SwanMesh: A Multicast Enabled Dual-Radio Wireless Mesh Network for Emergency and Disaster Recovery Services

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***Abstract*—In this paper we present the design and implementation of our multicast enabled dual-radio wireless mesh network for emergency communications. We have developed a novel implementation of a Multicast extension to the AODV (MAODV) protocol in Linux Kernel 2.6 user space to support multicast operation of our SwanMesh testbed. This paper presents the architecture of our SwanMesh testbed. Furthermore, we present unicast communication throughput test results. We observed that SwanMesh can efficiently deliver data services such as broadband internet in emergency situations using its unicast functionality although there were noticeable throughput drops after each hop. Therefore the SwanMesh multicast operation may be suitable for delivery of real time applications in emergency communication, such as audio and video teleconferencing. We also performed validation tests to ensure correct multicast functionality of our MAODV implementation. The possible application of WMN in emergency is discussed.**

***Index Terms*—MAODV, multicast, routing, adhoc, wireless mesh network**

I. INTRODUCTION

In recent years the world has seen large scale emergency and disaster situations such as flood, fire, earthquakes and terrorist attacks. Experiences gained from major natural disasters such as Hurricane Charley in August 2004 and Katrina in August 2005 in the USA, the Asian Tsunami in December 2004, an Earthquake in China in May 2008 and recent fires in Australia in February 2009 show that one thing all of these natural disasters have in common, besides the tremendous loss of life, is that they completely destroy communication and power infrastructure; this results in loss of ability to communicate locally and with the outside world. Power infrastructure may be destroyed, telephone services may be shutdown, and mobile phone service can either be unavailable or so congested that it takes hours to get a call through. Thus failure in communication and information exchange during the early response efforts can result in further heavy morbidity and mortality.

An alternative reliable technology would be helpful that is capable of delivering wireless mobile broadband, wireless telephony services and wireless multimedia audio and video data exchange offers and so an effective solution to the problem. Wireless Mesh Network (WMN) technology should be capable of offering such solutions during emergency and disaster recovery process [1, 2].

The idea of WLAN based WMN was first presented in 1995 by Victor Pierobon [3]. However, because of the limitations of WLAN technology itself in the 1990s, WMN technology was not able to grow until companies, started to develop WMN products. Survey of WMN technology, its characteristics and applications have been presented in [1, 4].

The major challenges facing wireless mesh network are limited bandwidth resources of the wireless medium. During rescue operations various teams work together. Exchange of data and live multimedia information among the different response teams is very important. Unicast transmission can be used for broadband services such as email and www but if unicast transmission is used to deliver live multimedia information to multiple clients, this could result in network failure due to limited bandwidth resources of the wireless medium. Multicast transmission saves network resources by replicating live multimedia images from one source camera to multiple recovery team clients.

Therefore we have developed a multicast enabled dual radio wireless mesh network called SwanMesh. Our SwanMesh is based on Linux kernel 2.6. We have used

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an Adhoc On-Demand Distance Vector (AODV) kernel user space implementation developed by Uppsala University Sweden [5] for unicast routing. Unicast communication in our SwanMesh is used to deliver non real time broadband services such as email and www. We are not aware of any implementation of multicast extension to AODV (MAODV) [6] that support Linux kernel version 2.6. Therefore we have developed a novel implementation of MAODV in kernel user space. The multicast functionality in our SwanMesh is used to deliver live video and audio real time data to multiple clients using the same bandwidth stream. A one-to-many multicast video transmission can help rescue teams exchange live information.. This paper will describe the development of the SwanMesh testbed in Section II. In Section III we explain why we need to develop a novel implementation of MAODV. In Section IV multicast operation of SwanMesh is validated to ensure correct functionality of our implementation of the multicast protocol. We present throughput performance and multimedia test results of SwanMesh in section V. Finally in section VI we present our conclusion of the potential applications of our SwanMesh in emergency situations.

