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SCRIPTED MOBILE NETWORK ROUTING IN A CONTESTED ENVIRONMENT

THESIS

Anthony R. Otto, Captain, USAF

AFIT/GIR/ENG/08-03

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

AFIT/GIR/ENG/08-03

SCRIPTED MOBILE NETWORK ROUTING IN A CONTESTED ENVIRONMENT

THESIS

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Anthony R. Otto, BS
Captain, USAF

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AFIT/GIR/ENG/08-03

SCRIPTED MOBILE NETWORK ROUTING
IN A CONTESTED ENVIRONMENT

Anthony R. Otto, BS

Capt, USAF

Approved:

/signed/	13 Feb 2008
Scott R. Graham, Maj, USAF (Chairman)	Date
/signed/	13 Feb 2008
Kenneth M. Hopkinson, PhD (Member)	Date
/signed/	13 Feb 2008
Michael R. Grimaila, PhD (Member)	Date

AFIT/GIR/ENG/08-03

Abstract

Mobile wireless network protocols currently run on optimistic routing algorithms, adjusting node connectivity only when the chosen connectivity metrics, such as signal strength, pass beyond minimum thresholds. Optimistic routing has several weaknesses. Optimistic routing suffers from increased network overhead during increased frequency of node movement and increased node density per area, and optimistic routing also suffers from non-optimistic access change for individual nodes. The overall communication throughput of a network may be increased if the network topology change is scripted; a scripted plan can allow messages to travel along a more efficient topological path while creating less topology control traffic. This would increase the overall network bandwidth and may be an alternative solution to current network routing problems such as route loop creation.

This thesis tested a network with scripted movement against an unscripted network in a simple network featuring mobility, for increases in bandwidth due to scripted node access changes over optimistic access changes. The results showed significant improvement in the data throughput in the scripted network when there were multiple overlapping networks contending for the same node.

Acknowledgments

I would like to thank my thesis advisor, Maj Scott Graham, for helping me down this long and winding road; I could not see the true end of the tunnel except with his guiding light. I would also like to thank the Air Force and AFIT for giving me this enormous opportunity to better myself and, possibly, the world.

Anthony R. Otto

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I. Introduction

Modern computing increasingly focuses on disconnecting the computer from the wall. Devices are decreasing in size and increasing in portability while keeping the full functionality of a desktop computer; full computers are now the size of a paperback and can run any modern software for hours (OQO Products, 2008). Unfortunately, communicating with other machines in a mobile environment is more difficult than in a wired network, as the movement of machines can break links to the network indiscriminately. A significant portion of all modern computational research is now in the realm of mobile computing; for example, more than sixty papers for mobile systems, mobile computing and ubiquitous computing were submitted for the 2006 ACM Symposium on Applied Computing alone (SAC 2006 Paper Count, 2006). This compares to only eighteen in 2003 (SAC 2003 Paper Count, 2003).

Modern mobile computing research includes creating and improving routing protocols in attempts to improve the throughput by increasing the average number of bits per second of usable communication bandwidth or decreasing the delay between successive communications. One constant in all current research is that nodes will move randomly and protocols are optimistic; in all current research, each node does not know where another node will be travelling to at any point in time, does not know where any node is at any point in time, and does not know its own planned path or velocity at any point in time. These protocols have a limited velocity and network node population, due to the increasing traffic such environments cause.

Nodes can know, at least within a limited duration of seconds to minutes, their future physical or topological travel path. A Global Positioning System connected to an automobile, for example, would expect to continue down an interstate at least until the vehicle arrived at an intersection. In some situations, such as in a military battlespace, a node's movement may be known hours or even days in advance.

If the foreknowledge of nodes can be correlated into a plan, mobile nodes knowing this overall plan for network topology changes do not have to communicate changes, reducing network bandwidth used for topology control and increasing the amount of bandwidth for data transmission. Additionally, nodes can plan their movement to use higher bandwidth paths sooner and avoid connections to areas containing expected network congestion or contention. A system utilizing a scripted topology can improve average usable bandwidth and increase the overall efficiency of network communications, enabling the implementation of larger scale mobile networks that do not fail from excessive topology control overhead.

Background

Modern networking began about 1974, when the Ethernet was first presented by Robert Metcalfe and David Boggs (Kurose, 2005:459). The continuing explosion of computer use and the resultant desire to share information drove the creation of a network of networks, the internet, and pushed the number of systems that comprised the internet to over 433 million by 2007 (Internet Domain Survey, 2007). The use of networks fostered the development of robust routing protocols able to handle large numbers of computers, including RIP (Handrick, 1988) and OSPF (Moy, 1998).

The advent of wireless networking occurred in 1969 with ALOHAnet in Hawaii (Kurose, 2005:439), but such networks were limited by cost, size, and maturity of control. Evidence of increasing availability of wireless networking was shown with the first IEEE Workshop on Wireless LANs, in 1991 (Pahlavan, 2001). The decreasing size and cost of computers and wireless network components has now placed over two hundred fifty million subscribers to some form of wireless communication, including over twenty-two million mobile high-speed connections (U.S. Wireless Subscribership, 2007). The rapid expansion of wireless networking, coupled with the decreasing size of computers, has caused development of network protocols which allow mobility while networked.

Many mobile networking protocols focus on ad-hoc networks, as in AODV (Perkins & Belding, 2003), DSDV (Perkins & Bhagwat, 1994) and OLSR (Clausen & Jacquet, 2003). An ad-hoc network is a network with no pre-arranged structure, in contrast to wireless cell networks or wired static networks.

Problem Statement

Although extensive work has been done on wireless protocols and optimizations, relatively little research has been done in the area of preplanned, or scripted, routing. The potential for improvement due lessened topology control traffic and increased bandwidth during optimized node movement is unknown.

Research Objectives/Questions/Hypotheses

The objective of this paper is to perform an initial exploration of scripted mobility to determine whether there are any obvious advantages to scripted movement on a network over an optimistic network. This thesis specifically tests for differences in throughput between scripted network movement and an unscripted network movement, when a node is moving through an environment with multiple networks.

H_0: There is no significant difference in throughput, on a network with elements of mobility, between a network using a script to control topology changes and a network using no plan.

The intent and focus of this paper is on finding situations and potential topological situations in which a plan influences network throughput, if any such situations exist.

Methodology

This paper uses a network simulator to test multiple identical situations under both scripted mobility and unscripted mobility. Simple situations are used to look for indications of improvements due to scripting independent of network load. The simulations test a single node moving under a single network protocol, AODV, with scripted topology change and without in a single-network environment, then test the same setup in a multiple-network environment. The results are statistically and visually compared to determine differences in throughput.

Assumptions/Limitations

This paper assumed network simulations are viable methods for investigating this type of protocol change. Although network simulators have been evaluated for suitability in performing experiments, there is always a chance some issue with simulations in general or a specific simulator will skew the research results. This assumption includes many smaller assumptions, such as the suitability of a chosen simulator's random number generation, protocol implementation, and model representation.

The modifications done to the various processes within the simulator are assumed to not significantly influence the simulator results. The model changes were tested both with and without an active script; however, there is always a possibility that some variable or process invoked causes unintended side effects only during implementation, and such side affects may skew research results.

This research assumes the chance of two separate networks being accessible to a single node at the same time, during some point in its mobility path, is high. With the number of devices that connect to the internet constantly growing, and the availability of consumers to obtain increasingly sophisticated wireless networking technologies increasing, there seems to be a time coming when there will be more than one network accessible in at least a portion of areas a mobile node is travelling through. For an area such as a battlespace containing an extensively networked military, the possibility that there are two networks or subnetworks in an area, such that a device common to the military could potentially talk on either network, seems high. If future situations or future technology avoid network overlap, the experiments in this thesis would not have direct application to wireless network routing.

