Testbed Validation for the Evaluation of a Delay Aware Routing Metric for Ad Hoc Networks

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***Abstract*—There is a growing need for real-time multimedia applications to be supported in ad hoc networking environments. Most current ad hoc routing protocols only support best-effort routing. By adopting Quality of Service (QoS) aware routing metrics, one can extend the set of multimedia services that run in an ad hoc network. Firstly, in this paper we present a 4 node wireless prototype testbed that was constructed to analyse ad hoc routing protocol behaviour. The testbed architecture is described and its ability to allow for repeatable and reproducible experimentation is verified. Secondly, we practically implement enhancements to the AODV (Ad Hoc On-demand Distance Vector) routing protocol. The routing metric is changed from hop count to measured end-to-end delay. This allows AODV to take the requirements of delay-sensitive applications such as voice and video services into account when selecting a route. Evaluation in the prototype testbed shows that the delay metric exhibits beneficial QoS properties.**

***Index Terms*—AODV, Ad Hoc Networks, Delay Metric, Implementation, QoS, Routing Protocols, Wireless Testbed.**

I. INTRODUCTION

WIRELESS ad hoc networks are a type of wireless network that is regarded as infrastructureless, dynamic and self-organising. The absence of infrastructure in the network implies that there is no centralised form of control. Nodes in such a network are able to communicate with each other via single- or multi-hop paths. Data can be forwarded in a node to node fashion until the destination is reached. These networks are dynamic as the network topology can be altered due to node failure or node mobility. [1]

Wireless ad hoc networks can be subdivided into MANETs (Mobile Ad Hoc Networks) and mesh networks. The former has the added characteristic of mobility, i.e. nodes are mobile and can therefore join or leave the network at any time. The latter refers to networks where nodes are assumed to be stationary.

Routing in wireless ad hoc networks has to take place in a fully distributed manner, which poses unique challenges. The routing protocol is also responsible for the self-organising characteristic of wireless ad hoc networks. There is a growing need for real-time multimedia applications to be supported in ad hoc networking environments [2]. Most current wireless ad hoc routing protocols only support best-effort routing. By adopting Quality of Service (QoS) aware routing metrics, one can extend the set of multimedia services that run in a wireless ad hoc network.

To this end the main contributions of this paper are the following:

- We describe the architecture of a 4 node wireless prototype testbed.
- We verify the testbed's ability to allow for repeatable and reproducible experimentation (in the context of our work we refer to this as the validation of the testbed).
- We present observations on the real-life effectiveness of a delay aware routing metric for AODV.

The work presented forms part of a bigger undertaking. The prototype testbed serves as a preliminary evaluation ground for routing protocol modifications, prior to performance evaluation in a time- and availability-restricted full scale testbed.

The rest of the paper is organised as follows: Section II details related work. Section III elaborates on the wireless testbed architecture. Section IV presents validation measurements for the testbed. Finally, section V details the AODV and DA-AODV (Delay Aware Ad Hoc On-demand Distance Vector) comparison in the testbed.

II. RELATED WORK

Experimental evaluation of wireless technologies gives researchers a better understanding of how wireless technologies function in the real world. In [3] it is reported that discrepancies between real-life and simulation results can be attributed in numerous cases to the use of inaccurate or over-simplified models of reality. To this end, numerous experimental radio grid testbeds have been established to aid in the research and development of wireless ad hoc networks.

The ORBIT wireless testbed consists of 400 nodes arranged in a 20 X 20 grid structure, equally spaced, 1 m apart. Multi-hop topologies can be created in the grid through MAC filtering or noise injection. [4]

The Meraka Institute has a 7 x 7 grid with 49 nodes spaced 80 cm apart. Multi-hop topologies are created through the use of hardware attenuators and the varying of transmitter power levels. [5]

The APE testbed [6] is a bootable linux distribution that is developed for wireless ad hoc routing protocol experimentation. The idea is that a live boot of the distribution is performed on numerous laptops. The experimenters that man these laptops are then choreographed through on-screen prompts to move about in their physical environment. The

