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MODELING AND SIMULATION OF TELECOMMUNICATION NETWORKS FOR CONTROL AND MANAGEMENT

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ABSTRACT

In this paper we describe methodologies for telecommunication networks modeling and simulation that are targeted to be useful as tools in on-line and off-line decision making of the type encountered in network control, management and planning problems. We describe the development, validation and use of self-similar and multi-fractal models, queuing control and performance evaluation, assessing the incremental utility of various models, hierarchical models based on aggregation, analytic approximation models for various performance metrics, trade-off and sensitivity analysis using a multi-objective optimization framework and automatic differentiation. We also describe four illustrative examples of applying these methodologies to dynamic network control and management problems. The examples involve primarily mobile ad hoc wireless and satellite networks in changing environments.

1 INTRODUCTION

The principal challenge we address in this paper is the development of robust multi-models of networks and network traffic of minimum complexity for network control and management. The model classes are rich enough to allow a variety of on-line network measurements to be used to select the appropriate models and adjust their parameters on-line. We propose innovative analytical and experimental methods to assess the incremental utility of various network and traffic models and classes with respect to speed, complexity and performance of the function (i.e. control or management function) that uses them. A critical innovation of the research described herein is the development of systematic methodologies for evaluating the impact of various network traffic models (fitted to measured network traffic data) on control performance (e.g. response time, fairness, priority fidelity, packet loss), on allocation of network resources (e.g. buffer sizes, capacities), on network performance predictability (e.g. QoS predictions *vs* actuals, proactive fault management, network availability).

We also describe the utilization of on-line measurements for both off-line and on-line model construction, adaptation and selection. The long term objective of the research described is the development of self-organized algorithms and systems that automatically select the appropriate models and scale for the function (i.e. control or management function) requesting their use. This self-organization is essential in the context of the polymorphic models for network traffic and control that we have developed and used. Self-organization is needed for both off-line and on-line processing. It is also necessary because it is not possible to predict or simulate all the scenaria that will be encountered in the operation, management and control of complex heterogeneous networks. Our methods incorporate learning and adaptation as essential components. Learned patterns, models or strategies are communicated between the off-line and on-line schemes, and also between different levels of our hierarchies.

2 NETWORK MODELING AND SIMULATION METHODOLOGIES

Networks are rapidly becoming heterogeneous and carry mixed traffic from different applications, distinctly different requirements with respect to quality of service (QoS), i.e., delay, delay jitter, packet loss, throughput. These trends will continue and create the need for sensing and measurement of network traffic characteristics for monitoring, control, management and design. Network heterogeneity and service variability require the development of classes of traffic models in various operating regimes, scales, and parametrizations. The intended utilization of the traffic models must be taken into account in the selection of the traffic model: e.g. different traffic models are used for the on-line control of queues in a concentrator or a switch, than for the planning and dimensioning of a network. In addition the traffic models used must be provably robust with respect to reasonable variations within the network operating domain of interest.

The increasing complexity, size and heterogeneity of current and future telecommunication networks require the development of automatic network management, control and operation systems. Todate the majority of deployed networks utilize human operators at the network operation centers (NOCs) for decision making related to management, control and operations based on data collected from network elements and residing in the management information base (MIB). *Intelligence* (non human) *in the feedback loop* from measurements to decisions and automation is required for future large and high data rate networks. Such autonomous feedback management and control must be model-based. And the models used *must fit the function* (or use) and *must be robust*. Their complexity must match the required operational time scale of the function they are used for.

2.1 Network Modeling for Control and Management

The challenge of intelligent control and management of telecommunication networks can only be met by linking modeling and simulation with network control and management. Models and simulations are used to analyze traffic load, network behavior, to predict traffic load, network behavior, and to select high performance control and management strategies and policies. For such an effort to be successful, different models should be used at different time and size scales and for different functionalities in network control and management.

2.2 Multi-Scale Network Traffic Models

Since the Bellcore LAN measurement studies, there is inreasing evidence that "Poisson modeling" may have become inadequate to model traffic flows carried by existing and emerging networks. This has resulted in efforts on the part of the traffic engineering community to develop alternate models which focused on various scalings properties, such as self-similarity and multi-fractality. Such time scales are essential for answering key questions posed in modeling and simulation methods for network control and management: What can be predicted from on-line network data? For how long the prediction error is within reasonable bounds? What is the appropriate linkage between off-line and on-line estimation and control schemes? What is the trade off between model complexity and control performance?

