Dynamic Topology Control to Reduce Interference in MANETs

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ABSTRACT

The presence of transient network links and mobility of nodes in MANETs (Mobile Ad Hoc Networks) poses a hefty challenge for such networks to scale and perform efficiently when subjected to varying network conditions. As such, nodes in a MANET can make use of topology control – which is the deliberate adjustment of certain system parameters such as antenna direction and transmission power to form a particular network topology – as a means of improving the routing protocol performance. In this paper, we study some of the methods of topology control used in previous work and propose the Critical Neighbour (CN) scheme, which adaptively adjusts the transmission power of individual nodes according to route and traffic demands, to reduce the level of interference amongst nodes in the network. This helps to increase spatial reuse of the channel bandwidth and reduces the number of collisions, resulting in higher throughput and lower end-to-end delay. We implement our CN scheme on AODV-LR, and simulation results highlight that our scheme is able to achieve better performance than the unmodified version.

Keywords: Topology control, adaptive protocols, scalability, transmission range, interference.

1 INTRODUCTION

Mobile Ad Hoc Networks (MANETs) are wireless networks that offer multi-hop connectivity between self-configuring and self-organizing mobile hosts. These networks are characterized by [1] dynamic network topology, lack of central administration and limited resources such as power and bandwidth.

The network size of a MANET is given by the total number of nodes in the network, which is a fixed number (assuming that no nodes enter or leave the network). Large networks are depicted by a sizeable number of nodes of up to 10 000, while small networks correspond to networks with very few nodes within the same terrain size. While the number of nodes may be a good estimate of network density in homogenously distributed networks, this value may not be indicative of any specific network characteristics in a heterogeneous network where nodes are randomly positioned in the terrain.

From the literature we can identify a few key problems associated with network topology, that are faced by routing protocols in ad hoc networks with varying network sizes and densities. In sparse networks with low node densities, network partitions [2] may be formed when mobile hosts move with contrasting patterns and cause the network to divide into two or more disconnected portions. This can lead to low connectivity and lack of routes to targeted destinations, resulting in higher packet loss and higher control overhead. Although path lengths might be comparatively shorter, this is because routes to further destinations cannot be discovered. The throughput is also lower in such partitioned networks.

As node densities increase, it may be possible to establish path routes to destinations that are further away. Inevitably, the frequency of link breakages within active routes will also increase. More Route Error (RERR) messages will have to be transmitted to nodes which utilize these broken links, resulting in higher rate of occurrence of route repairs. These factors will lead to higher control overhead, increased congestion, greater contention for bandwidth and lower packet delivery ratio.

Dense networks are also characterized by higher node degrees, where each node has more neighbours within its transmission range. This implies higher connectivity between nodes in the network, which can lower the mean number of hops needed between a source and its destination and improve the data delivery ratio. However, a high node degree can also result in more collisions between neighbouring nodes, which means that more energy is wasted at the radio level.

Nevertheless, the network size and density are often invariable parameters in an ad hoc environment. The main focus of previous work has been to reduce the routing overheads caused by routing protocols in dense networks that have uniform node densities and hierarchical routing methods which can incur additional overhead. These methods do not take into account the dynamic network topologies due to node mobility in MANETs, and are inefficient for heterogeneous networks which may not have uniform node distributions.

In this paper, we develop a scheme to improve the scalability of a routing protocol using topology control. The proposed Critical Neighbour (CN) scheme dynamically adjusts the transmission power of individual nodes according to route and traffic demands. This reduces the amount of overlapping interferences between nodes and allows more simultaneous transfer of packets in the network. Hence, performance of the protocol can be greatly improved, especially for dense networks.

The rest of the paper is organized as follows: The next section discusses related work and motivation. Section 3 describes some of the previous work on topology control. In Section 4, we provide a detailed outline of our CN scheme. Simulation results and analysis are presented in Section 5. We conclude with directions for future work in Section 6.

