Overview of the Meraka wireless grid test bed for evaluation of ad-hoc routing protocols

David Johnson and Albert Lysko
Meraka Institute, CSIR, {djohnson,alysko}@csir.co.za

***Abstract*—Predicting the performance of ad-hoc networking protocols has typically been performed by making use of software based simulation tools. Experimental study and validation of such predictions is vital to obtaining more realistic results, but may not be possible under the constrained environment of network simulators. This paper presents experimental comparisons of routing protocols using a 7 by 7 grid of closely spaced WiFi nodes. It firstly demonstrates the usefulness of the grid in its ability to emulate a real world multi-hop ad-hoc network. It specifically compares hop count, routing traffic overhead, throughput, delay and packet loss for three protocols which are listed by the IETF MANET working group. These are AODV, OLSR and DYMO**

***Index Terms*—ad-hoc networks, IEEE 802.11 standard, wireless grid test bed**

I. Introduction

One of the key challenges for researchers in the field of wireless networking protocol design, is the ability to carry out reliable performance measurements on their protocol. Parameters that need to be evaluated are typically, scalability, delay, throughput and network convergence in the presence rapidly changing link quality and route optimization.

Unfortunately most of the work done so far makes use of simulations which over simplify the physical layer and even aspects of the Medium Access Control layer. There is also a lack of consistency between the results of the same protocol being run on different simulation packages [1].

Mathematical models are useful in the interpretation of the effects of various network parameters on performance. For example, Gupta and Kumar [2] have created an equation which models the best- and worst-case data rate in a network with shared channel access, as the number of hops increases. However, recent work done by the same authors [3] using a real test bed, employing laptops equipped with Standard ("802.11") based radios, revealed that 802.11 multi hop throughput is still far from even the worst case theoretical data rate predictions. This illustrates the importance of verification using physical test beds.

A recent "Network Test Beds workshop" report [4] highlighted the importance of physical wireless test bed facilities for the research community in view of the limitations of available simulation methodologies. This was the motivation for the ORBIT project [5], which describes a wireless grid similar to the one that is discussed in this paper.

The ORBIT mesh lab has a small 8x8 grid and a larger 20x20 grid, which makes use of 802.11 wireless equipment based on the same Atheros chipset used by the authors at the Meraka Institute. The ORBIT laboratory makes use of Additive White Gaussian Noise (AWGN) to raise the noise floor, whereas Meraka makes use of attenuators.

These mini scale wireless grids can emulate real world physical networks due to the inverse square law of radio propagation, whereby doubling the distance increases the attenuation loss in the electric field strength by 6.02 dB.

Most of the indoor test beds, such as the one used by Microsoft's Wireless Research lab [6], have been created by placing computers with wireless cards in offices and relying on the walls of the building structure to attenuate the signal sufficiently to create a multi hop environment. Although these setups have been useful, they generate results that will be very difficult to repeat and verify due to the complex nature of signal prorogation in an office environment.

In this paper, experimental comparisons of the performance of routing protocols, using a 7x7 grid of closely spaced WiFi nodes, are presented. The usefulness of the grid in its ability to emulate a real world multi-hop ad-hoc network is demonstrated, comparing hop count, routing traffic overhead, throughput, delay and packet loss for three protocols which are listed by the Internet Engineering Task Force (IETF) Mobile Ad-hoc Networks (MANET) working group, *viz* AODV, OLSR and DYMO.

II. Ad-hoc networking protocols: Background

An Ad hoc network is a cooperative engagement of a collection of wireless nodes without the required intervention of any centralized access point or existing infrastructure. Ad hoc networks have the key features of being self-forming, self-healing and do not rely on the centralized services of any particular node.

Three main categories of ad-hoc routing protocols have been developed over the past decade; these are reactive routing protocols, proactive routing protocols and hybrid routing protocols. This paper only concerns itself with reactive and proactive routing.

Pro-active or table-driven routing protocols maintain fresh lists of destinations and their routes by periodically distributing routing tables in the network. The advantage of these protocols is that the route to a particular destination is immediately available. The disadvantage is that unnecessary routing traffic is generated for routes that may never be used. This paper evaluates Optimized Link State Routing (OLSR) [7] pro-active routing protocol on the test bed.