We now understand that these fractal behaviors have completely different character at two time scales. For the “fast” time scale, i.e. less than 100ms, the behavior is basically multi-fractal. For the “slow” time scale, i.e. larger than 100ms, the behavior is typically fractal. These two different type models have different properties and should be used for estimating performance and deriving controls and decisions for different problems. The fractal one for dimensioning, while the multi-fractal one for dynamic service allocation to queues of TCP traffic. We have developed traffic models, statistical methodologies for extracting model parameters from traffic traces and efficient simulation techniques for addressing some of the unique issues that arise in the context of these non-traditional traffic models. We have developed, and successfully used, such models in simulations for terrestrial wireline, terrestrial wireless, mobile ad hoc, satellite and hybrid (mixture of all the above) networks. We have recently succeeded in developing multiple scale traffic models for various types of networks. These models work at all scales through structure or parameter adjustments and their parameters can be easily and accurately estimated from on-line traces. We have successfully used these models in modeling and simulation studies for network control and management.

2.3 Queuing Theory and Control

Recently, using the new multi-scale models and appropriate analytical and simulation techniques we have been able to evaluate, estimate, and predict the performance of queuing control algorithms with realistic payloads. We have validated our estimation and prediction results with real-life traffic traces and detailed simulations. We have been able to develop and use accurate estimates of cell loss rates and blocking probabilities, and to assess the impact on performance of short-time fluctuations inherent in these models. We have also been able to evaluate the performance of buffer management policies such as various versions of RED, ECN, AQM, and combinations thereof. In these efforts we have shown the validity of using different models, different accuracies for simulations aimed to be used for different control and management functions. A useful product of these studies is the assessment of the impact of these new and non-traditional traffic and workload models on network control, planning and management. We have been able to deduce simple characterizations and parametrizations of these effects that would clearly have profound impact on the design of applications, the provisioning of network resources and the design (and fine tuning) of network protocols.

Problems that we have investigated at the “fast” time scale are model based prediction and related accuracies; scheduling of service in a multi-input queue; dynamic bandwidth allocation in wireless networks; buffer and packet drop policies; model complexity *vs* performance. Problems that we have investigated at the “slow” time scale are network resource planning, design and dimensioning (e.g. questions like how many typical customers we can serve with a given satellite bandwidth in an Internet via satellite service).

2.4 Adaptive Hierarchical Modeling Incorporating On-line Measurements

Telecommunication networks are increasing in size, where future networks will have hundreds of thousands and even millions of nodes. The only way to arrive at modeling and simulation of reasonable time and computational complexity is through aggregation. Aggregation in networks can occur because of topology, because of routing, because of time scales and because of size. Aggregation is natural for both modeling and for network management. In our work we have developed adaptive aggregation methods that lead fast to hierarchical models for network traffic, network management and control policies, and network performance metrics. We have investigated aggregation based on time scales, topology, routing, and more interestingly variation of network performance metrics.

2.4.1 Hierarchical Loss Network Model

We have investigated various approximation schemes that result in fast and inexpensive end-to-end performance estimation. One of the approximation schemes we have investigated is a reduced load approximation, where the fixed point is obtained by iteration between four sets of unknowns, namely, the reduced load/arrival rate of a certain class of traffic on a certain link, the probability that a link is in a state to admit a certain class of traffic, the steady state occupancy probability distribution of a link, and the probability that a call request is attempted on a certain route. We have demonstrated that this approximation works for random networks with dynamic routing policy, with or without trunk reservation type of admission control and multiple traffic classes. Our results with this approach show good conservative estimates for networks under heavy traffic, and the scheme performs better as networks become larger and more random. Our modeling and simulation results with this approximation show a three orders of magnitude speed-up in comparison to plain discrete event simulations. We have also investigated a hierarchical version of the loss network model for estimating end-to-end blocking probabilities.

We have investigated several types of hierarchical routing schemes and the corresponding end-to-end connection level models. The abstraction of the physical network results in interconnected gateways on higher layer(s). Networks are divided into clusters or peer groups that consist of neighboring nodes, with some nodes being “border nodes” that connect to other peer groups. All non-border nodes are only aware of their own peer group, while all border nodes are only aware of their own peer group and border nodes of other peer groups. Clearly border nodes represent some form of aggregation of the rest of the network in terms of routing. Routes are established on different layers based on complete information within a peer group and aggregated information between peer groups. Our modeling and simulation results have shown an approximately 4-fold improvement in computational cost.