2 RELATED WORK AND MOTIVATION

There has been much published work in the literature which studies the issue of scalability faced by MANETs. Lee, Royer and Perkins [3] examine the scalability of AODV using different combinations of modifications which can be integrated into generic reactive routing protocols. These modifications include the expanding ring search for Route Requests (RREQs), query localization and local repair of link breaks in active routes. Simulation results show that local repair is more effective in improving the performance of large scale networks of up to 10 000 nodes, but it may waste processing power and incur additional overhead because more than one repairs for the same route can occur concurrently.

[4] introduces two new schemes – Fisheye State Routing (FSR) and Hierarchical State Routing (HSR) – which aim to address the shortcomings of existing proactive and reactive protocols via a hierarchical approach. As compared to flat, table driven routing schemes, the proposed solutions are able to scale better at the cost of increased routing inaccuracy and complexity. As compared to reactive schemes, the solutions are able to provide lower control overhead and lower latency but at the cost of routing table storage overhead.

Passive Clustering (PC) and Landmark Routing are suggested in [5] as techniques to overcome scalability problems faced by conventional proactive link state routing protocols. Passive clustering is a cluster formation protocol that can dynamically reconfigure clusters during mobility and topological changes. Landmark routing uses truncated local routing tables and summarized routing information for remote groups of nodes. Both techniques help to reduce the routing table size and the control overhead effectively for dense and large scale networks.

The existing methods which attempt to improve the scalability of routing protocols use hierarchical routing strategies or mechanisms which incur additional overheads. In addition, they are unable to adapt to rapid changes in network environments, which is typical of MANETs. As such, there is a need for an adaptive scheme that is sensitive to network dynamics and can improve the scalability of MANET routing protocols.

3 TOPOLOGY CONTROL IN MANETS

The network topology is defined as the set of communication links between node pairs used explicitly or implicitly by a routing mechanism. Due to the indeterministic nature of MANETs, the topology of the network is often dependent on a number of dynamic factors such as traffic patterns, node mobility, noise, interference, antenna sensitivity and transmission power of nodes.

Methods for network topology control and their effects on network performance have been extensively studied in recent years. The topology of a network can have a tremendous effect on the performance of the network because it influences the way which packets are routed to their destinations. Sparse networks face the possibility of being partitioned while dense networks are subject to high collision rates and bandwidth contention amongst nodes. Furthermore, nodes in MANETs are constantly in motion, making it harder to predict distribution patterns and handle routing decisions.

Ramanathan and Rosales-Hain [6] discuss two decentralized heuristics that adjust the transmission powers of nodes according to topological changes, and which attempt to maintain a connected topology using minimum power. However, these heuristics do not perform well in worst-case scenarios and provide poor approximations in power minimization.

Jia, Li and Du [7] examine the energy efficient QoS (Quality of Service) topology control problem and tries to find an appropriate network topology that can meet certain QoS requirements such as bandwidth and delay constraints while minimizing the maximum transmitting range of nodes.

There are pros and cons related to the extent of transmission ranges covered by nodes in MANETs. A node with high transmission range usually has a higher value of node degree – which is the total number of nodes that are within the transmission radius. This means that there are more one-hop neighbours that can be reached by that particular node, which helps to decrease the average path length and propagation delay during data transfer. However, a high node degree can also lead to greater contention for bandwidth, which reduces the spatial reuse of the channel access by nodes in the network and hence lowers the throughput. Conversely, nodes with low transmission ranges tend to have lower node degrees and lower connectivity. Although there is higher spatial reuse of the channel access, network partitions may form, which could lead to lack of routes and lower throughput.

As such, it appears that there ought to be an optimal node degree which networks should adhere to for maximum performance. According to Kleinrock and Silvester [8], the optimal number of neighbours for each node in a stationary network is six, and the transmission radius should be adjusted accordingly to allow each node to maintain this node degree. However, this analysis does not take into account the mobility effects that mobile hosts in MANETs experience.