Implications

If network planning is shown to increase the average throughput of a network compared to a network with no plan, then adding planning to a network would increase the average throughput of a network. Wireless networks would be able to send increased amounts of data, and would be able to support larger-scale networks. Planning could become an integral part of mobile communication, increasing a mobile network's overall efficiency in using its bandwidth. This has direct implications on planned networks, such as deliberately deployed sensor arrays and battlefield networks; further research may find a method to develop a script for a broader range of mobile networks.

II. Literature Review

Chapter Overview

This chapter reviews various factors and design considerations for the experiment performed. Several papers identify the capacity of wireless networks, the advantages to hierarchical routing, and the difficulties in creating or maintaining that hierarchy. Several protocols identify the history of networking protocols, and various wireless protocols represent key differences between the algorithms used in wireless networking. Works pertaining to performance differences between protocols are discussed, with differences in experiments noted and relevance to large-scale mobile networking identified. A comparison between two different simulators highlights the advantages of each in simulation and future experiment portability.

The Capacity of Wireless Networks

The scalability of wireless networks has been a constant issue and driving force in wireless protocol development.

Wireless networks have been shown to have limited scalability (Kumar, 2000). Specifically, the most optimal possible throughput is on the order of $\frac{W}{\sqrt{n}}$, where W is the capacity of a single link, and n is the number of nodes in the network. Wireless networks can show improved throughput with the support of an infrastructure or other out-of-band communication, on the order of $\frac{W}{\log(n)}$ or even close to 1 (Kozat, 2003). The issue is putting such an infrastructure in place. Attempts have been made to use additional wireless nodes as a backbone for the wireless network; one such protocol paper noted such a hierarchy is more suited to low mobility environments, where control traffic would not overwhelm the data traffic (Banerjee, 2001).

The Internet Protocol, and IPv6

The Internet Protocol, or IP, is a protocol handling the transmission of data from a source to a destination in a network or between networks (Postel, 1981:1). With the explosion of networks, the number of addresses in the 1981 specification was predicted to be insufficient for future needs, and a new specification was formed in 1998 called IPv6 (Deering and Hinden, 1998) to increase the total address space significantly, simplify the data packet addressing header, and add extensions and options not envisioned in the 1981 specifications (Deering and Hinden, 1998:2).

IPv6 was chosen as the underlying end-to-end protocol for the thesis experiments. The thesis exclusively performs experiments that do not impact this network protocol level. IPv6 was chosen due to the increasing importance predicted for IPv6 and the potential removal of IPv4 in the near future; choosing IPv6 may lessen the number of changes needed in future research to bring the research closer to practical use.

Wired Network Protocols

Wired networks are characterized by high bandwidth, relatively stable topologies, and relatively few issues with detecting nodes. Wireless network protocols focus on allowing a topology to be efficiently and completely represented and modifying the topology representation quickly to minimize connectivity issues. Features such as quality of service levels, multicasting, and special area representation have become more important factors to wired network protocol design.

RIP

RIP, or Routing Information Protocol, was a standard created from a common and prevalent routing protocol developed from the early days of ARPAnet (Hedrick, 1988:2).

Routers using the RIP protocol iteratively share information with neighbors through a distance-vector algorithm. Each router can route progressively farther as other systems share data from progressively more distant routers during each iteration of the protocol. Thus, given enough iterations, a single router’s table will contain the route to send any packet of information to get the packet to its destination. A router will periodically send messages to ensure the links to other routers are still viable. The iterations of RIP and periodic messages were timed randomly and at sufficient intervals to not overload the network with synchronized network control traffic (Hedrick, 1988:23).

Although RIP converges in a finite time (given a static network), the time required to converge is not determinable (Hedrick, 1988:8). RIP is designed for moderate size, homogeneous networks where the number of links traversed between source and destination nodes is less than 15 (Hedrick, 1988:4).   RIPng is a version of RIP created to handle the requirements of an IPv6 internet (Malkin and Minnear, 1997).

OSPF

OSPF, or Open Shortest Path First (routing), was published by the OSPF working group of the Internet Engineering Task Force (IETF) in 1989 (Moy, 1989), and was updated to OSPF version 2 in 1991 (Moy, 1991). OSPF was developed because RIP, the standard of the time, was limited in the size of the network it could handle (Hedrick, 1988:11). OSPF attempted to solve some of the issues that had arisen with RIP, including the potential for loops, the slow convergence of RIP routing tables for large systems, and the lack of authentication of route updates. The result of the working group was a protocol that used a completely different style of algorithm, called a link-state algorithm.

Routers using OSPF periodically flood the network with their neighbor information, and use all router information received in the link-state algorithm to determine the shortest path to each router area. Like RIP, OSPF sends updates at randomized times to de-synchronize updates sent by routers.

The OSPF routing table converges in a finite, known time for a given number of routers, unlike RIP. The restriction on the number of links traversed between a source and a destination is very high, on the order of a thousand. OSPF for IPv6, sometimes called OSPF v3, is a version of OSPF created to handle the requirements of IPv6 (Coltun, 1999).

IS-IS

IS-IS, or Inter-System to Inter-System (routing), started development in 1987 from the DECnet Phase V routing algorithm (Bhatia, 2006:4). IS-IS was developed as part of a protocol stack conforming to the OSI layers, interfacing with other protocols at approximately the same level as IP, sending data directly through layer 2 protocols (Bhatia, 2006:7). Soon after its initial publication, the IETF IS-IS working group published an extension of IS-IS to handle both an IP-only network and a dual IP and OSI network (Callon, 1990).

IS-IS, like OSPF, is a link-state algorithm-based protocol. Unlike OSPF, IS-IS does not communicate between routers via IP, but rather a proprietary message format. There are advantages and disadvantages to this non-IP routing traffic, but overall it causes little impact. IS-IS sends periodic floods of routing messages to ensure updated route tables, and has extensions to support most current topology and traffic considerations (Bhatia, 2006: 12).

The IS-IS routing table converges in a finite, known time for a given number of routers. The restriction on the number of links traversed is somewhat high, on the order of sixty, with extensions allowing thousands of consecutive links between source and destination. IS-IS needed no significant change to be able to handle IPv6 (Bhatia, 2006:23).

Wireless Network Protocols

Wireless networks are characterized by changing bandwidth and unstable topologies, making it difficult to detect all nodes in the network at any one time. In addition, many wireless applications, such as remote sensors and networked digital assistants, are constrained by power. Wireless protocols focus on aspects of minimizing control transmissions, maximizing connectivity, and maximizing fault tolerance of routes, although usually not in equal portions. Each protocol attempts to maximize average usable bandwidth, given certain constraints on network mobility and size.

AODV

AODV, or the Ad-hoc On-demand Distance Vector protocol, was published by the IETC MANET working group in 2003 (Perkins and others, 2003). The MANET working group was created to standardize IP routing in topologies with increased dynamics, such as mobile networks (MANET, 2007). AODV was designed to allow quick, on-demand routes to be created from source to destination, without loops and with low overhead (Perkins and others, 2003:1).

Each device using AODV has the potential to route traffic, and each keeps a table of current routes. A device wishing to contact another using AODV floods the network to a limited routing distance with a request to communicate with the destination. The flood messages record the path each takes, and the one that reaches the destination has a complete path from source to destination. Additional considerations are handled, such as using specific sequence numbers to stop loops and handling breaks in the route (Perkins and others, 2003:3-4). Routes have a short time they are kept, essentially causing only used routes to stay active in the tables of any one node.

The AODV routing algorithm does not necessarily ever learn the entire network topology; AODV need not communicate as much topology information and can conserve bandwidth. AODV can handle a large number of links between source and destination.

OLSR

OLSR, or Optimized Link State Routing, was published in 2003 (Clausen and Jacquet, 2003). OLSR was designed to allow efficient routing in dense but dynamic networks through the use of proactive routing and designated relays (Clausen and Jacquet, 2003:1).