Reactive or on-demand protocols find routes on demand by flooding the network with Route Request packets. This allows only the routes that the network needs, to be entered into a routing table. The disadvantage of this method is that there will be a startup delay when data needs to be sent to a destination to allow the protocol to discover a route. This paper evaluates On-demand Distance Vector routing (AODV) [8] and Dynamic Manet On-demand routing (DYMO) [9] reactive protocols on the test bed.

1)The Optimized Link State Routing (OLSR)

OLSR reduces the overhead of flooding link state information by requiring fewer nodes to forward the information. A broadcast from node X is only forwarded by its multi point relays. Multi point relays of node X are its neighbors such that each two-hop neighbor of X is a one-hop neighbor of at least one multi point relay of X. Each node transmits its neighbor list in periodic beacons, so that all nodes can know their 2-hop neighbors, in order to choose the multi point relays (MPR).

The IETF "Request for Comments" (RFC) for OLSR makes use of hysteresis to calculate the link quality between nodes in order to stabilize the network in the presence of many alternative routes. Hysteresis produces an exponentially smoothed moving average of the transmission success rate and the condition for considering a link established is stricter than the condition for dropping a link.

An alternative metric, Expected Transmission Count (ETX)[10], calculates the expected number of retransmissions that are required for a packet to travel to and from a destination. In a multihop link, the ETX values of each hop are added to calculate the ETX for the complete link including all the hops.

Version 0.4.10 of the olsr.org implementation developed by Tønnesen [11], which includes the hysteresis and ETX metrics, was used in the test bed.

2)On-demand Distance Vector (AODV)

AODV employs destination sequence numbers to identify recent and up to date paths. Source node and intermediate nodes only store the next-hop information corresponding to each flow for a data packet transmission. A node will update its path information only if the destination sequence number of the currently received packet is greater than the last destination sequence number stored at the node.

If an intermediate node already has a valid route to a destination it will send a gratuitous route reply otherwise it forwards the route request. Route errors are determined using periodic beacons to detect link failures. Link failures cause a route error message to be sent to the source and destination nodes.

Version 0.9.3 of the AODV-UU [12] implementation by Nordström was used in the test bed.

3)Dynamic Manet On-demand Routing (DYMO)

DYMO is the most recent ad hoc networking protocol proposed by the MANET working group. It seeks to combine advantages of reactive protocols, AODV and Dynamic Source Routing (DSR) [13] together with some link state features of OLSR. It makes use of the path accumulation feature of Dynamic Source Routing (DSR) by adding the accumulated route, back to the source, to the Route Request packet.

It retains the destination sequence number feature of AODV but HELLO packets are an optional feature and are normally left out by default. It also does away with the gratuitous RREP feature of AODV. Routing information is kept up to date by expiring unused routes after a specific time interval. DYMO is also able to make use of periodic beacons to monitor link status and send route errors when failures occur.

Version 0.3 of the DYMOUM [14] implementation by Ros was used in the test bed.

III. Construction of the mesh test bed

A.Physical construction of the 7x7 grid

The mesh test bed consists of a wireless 7x7 grid of 49 nodes, which was built in a 6x12 m room as shown in Fig. 1. A grid was chosen as the logical topology of the wireless test bed due to its ability to create a fully connected dense mesh network and the possibility of creating a large variety of other topologies by selectively switching on particular nodes.

Each node in the mesh consists of a VIA 800 C3 800MHz motherboard with 128MB of RAM and a Wistron CM9 mini PCI Atheros 5213 based WiFi card with 802.11a/b/g capability. For future mobility measurements, a Lego Mindstorms robot with a battery powered Soekris motherboard containing an 802.11a (5.8GHz) card and an 802.11b/g (2.4GHz) can be used

Every node was connected to a 100Mbit back haul Ethernet network through a switch to a central server. This allows nodes to use a combination of a Preboot Execution Environment (PXE), built into most BIOS firmware, to boot the kernel and a Network File System (NFS) to load the file system.

