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IMPROVING NETWORK PERFORMANCE IN HYBRID WIRELESS NETWORKS USING A SATELLITE OVERLAY

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Abstract

Large wireless networks have the ability to provide rapid connectivity in disaster areas, or to inter-connect users in far-flung geographical locations. However, limitations on performance and robustness have delayed the adoption of such networks. In this paper we show that by the addition of a satellite overlay network, the performance and robustness of large-scale wireless networks can be greatly improved and thus make their deployment possible. We define a satellite overlay network as consisting of one or more satellite nodes and multiple terrestrial ``gateway" nodes that have interfaces for both satellite links and terrestrial wireless communication. We divide the terrestrial network into multiple ``clusters" of wireless nodes, with each cluster being served by one or more gateway nodes. Ordinary terrestrial user nodes reach the gateway node through multi-hop terrestrial paths. We thus propose a design for a hybrid satellite and terrestrial wireless network. Through network modeling and simulation, we show that significant improvement in end-to-end performance is possible in a wireless network when the satellite overlay is present, in comparison to the performance in flat wireless networks. Our results are for both stationary and mobile ground wireless nodes.

1. Introduction

Deployment of large-scale ad hoc wireless networks suffers from several major problems. Recent studies have shown that the per-node wireless channel throughput in a wireless network is inversely proportional to the square root of the number of nodes in the network [1]. Therefore as the network increases in size, the individual throughput of the nodes decreases rapidly. Even if the network is connected, the ad hoc routing protocol might fail to find routes between the source and the destination when they are widely separated. For many traffic profiles, a fully wireless network might not be able to satisfy the quality of service (QoS) requirements of the traffic. For example, the end-to-end delay for voice traffic might be unacceptably high. Also, wireless ad hoc networks are ideally suited for applications like military battlefield and disaster relief due to the lack of infrastructure requirement and rapid deployment capability. Such applications are typically in hostile environments where there is a high probability of failure of the wireless nodes. In the event of node failures, the network might get partitioned and the path between sources and destinations might become unavailable. Wireless networks therefore are not robust to node failures.

Based on the above issues with wireless networks, we address the question of feasibility of large-scale wireless networks. We propose that the addition of a satellite overlay network can effectively solve the problems with performance and robustness of wireless networks and make it possible to implement wireless networks with a large number of nodes.

We define a satellite overlay network as consisting of one or more satellite nodes and multiple terrestrial "gateway" nodes that have interfaces for both satellite links and terrestrial wireless communication. For our network model, we consider one satellite in geostationary orbit. We divide the terrestrial network into multiple "clusters" of wireless nodes, with each cluster being served by a gateway node. Ordinary terrestrial user nodes reach the gateway node through multi-hop terrestrial paths. This satellite overlay network provides multiple advantages to the wireless network:

- The forwarding over the satellite links is single-hop, compared to multi-hop forwarding path on the ground. Thus the overlay provides shortcut paths between a terrestrial source and a destination when the source and destination are separated by several hops, provided the propagation delays are comparable in both cases (typically, the propagation delay over satellite links, especially for geostationary satellites, would be several orders of magnitude higher than the propagation delay over terrestrial links).
- The bandwidth of the satellite link is usually much higher than that of the terrestrial wireless channels, and thus the overlay network can provide alternate high-bandwidth paths for the application traffic.
- The satellite is always on, and the characteristics of the satellite links are well- known. In the event of forwarding node failure on the terrestrial path between a source and destination, the satellite overlay provides alternate, forwarding paths. The satellite overlay thus provides reliable communication paths to the terrestrial nodes.

The rest of the paper is organized as follows. In section 2 we describe the proposed hybrid network model and outline a few example applications. We describe our experimental simulation model in section 3, and analyze the results of the simulations. We highlight further work in this context in section 4, and we conclude the paper with a review of related work in section 5.