The effects of transmission power on the performance of MANETs are studied in [9], which also attempts to determine the optimum node density for maximizing throughput. Simulations performed on AODV show that while there does not exist a global optimum density, the node density should be proportional to the rate of mobility to achieve better network performance. Furthermore, increasing the power transmission of nodes at high mobilities can result in a higher percentage of data packets reaching their destinations, which consequently leads to higher throughput.

Nilson [10] describes the performance analysis of traffic load and node density in ad hoc networks. Through simulations performed using the Modified Random Direction model, it was shown that the optimum node density depends on both the traffic load and the mobility of the nodes. In sparser networks, high delivery rates can be achieved up to a certain threshold (i.e. traffic saturation point), after which it starts to decline. In denser networks, there is usually higher packet delivery ratio at the cost of more power consumption and channel bandwidth.

Most of the previous work done on topology control have been used to optimize power consumption in networks, which is undeniably an important constraint faced by ad hoc networks. However, this paper focuses on how topology control of the network can be used to improve the scalability of the routing protocol by adjusting the transmission power of nodes according to network dynamics.

4 CRITICAL NEIGHBOUR SCHEME

4.1 Preliminaries

We classify the neighbouring nodes of the node of interest into two categories:

- Critical nodes, $C[x]$ = {set of nodes that are required to transmit data}
- Non-critical nodes, $N[x]$ = {set of nodes that are not required to transmit data}

Therefore, the set of all neighbouring nodes of an arbitrary node x can be given as the union of the set of critical and non-critical nodes:

$$A[x] = C[x] \cup N[x]$$

Furthermore,

$$C[x] \cap N[x] = \emptyset,$$

which means that the set of critical and non-critical nodes are two mutually exclusive sets.

We use the Ground Reflection (or Two-Ray) model in our simulations, which considers both the direct path and the ground reflected propagation path between the transmitter and the receiver:

$$P_r = P_t \times \frac{h_t^2 \times h_r^2}{d^4} \times G_t \times G_r$$

where P_r = received power; P_t = transmitted power; G_t = antenna gain at the transmitter; G_r = antenna gain at the receiver; h_t = height of the transmitter antenna; and h_r = height of the receiver antenna.

We hence derive the estimated distance between node x and its i^{th} critical neighbour as:

$$E_{dist}[x_i] = \sqrt[4]{\left(\frac{P_t \times h_t^2 \times h_r^2 \times G_t \times G_r}{P_r}\right)}$$

Taking $G_t = G_r = 0$ dBm = 1,

$$E_{dist}[x_i] = \sqrt[4]{\left(\frac{P_t \times h_t^2 \times h_r^2}{P_r}\right)}$$

While evaluating the estimated distance as above, we keep in mind that this value may not be a true reflection of the actual distance between any two nodes. This is because two nodes in close proximity may also be subject to interferences from the noise in the environment, as well as from surrounding nodes that are transmitting data or control packets.

We also define the critical transmission range of an arbitrary node as the minimum distance required to keep the set of critical nodes $C[x]$ within connectivity:

$$C_{txn}[x] = \mathrm{Max}(E_{dist}[x_i], E_{dist}[x_{i+1}], \ldots, E_{dist}[x_n]), \ 1 \le i \le n$$

where n is the total number of nodes belonging to the set $C[x]$; and $E_{dist}[x_i]$ is the estimated critical distance between node x and its i^{th} critical neighbour.

4.2 Our Adaptive Algorithm

Nodes in wireless networks are subject to interferences from neighbouring nodes within the transmission and interference ranges. These neighbouring nodes may cause higher delay due to contention of bandwidth, as well as higher packet loss due to collisions.

The CN scheme (see Figure 2) attempts to reduce the interference caused by adjacent nodes that are not part of the forwarding routes of a particular node. This is commonly known as the hidden/exposed terminal problem as shown in Figure 1, where a receiving node may experience interferences from other adjacent nodes, resulting in packet loss. There have been attempts to solve this problem in the literature, one of which includes the RTS/CTS dialogue – which necessitates handshakes between the transmitting and receiving nodes that precedes the actual transmission. In the RTS/CTS scheme, a node that wants to transmit data has to send a Request To Send (RTS) control packet, which defers all nodes that hear the RTS from accessing the channel for a specified time period. The destination node responds with a Clear To Send (CTS) control packet upon reception of the RTS. However, the use of the RTS/CTS dialogue will only eliminate collusions caused by nodes within the transmission range and not the interference range.