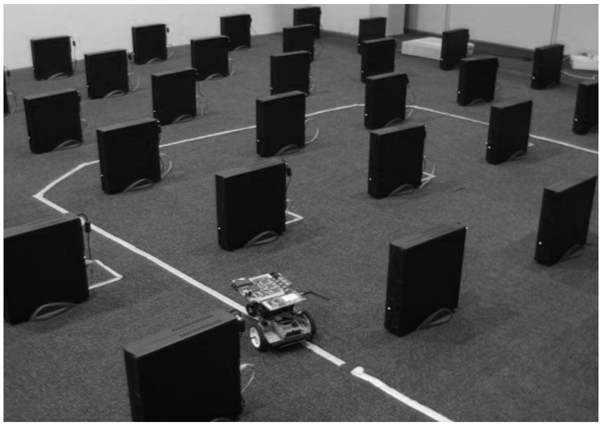

Fig. 1. Layout of the 7 by 7 grid of WiFi enabled computers, the line following robot is an option, which will be explored in the future to test mobility in a mesh network.

The physical constraints of the room, with the shortest length being 7m, means that the grid spacing needs to be about 800 mm to comfortably fit all the PC's within the room dimensions.

At each node, an antenna with 5dBi gain is connected to the wireless network adapter via a 30 dB attenuator. This introduces a path loss of 60dB between the sending node and the receiving node.

Reducing the radio signal to force a multi hop environment, is the core to the success of this wireless grid. The receive sensitivity of the radio, which is the level above which it is able to successfully decode a transmission, depends on the 802.11 mode and data rate being set. The faster the rate, the lower the receive sensitivity threshold.

This network was operated at 2.4GHz due to the availability of antennas and attenuators at that frequency, but in future the laboratory will be migrated to the 5GHz, which has many more available channels with a far lower probability of being affected by interference.

B.Electromagnetic modeling

In order to understand the stochastic behavior of the wireless nodes in the grid, the underlying electromagnetic properties must be understood.

The test-bed was modeled using numerical electromagnetic (EM) modeling, based on the method of moments [15]. This modeling was used to obtain the values of the coupling coefficients (scattering matrix elements) between nodes.

The single node model consists of a rectangular metallic PC case and a 5dB gain dipole antenna. The EM modeling showed that, for a single node, the presence of the PC case changes the effective horizontal plane radiation pattern from omni-directional to a more complex pattern. The maximum variation from the omni-directional gain pattern was found to be 1.5 dB. This effect is due to close proximity of the PC working as an offset reflector.

Once the nodes are assembled into an array, the effective radiation patterns of individual nodes become even more distorted, with dependence on the position in the array; it also manifests itself in deviation from the line-of-sight free-space propagation loss.

In the case of a linear 1 x 7 array with 0.8 m inter-node spacing, dependence on position was found to be negligible (within 0.3 dB). However, for a rectangular, 7x7 array, the effect of arraying became much stronger , with variations in signal strength of up to 3 dB.

It is also clear that as the nodes are chosen further apart, the number of PC cases that can possibly lie within the first Fresnel zone, increases, with concomitant increase in interference.

It was also found that the propagation is affected by the specific position of the PC cases associated with the nodes in the test bed. In one direction the wide sides of the cases are presented, while in an orthogonal direction, the narrow sides, with the antennas partially obscured, are presented. This can affect the signal strength by as much as 1.5 dB.

Experimental tests were run on the test bed by measuring the Received Signal Strength Indicator (RSSI) value between all possible pairs of nodes, while keeping all other nodes in the network switched off. Measured values of RSSI versus distance for two models of transmitter and computer (one with cases and one without) are shown in Fig. 2.

It was found that a strong correlation existed with the case where the PC cases were included in the simulation and there is best agreement with the experimental data for long distances.

The boundaries of the mean values of the RSSI values shown in the figure show variation in the coupling for nodes with the same separation. In practice the signal strength between two pairs of nodes, both being separated at the same distance, may vary by as much as 10dB.

These variations must be taken into consideration in later experiments with ad hoc routing protocols where routing paths will vary between short and long hops due to these signal strength fluctuations.