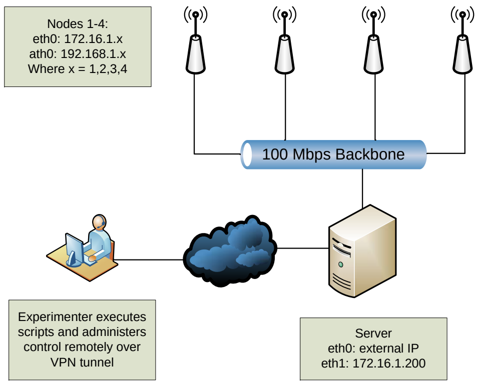


Fig. 1. Prototype Testbed Physical Layout

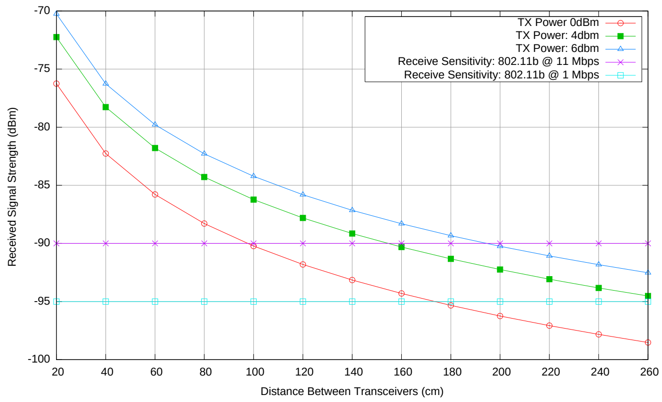


Fig. 2. Predicted Receiver Signal Strength vs Distance Between Transceivers

result is the ability to conduct mobility experiments in a relatively repeatable manner.

In [7] the ETX (Expected Transmission Count) metric is implemented on the DSDV (Destination Sequence Distance Vector) and DSR (Dynamic Source Routing) protocols. The ETX metric is compared with the hop count metric through performance evaluation in a 29 node wireless testbed that is spread out across one floor in an office building.

In [8] the performance evaluation of 3 MANET routing protocols commences on the Meraka wireless grid testbed. AODV, DYMO (Dynamic MANET On-Demand) and two metrics for the OLSR (Open Link State Routing) protocols are evaluated to determine the most suitable candidate for mesh networking.

It follows from the aforementioned work that more realistic results are obtained with experimental evaluation. We now proceed to implement a wireless prototype testbed to conduct our experiments on.

III. PROTOTYPE TESTBED

The prototype testbed consists of 4 identical nodes that are connected to a server via the Ethernet interfaces. The server acts as a DHCP server, time synchronization server, data collection server and experimental coordinator. Figure 1 provides a diagram of the physical layout and addressing scheme of the prototype testbed. The server and nodes coordinate and communicate through the Ethernet network, allowing unaffected experimentation to commence on the wireless interfaces of the nodes. The prototype testbed design has similarities to the ORBIT and Meraka wireless grid testbeds and draws inspiration from these.

A. Hardware Architecture

The testbed nodes are all identical in hardware layout:

- Pentium 4 1.8 GHz CPU
- Intel 845G chipset
- 512 MB DDR RAM
- 4 GB hard drive
- 3Com 100 Mbps Ethernet interface

The nodes are placed in a straight line, 80 cm apart. This is due to the length constraint (320 cm) of the room in which the testbed resides. The wireless hardware used on each node is as follows:

- Wistron NeWeb CM9-GP mini-PCI 802.11/a/b/g module.
- MikroTik RouterBOARD RB11 PCI to mini-PCI adapter.
- Aeroflex Inmet 6AH-30, 30 dB attenuator.
- Planet HPA 110 4dBi half wave dipole antenna.

The CM9 cards were chosen because they use the Atheros AR5212 chipset, which has very good and flexible driver support in the Linux environment due to the MADWIFI driver project [9].