2. Proposed Network Model

We consider the terrestrial network to be composed of wireless nodes that are grouped into either separate local area networks (LANs), or they are spread in a single large wireless network covering a large area. We assume that the terrestrial network has no wired infrastructure. The wireless nodes have limited energy and processing power, and they are also limited in their transmission range. The source and destination can be in different physical LANs, or they might be widely separated in the same wireless network. At a given time, there can be multiple source-destination pairs communicating with one another. Communication between the source and destination pairs is via multi-hop routing paths established with intermediate nodes acting as forwarding routers. The bandwidth available is limited by the maximum bandwidth of the wireless channel, which is shared by all the nodes. The communication can involve a wide range of applications with different QoS requirements:

- Video stream: high bandwidth, low jitter
- Voice: low bandwidth, low jitter
- Data traffic: high reliability, medium delay

Based on the above traffic types and communication capabilities of the user nodes, we propose to add a satellite overlay network for improved performance and network availability in the event of node failures. The satellite overlay network consists of a geostationary (GEO) satellite and multiple terrestrial "gateway" nodes that have interfaces for both satellite links and terrestrial wireless communication. In our present model, we assume each ground cluster is served by one gateway node. A cluster can be a physical wireless LAN, or clusters can be logical subdivisions of a large wireless network, created using different wireless base station set (BSS) identifiers. We assume that the GEO satellite has multiple spot-beams. It is capable of on-board processing and switching between the different spot-beams. The GEO satellite has a large footprint and therefore it can interconnect all the terrestrial LANs in a large area. The satellite is managed from a remote Network Operations Center (NOC) through a dedicated high-bandwidth channel. The NOC has wired broadband link to the Internet. The satellite supports high bandwidth for downlink (approximately 90 Mbps) and moderate bandwidth for uplink (approximately 1.5 Mbps). These assumptions about the GEO satellite are consistent with the features of several next-generation satellites in development (for example, [2]). The wireless terrestrial network and the satellite overlay together form a hierarchical hybrid network with varying node capabilities and different channel characteristics. We assume that every node in the network, including the satellite, is IP-addressable and can support IP based protocols. The wireless user nodes in a cluster or LAN communicate with one another and the local gateway node using multi-hop ad hoc routing protocols over the terrestrial wireless channels. The gateway nodes have multiple communication paths to other gateway nodes: either through terrestrial multi-hop wireless paths using ad hoc routing protocols or in a single hop over the satellite channel. The satellite overlay thus provides space diversity to the network. Communication between a source and a destination located in different LANs can take one of multiple forwarding paths: multi-hop ad hoc paths through forwarding user nodes (assuming the LANs are connected terrestrially), or multi-hop ad hoc paths to the local gateway, which forwards to the destination gateway either terrestrially or over the satellite links, and from there to the destination node. If the gateway nodes can route terrestrially or through the satellite links, the path selection is based on the end-to-end delay and the throughput required for the data traffic. In the overlay level, the terrestrial paths between the gateway nodes create a mesh architecture, while the satellite defines a star network where the bandwidth can be dynamically distributed amongst the underlying gateway nodes. This locally centralized architecture allows for bandwidth guarantees and preferential bandwidth allocation between the covered LANs.

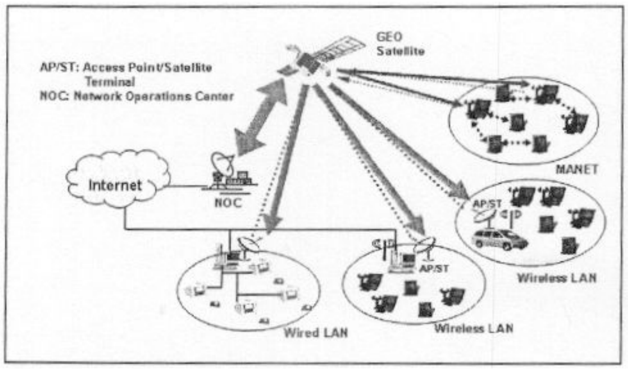


Figure 1: Hybrid network topology with a satellite overlay for civilian/commercial applications.