OLSR allows limited flooding for determination of short-distance neighbors, but minimizes large-area flooding through the use of multipoint relays, which are selected dynamically through algorithms to ensure both a minimized set of relays and a maximally connected network. The algorithm utilizes a link-state routing algorithm like OSPF or IS-IS, and potentially learns the entire network topology.

TORA

TORA, or Temporally Ordered Routing Algorithm, was published in 2001 as an alternative to link-state or on-demand protocols (Park and Corson, 2001). TORA was specifically designed to handle sparse networks with a minimum of route update traffic, while allowing both proactive and reactive routing when requested (Park and Corson, 2001:2).

TORA performs routing through a link-reversal algorithm; this algorithm is run once per route required and assigns values to each routing node, such that higher-value nodes can only forward traffic to lower-value nodes, and the destination has the lowest value. Thus, traffic being forwarded must eventually reach the destination node. Cases such as link loss and network partitions are handled (Park and Corson, 2001:3-8).

TORA is not designed to provide routes to all network nodes. TORA can handle on the order of four billion links between source and destination nodes (Park and Corson, 2001:12-13). TORA's algorithm allows re-routing of traffic without new network control traffic.

ZRP

ZRP, or Zone Routing Protocol, was published in 1997 by Cornell University (Haas, 1997). ZRP was an attempt to reduce network control traffic through the hybridization of proactive and reactive protocols (Haas, 2002).

In ZRP, each routing node keeps a periodically updated, proactive record of other nodes within a certain hop distance from the routing node; this is the routing node's "zone". To communicate beyond its zone, a routing node floods route request messages from the border of its zone to other zones (Haas, 2002); this reduces the overall traffic involved by the factor of the zone radius.

Routing Concepts

LAR

LAR, or Location Aided Routing, was published in 1998 from the Department of Computer Science at Texas A&M University. More of a concept than a fully-developed protocol, LAR showed the potential gain of leveraging a node's location during routing to improve routing performance (Ko, 2000).

LAR showed that there was significant improvement in routing when nodes routed using information on the destination's last known location, over many densities and speeds of simulated MANET random movement. The improvement, in terms of routing packets per data packet and number of routing packets per route discovery, was on the order of twenty to fifty percent over all densities and speeds of nodes.

Simulators – OPNET and NS2

OPNET models networks in a multi-layer GUI approach; nodes, processes and states are each modeled at a different layer. OPNET allows the user to change any of these layers separate from other layers. A state can be changed for a common process, affecting all nodes using that process and therefore the entire network; a new process can be added to just one node type, changing those nodes but leaving all other nodes untouched (Begg, 2006:10).

NS2 models simulate networks through text definitions of the nodes and links in a two-layer approach; a definition of the object type, and a list of objects and their associations (Altman and Jimenez, 2003:14). NS2 can also have different objects modified with or without changing other objects, but the process is intrinsically different due to the emphasis on written definition in NS2 over GUI modeling in OPNET. NS2 includes a visualizer to graphically show the network simulation, but this visualizer only shows the finished network; it is not used in network simulation set-up directly.

Protocol Comparisons

Iwata measures on-demand routing, such as AODV, Fisheye State Routing (FSR), and Hierarchical State Routing (HSR, developed in-house) (Iwata and others, 1999). This comparison was geared toward large networks and validating the HSR protocol as advantageous in large situations; the tests used the number of nodes as one factor, and mobility of one hundred communication pairs as a separate factor.

Their conclusion shows on-demand routing is better for smaller networks, while proactive routing and hierarchical routing has definite benefits for networks containing more than one hundred communication pairs.

Latiff and Fisal compared DSDV, AODV, DSR, TORA, ZRP, LANMAR and LAR; the results show again that the size of the network determines the best protocol for the situation; DSDV, AODV, TORA and DSR are favored smaller networks, while ZRP, LANMAR and LAR perform better in larger networks (Latiff and Fisal, 2003).

Royer performs a broad comparison between DSDV, CGSR, The Wireless Routing Protocol (WRP), AODV, DSR, TORA, Associativity-Based Routing (ABR) and Signal Stability Routing (SSR) (Royer, 1999). Royer compares table-driven and source-initiated protocols separately and all together.

Among the table-driven protocols, WRP, DSDV and CGSR all have the same amount of communication complexity to solve link failures and additions, but WRP has a lower time complexity, since a single node does not communicate changes to the entire network, but only to neighbors (Royer, 1999:52-53).

Among source-initiated protocols, Royer describes each protocol as best for a specific situation. DSR is efficient for small, moderate-mobility networks; TORA is best for large, dense networks; ABR is useful when stable routes are required, and SSR has potential to be more efficient than ABR, but also has a lack of partial route recovery and lack of partial route discovery, both of which can speed up connection time (Royer, 1999:53-54).

Royer's comparison of table-driven routing versus source-initiated routing notes the advantages of route discovery for table-driven protocols in general, and the disadvantages of higher bandwidth and power use due to the need for periodic updates (Royer, 1999:54).

Summary

Numerous routing protocols have been developed over the course of computer networking. There is a marked difference between the requirements for a protocol in the static, wired network environment and the dynamic environment of a wireless network. Specifically in a MANET, the optimal routing algorithm can be markedly different based on the density and speed of the nodes.

A key to all MANET routing protocols studied is the minimization of route control traffic to increase the ratio of possible data traffic. This minimization can be accomplished through on-demand routing (Perkins and others, 2003), minimizing the scale of request flooding (Clausen, 2001), minimizing the number of messages through hybridization (Haas, 2002) or unique routing schemes (Park and Corson, 2001) (Ko, 2000).

There tends to be at least two types of MANET protocols: proactive, table-driven protocols which maintain nearly up-to-date paths in memory at all time; and reactive, on-demand protocols which develop routes only when needed. Different protocols differ in method and designed scale, and each can be best for a given situation.

III. Methodology

Chapter Overview

This chapter details the logic, methods, and instruments used in testing the research hypothesis. A scripted network is only useful if there is a significant improvement of a scripted network over an unscripted network. Proper testing is the only way to determine differences that arise between a scripted and an unscripted network; proper testing involves isolating the factor to be tested, such as the presence of a script, from outside factors, such as the performance of one specific protocol over another. The experiment was designed to minimize undesired factors, to give more accurate and reliable results on the difference between the scripted and unscripted network. The simulation runs the same network with the same code, environment and random seeds; the only item that changes is the inclusion of data that constitutes a set of scripted movements within the topology.

Simulator Choice

Begg noted that both OPNET and NS2 were the best choices for their simulations (Begg and others, 2006:52). NS2 handles models programmatically, while OPNET handles models in a graphically modular fashion, but both had adequate levels of support and would be able to simulate a wireless environment with appropriate results. These two simulators were the only two readily available for this project. OPNET was chosen for the simulator because future theses would most likely build upon this work, and

OPNET’s modules allow developed functionality to be modularized for future simulations.

Protocol Logic

The proposed protocol modification uses a script to plan node movement. The modifications to the simulator processes utilize aspects of common wireless and router implementations to control topological node movement in the network. At a given time, the node first forcibly changes its physical-layer channel. The node then updates its address. Finally, the source and destination nodes send traffic with source and destination reflecting the current addresses of the communication pair.

Protocol Implementation

The choreographing of node movement through a plan is done through two functions already present in current wireless internet protocols: wireless channel changing and router soliciting. OPNET simulator processes are then used to automatically handle re-addressing of traffic in response to node movement.

A script describing all network movement in terms of topology changes is distributed at initialization of each node; each node reads a file containing a node index, the time, and new channel the node will connect to. The modified processes use this data to trigger wireless channel and node address changes at the specified script times.

The modified processes add time-based channel changing to the wireless model, to support scripted movement based on the time triggers in the script. Wireless channel changing is a required part of wireless access cards supporting mobility; there is always a chance a node will move out of range of its current access point and will need to find another. Channel changing usually involves scanning for the next available channel; the script protocol adds a modified procedure which mimics changing to a new channel after a successful scan.