II. Development of SwanMesh

In the last few years, several wireless mesh network projects have been developed. Many are open source projects aiming to provide community wireless broadband services. Roofnet is one of the earliest research projects developed by researchers at MIT [7]. It is an experimental 802.11b/g mesh network which provides broadband Internet.. Berlin RoofNet is a counterpart project in Europe, which was developed at Humboldt University Berlin [8]. VMesh is a testbed developed at University of Thessaly, Greece [9]. Mesh@Purdue is the Purdue University testbed [10]. iMesh was developed at Stony Brook University[11]. MobiMESH is a testbed specifically aiming at seamless mobility which was developed at Politecnico di Milano, Italy [12]. All the above testbeds are based on 802.11 technology for mesh networking. These mesh networks are based on single radio to form the network, whereas our SwanMesh is based on dual radio communications,.

Apart from academic testbeds, some community mesh projects have also been developed to provide community wireless broadband access. CUWiN is one of the biggest community groups which develops the software, provides wireless consulting, and community education [13]. OpenWrt [14] and DD-WRT [15] are firmware specifically for the Linksys WRT54G router.

We have developed a multicast enabled dual radio wireless mesh network testbed called SwanMesh. Further in this section we are going to describe the architecture of our SwanMesh testbed.

A. Architecture of SwanMesh

The architecture of the developed wireless mesh networking testbed is illustrated in Figure 1. The operating system of the wireless mesh network is Linux with kernel version 2.6 [16]. Inside each mesh node, the necessary modules/drivers to support the hardware architecture of the platform have been compiled inside the Linux kernel and run under Linux kernel space. The Linux kernel user space is used to run other necessary modules and applications required to form and configure the wireless mesh network. The strength of our testbed lies in the application of our custom configurations of network components in kernel user space which provides self-organized, self-managed, self-healing and location independent connectivity to wireless audio, visual and data devices.

The client access interface is used to serve the data, audio and video facilities provided by the wireless mesh network. The backbone interface is used to communicate with other mesh nodes and to maintain the route to the gateway node. The gateway node uses a gateway interface to link the mesh network with external networks.

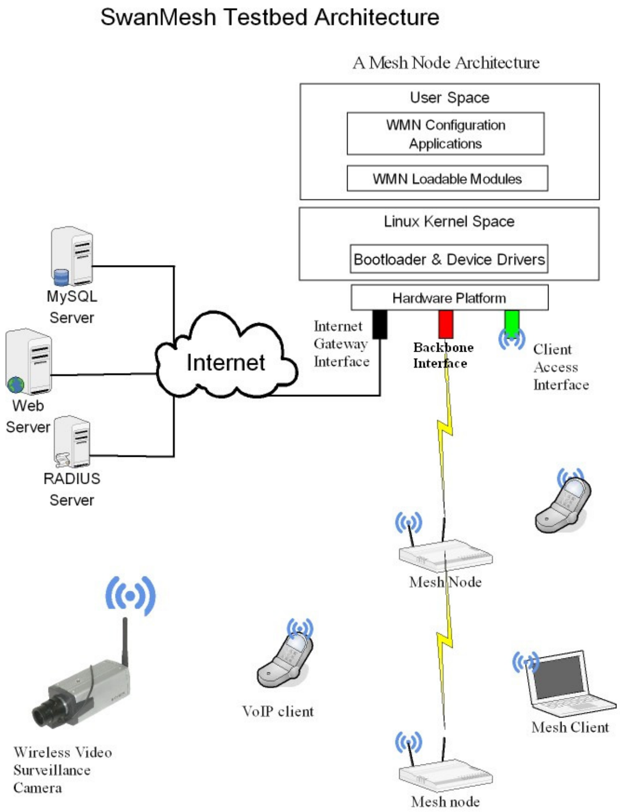

Figure 1. Architecture of developed WMN Testbed

The current system supports both X86 and ARM architectures.

B. Mesh Networking of SwanMesh

Each mesh node has the general router functions . This includes NAT (Network Address Translation), DHCP (Dynamic Host Configuration Protocol), DNS (Domain Name Service), Firewall. These functions can be implemented very easily on Linux as they can be easily installed as dependable modules. In order to achieve mesh networking, it is important to route the data from router to router.