2.1. Example Hierarchical Topologies

Based on the network model outlined in section 2, figure 1 shows a representative architecture that is suitable for civilian or commercial use. The network comprises wired LANs, wireless LANs with fixed and mobile access points (APs), and mobile ad hoc networks (MANETs) that are connected to one another, and to the wired Internet, through a GEO satellite. Mobile APs serve networks where the infrastructure is not readily available. A subset of the nodes in the MANET has satellite uplink/downlink capability and thus connects to the rest of the hybrid network.

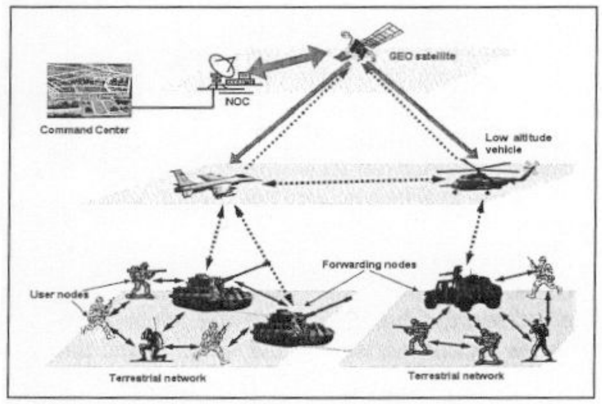


Figure 2: Hybrid network topology for military applications.

Figure 2 illustrates a hybrid wireless network for military use. The terrestrial segment is composed of MANETs with wireless mobile nodes (e.g., ground soldiers). Each MANET has one or more *forwarding nodes* (FN) with higher capabilities (e.g., armored vehicles). The FNs have wireless communication with both the ground nodes, and with spacecraft flying at low altitudes. The spacecraft are unmanned aerial vehicles (UAVs) or manned aircraft like helicopters. The ground nodes can communicate with the spacecraft through the FNs. The UAVs and other low-altitude spacecraft have satellite uplink/downlink to a GEO satellite. The different spacecraft can communicate with one another either through horizontal communication links or through the satellite. The satellite connects the MANETs and the low altitude spacecraft to remote command and control center.

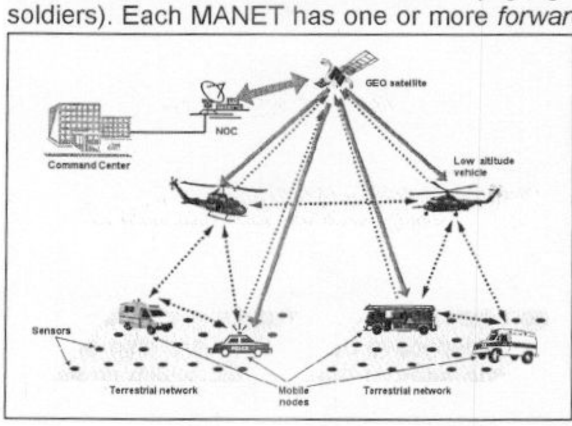


Figure 3: Hybrid network topology for emergency operations/disaster relief.

Figure 3 illustrates a hybrid wireless network suitable for emergency operations like disaster relief. The terrestrial segment consists of low-power sensor nodes grouped into clusters. Each cluster has one or more mobile base station nodes with higher capabilities. The mobile nodes communicate with the sensors, with low altitude spacecraft, and with a GEO satellite. The low altitude spacecraft (UAVs and/or helicopters) have satellite uplink/downlink. The satellite connects the low altitude spacecraft and the mobile nodes on the ground to a command and control center. The mobile nodes, which can be emergency vehicles, process the data collected from the sensors and relays the data via the spacecraft and satellite to the command center. The command center processes the collected information and sends operational commands to the spacecraft and the mobile vehicles to facilitate the disaster relief operations.

3. Simulation Model and Results

We have created several hybrid wireless network models in Opnet Modeler [3] and obtained preliminary performance results for voice and video traffic through simulations. For the simulation runs, we considered scenarios with stationary terrestrial user nodes and also scenarios with mobile user nodes.