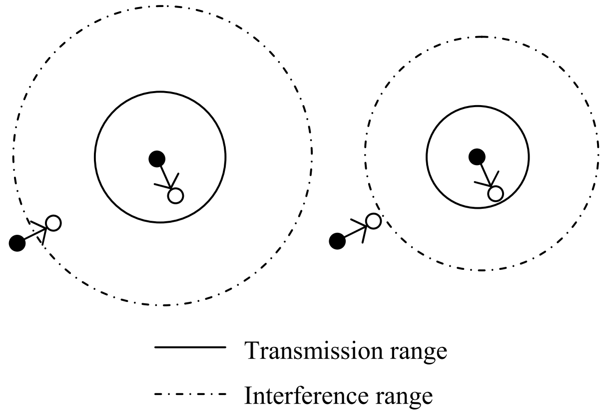

Figure 1: Hidden/Exposed Terminal Problem   Figure 2: Critical Neighbour (CN) scheme

The Critical Neighbour scheme complements the RTS/CTS dialogue to reduce the collisions within the interference range. By reducing the transmission range of nodes such that they reach the minimum distance required to maintain connectivity with the neighbouring nodes that are part of the active routes, unnecessary interferences experienced by other neighbouring nodes can be minimized.

Our adaptive Critical Neighbour (CN) scheme comprises of three main components:

- Measurement of estimated critical range;
- Estimation of the ideal power; and
- Adjustment of the ideal power based on constraints.

When periodic beacons such as Hello packets in AODV are received, the node will calculate the critical transmission range, C_{txn}. This is then used to estimate and adjust the transmission power so that the performance of the routing protocol can be improved.

As such, we estimate the corresponding ideal transmission power as follows:

$$P_{ideal} = P_{min\_r} \times \frac{C_{txn}^{4}}{h_t^2 \times h_r^2 \times G_t \times G_r} \times tolerance\_factor$$

Since $G_t = G_r = 0$ dBm $= 1$,

$$P_{ideal} = P_{min\_r} \times \frac{C_{txn}^{4}}{h_t^2 \times h_r^2} \times tolerance\_factor$$

where P_{min_r} is the minimum signal strength for a packet to be received correctly; and *tolerance_factor* is a percentage which allows for node mobility, as well as some noise and interferences in the environment.

After obtaining the ideal power, it is checked to ensure that it remains within a low power threshold and a high power threshold. This is to avoid nodes that are currently not involved in the sending of any data packets from adjusting their transmission powers to a value that is too low to be of use later on, as well as to eliminate the possibility that nodes will adjust their transmission powers to a value that is too high, which could waste energy resources. Our CN scheme is summarized in Figure 3.

```
/* Handling of Hello packets */
FOR each Hello packet received {
  IF it is received from a critical neighbour {
    Determine the critical transmission range Ctxn;
    Determine the ideal transmission power Pideal;
    IF Pideal is within constraints
      Adjust the transmission power accordingly;
  }
  Update routing and neighbour tables;
}
```

Figure 3: Pseudocode for CN scheme

5 SIMULATION RESULTS & ANALYSIS

We implemented our CN scheme on AODV-LR, which is an enhanced version of AODV with Local Repair and run simulations on GloMoSim [11], which provides a scalable simulation platform for wireless networks. The Random Waypoint mobility model is used with minimum and maximum speeds of 10 ms^{-1} and 20 ms^{-1} respectively and the pause time is set to 30s. Nodes are uniformly distributed and CBR (Constant Bit Rate) traffic with data packets of size 512 bytes are transmitted at an arrival rate of 10 packets per second. The terrain size is set to 2000×2000 metres. Each scenario is also run with at least 5 different seed numbers to minimize any arbitrary randomness.

