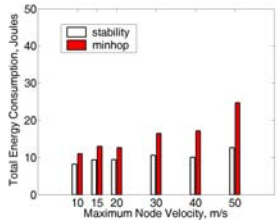

Figure 7.1
64 Bytes / Packet

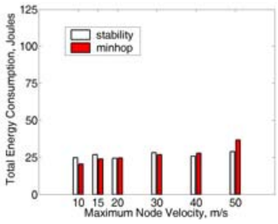

Figure 7.2
512 Bytes / Packet

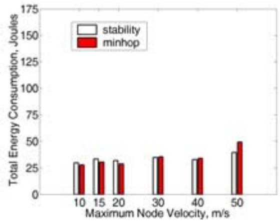

Figure 7.3
64 Bytes / Packet

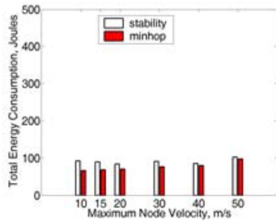

Figure 7.4
512 Bytes / Packet

Figures 7.1 – 7.2: 1 Packet / Second **Figures 7.3 – 7.4:** 4 Packets / Second

Figure 7: 25 Nodes

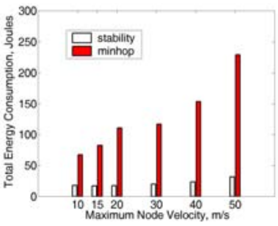

Figure 8.1
64 Bytes / Packet

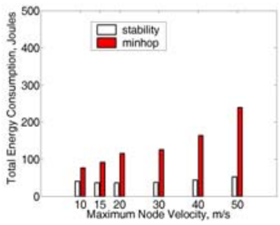

Figure 8.2
512 Bytes / Packet

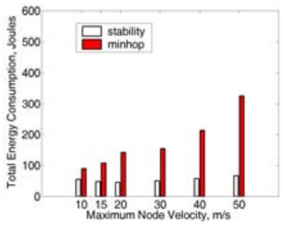

Figure 8.3
64 Bytes / Packet

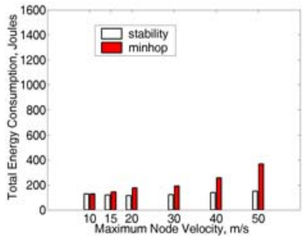

Figure 8.4
512 Bytes / Packet

Figures 8.1 – 8.2: 1 Packet / Second **Figures 8.3 – 8.4:** 4 Packets / Second

Figure 8: 75 Nodes

Figures 7 – 8: Stable Mobile Path Vs Minimum Hop Mobile Path (No Overhearing)

the density increases, the link length increases up to 230 m. As the maximum transmission range of the nodes is 250m, the links in a minimum hop path fail at a faster rate as the density increases.

5.2 Energy Consumption Analysis

As we proceed from complete overhearing to no overhearing, the stability-based routing strategy reduces the total energy consumption significantly when compared to that of minimum hop based routing. For example, consider the simulation condition of 75 nodes, 10 m/s, 4 packets / sec and 512 bytes / packet (refer Figures 4.4, 6.4 and 8.4). With complete overhearing, minimum hop based routing makes the maximum energy gain (82%) in comparison to stability based routing. But, for the same simulation conditions, when overhearing cost is totally negligible, stability-based routing actually slightly outperforms minimum hop based routing. In the absence of any overhearing, stability based routing reduces the total energy consumption (compared to that at complete overhearing) by 11 times, where as minimum hop based routing reduces the energy consumption by only 6 times.

In the presence of a reduced overhearing strategy (refer Figures 5 and 6), stability-based routing reduces the total energy consumption by at most 3 times the cost at complete overhearing, where as the minimum hop based routing strategy reduces the total energy consumption by only at most 2 times. Similar observations can be made in all the figures of the simulations. This confirms our earlier claim that as the energy consumed per hop for data packet transfer is reduced, stability-based routing strategy can bring significant energy savings than what is obtained by a minimum hop path based routing.

At low packet rates, stability-based routing seems to be better than minimum hop based routing for a majority of the conditions, especially at 64 bytes/packet. Thus, when data packets are sent continuously but at a reduced rate, it is better to use a long-living stable path. If minimum hop paths are used, we may have to discover route to send every packet, nullifying the energy savings obtained due to a reduced hop count. Refer Figures 4.1 and 4.3 where stability-based routing out performs minimum hop based routing even with complete overhearing.

In the presence of complete and reduced overhearing, we observe a trend opposite to that observed at low packet rates: minimum hop based routing out performs stability based routing. The number of hops in a stability-based routing is greater than that in a minimum-hop path based routing at most by a factor of 2.5, where as the number of route transitions in a minimum-hop path based routing can be at worst 10 times larger than that incurred in a stability-based routing. But it seems that at high packet rates, even a slight increase in the hop count can be destructive for energy consumption, especially in the presence of promiscuous listening (complete overhearing).

Except for the condition of 25 nodes, 512 bytes / packet, stability-based routing outperforms minimum hop based routing. In figures 7 and 8, in the absence of overhearing at high network density (75 nodes) and high velocity (50 m/s), stability-based routing is better than minimum hop based routing by at least 150%. This shows that even when the power-saving strategies are not 100% effective, stability-based routing can perform comfortably better than minimum hop based routing.