3.1. Network Models with Stationary Nodes

We performed simulation experiments for network sizes of 200 stationary nodes and 1065 stationary nodes. In the network models, we have used IEEE 802.11 11 Mbps as the medium access control (MAC) layer protocol for the wireless ground segment. We use AODV [4] as the ad hoc routing protocol for the ground segment. For the satellite overlay network, the ground wireless segment is divided into four clusters, with one gateway in each cluster. The gateways are located within one hop transmission range of the source and destination nodes. Over the satellite links, we used point-to-point static routing. The satellite is located in geostationary orbit. For the 200-node network, there are two source-destination pairs sending medium data rate voice traffic using multi-hop forwarding paths. The voice traffic received by the destinations in the hybrid wireless network with satellite overlay, compared to a similar flat network without the overlay, is shown in figure 4. For the hybrid network, all the voice traffic is received, while a large percentage is dropped by the flat network. This is primarily due to the difference in stability and capacity between the satellite and terrestrial links, and their effect on the link layer and the routing protocol, as explained below. A comparison of the voice traffic parameters is given in figure 5. The end-to-end delay for the voice traffic is substantially less in case of the hybrid wireless network, and is mostly due to the propagation delay over the satellite links (figure 5(a)). Similarly, the voice traffic delay variation (figure 5(b)) and the voice jitter (figure 5(c)) are much less when the satellite overlay is used for forwarding the traffic. For the ad hoc routing protocol AODV, the time taken to discover routes to the destination, and the number of hops in the route are shown in figure 6. As shown in figure 6(a), the satellite overlay provides a reliable forwarding path that is available for the duration of the traffic flow, while the terrestrial forwarding paths change due to route timeouts, wireless channel contention, etc, and thus the forwarding path has to be re-established multiple times. This also contributes to the delay and the data drop. The number of hops is also limited in the case of the overlay forwarding, compared to terrestrial paths (figure 6(b)).

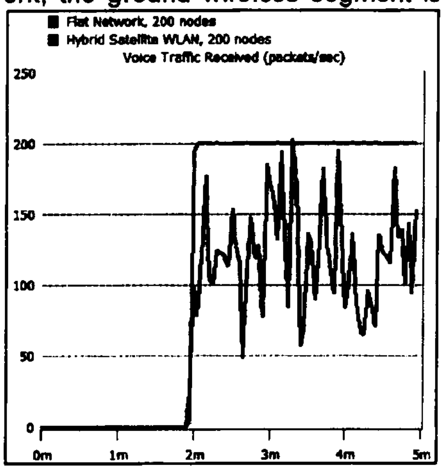
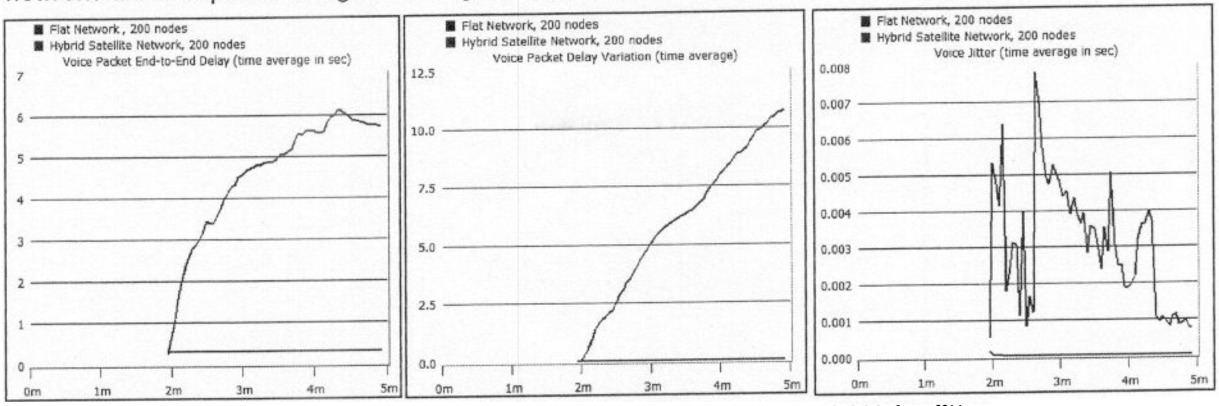


Figure 4: Comparison of voice traffic received in the 200-node flat wireless network and hybrid wireless network with satellite overlay (X-axis is the simulation duration in minutes).