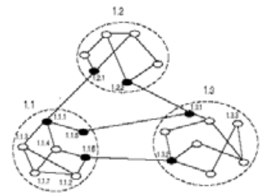


Figure 1: Layer1– Connectivity (Border Nodes In Black)

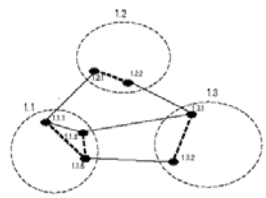


Figure 2: Layer2 – Abstraction (Logic Links In Dash Lines)

2.4.2 Multi-Objective Design and Sensitivity Analysis

The technique of Automatic Differentiation (AD) is based on the fact that differentiation of functions defined by formulas is a mechanical process done according to fixed rules, e.g., the chain rule. Therefore it is highly suitable for automation along the same lines as function evaluation. Using AD for sensitivity analysis together with our reduced load approximation represents a novel approach for network performance evaluation. We have shown that using AD for computing derivatives of the fixed point along with the calculation of the fixed point itself is both accurate and efficient. Our numerical experiments and analysis of convergence show that this is a valid and efficient way of obtaining sensitivities of blocking probabilities w.r.t. offered traffic load. We have developed and used similar techniques with other network performance metrics. Network design and dimensioning often involve trade-offs between different objectives that sometimes may have opposing effects on design. We have developed and used a multi-objective optimization framework to investigate trade-off analysis. Our software implementation utilizes either our UMD package CONSOL-OPTCAD, or a combination of CPLEX with the ILOG SOLVER. We have successfully applied such ideas in the design of trunk reservation parameters and link capacities.

3 APPLICATION EXAMPLES

In this section we describe applications of the various methodologies we have developed and described in Section 2, to four challenging and dynamic network problems. These were selected in order to demonstrate how different modeling and simulation methodologies can be used for on-line and off-line decision making in network control, management and planning.

3.1 Simulation-Based Dynamic and Adaptive Selection of Routing Protocols for MANET

3.1.1 Scenario

The selected scenario imitates the activities of a group of soldiers operating in an urban area or searching the area. There are seven phases. In phase I, they act together as one group. In phase II, the group separates into four subgroups, which move to different locations. In phase III, each subgroup acts separately and visits different parts of the area. In phase IV, the four subgroups gather again into one group in front of a building. In phase V, the group enters the building and waits in the lobby. In phase VI, the group separates into two subgroups in the lobby, and each subgroup goes to opposite directions along the corridor and visits the building room by room. In phase VII, the two subgroups gather again into one group in the lobby after the visit, and move out of the building. The scenario covers outdoor and indoor environments in urban area, where electro-magnetic propagation properties are different. Mobility and traffic load change in the different phases. The performance of the adaptive routing protocol, selected using simulation-based routing protocol performance evaluation and decision making, is compared with using fixed routing protocols for the entire scenario.

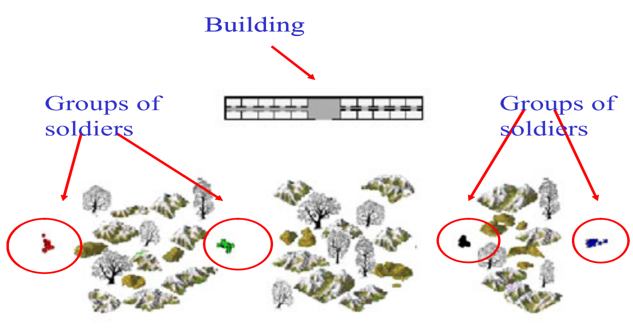


Figure 3: MANETs Transitioning from Outdoor to Indoor

3.1.2 Traffic, Mobility, and Propagation Models

Nodes communicate using voice, video, or data. Traffic type transfer is scheduled with a Markov model. UDP is used for video and voice traffic, and TCP for data. Traffic load is controlled with connection generating rate. We create a simple room-by room visiting model for indoor mobility, in which nodes move from a room one by one to the next, walk around, and leave for the next room. A compound mobility model involving group mobility and random waypoint mobility are used for outdoor movement. For outdoors, free space and two-ray ground models were used for propagation. For indoors, the following propagation (loss) model is used

$$
\begin{aligned}
Lpath &= 20 \log (4\pi d / \lambda) && d \leq 8\text{m} \\
&= 58.3 + 33 \log (d/8) && d > 8\text{m}.
\end{aligned}
$$

Here *Lpath* is the *path loss*, d is the distance between sender and receiver, and λ is the free space wavelength.

3.1.3 Routing Protocol Selection

Three routing protocols were used as candidates, AODV, DSDV, and DSR. At critical instances when the mobility and traffic will have a big shift, simulations are carried out to evaluate performance of routing protocols for the next scenario phase. The protocol that has best performance is selected for operation in the upcoming phase. The protocol selection algorithm is as follows.

Step 1: Do hypothesis test for loss measurements of all protocols. If one protocol is superior to the other two at a significant level, select it; otherwise, go to step 2.