A design decision was made to use attenuators to constrict radio propagation to a range that would allow for multi-hop behaviour in the testbed. This gives flexibility in experimentation, as multi-hop topologies can be enforced with MAC filtering or via the hardware attenuators. A link budget equation assuming a free-space loss model, revealed that 50 dB path loss needs to be introduced between neighbouring nodes for multi-hop characteristics to form, hence the choice of 30 dB attenuators and 4 dBi antennas, which gives a total path loss of 52 dB. It must be noted that the free-space path loss model assumes a line-of-sight channel and excludes the modelling of shadowing or multipath effects [1]. However, the transmit power of the CM9 can be varied between 0 dBm and 18 dBm, allowing one to compensate for shadowing and multipath.

Refer to figure 2 for an illustration of the multi-hop concept. The receive sensitivity for the 802.11b mode and free-space loss curves for different transmitter power settings is shown versus distance between nodes. Under the conditions of sufficient SNR (signal to noise ratio) and line-of-sight, nodes will be able to communicate at a given data rate and distance, if the free-space loss curve is above the required receive sensitivity.

B. Software Architecture

The testbed nodes are remotely configurable and controllable from the server via the backbone Ethernet network. This is done through use of the *netcat* and *ssh* packages, together with *bash* scripting to automate the process of node setup, running experiments and data collection. The experimenter therefore only interfaces with the scripts, and does not need to manually log into each node to execute commands.

TABLE I
HARDWARE PARAMETERS FOR EXPERIMENTS

Antenna Diversity	Off
TX/RX Antenna	1
TX Power	6 dBm
Unicast Rate	Locked to 11 Mbps
Broadcast Rate	Locked to 11 Mbps
Fragmentation	Off
MTU	1500 bytes
RTS-CTS Mechanism	Off
Mode of Operation: VAP1	Ad hoc, locked to 802.11b
Mode of Operation: VAP2	Monitor Mode, Radiotap headers enabled

All nodes in the testbed run kernel version 2.6.23 of the Fedora Core linux distribution. The MADWIFI version 0.9.4 driver is used for the wireless cards. A software only implementation of the IEEE 1588 Precision Time Protocol, *PTPd*, is used for time synchronization between nodes and the server [10]. Nodes in the testbed are able to synchronise to within 10 μs of the server time, with acceptable convergence after 10 minutes.

For data storage, a NFS (Network File System) was implemented on the server with the *nfs* and *nfs-utils* packages. The testbed nodes can mount the NFS and write experiment log files to the server hard drive over the backbone Ethernet network.

To test the routing protocols performance under network load, the *D-ITG* network traffic generator is used to recreate traffic workload. *D-ITG* can generate statistically correct application, transport and network layer traffic flows. After the completion of a traffic flow the throughput, delay, jitter and packet loss ratio is reported by the application [11].

C. Experimental Parameters

The parameters chosen for this set of experiments is shown in table I. Transmitter power is set at the indicated level, as it provisions for sufficient signal strength for 1 hop neighbours, whilst still maintaining good multi-hop characteristics in the attenuated wireless testbed. The broadcast and unicast rate is locked as shown, as this helps reduce the effect of communication grey zone problems with on-demand routing protocols such as AODV [12].

The RTS-CTS (Request-to-Send Clear-to-Send) mechanism was disabled as it proved to hinder throughput performance. This has also been confirmed by other researchers in [13] and [5].

The MADWIFI driver has a feature titled VAP (Virtual Access Point) that allows multiple virtual interfaces to be assigned to the same wireless NIC. Experimentation with this feature revealed that network performance was not affected when 2 VAPs where used on the same wireless NIC, subject to both VAPs using similar channel and modulation schemes. As shown in table I, an ad hoc and monitor interface was created on VAP1 and VAP2 respectively. The monitor interface allows raw frame capture of all frames received by the wireless NIC. The Radiotap header [14] is an optional header that is prefixed to each captured frame. Additional information such as signal strength, noise and SNR is included in the header fields.