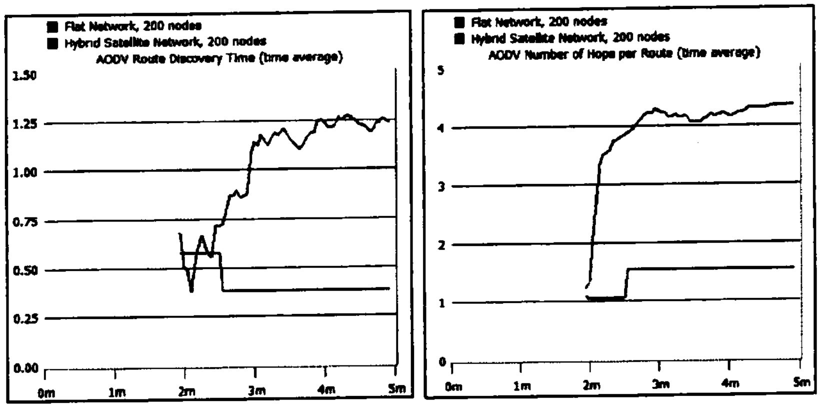
In the network model with 1065 nodes, there are three source-destination pairs. One pair of the sources is located one-hop away from each other, and their respective destinations are also one-hop neighbors. These sources and destinations are at the extreme ends of the network, which covers an area of 30kmX30km. The other source-destination pair is located close to the center of the network. A comparison of the voice traffic sent and received in the 1065 node network has is shown in figure 7. The graph shows that when the one-hop neighboring sources are transmitting simultaneously, there is a significant traffic drop due to buffer overflow in the forwarding nodes, and also collision in the wireless channel. When the overlay network is used, the high bandwidth provided by the satellite links ensures that traffic does not get backed up in the gateway, and there is no collision in the wireless channel. The statistics for the wireless channel for the hybrid overlay network and the flat wireless network are compared in figure 8. Figure 8(a) shows that even with limited application traffic, the



(a) End-to-end packet delay **(b) Packet delay variation** **(c) Voice jitter**

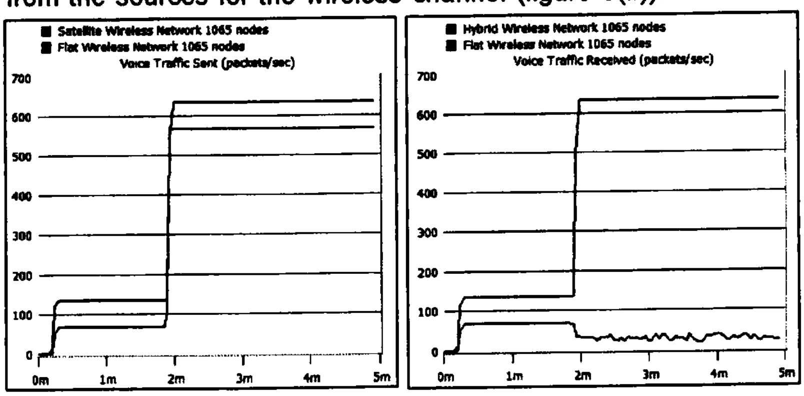
Figure 5: Comparison of voice traffic delay characteristics and jitter in 200-node flat wireless network and hybrid wireless network with satellite overlay (X-axis is the simulation duration in minutes).

wireless channel for the flat network drops a significant amount of data, while the satellite overlay network has no drops due to the very high bandwidth and the reliable forwarding path it provides. The wireless channel delay is much higher for the flat network as all the nodes contend for the shared medium, whereas for the hybrid network the delay is almost negligible because once the overlay forwarding path is established, all the traffic flows through it and there are no additional resource reservation requests from the sources for the wireless channel (figure 8(b)). For similar reason, the overall throughput for the wireless channel for the hybrid network is much less compared to the flat network, since most of the data is transmitted over the satellite links and the wireless channel is not utilized much (figure 8(c)). The voice traffic delay parameters comparison for the 1065-node network is similar to the 200-node network, and is therefore not shown here.