Step 2: Do hypothesis test for goodput measurements. If one protocol is superior to other two at a significant level, select it; otherwise, go to step 3.

Step 3: Do hypothesis test for delay measurements. If one protocol is superior to other two at a significant level, select it; otherwise, step 4.

Step 4: Select a routing protocol randomly.

3.1.4 Simulation Results

Loss, goodput, and delay are used as performance metrics. The load changes sequentially in time as shown in the table below. The best protocol selected for each period is listed correspondingly. Representative results of performance with adaptive protocol selection are given in Figures 4 and 5, compared with those when only one fixed routing protocol is used.

3.2 Adaptive Hierarchical Resource Management For Hybrid Satellite-MANET

The command center is connected to the command center gateway through a high bandwidth LAN. The command center gateway is connected to the vehicles through the satellite link. The propagation delay from the ground equipment to the satellite is 125 *ms*. Several MANETs are

Time	0 – 90	90 - 250	250 400	400 - 550	550 - 800	800 - 1000
Load*	0.2x	1.0x	0.4x	1.0x	0.2x	1.0x
Protocol	DSR	DSDV	DSR	DSDV	AODV	DSDV

* measured as percent of a benchmark level of load

— Adaptive — DSDV — AODV — DSR

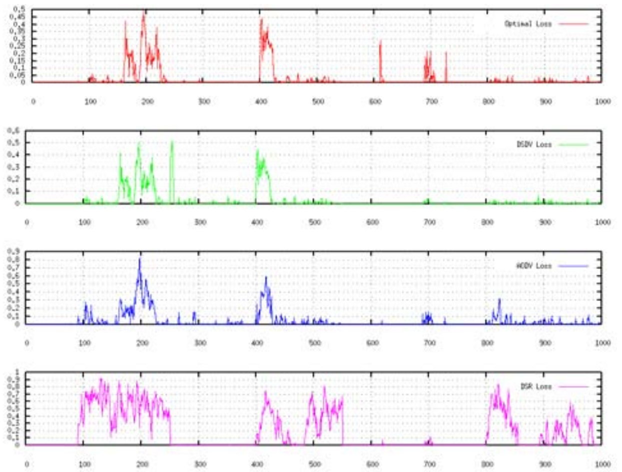


Figure 4: Loss Performance Comparisons

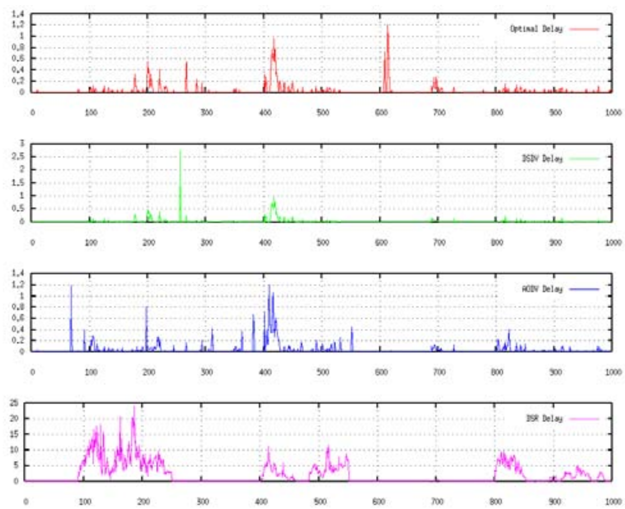


Figure 5: Delay Performance Comparisons

in the footprint of the satellite. For all experiments, the satellite downlink bandwidth is 2Mbps and the satellite uplink bandwidth is 256kbps. All experiments are performed on a real-life MANET. Assumptions:

1. Any session from/to a MANET may have bursts.
2. Number of sessions from/to each MANET may dynamically change.
3. Both uplink and downlink may have noise.

3.2.1 Experiment 1

The objective of this experiment (Fig. 6), is to demonstrate user and session level performance improvements, and bandwidth efficiency with adaptive hierarchical resource management (AHRM). The metrics we are interested in are response time for critical messages, packet delay for voice and video traffic, and link utilization (overall throughput). The baseline scenario is to use a proxy-enhanced gateway without AHRM. We used TCP Reno. The proxy-enhancements include connection splitting and rate control developed in our previous work. In this experiment, satellite services include critical messages (TCP), voice and video (UDP), and file transfer (TCP) between MANETs and wired backbone network. A strict priority scheduler is used for critical and non-critical messages.