The script-based protocol times a router solicitation to coincide with an access point channel change, to quickly get an address within the new subnet area the node moved into. Router soliciting normally allows a node to request a new address from a router when first connecting to the network (Deering, 1991); the node requests a new address after it has connected to the new access point. Without a new address to coincide with an access point change, the new router may not know of the movement of the node and won't forward traffic appropriately.

As nodes are changing addresses, the source-destination pairs must change their packet destination addresses to match the addresses based on the plan. OPNET automatically addresses packets with correct destinations, regardless of movement, if the application source and destination are defined by name instead of address. Although implementation was scripted to be implemented through code modification, OPNET showed the capability for automatically re-addressing packets between source-destination pairs in an application regardless of addresses. In the application setup of FTP file transfers, the source and destination were entered by name; the "by name" entry automatically modified packet destinations to match any new addresses as nodes moved. This method simulates the packet addressing by plan sufficiently and coordinates with the movement plan.

Dynamic routing tables were not implemented, and only end nodes show scripted mobility.

The initial experiment included a form of global geographic addressing connected to area routing; geographic routing has the potential to facilitate movement planning. Due to time constraints, the geographic routing portion of the experiment was removed from the research.

Base Protocol

For the purposes of this paper, the protocol modifications were created to coincide with AODV. The modified routing does not change AODV, and can be used with any routing protocol. AODV is tested with and without the plan for differences.

Protocol Performance Metrics and Measurement Tools

End-to-end data throughput will be used as the measure of MANET protocol performance; this is one of the performance measurements noted by the MANET working group RFC on MANET protocol performance issues and evaluation considerations (Corson, 1999).

OPNET's statistic measuring was used to collect data for analysis, and the number of IPv6 packets per second received by the server was chosen to represent end-to-end throughput. The IPv6 statistic was chosen over other statistics because this statistic seemed to exclude control traffic and showed no packets received when there was no network connectivity to the client. In comparison, client IPv6 packets showed traffic even without connectivity, as the client continued to connect to the routers. The data collection rate was set at one second intervals.

Each setup was run thirty times, each with a different random number seed; the results were averaged and compared. The packet throughput difference between unscripted and scripted AODV was statistically analyzed using JMP 6.0.2 for Windows (copyright 2006 SAS Institute, Inc.) to determine whether there was a statistical difference between a network with and without a plan, and, if possible, which protocol performed better than the other.

Common Experiment Settings

Each connection in the experiment uses a different non-interfering channel to eliminate the possible effects of interference on the experiment; 802.11a was chosen as the wireless protocol because it has more non-interfering channels than 802.11 b or g.

Applications and movement were delayed seventy seconds in all cases to allow the network to fully initialize, and only the server moves during the simulation.

In all cases, routers advertising an access point were denoted with a circle, centered on the router and with a range equal to the maximum range a node could communicate with the router meaningfully. Each router communicates with only one other router using a dedicated 802.11a channel. The network is based on a star pattern, with a four-interface wireless router in the center, labeled router_0. All other routers are two-interface wireless routers.

All routers were set up as identically as possible; when a setting was router-specific, each router has the same setting. When a setting was interface-specific, each interface was set as similarly as possible. Each interface set as an access point was given a unique subnet range for its access point. Each router interface and each client was given a unique IPv6 address. Any settings not dealing with the routing protocol, wireless channel number, or wireless protocol (as in 802.11a) was left at default settings. Any setting for the wireless protocol not dealing with either allowing or disallowing the protocol use was left at default settings.

Network Topology Experiment: Uncontested and Contested

A topology was created to explore the effect of planning in an environment involving multiple networks. See Figure 1 and Figure 2.

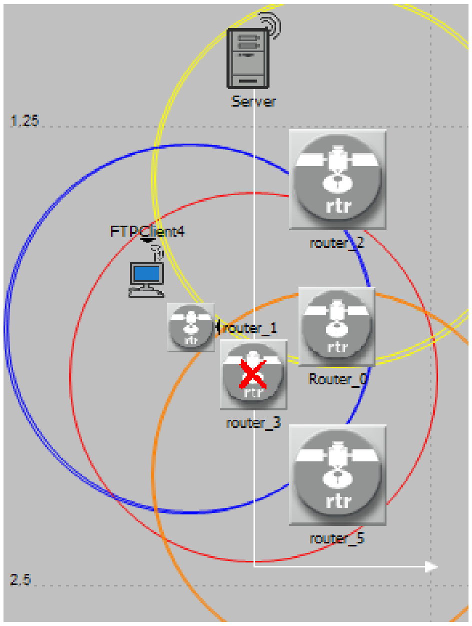

Figure 1: Network Setup (Uncontested)

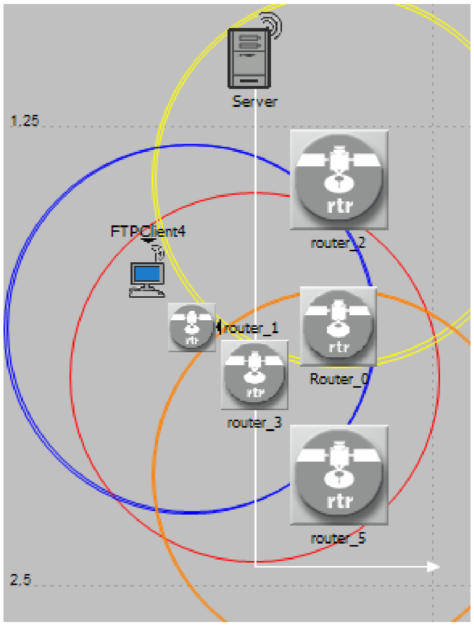

Figure 2: Network Setup (Contested)

Only a single client and server, using repeated FTP file transfers of fifty thousand bytes, tested connectivity and throughput, while the server moved along the white trajectory. The route is effectively a straight line, and the server is travelling at a constant thirty kilometers per hour. The turn close to the end is present to test server connectivity outside of router_3's AP, while ensuring the server does not leave the AP coverage of the larger network.

Routers hosting an AP are denoted by a circle centered on the router, with the circle width equal to the maximum effective communication range between the router and another node. Router_3 is a separate network, hosting its own AP and not connected to the other routers. All other routers are connected only to router_0. The router in the center, Router_0, hosts no AP. This network was tested with router_3 not interacting with the other network at all, as shown by the "x" on router_3 denoting a failed, or shut-off, node in

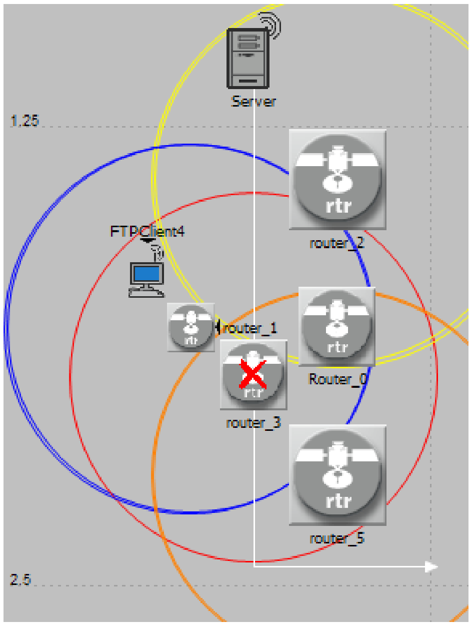

Figure 1, and with router_3 in direct contest with the connected network for the server when the server must change its AP, as shown in the center of Figure 2.

Summary

The experiment was designed to minimize undesired influences to the results; this increases the validity of the script as the source of any differences in throughput between the scripted and unscripted networks. Thirty simulation runs were performed on a simple structured network, involving a single mobile node, to average and minimize the effects of outlying data in a single experiment. The results are examined statistically to determine any difference between scripted and unscripted networks.