Mesh routing was adopted from Ad Hoc wireless networks. There are three types of routing protocols for

Ad Hoc networks: pro-active, reactive and hybrid. Pro-active protocols are table driven which maintain fresh lists of destinations and their routes by distributing routing tables in the network periodically. Alternatively, reactive protocols find the route on demand by flooding the network with Route Request packets. Therefore that is also called on-demand protocol. Reactive protocols can significantly reduce routing overheads when the traffic is lightweight and the topology changes less dramatically, since they do not need to update route information periodically and do not need to find and maintain routes where there is no traffic.

Both proactive and reactive protocols have been successfully applied in wireless mesh network, for example, OLSR [17] was implemented in Mesh@Purdue [10] and OpenWRT [14] projects, AODV[18] was implemented in Locustworld's meshbox [19]. Reactive protocols are widely accepted for WMNs. Among reactive routing protocols, DSR[20] and AODV are considered good in terms of overall performance [21]. AODV exhibits resilience to mobility and it is suitable for use in highly dynamic environments. Therefore, in this development, AODV was selected to implement routing in mesh networks.

III. MULTICAST OPERATION OF SWANMESH

Multicast communication is transmission of data from one sender to a group of hosts identified by a single destination address [22-23]. It utilises network infrastructure efficiently by requiring the source to send a packet only once. This is particularly useful for the transmission of multimedia data over wireless networks in emergency situations. The SwanMesh can efficiently deliver data services such as broadband internet in emergency situations using its unicast functionality though there are noticeable throughput drops on each hop between client and gateway node. Therefore SwanMesh multicast operation may be of use in delivering real time applications in emergency communications, such as audio, video teleconferencing and distributed database systems.

Multicast routing in wireless mesh networking is a key issue. Similar to unicast, multicast mesh routing has also been adopted from MANET (Mobile Ad Hoc Networks). Multipath passive data acknowledgement on-demand multicast protocol (MPDAODMRP)[24] uses a scheme to distribute data overhead to multipath based on diversity coding. RIPPLE [25] is an improvement of Multicast-enabled Landmark Ad Hoc Routing (M-LANMAR) [26] which employs flooding to deliver messages in a group for mobile ad hoc networks using directional antennas. [27] is a multicast wireless mesh network routing algorithm which uses Ant Colony Optimization (ACO) that is a Swarm Intelligence paradigm. Multiple edge-sharing trees (MESTs) [28] provides several paths for the multicast content and involves more nodes in implementing multicast functionality. Neighbour Aware Multicast Routings Protocol (NAMP) [29] is a tree based multicast routing protocol which uses neighboring information to create a route. Hierarchical Rendezvous Point Multicast (HRPM) [30] is a stateless multicast protocol which decomposes large multicast groups into hierarchical subgroups. Semi-overlay multicast routing protocol (SOMRP) [31] is an overlay based scheme which uses a semi-overlay structure; overlay multicasting schemes introduce redundant data transmissions which waste network bandwidth and battery power of relay nodes. [32] uses a scheme to reform core-based group-shared multicast tree in mobile adhoc networks. Distributed Maximum life time in multicast (DMLM) [33] and Distributed Minimum Energy Multicast (DMEM) [34] multicast routing algorithms focus on energy consumption. DODMRP [35] is a destination driven extension to ODMRP [36]. ODMRP is an on demand multicast routing protocol which works independently. MAODV [6, 37] is also an on demand tree based multicast protocol which is an extension to AODV unicast routing protocol. Unlike ODMRP, MAODV depends on its underlying unicast AODV protocol to provide multicast functionality. MT-MAODV [38] is an extension to MAODV which establishes multiple trees to provide multiple routes for multicast. Fuzzy logic Modified AODV routing (FMAR) [39] also uses a scheme to provide multiple paths. Construction of multiple routes incur extra overheads.