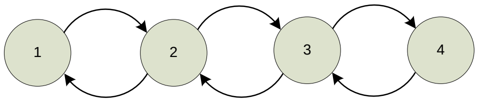


Fig. 3. Nodes Arranged in a String Topology

TABLE II
RESPONSE VARIABLES MEASURED DURING EACH SAMPLE

Response Variables
TCP Throughput
Jitter
Delay
Packet Loss Ratio

TABLE III
PREDICTORS MEASURED DURING EACH SAMPLE

Predictors
Mean Received Signal Strength at Sender
Standard Deviation of Received Signal Strength at Sender
Mean Received Signal Strength at Receiver
Standard Deviation of Received Signal Strength at Receiver
Node Distance

IV. BASELINE MEASUREMENT

The objective of the baseline measurement scenario is to find the effects of spatial (environmental) factors on the response variables. The wireless channel is prone to interference from spatial factors, which in turn causes variation of the indicated response variable. Fair comparison of different routing protocols, metrics, or strategies can only occur if it is known that a change in a response variable is due to the routing protocol, metric, or strategy and not due to a random spatial effect.

The baseline measurement is also motivated by the need to validate the testbed setup, so that measurement results that are obtained from testbed experiments can be considered reliable and trustworthy.

A. Methodology

For the baseline scenario, the effect of a routing protocol is omitted. The testbed is arranged in a string topology through MAC filtering and the use of static routes. This yields connectivity between nodes as shown in figure 3.

The parameters for the wireless NICs are configured as shown in section III-C. *tcpdump* is set up to capture *D-ITG* traffic on the monitor interface of each wireless NIC. *D-ITG* is used to generate constant bit rate traffic at 700 pkt/sec with a packet size of 1500 bytes, offering a throughput of 8400 kbps to the receiver. A TCP flow is generated for each permutation of sender/receiver pairs in the testbed. This gives a total of 12 permutations ($P_2^4 = 12$) for each experiment. Each flow is regarded as a sample and lasts 10 s. The experiment is repeated 12 times, at different times during the day, to capture environmental fluctuations over a greater time span. The *D-ITG* and *tcpdump* logs are post processed to extract the response variables (table II) and predictors (table III) for each sample.

B. Statistical Analysis

Before statistical analysis commences a definition is first in order:

Definition: *The node distance between two nodes in the testbed is the absolute difference in their assigned node numbers.*

For example, referring to figure 3, the node distance between node 1 and node 4 is 3. The node distance will be equal to hop count for the string topology of figure 3. There will, however, be topologies (when MAC filtering is not used) where the hop count is not necessarily equal to the node distance.

To understand the influence of the predictors on the response variables, ANOVA and multiple linear regression tests were performed on the data sets with the *STATISTICA* software package.

Figure 4a summarises the ANOVA test results as an effects plot. It shows how TCP throughput varies for the different link pairs and link directions. The link pairs notation corresponds to the numbering convention in figure 3.

It can be seen that there is no noticeable difference in throughput for the forward or reverse link directions for a given link pair. This indicates that for the given scenario and a given link pair, a symmetrical bidirectional link exists. The standard deviation on the mean throughput is also seen to be small. There is a clear difference in throughput between link pairs with a node distance of 1 (12,23,34), node distance of 2 (13,24), and a node distance of 3 (14). The difference in means for 1-hop link pairs is also very small. Link pair 24 seems to achieve a slightly higher throughput than link pair 13. This may be due to the presence of local interference near link pair 13.

Figure 4b shows the scatter plot for TCP throughput versus node distance. A multiple linear regression analysis was completed using all the predictors in table III. A linear regression model of the form in equation 1 was found to explain 97,66% of the variations in throughput ($r^2 = 0.9766$).

$$log_{10}(Throughput) = 3,9924 - 0,2573(nodedistance) \tag{1}$$

Figure 4c shows the scatter plot for jitter versus node distance. As with throughput, a multiple linear regression analysis was completed using all the predictors. A linear regression model of the form in equation 2 was found to explain 98.8% of the variations in jitter correctly ($r^2 = 0.988$).

$$Jitter = -0,381 + 4,2779(nodedistance) \tag{2}$$

Figure 4d shows the scatter plot for delay ($r^2 = 0.0051$). Delay showed a weak relationship to all predictors during multiple regression analysis, which suggests that the variation in delay is influenced by factors not included in the predictor list. The delay can be attributed to packet queuing in buffers, MAC retries and node processing delay as the experiments were conducted under full network load.