IV. Analysis and Results

Chapter Overview

This chapter details the results from the experiments between scripted and unscripted networks. The results were examined visually and statistically, to determine what results, if any could be determined from the data.

The data showed distinct sections where throughput showed significantly different characteristics; these coincided with topology changes. The data from each topology change area was grouped before statistical analysis to determine whether there were statistical differences in the medians of each section and within each section.

The experiments showed improvements of the scripted over the unscripted network, and suggested planning would have significant advantages when multiple networks were in the same area.

Visual Results of the Network Simulations

The results from the simulations were averaged, then graphed to visually examine the data; the difference between the scripted and unscripted network throughput was examined both visually and statistically. There was a statistically significant increase in the throughput of the scripted network when the network to connect to was contested.

AODV without Planning

The results from unscripted network between an uncontested environment and a contested environment showed significant differences; see Figure 3.

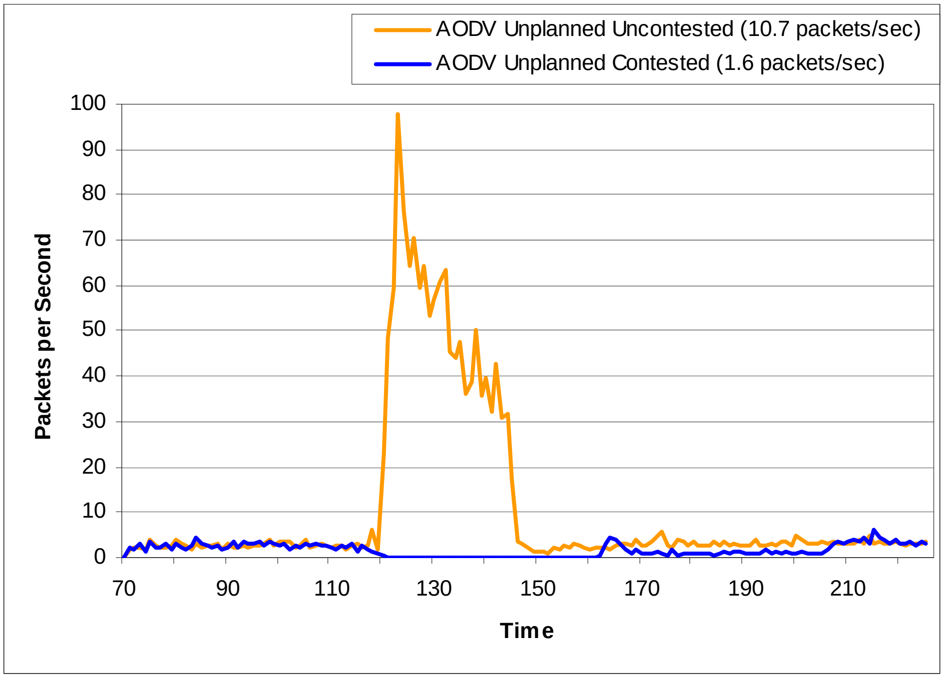

Figure 3: AODV Throughput without Planning

AODV exhibited increased throughput when the server was communicating on the same channel as the client; the throughput was greatly reduced other times. As expected, AODV exhibited no throughput when the server chose to connect to the contesting network.

AODV with Planning

The results from the scripted network in an uncontested and a contested environment were almost identical; see Figure 4.

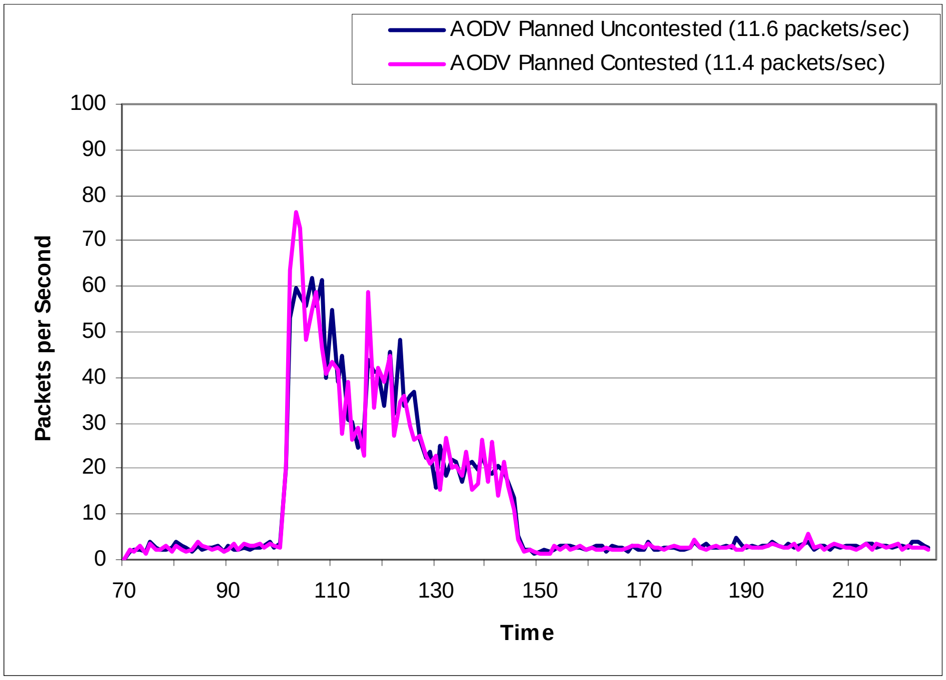

Figure 4: AODV Throughput with Planning

Again, AODV showed increased throughput when both client and server were communicating on the same wireless channel; in the contested case, the planning allowed the server to connect to a channel on the non-contesting network and continue to transmit to the client.

Partitioning the Data

In the network both with and without planning, there seem to be distinct sections of communication which correspond to the topology changes as the server moved. All graphs of network throughput were combined to visually identify different sections, as in Figure 5. These sections corresponded to wireless channel changes, which were used to partition the data for statistical analysis. The data was categorized as occurring before one hundred seconds, occurring between one hundred and one hundred fifty seconds, and occurring on or after one hundred fifty seconds.

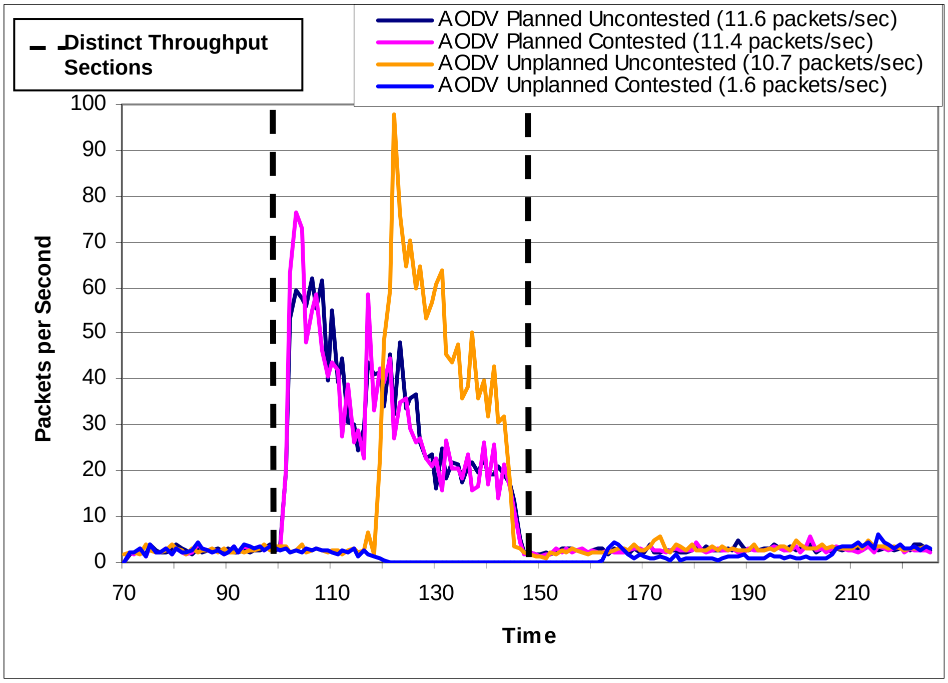

Figure 5: Throughput Sections of Scripted and Unscripted Networks

Difference between Unscripted Network and Scripted Network while Uncontested

Although there are visual differences between the scripted and unscripted network throughput for the uncontested case, statistics show the data to have no statistical significance. The data between one hundred and one hundred fifty seconds was not normally distributed, so the Krushkal-Wallis test was used to test the rank of the medians against each section against the others. The Krushkal-Wallace test showed no significant difference between the rank of the medians for the uncontested network (p=0.756), and we cannot reject the hypothesis that the difference between the scripted network and unscripted network is 0.