Several comparative analysis studies [40-44] have shown that these multicast protocols perform well under specific scenarios considering mobility, traffic loads, packet overhead, and network conditions. One protocol may not be optimal in all scenarios [45]. These protocols can be classified using two criteria [46-47]. The first criterion is based on maintaining routing state. Similar to unicast it classifies routing mechanisms into two types, proactive and reactive. Proactive maintains a routing state and reactive works on demand. The second criterion is based on the multicast packet forwarding global data structure which has basically two further types, mesh based and tree based. A tree-based multicast routing protocol creates a multicast tree from each of the sources to all receivers where as a mesh-based multicast routing protocol sustains a mesh consisting of a connected component of the network containing all the receivers of a group. Hybrid based multicast routing combines the above two structures. A review of the MANET multicast routing protocols was presented in [47]. We have used a reactive kernel space implementation of protocol AODV [5] for unicast communication in our SwanMesh. MAODV and ODMRP are two main reactive multicast routing protocols within the MANET working group at the IETF for ad hoc networks. MAODV is tree based and ODMRP is mesh based. Both are well known protocols used for wireless mesh networks. ODMRP works independently whereas MAODV is an extension to the unicast AODV protocol. Its route-discovery mechanism is based on AODV. MAODV also utilises the control messages that exist in AODV and employs the same route request and route reply discovery cycle during its multicast route discovery operation. Thus route information obtained during multicast route discovery operations increases unicast routing knowledge and vice-versa. Since SwanMesh uses reactive AODV user space based implementation [5]. MAODV is the best option to implement multicast communications in our testbed.

Our multicast implementation is based on [5] as a unicast base protocol. It runs in Linux kernel 2.6 as a dynamically loadable module.

IV. Multicast Operation Validation Tests

We used our wireless mesh network testbed to perform these tests. Mackill (An open source MAC filter Utility developed by Uppsala University Sweden) is a utility tool which can force different connectivity configurations of mesh nodes without the nodes being required to be physically separated. We have used this utility to establish our network topology scenarios during the tests. To cover all the aspects of the network behaviours we set up our testbed using four SwanMesh nodes shown in Figure 2.

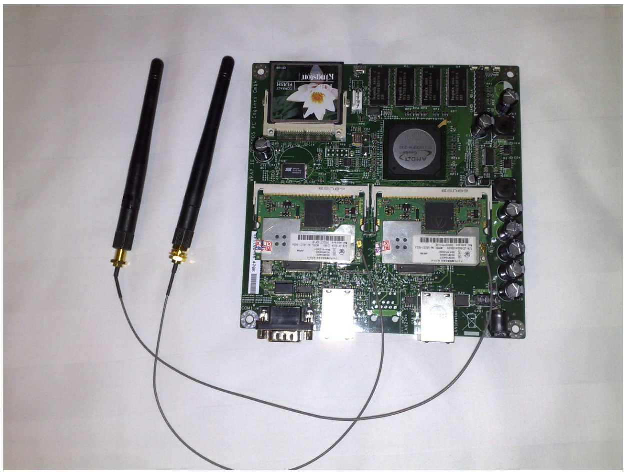

Figure 2. Picture of the X86 Architecture based SwanMesh node

We used our custom built multicast application during the tests. We verified and cross referenced the MAODV operation using a multicast route table and debugging reports to ensure correct functionality of our implementation.

To understand the tests it is important to understand the MAODV protocol functionality. A detailed description of MAODV operations can be found in [6, 37].

A. *First Stage*

In the first stage of our test we turn on a single node A. We run a multicast application on Node A which after joining the group initiates a route discovery process by sending a multicast Route Request (RREQ). On not having received multicast (Route Reply) RREP message during the Route Discovery process Node A becomes a group member and group leader of the multicast group itself and starts routing. Node A starts broadcasting multicast Group Hello(GRPH) control messages with GROUP_HELLO_INTERVAL milliseconds.

Now we turn on Node B. When Node B receives a GRPH message from Node A, it processes the GRPH message. Node B updates the multicast route table with the group and group leader information provided by the GRPH massage and rebroadcasts the GRPH.

Node B keeps the membership, router and leader flags off in its multicast routing table to indicate that it is not yet a member or leader or router for the group.

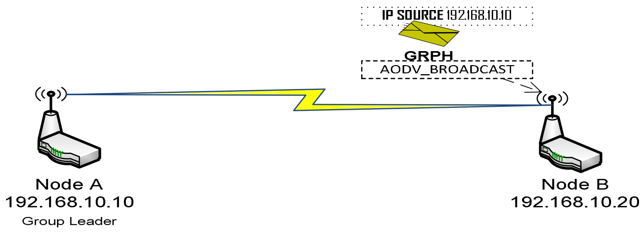

Figure 3. First GRPH multicast control message received by Node B

Now we turn Node C on We use Mackill to block direct communication between node A and C to create a topology as shown in Figure 4.