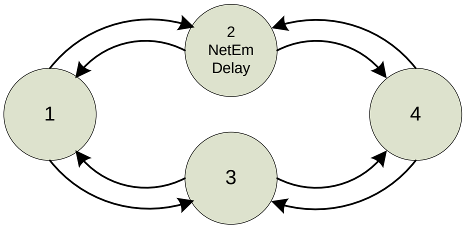


Fig. 6. Nodes Arranged in an Equal Hop Count Topology

From the statistical analysis, it follows that TCP throughput and jitter showed a strong relationship with node distance, and high values for the coefficient of determination (r^2), indicating a good fit of the linear regression model. As a result, future measurements of other scenarios will be performed using only node distance as a predictor.

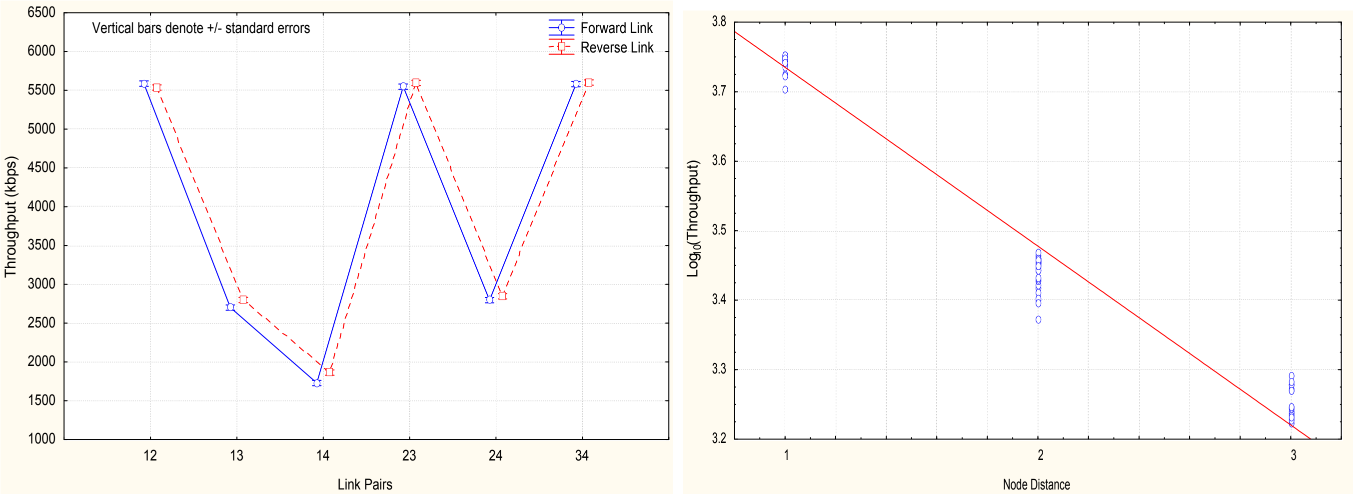
To conclude, the following remarks can be made about the baseline scenario:

- An ideal routing environment is created by enforcing a string topology. Under normal conditions a routing protocol would have to do connectivity sensing to infer the topology.
- The baseline scenario presents the best case scenario for performance. When a routing protocol is used, performance will be lower due to routing protocol overhead.
- The best throughput path for a given link pair is assigned by a static route in the baseline scenario. In reality, the purpose (and challenge) of a routing protocol is to find the best path automatically.
- The wireless NICs on the testbed nodes are under full load to forward the data when taking a sample. This is because the TCP flow generated by *D-ITG* offers as much data as the NIC is able to transmit.
- In a physically deployed wireless ad hoc network, the forwarding nodes will forward other traffic flows too. The performance in these networks will deviate from the presented results. Performance in deployed networks is highly dependant on the workload characteristics of the network and can only be addressed in experimental analysis through the use of a realistic workload model.