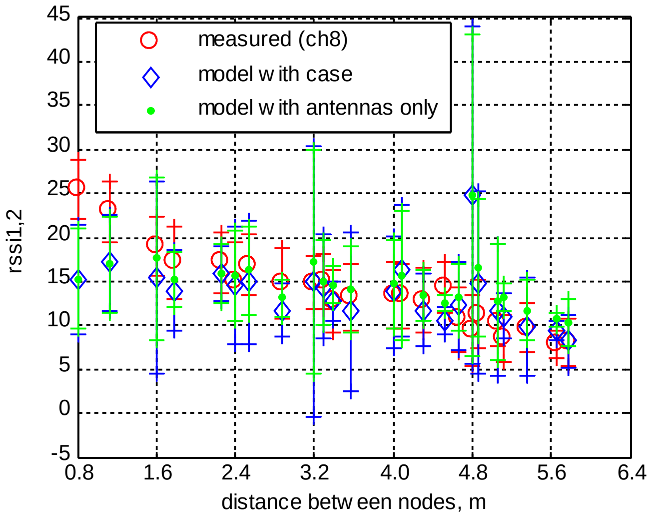

Fig. 2. Received signal strength indicator (RSSI) value versus distance between nodes - measured and simulated results for a rectangular 7x7 test-bed. Crosses define the standard deviation-based range of RSSI with respect to mean values shown with circles, diamonds and dots.

IV. Results

A. Hop count distribution

The ability to create a multi hop network in the mesh test bed is a key measure of the ability of the lab to emulate a real world wireless mesh network.

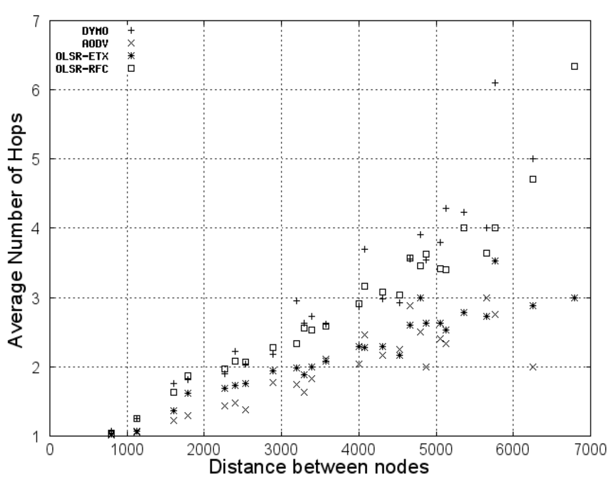

Fig. 3. Average number of hops versus distance for full 7x7 grid between all 2352 possible pairs

The tendency of a routing protocol to choose a longer or shorter path depends on the strategy of the routing algorithm. For example AODV tries to minimize hop count whereas OLSR-ETX tries to minimize packet loss. Fig. 3. shows a comparison of AODV, DYMO, OLSR-RFC and OLSR-ETX in terms of average hop count versus distance.

It is clear from this graph that AODV is trying to minimize hop count. OLSR-RFC tends to use more hops because links with long distances between them tend to be penalized by its steep downward hysteresis curve when packets are dropped (see Section II). DYMO picks the first possible route it can obtain and doesn't try to continuously optimize for shorter hop links. OLSR-ETX has decided that shorter hops are better in the grid in terms of minimizing packet loss.

B. Routing traffic overhead

The ability of a routing protocol to scale to large networks is highly dependent on its ability to control routing traffic overhead. The following graphs show the results of measuring routing traffic as the network size grows in spiral fashion.

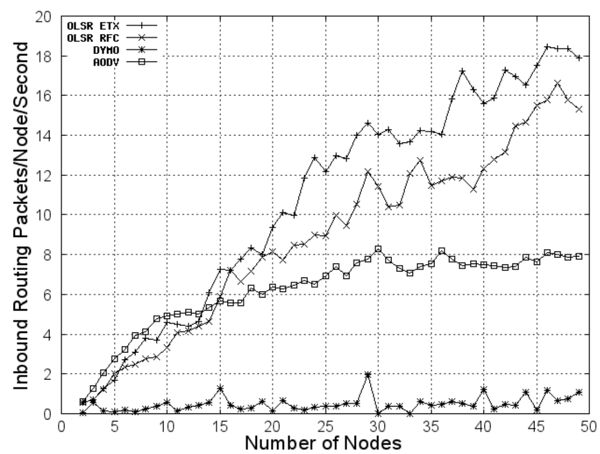

Fig. 4. Inbound routing packets per node per second versus increasing number of nodes using a growing spiral