As expected, the strategy of discarding a data packet after receiving only its header at the non-destination nodes pays off better as the data packet size increases. For example, when the data packet size is 512 bytes (refer Figures 5.2, 5.4, 6.2 and 6.4), reduced overhearing strategy decreases the energy consumption by a factor of 2 – 3; where as if the data packet size is 64 bytes (refer Figures 5.1, 5.3, 6.1 and 6.3), the decrease in energy consumption is only by a factor of 1.2 – 1.3.

In general, it seems minimum-hop based routing is to be preferred for low network densities and stability-based routing at high network densities. At low network density, the energy consumption overhead due to flooding is relatively less due to the reduced number of retransmissions of the route request packets (because of a reduced neighborhood size). At high densities, energy consumption due to flooding is high due to multiple retransmissions of the route request packets because of the increased neighborhood size.

6 Conclusions

The high-level contribution of this paper is in setting up a framework to derive benchmarks to help decide the appropriate routing strategy to minimize the overall energy consumption for a given set of experimental conditions and application requirements in mobile ad hoc networks. We compare the pros and cons of two contrasting routing strategies – routing based on minimum hop path and routing based on stability. This is the first attempt in the literature to study the energy consumption of these two contrasting routing strategies for on-demand routing, in the presence and absence of overhearing and by varying the network densities, node mobility and offered traffic load. The performance results break the myth that in the absence of power control, minimum hop routing gives the least energy consumption for an *s-d* session. The results indicate that in the presence of a dynamically changing topology, selecting stable paths can help to reduce the energy loss due to route discoveries significantly. When the energy loss due to overhearing can be reduced or totally avoided, stable paths start outperforming minimum hop paths by incurring reduced energy consumption per *s-d* session, especially at low values of offered data traffic load. At high traffic load, minimum hop routing is to be selected, especially when overhearing cannot be avoided.

References

[1] S. Agarwal, A. Ahuja, J. P. Singh and R. Shorey, "Route-Life Time Assessment Based Routing Protocol for Mobile Ad Hoc Networks," *Proceedings of IEEE ICC*, June 2000.

[2] C. Bettstetter, H. Hartenstein and X. Perez-Costa, "Stochastic Properties of the Random-Way Point Mobility Model," *Wireless Networks*, pp. 555 – 567, Vol. 10, No. 5, September 2004.

[3] M. S. Corson and V. D. Park, "Bandwidth-Efficient Link State Routing in Wireless Networks," *Ad Hoc Networking*, edited by Charles E. Perkins, Chapter 10, pp. 323 – 350, Addison Wesley, 2001.

[4] R. Dube, C. D. Rais, K-Y. Wang and S. K. Tripathi, "Signal Stability based Adaptive Routing for Ad hoc Wireless Networks," *IEEE Personal Communications*, Vol. 4, No. 1, pp. 36 – 45, February 1997.

[5] K. Fall and K. Varadhan, "ns notes and documentation," The VINT Project at LBL, Xerox PARC, UCB, and USC/ISI, http://www.isi.edu/nsnam/ns, August 2001.

[6] A. Farago and V. R. Syrotiuk, "MERIT: A Scalable Approach for Protocol Assessment," *Mobile Networks and Applications*, Vol. 8, No. 5, pp. 567 – 577, October 2003.

[7] L. M. Feeney, "An energy-consumption model for performance analysis of routing protocols for mobile ad hoc networks," *Journal of Mobile Networks and Applications* Vol. 3, No. 6, pp. 239 – 249, June 2001.

[8] IEEE Standards Department, Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, IEEE Standard 802.11-1997, 1997.

[9] D. B. Johnson, D. A. Maltz and J. Broch, "DSR: The Dynamic Source Routing Protocol for Multi-hop Wireless Ad hoc Networks," *Ad hoc Networking*, edited by Charles E. Perkins, Chapter 5, pp. 139 – 172, Addison Wesley, 2001.

[10] E-S. Jung and N. H. Vaidya, "An Energy Efficient MAC Protocol for Wireless LANs," *Proceedings of IEEE INFOCOM*, pp. 1756 – 1764, June 2002.

[11] B. S. Manoj, R. Ananthapadmanabha, and C. Siva Ram Murthy, "Link life Based Routing Protocol for Ad hoc Wireless Networks," *Proceedings of the 10th IEEE International Conference on Computer Communications 2001 (IC3N 2001)*, October 2001.

[12] N. Meghanathan and A. Farago, "Comparison of Routing Strategies for Minimizing Energy Consumption in Mobile Ad Hoc Networks," *Proceedings of the 4th Asian International Conference on Mobile Computing*, January 2006.

[13] N. Meghanathan and A. Farago, "An Efficient Algorithm for the Optimal Number of Route Transitions in Mobile Ad Hoc Networks," *Proceedings of the IEEE International Conference on Wireless and Mobile Computing, Networking and Communications*, Vol. 3, pp. 41 – 48, August 2005.

[14] N. Meghanathan and A. Farago, "*Survey and Taxonomy of 55 Unicast Routing Protocols for Mobile Ad Hoc Networks*," Technical Report UTDCS-40- 04, University of Texas at Dallas, November 2004.

[15] C. E. Perkins and E. M. Royer, "Ad hoc On-demand Distance Vector Routing," *Proceedings of the 2nd Annual IEEE International Workshop on Mobile Computing Systems and Applications*, pp. 90 – 100, February 1999.