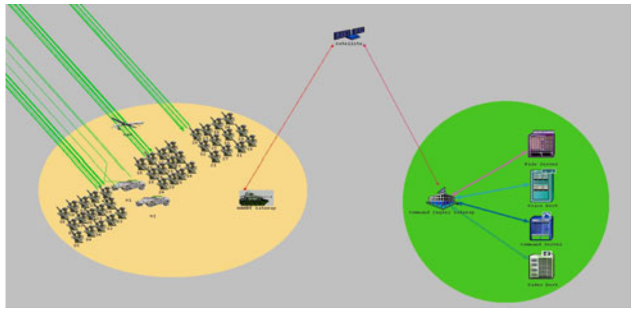


Figure 6: Configuration for Experiment 1

The short critical messages are given higher priority, while all other lower priority traffic such as voice, video and large file is served with a second level scheduler (WFQ). All traffic is sent from the command center to the MANET.

The strict priority scheduler can guarantee that the critical messages get through with the shortest delay no matter what the traffic arrival patterns of voice, video and large file are. The algorithm for the dynamic weight assignment of the weighted fair queuing (WFQ) scheduler is based on the average queue sizes. For example, if the average queue size of the video traffic queue keeps on increasing, its weight will be increased by some amount. By doing this, the scheduler gives more bandwidth to video traffic when a sudden video stream burst arrives. The weight changing will stop as soon as the average queue size begins to decrease. This (AHRM) algorithm can adapt to the channel status. Channel bandwidth may change due to bad weather. Noise is introduced to the link at certain periods. The above experiments are repeated in this setting and performance metrics are collected and compared (between baseline scenario and the one employing the AHRM algorithm).

3.2.2 Experiment 2

The objective of this experiment (Fig. 7) is to show user and session level performance improvements, and bandwidth efficiency when dynamic bandwidth allocation is used in the return channel. The metrics we are interested in are packet delay for voice and video traffic. In this scenario, three MANET gateways send traffic back to the

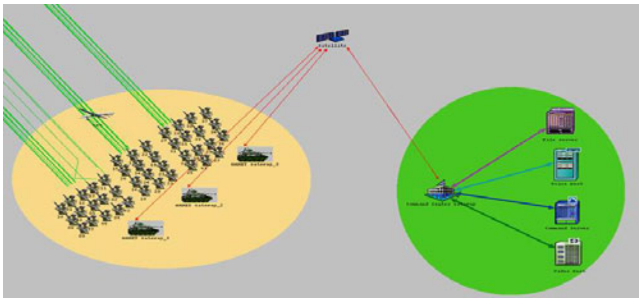


Figure 7: Configuration for Experiment 2

command center. Gateway 1 always has traffic to send, while gateway 2 stops sending traffic at 21 seconds and gateway 3 stops at 42 seconds.

The baseline scenario is to set a fixed channel from each gateway to the satellite. This gives the worst delay performance; unused channel bandwidth occupied by a gateway cannot be used by other gateways. A better scheme is to divide the idle bandwidth of one gateway equally among the remaining two. This performs better, however if the idle bandwidth assigned to a specific gateway cannot be used, it will be wasted. The best scheme is to assign the bandwidth dynamically based on traffic demand: larger share of idle bandwidth is assigned to the heavily loaded gateways and as a result overall packet delay performance is substantially improved.

3.2.3 Results

Figure 8 below demonstrates performance improvements for various services in Experiment 1, while giving top priority to short critical commands. Critical commands (a) go through with only the physically imposed satellite delay, while the disturbance to other traffic (voice (b) and video (c)) is minimal when our control algorithm is applied and substantial without our control algorithm.

3.3 Dynamic Placement of Multiple Aerial Platforms for QoS Improvement in Battlefield MANETs

Here we demonstrate:

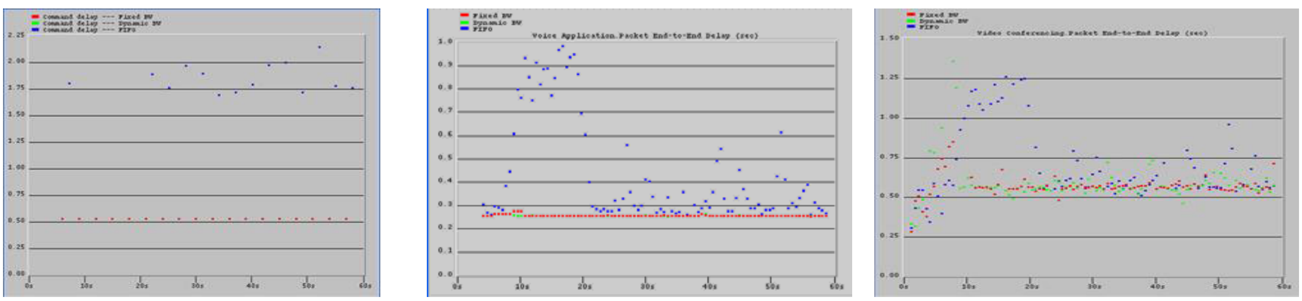
1. Effectiveness of Aerial Platforms (AP) (UAVs, Helicopters…) in establishing or re-establishing connectivity of the mobile wireless networks and/or improving the Quality of Service (QoS) for multi-service (voice, data, steams) communications.
2. Optimal placement algorithm that finds the minimal number of APs required for connectivity. For a given number of APs the algorithm gives maximal network connectivity. The algorithm also provides the trajectories of the APs (kinematics of the APs).
3. Placement algorithm that dynamically updates the APs trajectories based on current network information from the nodes. It uses fast, short look-ahead time, on-line simulation of mobility, terrain, transmission to predict where connectivity improvement will be needed.