(a) Route discovery time (seconds) **(b) Number of hops per route**

Figure 6: Comparison of AODV parameters in 200-node flat wireless network and hybrid wireless network (X-axis is the simulation duration in minutes).

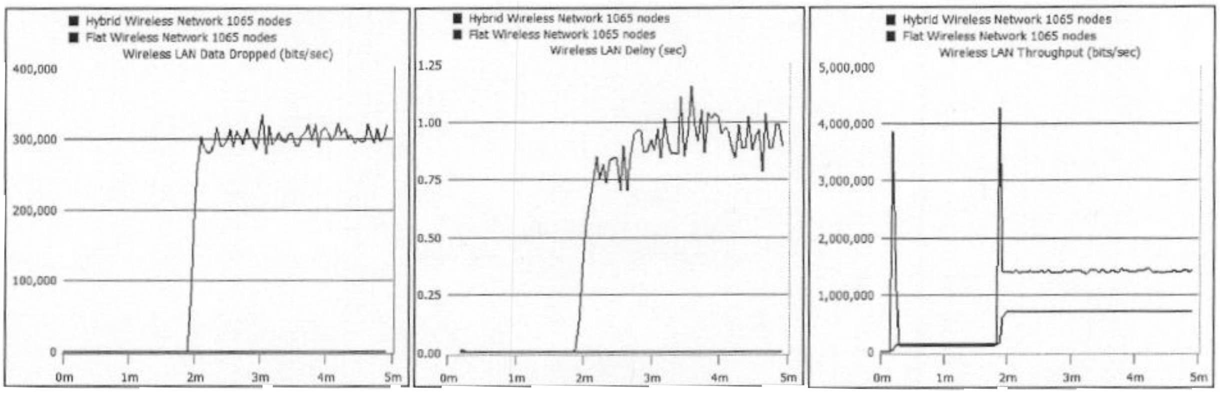


(a) Traffic sent **(b) Traffic received**

Figure 7: Comparison of voice traffic sent and received (packets/sec) in a 1065-node flat wireless network and a hybrid wireless network with satellite overlay (X-axis is the simulation time in minutes).

3.2. Network Model with Mobile Nodes

We have modeled a hybrid network topology with mobile user nodes (figure 9) in Opnet Modeler. The network scenario is demonstrative of an urban rescue



(a) Data dropped by channel **(b) Channel delay** **(c) Channel throughput**

Figure 8: Comparison of the wireless channel statistics in 200-node flat wireless network and hybrid wireless network (X-axis is the simulation duration in minutes).

mission where pre-existing infrastructure is not available and remote connectivity is provided by a satellite only.

In this scenario, there are wireless sensor nodes deployed on different locations on the ground to collect and transmit information on terrestrial conditions. There are low altitude spacecraft, OAV (for example, helicopters) flying over the scenario and gathering information. UAVs flying at medium altitude function both as sensors and relays for the data collected by the ground sensors and the OAVs. The UAVs are covered by a GEO satellite that relay the data collected from the UAVs to a remote command center. Data from the remote command center is also relayed by the satellite and the UAVs to ground vehicles which direct their trajectory based on the information from the sensors. The UAV relays therefore act as the gateway nodes for the ground sensors and the OAVs. The ground sensors, OAVs and the ground vehicles constitute a mobile ad hoc mesh network that increases the possibility of finding paths from the ground sensors to the UAV relays. Each relay acts as a gateway for a local star network where the bandwidth can be dynamically distributed between the underlying nodes. To provide constant coverage, the trajectory of each UAV relay is based on the movement of the ground nodes. Each ground sensor has a single wireless interface to the OAVs, while each OAV and vehicle has two interfaces - one for terrestrial wireless communication and another for communicating with the UAV relays. Each relay has one interface for talking to the OAVs and vehicles, and a second interface for satellite communication. The number of ground nodes, their locations and movement patterns are obtained from US military data. The number of UAV relays and the location of the UAV relays are determined by a heuristic placement algorithm proposed in [5]. The network has 118 ground sensors, 122 OAVs and 28 vehicles. There are 4 UAV relays for the network at altitude of 4.5 km, while the communication range with each OAV is set at 6km. DSR [6] is used as the terrestrial routing protocol, while the terrestrial MAC is IEEE 802.11 1Mbps. The bandwidth for the UAV to OAV link is 2.5Mbps each. The UAVs do static routing. The UAV link layer protocol and the satellite access are both reservation-TDMA. For the simulations, the nodes are configured with custom traffic. 20 OAVs generate simultaneous streaming traffic on average and send to the UAV relays for further transmission to the satellite. 8 ground sensors generate detection frames in random times throughout the simulation and send to the UAV relays through the OAVs.