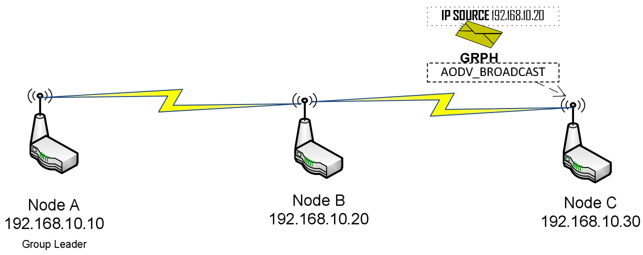

Figure 4. First GRPH multicast control message received by Node C

Node C receives GRPH originated by group leader Node A and forwarded by Node B. It processes the GRPH and updates the multicast route table. with group and group leader information. Finally Node C rebroadcasts the multicast GRPH control message. Now we run a multicast application on Node C. After joining the group it initiates route discovery processing by sending multicast RREQ control message as shown in figure 5.

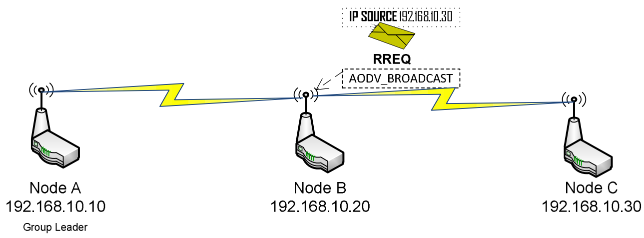

Figure 5. First multicast RREQ control message originated by Node C

Node B receives the broadcasted RREQ for multicast destination from Node C. It processes the multicast RREQ and makes an inactivated next hop entry for Node C. Node B is not on the multicast tree therefore it will rebroadcast the RREQ. Now Node A receives the broadcasted RREQ; it processes it by updating its multicast route table with an inactivated next hop entry with DOWNSTREAM direction for Node B. Node A is a multicast group tree member for the same group for which it has received a Route Request. Therefore it will send a Route Reply back to Node B. Node B processes the RREP after updating its multicast route table entry. It makes an inactive next hop entry with the Direction set to UPSTREAM for node A. After that Node B forwards the RREP back to Node C. Node C is the originator of RREQ for which it received RREP so at the end of multicast route discovery process it activates its next hop upstream node. Node C starts routing by sending a Multicast Activation Message (MACT) with J (join) flag to Node B. When node B receives the MACT it activates the next hop DOWNSTREAM entry in the multicast route table. Now Node B updates its multicast route table and starts routing as an active non member router by sending a Multicast Activation message with J (join) flag to Node A. When Node A receives the MACT from Node B with Join flag on, it activates the next hop DOWNSTREAM entry in its multicast route table for node B and starts routing. Finally our multicast communication has been established in three node scenario as shown in figure 6.

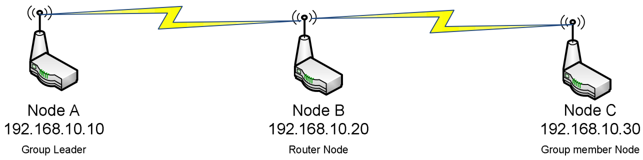

Figure 6. Three node multicast communication topology

Node A is group leader, Node B is router node and Node C is group member.

B. Second Stage

Once the first stage is completed we turn on another node D on and use Mackill to establish the topology so that Node D can only see Node C.

Now we start the multicast application on Node B and Node D and after going through the route discovery process both nodes become members of the group and we get the topology established as shown in Figure 7. Node A is group leader and Nodes B, C and D are group members.

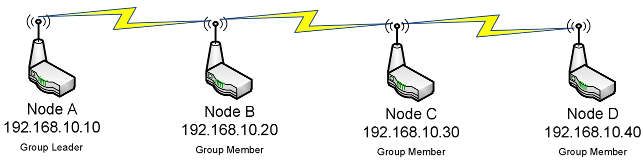

Figure 7. Four nodes multicast communication topology

We break the link between Node B and C using Mackill which initiates the tree link breakage process as shown in figure 8. After Node B realises that it has lost a DOWNSTREAM node it simply removes the node from its multicast route table next hop entry.