3.3.1 Scenario 1: Slow Speed MANETs

This scenario (Fig. 9) represents movement of tanks along with foot-soldiers. There are 41 tanks in the network (soldiers are abstracted out as they cannot communicate with the AP). There are 3 UAVs.

3.3.2 Scenario 2: Fast-Moving MANETs

In this scenario (Fig. 10) the ground nodes (tanks) move at high speeds (40+ *mph*). Fast moving helicopters follow the ground nodes and patch partitions on the ground. There are 2 tank groups of 4 and 6. The tanks within each group move as a formation along their assigned paths. The groups communicate directly as long as any pair of tanks, one from each group, are within the communication range. As the groups move apart from each other (cause: terrain, etc.), a helicopter is dispatched to reestablish the commu-



(a) (b) (c)

Figure 8: Delay Performance for Critical Commands (a), Voice (b) and Video (c) Traffic; Green are the AHRM Results

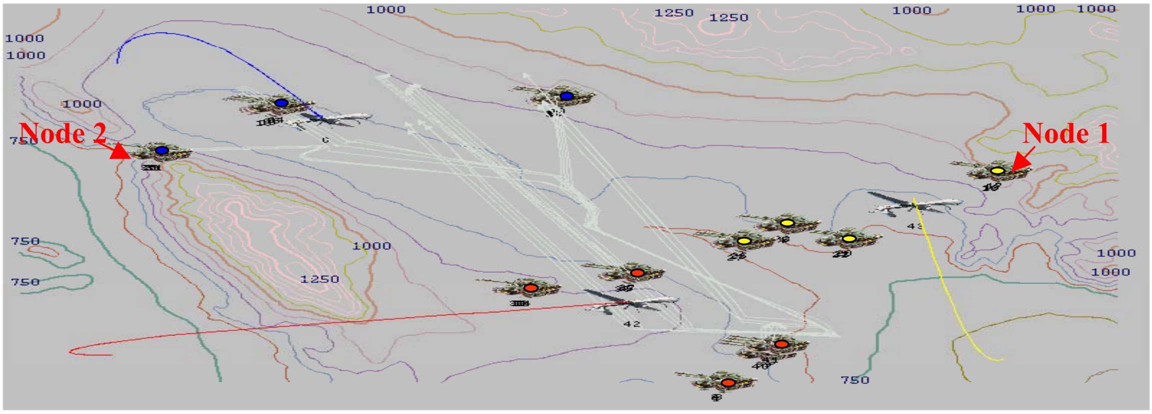


Figure 9: Slow-Moving MANET

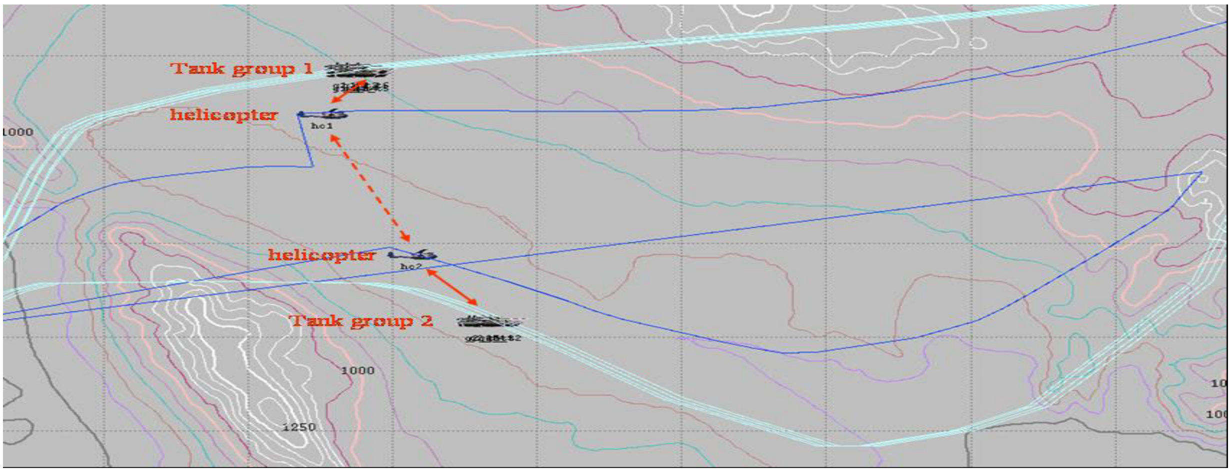


Figure 10: Fast-Moving MANET

nications between the groups. With the groups moving further apart, if the single helicopter cannot patch the partition, it will move closer to one of the groups and a second helicopter is dispatched and assigned to the other group to establish the ground-helicopter-helicopter-ground paths.

3.3.3 Simulation Tools

OPNET was used as the main tool that runs the network scenario. MATLAB integrated with OPNET is called periodically to predict the movement and future connectivity of the tanks and run the UAV placement algorithm to update the locations of the UAV and move them to appropriate locations. UAV trajectories evolve and get updated as the scenario progresses in time.

3.3.4 Experimental Setup

Full protocol stack: TCP/UDP over IP, MAC, physical layer path loss is based on terrain.

Routing: AODV is run over multiple interfaces for inter tank and inter UAV communications.

Mobility: As specified by realistic military scenaria.
Application traffic: voice and video.
Communication model:

1. Vehicle to vehicle range is 2 *Km*. Vehicle to UAV range is 6*Km*.
2. Inter vehicle pathloss is determined by the terrain model (ITM). Tank to UAV and inter UAV pathloss is based on free space propagation.
3. Links between tank to UAV and UAV to UAV are symmetric and bi-directional.
4. Inter tank communication and communications involving UAVs use appropriate transmit powers.