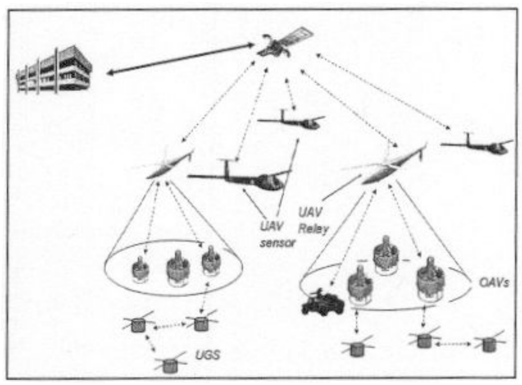
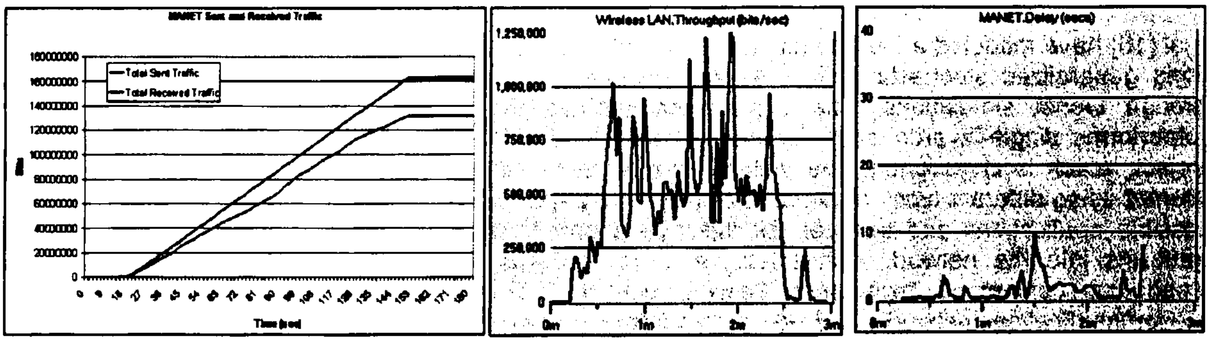


Figure 9: A hybrid wireless architecture for urban rescue operations with satellite-UAV overlay.

The traffic generated by the ground nodes is shown in figure 10(a). The ground sensors generate about 25% of the total traffic, and the OAVs generate the rest. The traffic reception delay is primarily a result of the event when a sensor node cannot connect to an OAV. The node continues to generate DSR route requests until an OAV comes within transmission range. Figure 10(b) shows that high traffic generation by the ground sensors loads the wireless LAN. The throughput can be greater than the link capacity of 1Mbps because two or more sensors can transmit simultaneously by sending traffic through separate OAVs and thus do not interfere with each other's transmission (space



(a) MANET Sent and Received Traffic (b) Wireless LAN throughput (c) End-to-end traffic delay

Figure 10: Simulation results for urban rescue scenario hybrid wireless network with satellite-UAV overlay (X-axis is the simulation duration in seconds (figure a) and in minutes (figures b and c)).

diversity). The higher delays in traffic reception in figure 10(c) are primarily due to the ad hoc multi-hop routing delays of the ground sensor frames. The storage delay when a path is not initially available but established later, also contributes to this delay. Since the OAVs have direct links to the UAV relays, the delays due to the OAV frames are much smaller in comparison.