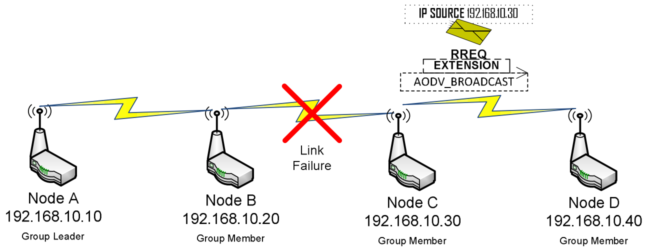

Figure 8. Link breakage in four node scenario

When Node C detects the link failure with its UPSTREAM node, it initiates the route discovery process and starts broadcasting a RREQ. It turns on certain procedures controlled flags and group merger extension in RREQ to indicate that a group tree is broken and the nodes wish to rebuild its tree. At the end of the multicast route discovery process Node C becomes a group leader itself and broadcasts a GRPH packet with update flag. On receiving that GRPH, Node D processes the GRPH and updates its new group leader information in its multicast route table. Finally our tree is split into two different trees each with a different group leader. We have the following topology established as shown in figure 9.

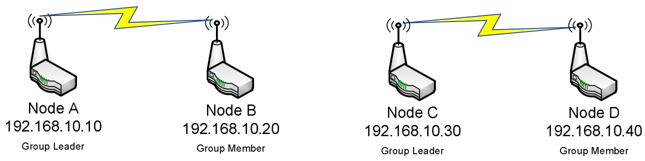

Figure 9. Multicast tree split after link breakage

C. Third Stage:

Now we enter into the final stage of our multicast validation test where we unblock Node C's MAC address on Node B and vice versa to create a bi-directional link which initiates the tree merger.

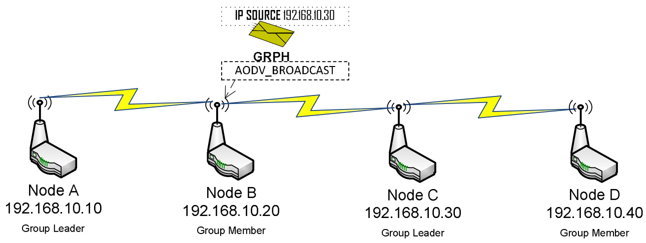

Figure 10. Tree merger process

When Node B receives a GRPH from Node C, it processes the received GRPH message. Since Node B is not a group leader and it has received group leader information for a different group leader via GRPH, it simply unicasts the GRPH to its next hop activated UPSTREAM which is node A. Node A is also a group leader. On receiving GRPH from a different group leader, it first compares the IP addresses. It does this because the group leader with a lower IP ADDRESS will have to give up its leadership during the tree merger process. Node A's IP ADDRESS is lower than C's so it initiates the tree merger process by updating its multicast route table to indicate that it is repairing the multicast route. As shown in figure 11, Node A initiates the multicast route discovery by sending a RREQ with certain procedures control flags and group merger extension.

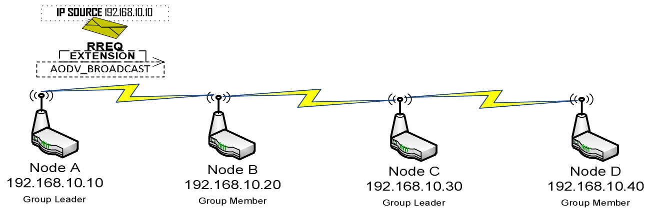

Figure 11. Tree merger process

Procedure control flags and group merger extensions indicate that it is tree merger and only the destination node can send a RREP. Therefore when Node B receives the RREQ it will not send a RREP, instead it will unicast the RREQ to Node C. Node C realises that it has received this RREQ because it is a group leader so it sends a RREP with procedure control flags and extensions indicating that this is a tree merger Route Reply. On receiving the RREP, Node B starts the group merger process by deactivating its current next hop upstream node. It updates it multicast route table to join the new group leader and sends a MACT message to Node C with J (join) flag. Now Node B forwards the RREP to Node A. When Node C receives a MACT message from Node B it also activates Node B as the next hop DOWNSTREAM node. When Node A receives RREP from Node B indicating the group merger, it sets Node B as an active UPSTREAM next hop. It starts routing by sending a MACT message with J (join) flag to Node B which activates Node A as a DOWNSTREAM next hop node on the tree on receiving the MACT.