Difference between Unscripted Network and Scripted Network while Contested

Both visually and statistically, the network with planning performed better than the network without planning when there were contesting networks involved. The data between one hundred and one hundred fifty seconds was not normally distributed, so the Kruskal-Wallis rank test was performed; the test showed a definite rejection of the hypothesis that the medians were equal ($p<0.0001$). A z-test was performed on the data from the section one hundred to one hundred fifty seconds. The results showed any differences between the means of the network types were almost certainly not due to chance, and the difference was most likely in the favor of the scripted network. The mean difference in the data showed the scripted network averaging almost twenty-nine more packets per second than the unscripted network.

Summary

The average simulation run throughput in the networks without contention showed no difference with or without planning, statistically, but some difference visually. The network with planning had a higher mean throughput than the network without planning.

V. Conclusions and Recommendations

Chapter Overview

This chapter discusses the results and implications of Chapter four, and indicates avenues for further research. The research shows increased throughput when contesting networks are involved in the environment; this could have significant results in all aspects of wireless networking, as the number of overlapping networks increases. There are significant potential scalability advantages to a scripted network, as control of a network with a plan can simulate a hierarchical static network. Many aspects of network movement planning have not been researched, and such research could reap significant increases in average throughput for wireless networks.

Experiment Conclusions

The planning test did not show significant differences between the unscripted network and the scripted network in a low-mobility environment with no contesting networks. The scripted protocol was very beneficial in an environment where multiple distinct networks using the same wireless technologies coexist, as it can increase throughput through optimal AP choices.

Significance of Research

The future military battlefield networks could immediately see benefits to the use of this research. The current military battlefield is quickly becoming a mass of semi-connected networks. Even if two sub-networks are connected through a common backbone, each may use different means to reach that backbone; a single unit connecting to the wrong network would experience significant data delays and additional chances to lose data as the traffic travels through longer paths. Even in a homogeneous network, scripted movement and access point changes have the potential to optimize bandwidth use and minimize AP or MANET topology changes. The military already plans its movements, so developing the network movement plan can simply build on battle plans already formulated.

Mobile networks are increasing in number; there is a much greater chance for nodes to choose an incorrect AP and lose significant bandwidth. A mobility plan may also increase the average throughput of a connection by changing to a new AP while both APs have a strong signal, decreasing the likelihood of interference causing errors. Adding a plan to mobile protocols will reduce the throughput loss that occurs with loss of connectivity.

Planned Movement against Common 802.11 Wireless Channel Changing

The common method for 802.11a, b and g to change channels is to scan each frequency channel, in order of frequency, until a new access point is found. This opportunistic channel changing will scan all channels for a signal, as nodes do not know when a channel will contain an access point. With a script, the node can change to the channel containing the access point immediately. This scenario was initially tested; the results showed a scripted access point change can be up to five times faster than the standard change, occurring in one tenth of a second instead of up to half a second. However, these results were found to be insignificant in the low-mobility setting of the tested scenario.

Using a Distributed Plan to Emulate a Static Hierarchical Network

A mobile network is characterized by its ubiquitous node movement and frequent topology changes. Both proactive and reactive protocols can cause increased network control message traffic in networks where there are increasing numbers of nodes and when nodes move at increasingly higher velocities, limiting the overall scalability of these types of protocols. By scripting both node movement and routing changes, the two types of topology change in the network are isolated from each other. The scripted network's traffic can flow along paths which minimize control message traffic. A scripted network could be implemented in a distributed manner with almost no control traffic overhead using scripted address changes, scripted routing changes, and a set of hierarchical nodes for computer lookup.

The key to emulating a static network would be a geographic addressing scheme. A geographic-based routing protocol allows emulation of a static network through separation of the node movement and the routing changes, allowing each to be handled separately. Each can be linked to the geographic map as a common reference instead of to the other change type. Thus, for each of the two changes, it is possible to map the other topology change statically. IPv6 has enough space in its addressing scheme to hold addressing space to map the entire world to less than one square meter two-dimensional resolution, a unique ID that will allow any number of interfaces to coexists at the same fifty-bit location address while providing possibilities for finding nodes that did not follow the script, and a small amount of space to specify both IPv6 address type and subnets. There would still be room for optimization in this addressing system, as the mapping also maps the almost empty oceans to one-meter resolution as well.

The key to distributing this scripted network control would be a distributed DNS-style node lookup. The nodes for this lookup would have a portion of the plan related to nodes below them in the hierarchy, transmitted from the nodes themselves. These servers could be polled for a node's address by node ID and any part of an address; the distributed hierarchy would allow the IDs to be searched efficiently. Additionally, node lookup could be cached, sending fewer messages to find frequented nodes. The hierarchy allows the lower-level ID servers to keep track of node movement changes without flooding the entire network.

Nodes could keep track of their own expected path, and from their path make their own "script", which they send to the ID server. The node would know of its own movement, which it would use to create its change script. The node would update the server every update period plus a random amount, avoiding the synchronization problem which was shown to occur in "timed update" scenarios (Hendrick, 1988:23). The updating node would send updates long enough to cover the maximum time before the next update. When sending messages to other nodes, the sending node would send enough of its future movement within the message header to ensure the receiver knew where to send the return message, eliminating the need for multiple node lookups for one communication stream.

The routing in such a system would use area routing to separate node movement from routing changes. Each router could router over a certain geographic area, based on the extent of their wireless coverage. A hierarchy of areas could be covered by a hierarchy of routers; higher-level routers would cover a larger "virtual area" of routers subdividing the large area. At the highest level, multiple routers would share their scripts denoting planned coverage with each other to resolve conflicts of coverage. One possible method to map an area of coverage would be to note the expected range of the wireless broadcast, and map a rectangle, cube or pyramid within that area. Whether a node was covered would be two lookups in a table, corresponding to the upper-right and lower-left corners of the large area, and also corresponding to the edges of each sub-area covered by lower-level routers.

For an area always connected, the routers could change their coverage based on their movement; as the routers moved, the areas covered by the routers would also change, but the addresses would be routed to the same geographic locations as another router moved to cover the area. This could correspond to multiple aircraft, each a separate router, providing wireless coverage of a single area, for example.

For an area not always connected, the routers at the highest hierarchy which does cover the area could send a message back to the sending node noting the time the area is planned to be covered, allowing the node to plan its next transmission without polling the network and increasing control traffic.

This area routing style could also be improved; the addressing scheme might be optimized for the most common aspect of looking up an area, for example.

Such a described plan, if proven feasible, could host many nodes or high-speed nodes without significant loss of network throughput due to topology control messages.

Recommendations for Future Research

There are many areas in network movement planning that must still be researched to determine the true impact of a network plan. The direct areas of research stemming from this study include creating a more robust protocol to investigate high-speed movement and protocol optimization. The addition of mobility to a wireless structure network, in the form of mobile routers, can also be investigated for throughput improvements. Other aspects of protocol performance, such as network control overhead, end-to-end delay and dropped packets could be researched. Many areas in planning can be explored, such as exploring alternative implementations of planning, attempting to design and implement a self-sustaining plan, and exploring locally omniscient plan compared to the centralized plan used in the test simulations. The effects of planning with respect to various protocol algorithms could be explored, to determine what the most efficient protocol-planning combination would be.