5. The maximum height of the UAV is 6*Km* and the minimum height is taken as a constraint for the optimization algorithm to minimize the hit probability.

3.3.5 Sample Results

Figure 11 shows scenario1 with and without the APs: Connectivity between nodes 1 and 2. The top part of the figure shows communication traffic when the UAVs are em-

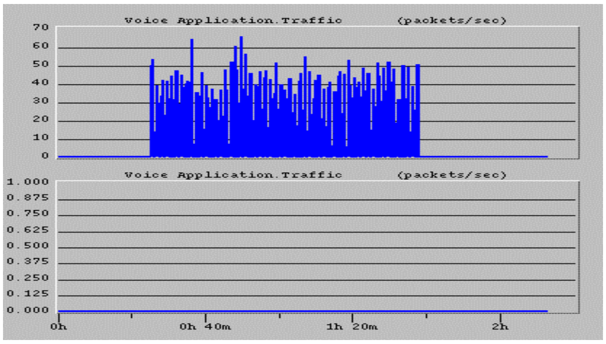


Figure 11: Connectivity Improvements with UAVs

ployed. The UAVs dynamically track the movement of the tank nodes providing optimal connectivity for the ground nodes. The bottom part of the figure shows communication traffic without the intervention of the UAVs. Tank communication is based on multihop communication limited by distance and terrain. Thus, many of the tanks are not able to communicate with other nodes in the network.

3.4 Modeling, Worm Spreading, Distributed Denial of Service and Routing Attacks in Wireline and Wireless Networks

We present two attacks to a fixed network infrastructure and two attacks to the routing protocol of a mobile wireless ad hoc network.

3.4.1 Fixed Network: Large Scale Attacks

3.4.1.1 Worm

We consider an active worm that self-propagates across a network by exploiting security flaws in widely-used services offered by a set of vulnerable computers. The simulation follows closely the behavior of the worm Sapphire (a.k.a. Slammer) which in January 2003 became the fastest growing worm in the Internet due to the UDP connectionless infections it generated. In order to locate these vulnerable computers, the worm probes by UDP packets different computer addresses generated in a pseudo-random way. After one of the UDP probe packets reaches a vulnerable machine, the worm copies and executes itself in the compromised machine. We assume we are monitoring the traffic for a specific UDP service that the worm is going to attack. The background traffic for this distribution is Pareto generated. The attack is initiated by a single host at 6 seconds. The change detection statistics in the routers of the network signal an anomaly based on the sudden change of the arrival process of connections for the given UDP service. We use parametric and non-parametric sequential statistics for the statistical tests. The attack is then filtered at the routers based on traffic volume. At 10 seconds of the simulation, all routers get a signature of the worm packet and start filtering using the signature. At 16 seconds the infected hosts are rebooted and "patched". The network then returns to normal condition.