Our simulations are evaluated according to the following performance measures:

- Throughput – total number of successfully delivered data (in kilobytes);
- Packet delivery ratio – total number of data packets received as a fraction of the total number of data packets originated from all the nodes in the network;
- End to end delay – average time taken to transmit a packet from source to destination; and
- Normalized routing overhead – total number of control packets as a fraction of the total throughput.

Figure 4 to Figure 7 show the comparative results between the performances of AODV-LR and the adaptive AODV-LR enhanced with the CN scheme under varying network sizes. In Figure 4, we observe higher throughput for larger network sizes of more than 50 nodes. Large networks with many nodes tend to have higher node densities. This results in more overlapping transmission ranges amongst the nodes, increased number of collisions and higher packet loss.

In our CN scheme, we adaptively reduce the transmission range of nodes such that there is less overlapping interferences. This helps to increase the spatial reuse of the channel bandwidth. Consequently, there is higher throughput in the network, which also results in higher packet delivery ratio as shown in Figure 5. However, for small network sizes of 50 nodes, the average network density is typically small and reducing the transmission radii of the nodes may result in network partitions.

Figure 6 shows the average delay for the transmission of data in the network. Under the CN scheme, the reduced transmission ranges allow for more spatial reuse of the channel and data packets can reach their destinations faster.

The normalized routing overhead, which is indicative of the efficiency of a routing protocol, is illustrated in Figure 7. Our adaptive CN scheme results in lesser normalized routing overhead because each node has a smaller node degree. As such, during propagation of control packets, there are lesser nodes within the transmission range of the broadcasting node, resulting in less control overhead.

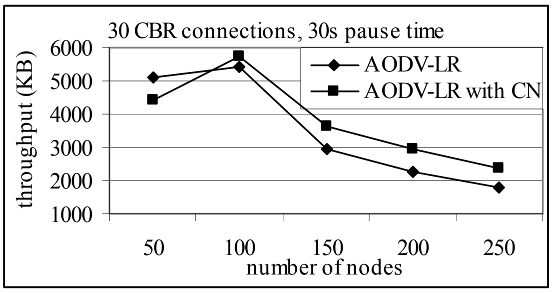

Figure 4: Throughput vs network size

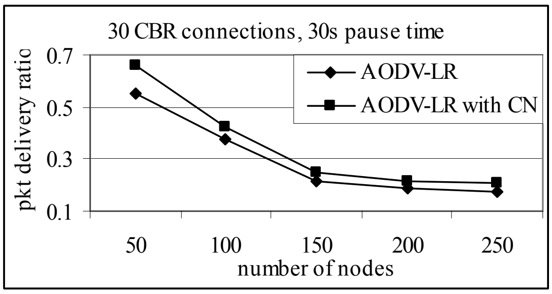

Figure 5: Packet delivery ratio vs network size

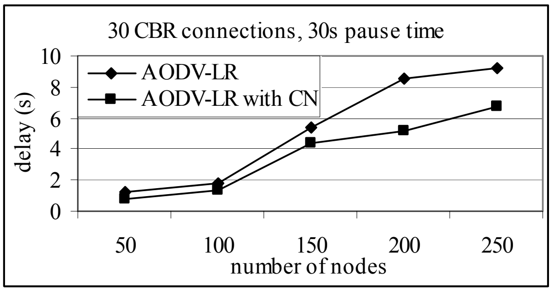

Figure 6: End to end delay vs network size

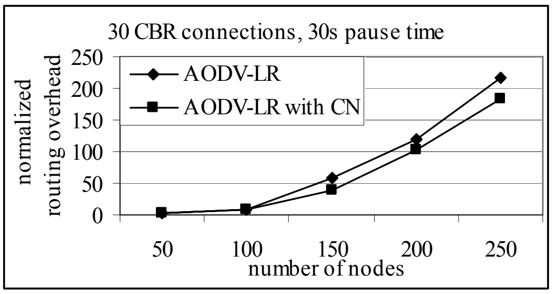

Figure 7: Normalized routing overhead vs network size

We also compared the performance of AODV-LR and our adaptive schemes under varying traffic conditions. 200 nodes were uniformly distributed and simulated under the Random Waypoint mobility model with the same mobility parameters as before. CBR traffic is also used with data packet sizes of 512 bytes transmitted at intervals of 100 milliseconds.