Once the route is repaired Node A finally gives up its leadership and the multicast communication is re-established after tree merger with the following topology as shown in figure 12.

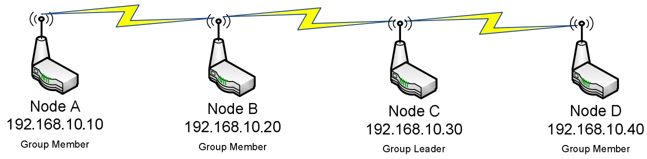

Figure 12. Final multicast communication topology after tree merger

V. PERFORMANCE OF SWANMESH

We conducted both indoor and outdoor tests. Indoor test were performed to evaluate throughput performance of SwanMesh. Outdoor tests were conducted to ensure the performance reliability of real time multimedia capability of SwanMesh in an urban environment.

A. *SwanMesh indoor throughput test*

The test was performed in an office building. In order to evaluate the performance after each hop, a chain network was formed to force the mesh nodes to link to each other as illustrated by Figure 13. All the six mesh nodes and laptops used during the test are shown in Figure 14.

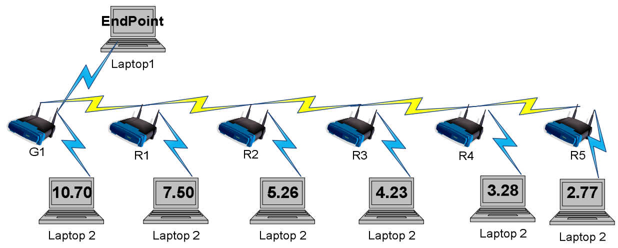

Figure 13. Single Gateway mesh topology throughput test

All the nodes were kept at a reasonable distance and the Mackill utility was used to establish the topology shown in Figure 13. Each node can only communicate to its neighbour node.

Each of our SwanMesh nodes is built using a WRAP board (as shown in figure 3 above) designed by PC Engines™ Switzerland. The CM9 wireless MiniPCI cards, made by Winstron™, it supports IEEE 802.11b/a/g standards. A typical Omni 5dB antenna at 5.8GHz and a 3 dB antenna at 2.4GHz were used for signal transmission.


Figure 14. Picture of hardware used during the tests

We used IxChariot [Ixia, Calabasas, USA] performance tool which uses performance endpoint software running on two client laptops to perform client to client throughput tests. We performed the test on each hop in our mesh network. Laptop1 with endpoint software is connected to the gateway. We executed the high performance throughput script on laptop2 after connecting it to each mesh router as a client.

The throughput test is performed on each hop. Figure 13 above shows the average throughput gain in Mbps is on laptop2 screens.

A graphical representation of the throughput drop on each hop is shown in Figure 15. The minimum, maximum and average throughputs recorded between gateway client and each mesh node client are shown with different bar colours.

The test results show a noticeable throughput drop between the mesh gateway and mesh router client over each hop. The throughput drop on each hop results in network resource starvation as it grows. Thus it may becomes very expensive and difficult to use one to many unicast video streaming during emergency and disaster recovery process; therefore we have implemented multicast functionality in our testbed.

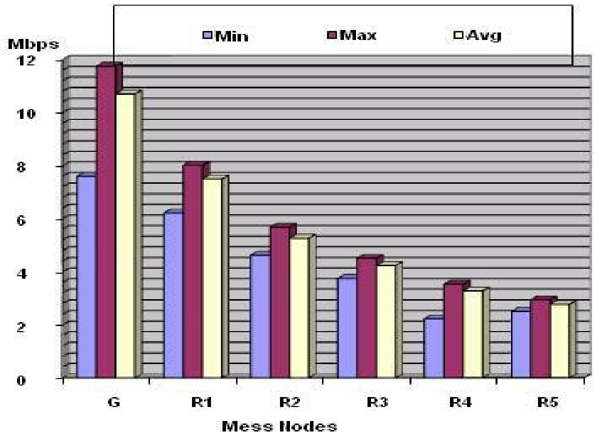

Figure. 15. Single Gateway mesh topology throughput test graph

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B. *Multimedia Performance of SwanMesh in Urban Environment*