4. Conclusion

In this paper we have proposed a satellite overlay network model to improve the end-to-end traffic delivery performance and robustness of large wireless networks. We have built network models in Opnet simulation test-bed and obtained experimental results that demonstrate the improvement in end-to-end traffic delivery and delay when the overlay network is used.

We are currently investigating improvements to the proposed hierarchical network model, for example, the dynamic allocation of mobile gateway nodes based on the traffic characteristics in the network. The UAV placement algorithm used in our model [5] allocates the gateway nodes statically based on the number of clusters. However, if only a small subset of the clusters is involved in the communication at any given time, a smaller number of gateway nodes would suffice. Therefore, we are investigating whether we can achieve comparable performance with a smaller number of mobile gateway nodes, by moving around the gateway nodes to cover only the clusters that are involved in the communication. We are also working on developing analytical models to compare the system performance to the system cost, and thus obtain trade off estimates.

5. Related Work

Gupta and Kumar have obtained theoretical results that show that the capacity of wireless networks improves by a factor of 1.5 when the networks are 3-dimensional, for example, hierarchical networks with a satellite backbone [5]. In [6], the authors have considered a hybrid terrestrial cellular network with a satellite backbone and have formulated a multi-faceted cost function composed of call-blocking and dropping probabilities, to determine the optimal channel partitioning between the cellular and the satellite systems and to decide on the optimal call assignment policy. They have obtained optimal solutions for sub-problems of the original complex optimization problem, whereby they conclude that double coverage through cellular and satellite systems, results in substantial improvement over pure terrestrial or pure satellite systems. In [7], the authors propose a unified mathematical framework using a two-stage stochastic programming formulation, to find the most cost-effective network topology for hybrid broadband terrestrial/satellite networks. The solution to the problem formulation gives optimal link capacities and optimal routing strategy for different network topologies. The authors show that for certain parameter values, the hybrid topology is more cost effective than non-hybrid topologies. Dousse et al [8] study the connectivity property of large-scale ad hoc and hybrid wireless networks where fixed base stations can be reached in multiple hops. The authors find that the introduction of a sparse network of base stations increases the connectivity to a large extent. Ryu et al [9] have proposed an architecture for multi-tier mobile ad hoc networks and developed simulation tools for this hybrid network. To address the challenges of connectivity asymmetry and node heterogeneity, the paper proposes a cross-tier MAC protocol for the access layer, the multi-virtual backbone protocol for ad hoc routing using the hierarchical backbone architecture, and a multi-modal TCP protocol. Wu et al [10] have modeled a hierarchical low earth orbit/medium earth orbit (LEO/MEO) satellite network using generalized stochastic Petri nets and obtained performance results of the Petri nets model through Opnet simulations. The paper demonstrates that the double-layered satellite network outperforms single-layered ones for heavy traffic loads. [11] describes the European CAPANINA project, which is investigating the viability of integrating difficult-to-reach areas into the broadband Internet using different types of aerial platforms. The paper describes the work that are being done on possible applications and services for this hybrid architecture, on solutions to integrate the aerial platforms into the network architecture, and on methods to use the aerial platforms to deliver broadband content to high-speed moving vehicles. The role of satellite networks in future telecommunications networks and service provisioning is examined in [12]. The authors argue that the future of satellite systems is to complement terrestrial networks to provide multimedia services to fixed and mobile systems in an integrated architecture. Jetcheva et al [13] have designed *Ad Hoc City*, a multi-tier mobile ad hoc network architecture for wide-area communication, where the backbone network is a mobile multi-hop network composed of wireless devices mounted on moving vehicles. The design integrates cellular networks with ad hoc networking and uses a modified version of DSR for unicast routing.

6. Acknowledgement

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