In Figure 8, we observe that the throughput of AODV-LR with the CN scheme is much higher than that of AODV-LR for varying number of data connections. Under the CN scheme, the transmission range of nodes is typically smaller. As such, more nodes are able to transmit data at the same time and thus increase the throughput of the network. The smaller transmission range also results in a smaller interference range; therefore less packets are lost or corrupted, resulting in higher packet delivery ratios as seen in Figure 9.

Figure 10 and Figure 11 show the average end to end delay and the normalized routing overhead respectively. Our CN scheme is able to perform better because of the increased spatial reuse of the channel resulting from the reduced transmission and interference ranges of individual nodes. In addition, this also results in less normalized routing overhead because less nodes receive broadcasted control packets during route formation and maintenance.

We have used P_{min_r} = -81 dBm and tolerance_factor = 1.1 in all our simulations. The value of P_{min_r} is the minimum power of the received packet in order for it to be received correctly by the destination (based on static parameters used for the antenna gains and direction in GloMoSim).

The tolerance factor of 1.1 allows for a 10% inaccuracy in determining the critical transmission range, which could be influenced by both interferences in the environment (due to fading and noise) and node mobility. Having an allowance of 10% difference in the transmission power allows the nodes to maintain the same link even if they move about 10 metres (the minimum and maximum speeds of the current mobility model used in our simulations are 10 ms^{-1} and 20 ms^{-1} respectively) further away from the node of interest after the critical transmission range was calculated in the previous second. This value should be adjusted adaptively according to the speeds which nodes are expected to move under different scenarios.