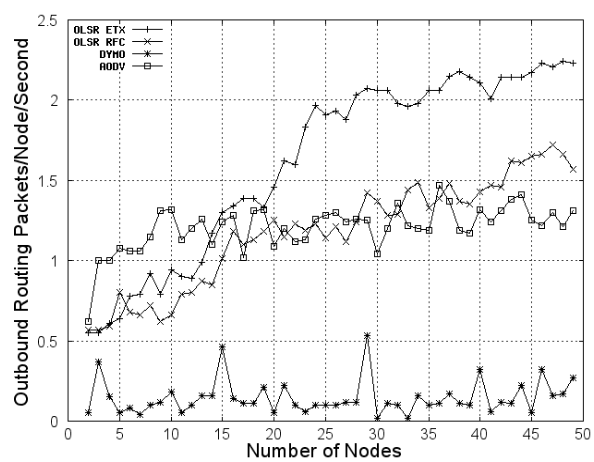

Fig. 5. Outbound routing packets per node per second versus increasing number of nodes using a growing spiral

Fig. 4. shows that OLSR traffic rapidly increases but then begins to level off after about 25 nodes due to the multi point relays limiting router traffic forwarding. Outbound traffic should always be less than the inbound traffic as the routing

algorithm makes a decision to rebroadcast the packet or not and Fig. 5. confirms this.

DYMO shows the least amount of routing traffic due to its lack of HELLO packets. This is also due to no further routing packets being transmitted once it has found a route to a destination. The occasional spikes in the routing traffic are for cases were it took longer than normal to establish a route.

C. Throughput, packet loss and delay measurements

The ability of a routing algorithm to find an optimal route in the grid will be exposed by its throughput and delay measurements.

A series of test were carried out staring with a simple string of 7 pearls and finally a full 7x7 grid.

Results for a string of pearls 7 nodes long.

Table. 1. table summarizes the results for all 42 possible pairs

OLSR_RFC had the highest number of route changes and forward hops over the 10-second measurement period but had the best average throughput. The route changes, therefore, must have converged the link towards a more optimal route. DYMO achieved the best performance in terms of delay. Only AODV had 1 case where the routing algorithm could not establish a link.

	Forward HOP count	Route changes	Packet loss	Delay	Delay(stddev)	TP	No link
AODV	1.33	0.43	11.19	37.24	116.64	2723.36	1
DYMO	1.52	0	9.52	3.65	2.37	2907.67	0
OLSR_ETX	1.43	0.1	8.57	27.56	101.91	2730.69	0
OLSR_RFC	1.67	0.76	2.14	5.35	5.35	2923.64	0

Table. 1. Comparison of throughput, delay and packet loss for a 7 node string of pearls topology

Fig. 6. shows the cumulative distribution function for all possible 42 pairs.

The graphs are very similar except for the fact that AODV and OLSR-ETX have approximately 20% of their links unable to achieve any throughput in the 10 seconds that they were tested. There are also clearly noticeable discrete clusters of throughput categories around approximately 2000 KB/s and 4200 KB/s, this is due to discrete collections of single or multi hop routes.

Results for full 7x7 grid (49 nodes)

The entire grid is now used to understand how the routing protocols perform with the maximum complexity available.

Table. 2. summarizes the results for all 2352 possible pairs. AODV was clearly the weakest protocol in this scenario, with more than half the links achieving no route at all. All the other protocols performance metrics were very close. On the whole OLSR-RFC was marginally better than the rest, achieving the top average throughput rate of 1330 KB/s.