Visual identification of changed process states

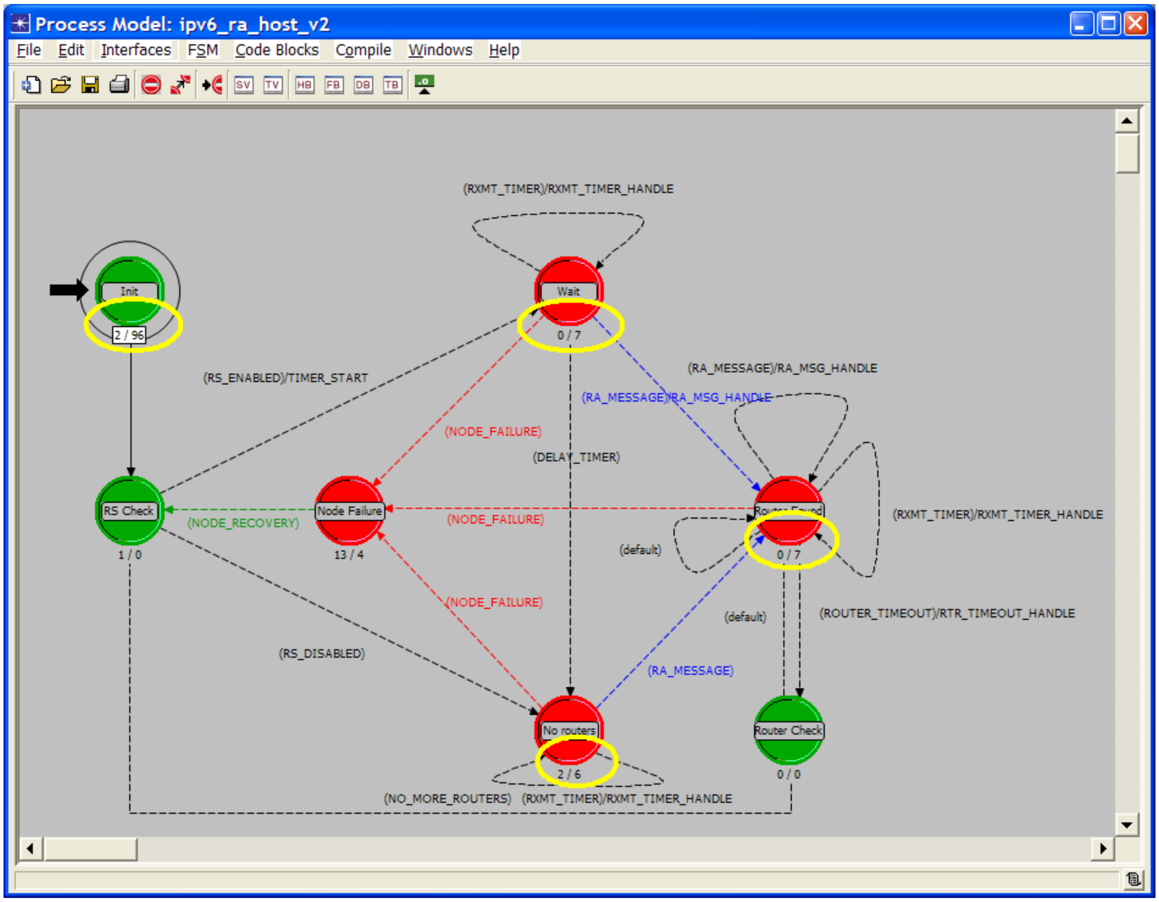

Figure 6: Changed sections of IP - IPv6_ra_host

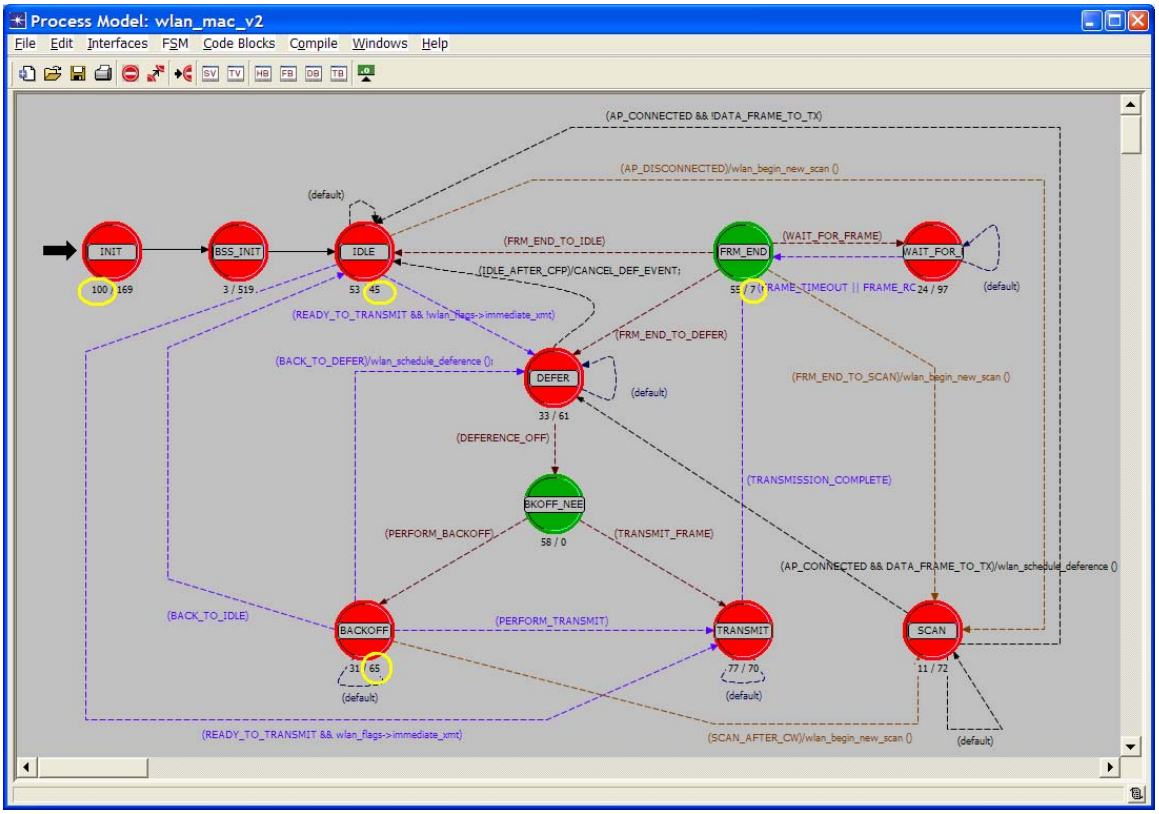

Figure 7: Changed sections of wlan_mac

Ipv6_ra_host and Wlan_mac INIT Changes

```
/* Temp variable to read the Node number, so it can be used to check for */
/* the end of the plan */
/* other temp variables read the AP BSS and Time */
int NodeCounter,NodeNumber=0,NodeBSS;
double NodeTime,NodePrevTime;

/* Address holder, to determine the UID from the address  */
/* UID_temp_str is used in a number to string conversion  */
/* to standardize the address strings                      */
char addr1[INETC_ADDR_STR_LEN];
char UID_str[20]="ffff:ffff:ffff:ffff";
InetT_Address addr0;

/* Opening the plan file for reading */
FILE * fp;
fp = fopen("I:\\My Documents\\OPNET\\Modified Models\\structure_plan.txt","r");



/* reading in the UIDs for the plan */
```

```
NodeCounter=0;
while (strncmp(addr1,"ffff:ffff:ffff:ffff",19))
	{
	fscanf(fp,"%s %*s", addr1);
	strncpy(Obj_Table[NodeCounter],addr1,19);
	NodeCounter++;
	}

fscanf(fp,"%d %lf %s %d\n",&NodeCounter, &NodeTime, addr1, &NodeBSS);
/* While the read node is not -1, continue to enter nodes into the table. */
while (NodeCounter > -1)
	{
	Time_Mark=0;
	NodePrevTime=-1;
/* While the current time is more than the previous time, continue to read times */
/* to the same node - this will cause errors if the time or node is incorrect    */
	while (NodeTime>NodePrevTime)
			{
			PMAP_Table[NodeCounter][Time_Mark].Time=NodeTime;
			PMAP_Table[NodeCounter][Time_Mark].bss=NodeBSS;
			strncpy(PMAP_Table[NodeCounter][Time_Mark].Addr,addr1,39);
			Time_Mark++;
			NodePrevTime=NodeTime;
/* read the next line */
			fscanf(fp,"%d %lf %s %d\n",&NodeCounter, &NodeTime, addr1, &NodeBSS);
			}
	}


/* close the plan file */
fclose(fp);


	/* Read the address attribute                                  */
	/* Read the top-level wireless attribute ID                    */
	op_ima_obj_attr_get (op_topo_parent(op_id_self()),"IP Host Parameters", &NodeBSS);
	/* (Copied from wlan_mac) get the (unnamed) child              */
	NodeCounter = op_topo_child (NodeBSS,OPC_OBJTYPE_GENERIC, 0);
	/* get Interface info from the child of IP Host Parameters      */
	op_ima_obj_attr_get(NodeCounter,"Interface Information", &NodeBSS);
	/* get the (unnamed) child */
	NodeCounter = op_topo_child (NodeBSS,OPC_OBJTYPE_GENERIC, 0);
	/* get IPv6 Params from the child of Interface Info             */
	op_ima_obj_attr_get(NodeCounter,"IPv6 Parameters", &NodeBSS);
	/* get the (unnamed) child */
	NodeCounter = op_topo_child (NodeBSS,OPC_OBJTYPE_GENERIC, 0);
	/* get Global Address(es) Info from the child of IPv6 Parameters */
	op_ima_obj_attr_get(NodeCounter,"Global Address(es)", &NodeBSS);
	/* get the (unnamed) child */
	NodeCounter = op_topo_child (NodeBSS,OPC_OBJTYPE_GENERIC, 0);
	/* copy the Addr attr. so we don't have to run through this again */
	Addr_Attr = NodeCounter;

	/* get Address from the Global Address(es)                     */
```

```
        op_ima_obj_attr_get(Addr_Attr,"Address", &addr1);

        /* create an address from the attribute, to pass to the GUID fn. */
        addr0 = inet_address_create(addr1,InetC_Addr_Family_v6);

        /* a function that pulls the GUID from a full IPv6 address       */
        /* the function returns a string, which matches the lower 4      */
        /* 4 octets of the IPv6 address.  The 64 bits will not normally  */
        /* fit in an int.                                                */
      InetT_addr_to_GUID(addr0,UID_str);

        Self_Index=str_binary_search(0,20,UID_str,Obj_Table);

    /* Setting Time_Mark to the first PMAP entry index.
    /* The Time_Mark is the next position(@time) the node will move to. */
    Time_Mark = 0;

        op_intrpt_schedule_self(PMAP_Table[Self_Index][Time_Mark].Time+0.2,IPV6C_RA_HOST_R
XMT_TIMER);
```

Function Called in All Other States of IPv6_ra_host

```
static void
ipv6_timed_solicit(int Addr_Id,PMAP_Address_Entry* PMAP)
        {
        /* internal variables for conversion of an IPv6 address to a string and back */
        char Addr_str[INETC_ADDR_STR_LEN];
        InetT_Address Addr;

        /* This function initiates a solicitation for a router at a specified time */