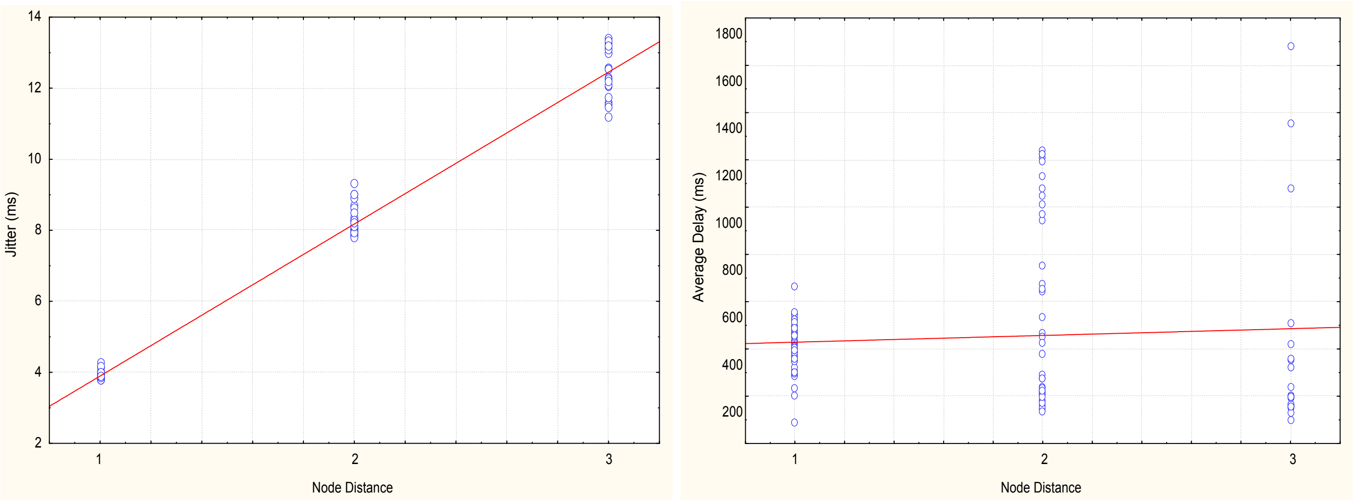
V. TESTBED IMPLEMENTATION OF AODV AND DA-AODV

AODV is classified as a reactive routing protocol. These protocols are also called on-demand protocols, as a route to a destination is only discovered once a node specifically requests it. Only the routes needed by nodes in the network are present in the their respective routing tables. This is contrary to a proactive (or table-driven) approach, where nodes maintain routes for all possible destinations in the network. The operation of AODV is described in RFC 3561 [15].

The motivation for implementing a delay aware metric in AODV flows from simulation work conducted in [16]: The effectiveness of changing the AODV routing metric from hop count to measured end-to-end delay is presented in the *OPNET* simulation environment. It is shown that DA-AODV