3.4.1.2 Distributed Denial of Service Attack (DDoS)

In a DDoS, an attacker compromises a set of Internet hosts (sometimes by using a worm) and installs a small attack daemon on each host, producing a group of "zombies". Using this basic setup, an attacker can generate a coordinated attack from several zombies installed across AS boundaries, onto a single site. In this scenario we have a transit network where several subnetworks are attached. There are different attackers in different subnetworks targeting a single node, causing excessive amounts of endpoint and possibly transit network bandwidth to be consumed. Since in this distributed attack, the attack traffic tends to aggregate from the attackers towards the destination, there is a sense of "directionality" to the attack that will help us reduce the false alarms. Each of these links will monitor, using change detection statistics, the amount of packets transmitted through them and generate an alarm if there is a sudden change in the traffic pattern. These set of alarms form a (possibly disconnected) directed graph. From this graph we obtain the different connected components and evaluate if they are *poly-trees* with nodes of outdegree one.

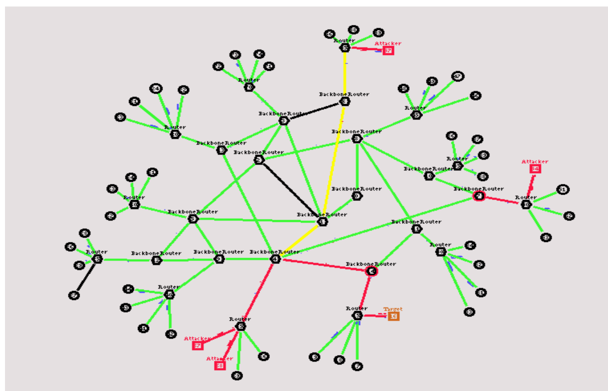


Figure 12: Simulation of DDoS Attack and Recovery

3.4.2 Wireless Attacks in Urban Environments

Here we demonstrate the impact of typical attacks in MANETs, including routing attacks, where nodes in the network become malicious, or external nodes colluding to attack.

3.4.2.1 Route Falsification

Attack: A malicious node in the network routinely sends out fake route update messages in which he claims he is one hop away from every node he knows. Other nodes choose this node in their routing paths as it provides the best path. The figure below shows how the attacker (red node) attracts packets from the source (green nodes) towards the destinations (blue nodes).

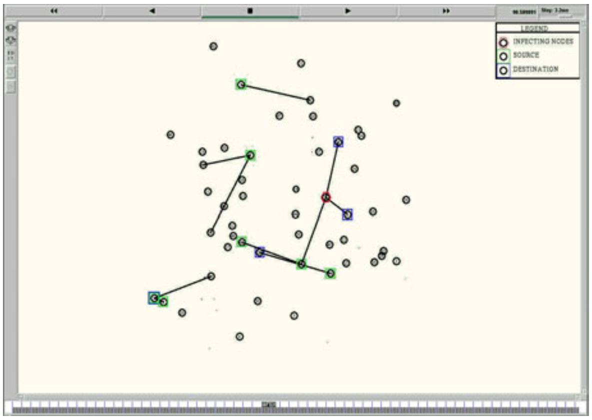


Figure 13: Simulation of Route Falsification Attack

Detection: A dynamic model of the hop count distribution is built using multiple HMMs. An abnormality in the model is flagged as an attack detected.

Defense: All nodes start rerouting to "clean" their routing tables and disregard the route update messages from the attack node.

3.4.2.2 Worm-Hole Attack

*Attack***:** Attacker records packets at a network location and tunnels them to a colluding attacker. At the end of the tunnel packets are retransmitted in the network.

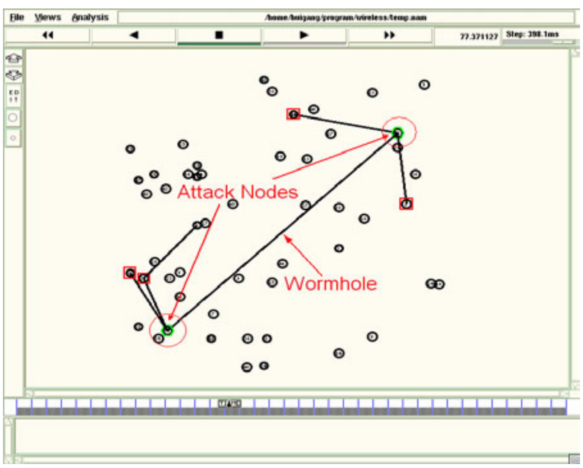


Figure 14: Simulation of Worm-Hole Attack

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