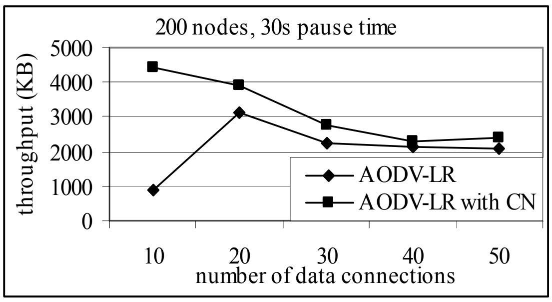

Figure 8: Throughput vs data load

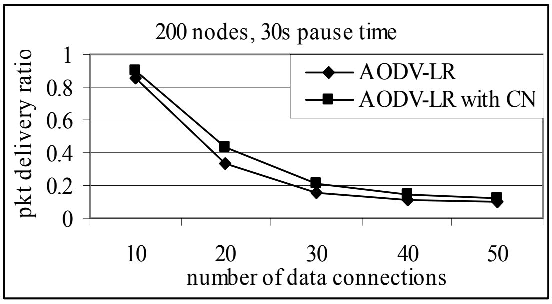

Figure 9: Packet delivery ratio vs data load

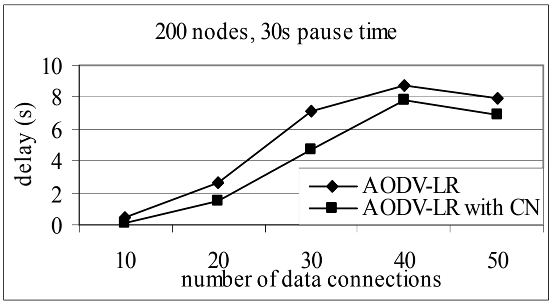

Figure 10: End to end delay vs data load

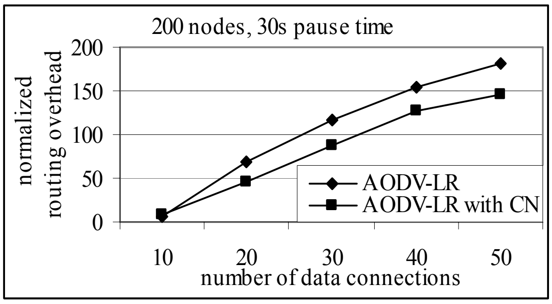

Figure 11: Normalized routing overhead vs data load

6 CONCLUSION AND FUTURE WORK

In this paper, we use dynamic topology control to improve the scalability of routing protocols by reducing interference via the Critical Neighbour (CN) scheme. The transmission power (and hence the transmission range) of nodes are adjusted so that there is reduced overlapping interference amongst neighbouring nodes. This not only helps to increase the spatial reuse of the channel bandwidth, but also reduces collisions among transmitted packets, resulting in higher throughput and better performance.

We have implemented our schemes on top of AODV-LR, an enhanced version of AODV with local repair, and simulation results have highlighted that our adaptive schemes can improve several performance metrics such as throughput, average delay and normalized routing overhead.

As part of future work, we will study the effects of the CN scheme in larger network sizes. Our continued research efforts include the investigation of other adaptive mechanisms to improve the scalability and performance of typical reactive routing protocols.

REFERENCES

[1] S. Corson and J. Macker, MANET: Routing Protocol Performance Issues and Evaluation Considerations, RFC2501, 1999.

[2] K. Wang and B. Li, Group Mobility and Partition Prediction in Wireless Ad Hoc Networks, Proceedings of the IEEE International Conference on Communications (ICC2002), New York City, New York, Apr 28 – May 2, 2002.

[3] S. Lee, E. M. Royer and C. E. Perkins, Scalability Study of the Ad Hoc On Demand Distance Vector Routing Protocol, International Journal of Network Management, Vol. 13, No. 2, Mar 2003.

[4] A. Iwata, C. Chiang, G. Pei, M. Gerla and T. Chen, Scalable Routing Strategies for Ad Hoc Wireless Networks, IEEE Journal on Selected Areas in Communications, Vol. 7, No. 8, Aug 1999.

[5] X. Hong, M. Gerla, Y. Xi, K. Xu and T. Kwon, Scalable Ad Hoc Routing in Large, Dense Wireless Networks Using Clustering and Landmarks, Proceedings of the IEEE International Conference on Communications, (ICC2002), New York City, New York, Apr 2002.

[6] R. Ramanathan and R. Rosales-Hain, Topology Control of Multihop Wireless Networks using Transmit Power Adjustment, Proceedings of the IEEE Conference on Computer Communications (INFOCOM2000), Mar 2000.

[7] X. Jia, D. Li and D. Du, QoS Topology Control in Ad Hoc Wireless Networks, Proceedings of the IEEE Conference on Computer Communications (INFOCOM2004), Mar 2004.

[8] L. Kleinrock and J. Silvester, Optimum Transmission Radii for Packet Radio Networks or Why Six is a Magic Number, Proceedings of the IEEE National Telecommunications Conference, Birmingham, Alabama, Dec 1978.

[9] E. M. Royer, P. M. Smith and L. E. Moser, An Analysis of the Optimum Node Density for Ad Hoc Mobile Networks, Proceedings of the IEEE International Conference on Communications (INFOCOM2001), Helsinki, Finland, 2001.

[10] A. Nilsson, Performance Analysis of Traffic Load and Density in Ad Hoc Networks, Proceedings of the 5th European Wireless 2004: Mobile and Wireless Systems beyond 3G, Barcelona, Spain, Feb 24-27, 2004.

[11] L. Bajaj, M. Takai, R. Ahuja, K. Tang, R. Bagrodia and M. Gerla, GloMoSim: A Scalable Network Simulation Environment, UCLA Computer Science Department Technical Report 990027, 1999.