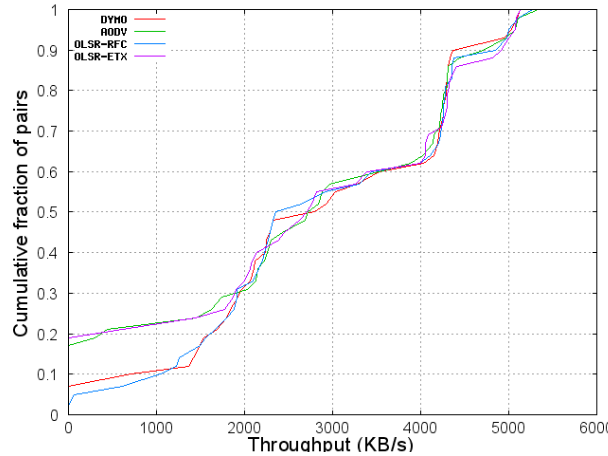

Fig. 6. Throughput CDF for 7-node string of pearls

	Forward HOP count	Route changes	Packet loss	Delay	Delay(stddev)	TP	No link
AODV	1.36	0.53	71.22	117.87	317.35	773.33	1425
DYMO	2.2	0.11	32.81	64.72	150.2	1165.66	413
OLSR_ETX	1.84	0.25	24.05	68.84	247.78	1187.57	453
OLSR_RFC	2.28	2.34	22.22	67.44	132.49	1330.05	381

Table. 2.Comparison of throughput, delay and packet loss for 7x7 grid

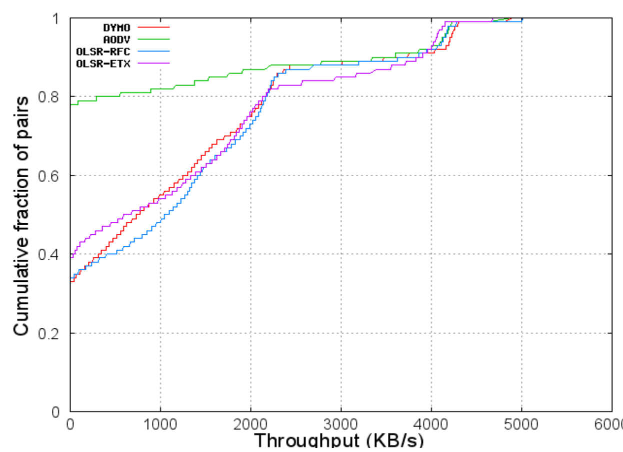

Fig. 7. Throughput CDF for 7x7 grid

Fig. 7. shows a far greater concentration of links with a lower throughput compared to Fig. 6 . AODV had close to 80% of its links unable to achieve any throughput whereas the rest were all around 40%.

These results demonstrate how network performance quickly degrades for all routing protocols as the network size and complexity increases.

Comparison of throughput results against baseline

Finally Fig. 8. shows how the routing protocols performance compares to the ideal multi hop network derived by Gupta and

Kumar [2],[3]. The 7x7 Grid baseline was established using ideal conditions in the grid with no packet loss.

This graph demonstrates how routing overhead, route flapping and non-optimal routes all contribute towards decreasing the throughput of all three routing protocols. The baseline presents the best possible throughput the routing protocols could achieve which will be asymptotically more difficult to reach, the closer you get. OLSR-RFC performed the best and came within and average of 76% of the baseline.

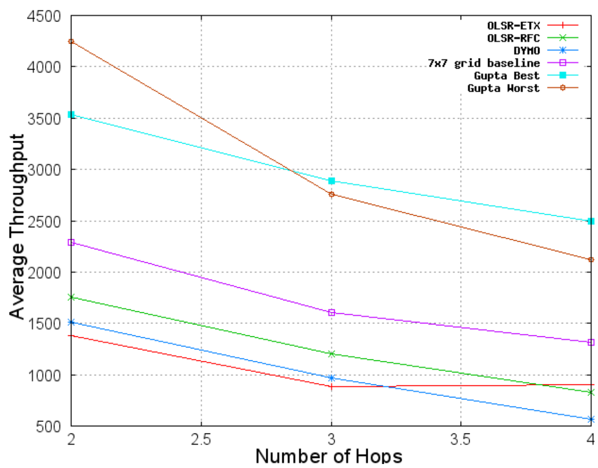

Fig. 8. Throughput performance of routing protocols against theoretical and baseline measurements

V. Conclusion

The results from experiments done in the wireless grid lab have shown that it is possible to build a scaled wireless grid which yields good multi hop characteristics. Currently hop counts up to 5 are achievable with routing protocols in the full 7x7 grid when the power is set to 0dBm with 30 dB attenuators.