        FIN (ipv6_timed_solicit(Addr_Id,PMAP[Time_Mark]));

        // Check to ensure the time is after the current indexed time
        if (PMAP[Time_Mark].Time<=op_sim_time())
                {
                // create a new address from the plan
                Addr = inet_address_create(PMAP[Time_Mark].Addr,InetC_Addr_Family_v6);
                inet_address_print(Addr_str,Addr);

                /* Set the new global address                          */
                op_ima_obj_attr_set(Addr_Id,"Address", &Addr_str);
                /* Get the new address (for debugging checks)                */
                op_ima_obj_attr_get(Addr_Id,"Address", &Addr_str);

                /*  Set new time to just after the wireless channel has been found (.2 sec)*/
                Time_Mark++;

        op_intrpt_schedule_self(PMAP[Time_Mark].Time+CHANNEL_CHANGE_TIME,IPV6C_RA_H
OST_RXMT_TIMER);
                }
```

```
        FOUT;
        }
```

Lines added to All Other States of Wlan_mac

```
if (op_sim_time() > PMAP_Table[PMAP_Index][Time_Index].Time)
        {
        roam_state_ptr->ap_reliability = WLANC_AP_RELIABLE;
        roam_state_ptr->scan_mode = OPC_TRUE;
        channel_num  = PMAP_Table[PMAP_Index][Time_Index].bss;
        Time_Index++;
        }
```

IP_Plan.h Declarations Included in Each Modified Process

```
typedef struct _PMAP_Entry {
double Time;
char   Addr[40];
int    bss;
      } PMAP_Address_Entry;

//binary search of an ordered list for a specific float-represented
time
static int
Time_binary_search(const int LowC,const int N,const double time,const
PMAP_Address_Entry * Table);

//binary search of an ordered list for a specific string
static int
str_binary_search(int low,int high,const char* string,const char
Table[40][20]);

//ascii to hexadecimal
static int atoh(const char* String);

// Returns the last 64 bits in hexadecimal form, with all zeros
static void
InetT_addr_to_GUID(const InetT_Address addr,char* UID_str);

//creates an OPNET IPv6 Address from a location x/y coordinates and a
UID string
static InetT_Address
PMAP_Addr_Conv(const char GUID[20], const int PMAP_x, const int PMAP_y,
const char Prefix[5]);
```

Example plan.txt File

```
0000:0000:0000:0001 [Record:0-Router_1:IF0]
0 9999.0 8000:0011:F900:17EA:0:0:04:7 1
```

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Air Force Institute of Technology
Graduate School of Engineering and Management (AFIT/EN)
2950 Hobson Way, Building 640
WPAFB OH 45433-8865

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David Luginbuhl (703) 696-6565
AFOSR/NM DSN: 426-6207
875 N Randolph St david.luginbughl@afosr.af.mil
Ste 325 Rm 3112
Arlington, VA 22203

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

Mobile wireless network protocols currently run on optimistic routing algorithms, adjusting node connectivity only when the chosen connectivity metrics, such as signal strength, pass beyond minimum thresholds. Optimistic routing has several weaknesses. Optimistic routing suffers from increased network overhead during increased frequency of node movement increased node density per area, and optimistic routing suffers from non-optimistic access change for individual nodes. The overall communication throughput of a network may be increased if the network topology change is scripted; a scripted plan can allow messages to travel along a more efficient topological path while creating less topology control traffic. This would increase the overall network bandwidth and may be an alternative solution to current network routing problems such as route loop creation.

This thesis tested a network with scripted movement against an unscripted network in a simple network featuring mobility, for increases in bandwidth due to scripted node access changes over optimistic access changes. The results showed significant improvement in the data throughput in the scripted network when there were multiple overlapping networks contending for the same node.

15. SUBJECT TERMS

Mobility, Protocol, Plan, Network, Ad-hoc, Script

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U	U	U	UU	55	**19b. TELEPHONE NUMBER** *(Include area code)* (937) 255-6565, ext 4918 (scott.graham@afit.edu)

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