Due to the shared nature of wireless medium the performance of wireless links in urban environment varies from area to area. Small amounts of RF interference from 802.11 and non 802.11 complaint devices that share the 2.4GHz ISM band can result in substantial performance problems for commodity 802.11 NICs [48]. In an urban environment our SwanMesh would compete for the wireless channel access with a wide range of these devices. We installed SwanMesh test bed in an outdoor urban environment. We conducted a multimedia test to investigate the performance reliability of the multimedia capability of our SwanMesh. The test scenario is shown in the figures 16 and 17 below. Figure 16 shows the SwanMesh Gateway node installed on the top of a building.


Figure 16. Picture of SwanMesh Outdoor Testbed.

Figure 17 shows the wireless camera we used to perform the multimedia tests. The wireless camera is connected to the Gateway node capturing live video images. In the bottom left hand corner of the figure 16, there is a tall building nearly one mile away from the gateway node. The SwanMesh repeater was been installed on top of that building.

Figure 17. Picture of Wireless Camera installed in outdoor Test Bed

We used a laptop client inside a car which is parked in a street out of the gateway node range and inside the repeater node range. We wirelessly connect to the Repeater node as a client inside the car and logged into the SwanMesh to see live video images being captured by the wireless camera using unicast operation. The video runs smoothly. The video demonstration clip of this outdoor video multimedia test is publicly available at [49].

We also used two VoIP Phones to test audio conversation. We established a successful conversation between the two phones. One phone was connected to the Gateway node and other to the Repeater node.

These tests ensured that apart from data, the SwanMesh can also deliver multimedia communication smoothly in an urban environment.

VI. Conclusion and Future Research

An ideal application of SwanMesh is likely to be in emergency and disaster recovery. Disaster situations destroy the traditional infrastructure for communication; therefore a reliable communication infrastructure is very important for the rescue and first response teams. The self-organized, self-managed and self-healing technology of our SwanMesh allows the deployment of an efficient network within minutes on a disaster site. The mesh nodes and devices such as wireless cameras and VoIP devices are capable of configuring themselves. Another challenge for rescue team is destruction of power supply infrastructure. SwanMesh nodes use low power of about 3 to 5 W at a range between 7 to 18V DC supply through a DC connector or passive power over Ethernet cable. This power can be easily supplied using batteries or solar power in emergency and disaster situations where other power sources are not available.

Thus SwanMesh could provide the first response and rescue teams a mean to exchange the crucial information via video, audio and data (email, www etc.) communication. During large scale disasters many rescue teams have to work simultaneously at different disaster affected geographical locations. Therefore an emergency response usually requires a central control to coordinate rescue efforts being carried by different teams at different locations. Our SwanMesh provides that central control through gateway nodes which connect to the backbone external network, thus building a bridge between the SwanMesh and external networks in order to share and exchange audio, video and data services.

Many emergency situations are in urban areas. The performance tests in section 5 have shown reliable multimedia performance of our SwanMesh in a real outdoor urban environment. Due to the shared nature of the wireless medium the appropriate use of bandwidth is important in wireless mesh networks. In emergency situations exchange of multimedia information among these different response teams is very important. Unicast transmission of multimedia images requires a lot of bandwidth resources, if a live video image needs to be shared among multiple clients of rescue teams. A one-to-many multicast video transmission can help solve this problem.

We are not aware of any other implementation of multicast extension to AODV which supports kernel 2.6, therefore we developed a novel implementation of MAODV in kernel 2.6 user space to enable multicast routing in our SwanMesh. With multicast operation our SwanMesh will allow smooth delivery of live multimedia images and information to multiple clients at different locations using a single bandwidth stream. Thus it will not only help saving the network resources but could help to save lives by exchanging information among different rescue teams and keeping teams up-to-date with live information

We are currently developing a multicast video transmission application and in the future we hope to use that to conduct multicast performance tests of our SwanMesh. Implementation of QoS routing is also being investigated.

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