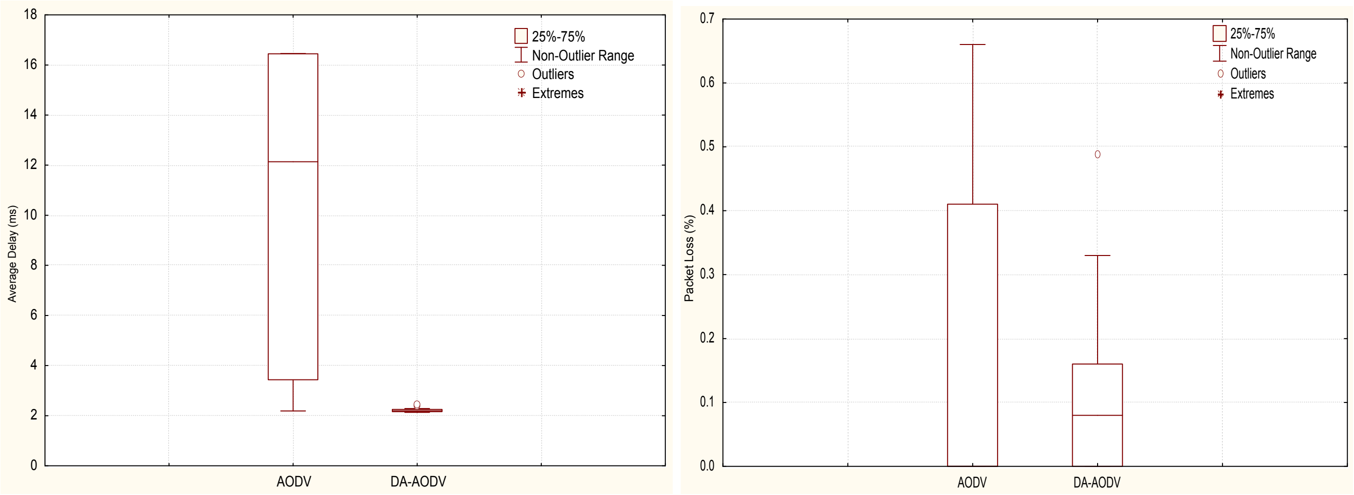


(a) Effects Plots for TCP Throughput (b) Scatter plot: Throughput



(c) Scatter plot: Jitter (d) Scatter plot: Delay

Fig. 4. Baseline Measurement Results



(a) Box Plot: Average Delay (b) Box Plot: Packet Loss Ratio

Fig. 5. AODV vs DA-AODV Measurement Results

selects better routes compared to AODV, which leads to better network performance in terms of delay, jitter and packet loss.

The *aodv-uu* [17] version 0.9.6 implementation is used for these experiments. The *aodv-uu* source code also serves as the basis on which the DA-AODV modifications are made. Due to space constraints, the implementation details of DA-AODV will not be discussed in this paper.

Refer to figure 6. The performance of AODV and DA-AODV will now be compared in a scenario where there are two equal hop count paths between communication pairs (node 1 and node 4). Path 1-2-4 has an induced delay of 15 ms. The delay is induced by using the *NetEm* [18] packages. We assume the network is not saturated, i.e. that some form of admission control is in place. This is a fair assumption, as QoS can not be provided under saturated conditions. The experiment parameters are the same as described in section IV-A, except for only node 1 and 4 acting as sender/receiver pairs and a constant UDP flow of 512 kbps is used.

Figure 5a shows the box plot for the average delay taken from the experiment. AODV changes routes between the two alternate paths (1-2-4) and (1-3-4). The median value of 12 for AODV indicates that the 1-2-4 route was used most of the time. AODV can not distinguish between the quality of the two routes as the hop count is the same. This influences the delay negatively. DA-AODV chooses the low delay route and keeps to that route. In a network with many hops between sender and receiver, the inability of hop count to select the low delay route, will become more pronounced.

Figure 5b shows the box plot for packet loss. The higher values of packet loss for AODV can be attributed to route flapping. DA-AODV minimises packet loss by finding the low delay route and then staying on the low delay route. Throughput and jitter did not show meaningful differences due to the light network traffic load.

In realising that the static induced delay may be regarded as unrealistic, we also considered inducing delay on nodes 2 and 3 using paretonormal distributions (with similar parameters). DA-AODV and AODV values for delay and packet loss were on par in such cases. A logical explanation is that path 1-2-4 and path 1-3-4 had different instantaneous delays but the same average delay over time. In such a scenario one path will momentarily be better than the other, but the average over time will be the same.

VI. CONCLUSION

In this paper we presented the architecture of our prototype wireless grid testbed. We then proceeded to do a validation of the testbed under full load and provided a statistical analysis of the results. We then briefly described and motivated the use of the delay metric. An equal hop count, but different delay scenario showed that DA-AODV shows improved results for delay and packet loss ratio when compared to AODV. This indicates that the delay metric exhibits properties beneficial to traffic flows that require low delay to assure an acceptable level of QoS. The results obtained in the prototype testbed looks promising and warrants further investigation. Future work will include the use of realistic workloads and thorough testing in a full scale testbed, such as the Meraka wireless grid.

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