A grid structure does yield a worst-case complexity problem for routing protocols in terms of the number of alternative routes available between distant points in the grid. This has a severe impact on route flapping if some kind of damping is not employed.

The AODV protocol showed the weakest performance in the grid with close to 60% of possible link pairs achieving no route for the full 7x7 grid. However it did present the least amount of routing overhead compared with other routing protocols. DYMO showed good results for its low routing overhead with the least amount of delay for the full 7x7 grid and the 2nd best throughput performance in a simple string of pearls topology.

The RFC version of OLSR had the best overall performance in a gull 7x7 grid in terms of throughput achieved and successful routes but OLSR with the ETX extension performed better in medium size networks of about 21 nodes.

All these performance tests were carried out using suggested configuration parameters that are published in MANET RFC's and Internet drafts. In the future it will be interesting to see how performance can be tweaked for specific topologies by changing parameters such as HELLO intervals. Some degree of node mobility and network load will also be the domain for future measurements in the wireless grid.

References

[1] T. R. Andel and A. Yasinac, "On the Credibility of Manet Simulations", IEEE Computer Society, July 2006.

[2] P. Gupta and P. R. Kumar, "The capacity of wireless networks," IEEE Trans. Inf. Theory, vol. 46, no. 2, pp. 388–404, Mar. 2000.

[3] P. Gupta and R. Drag, "An Experimental Scaling law for Ad Hoc Networks", Bell Laboratories technical report, 2006.

[4] NSF Workshop on Network Research Testbeds, Chicago, Il, Oct 2002. http://wwwnet.cs.umass.edu/testbed_workshop/

[5] S. Ganu, H. Kremo, R. Howard and I. Seskar, "Addressing Repeatability in Wireless Experiments using ORBIT Testbed" , Proceedings of IEEE Tridentcom 2005, Trento, Italy, Feb 2005.

[6] R Draves, J Padhye and B Zill, " Comparison of Routing Metrics for Static Multi-Hop Wireless Networks", in proc. SIGCOMM, August 2004

[7] P. Jacquet, P. Muhlethaler, T. Clausen, A. Laouiti, A. Qayyum and L. Viennot, "Optimized link state routing protocol for ad hoc networks," in proc. IEEE INMIC - Technology for the 21st Century, pp. 62-68, Dec 2001

[8] C. E. Perkins and E. M. Royer, "Ad-hoc on demand distance vector routing," in IEEE Workshop on Mobile Computing Systems and Applications (WMCSA), February 1999.

[9] E Belding-Royer, I Chakeres, D. Johnson and C Perkins, "DyMO – dynamic MANET on-demand routing protocol," Proceedings of the Sixty-First Internet Engineering Task Force, Washington, DC, USA, November 2004. IETF.

[10] D. S. J. De Couto, D. Aguayo, J. Bicket, and R. Morris, "A High-Throughput Path Metric for Multi-Hop Wireless Routing", in proc. 9th ACM International Conference on Mobile Computing and Networking (MobiCom '03), September 2003

[11] A. Tønnesen, "Implementing and extending the Optimized Link State Routing protocol" , Master's thesis. University of Oslo, Norway, 2004

[12] AODV-UU webpage, "http://core.it.uu.se/core/index.php/AODV-UU"

[13] D. Johnson and D. A. Maltz, "Dynamic source routing in ad hoc wireless networks," in Mobile Computing (T. Imielinski and H. Korth, eds.), Kluwere Academic Publishers, 1996

[14] DYMOUM webpage, "http://masimum.dif.um.es/?Software:DYMOUM"

[15] B. Kolundzija and A. Djordjevic, "Electromagnetic Modeling of Composite Metallic and Dielectric Structures", Artech House, 2002

[16] A. Tirumala and J. Ferguson, "Iperf 1.2 - The TCP/UDP Bandwidth Measurement Tool", http://dast.nlanr.net/Projects/Iperf. 2001.

D. Johnson received his B.Sc. (Electronic Engineering) at Cape Town University in South Africa. He is currently completing his M.Eng in Computer Engineering at the University of Pretoria in South Africa on scaled wireless grids for benchmarking ad hoc routing protocols. He leads a research team which is addressing the fundamental research questions around wireless mesh networks for rural connectivity at the Meraka Institute, CSIR, South Africa.