Abstract—Wireless ad hoc networks are a type of wireless network that is regarded as infrastructureless, dynamic and self-organising. To date, the challenges facing QoS in these networks have enjoyed much attention in simulation. To address this issue we practically implement enhancements on the Ad Hoc On-demand Distance Vector (AODV) routing protocol. We change the routing metric from hop count to measured end-to-end delay. The enhanced protocol, Delay Aware Ad Hoc On-demand Distance Vector (DA-AODV), will now be able to take the requirements of delay-sensitive services into account when selecting a route. We investigate whether the change of routing metric holds any real world benefit through experimental evaluation in a four node wireless prototype testbed. The experimental evaluation encompasses four distinct scenarios. Analysis of the experimental results show that the delay metric exhibits beneficial QoS properties, but the benefit of using DA-AODV seems to be outweighed by factors influencing both routing protocols when more than 3 nodes are traversed and the network load is high.


I. INTRODUCTION

WIRELESS ad hoc networks are a type of wireless network that is regarded as infrastructureless, dynamic and self-organising. To date, the challenges facing Quality of Service (QoS) in these networks have enjoyed much attention in simulation. In this paper we address this area of research through experimental results generated on a four node wireless prototype testbed. The protocols under test will be AODV and a delay aware metric enhancement of AODV entitled DA-AODV.

The latter protocol, DA-AODV has been developed in an attempt to better understand the real world benefit of using routing metrics that take QoS parameters into account. To this end the main contributions of this paper are the following:

- We present results on the real world effectiveness of a delay aware routing metric for AODV.
- We analyse the results from four experimental scenarios to determine whether the routing metric change holds any real world benefit.

The rest of the paper is organised as follows: Section II details the wireless testbed architecture and choice of hardware parameters. Section III provides information on AODV and DA-AODV. Section IV presents the testbed comparison of AODV and DA-AODV in the equal node distance scenarios. Section V details the AODV and DA-AODV testbed comparison in the string topology scenarios. Finally, section VI elaborates on some analysis remarks.

II. PROTOTYPE TESTBED

The wireless prototype testbed consists of four nodes, identical in hardware, that are placed in a straight line, 80 cm apart. The nodes are connected to a server via Ethernet interfaces. The server acts as a DHCP server, time synchronization server, data collection server and experiment coordinator. The server and nodes coordinate and communicate through the Ethernet network, allowing unaffected experimentation to commence on the wireless interfaces of the nodes.

The wireless hardware used on each node consists of a Wistron CM9-GP 802.11/a/b/g module, connected to a 4dBi dipole antenna via a 30dB attenuator. The attenuators are used to constrict radio propagation to allow for multi-hop behaviour in the testbed. The testbed architecture and the testbed validation procedure are detailed in [1].

The chosen hardware parameters for the experiments conducted in this paper are shown in table I. For the motivation on the parameter choices refer to [1].

III. AODV AND DA-AODV

AODV is classified as a reactive or on-demand routing protocol. These protocols only discover a route to a destination once a node specifically requests it. Only the routes needed by nodes in the network are present in their respective routing tables. The operation of AODV is described in RFC 3561 [2].

The motivation for implementing a delay aware metric in AODV flows from simulation work conducted in [3]: 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 selects better routes compared to AODV, which leads to better network performance in terms of delay, jitter and packet loss.

The aodv-uu [4] 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. The implementation details of DA-AODV will not be discussed in this paper due to space constraints [5].
TABLE I
HARDWARE PARAMETERS FOR EXPERIMENTS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna Diversity</td>
<td>Off</td>
</tr>
<tr>
<td>TX/RX Antenna</td>
<td>1</td>
</tr>
<tr>
<td>Unicast Rate</td>
<td>Locked to 11 Mbps</td>
</tr>
<tr>
<td>Broadcast Rate</td>
<td>Locked to 11 Mbps</td>
</tr>
<tr>
<td>Fragmentation</td>
<td>Off</td>
</tr>
<tr>
<td>MTU</td>
<td>1500 bytes</td>
</tr>
<tr>
<td>RTS-CTS Mechanism</td>
<td>Off</td>
</tr>
<tr>
<td>Mode of Operation</td>
<td>Ad hoc, locked to 802.11b</td>
</tr>
</tbody>
</table>

IV. EQUAL NODE DISTANCE SCENARIOS

AODV and DA-AODV are now compared in scenarios where there are two paths of equal node distance between sender/receiver pairs. This will allow us to determine whether the end-to-end delay metric has any noticeable effect on QoS parameters.

For these scenarios it is assumed that the network is not saturated, i.e. that some form of admission control is in place. This is a fair assumption, as bounded QoS can not be provided under saturated conditions.

A. Methodology

D-ITG [6] is used to generate constant bit rate User Datagram Protocol (UDP) traffic at 128 pkt/sec with a packet size of 500 bytes, offering a throughput of 512 kbps to the receiver.

The parameters for the wireless Network Interface Cards (NICs) are configured as shown in table I. The transmitter power for both scenarios was set to 13 dBm. A UDP flow is generated for each permutation of sender/receiver pairs. This gives a total of 4 permutations \( P_2^2 = 4 \) for each experiment. Each flow is regarded as a sample and lasts 10 s. Each experiment run is repeated 12 times.

The D-ITG logs are post-processed to extract delay, packet loss ratio and jitter as response variables for each sample. Node distance is used as a predictor and is defined as follows: The node distance between two nodes in the testbed is the absolute difference in their assigned node numbers.

B. Static delay scenario

1) Methodology: For the static delay scenario, the testbed is arranged in an equal node distance topology through Medium Access Control (MAC) filtering. This yields connectivity between nodes as shown in figure 1. Path 1-2-4 has an induced delay of 15 ms. The delay is induced by using the NetEm [7] packages.

2) Analysis: A summary of the average values for the response variables are provided in table II. It can be seen that the average values for delay, packet loss and jitter are reduced by DA-AODV. Most noteworthy is the delay and packet loss ratio.

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Delay (ms)</th>
<th>Packet loss (%)</th>
<th>Jitter (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AODV</td>
<td>10.74</td>
<td>0.19</td>
<td>0.64</td>
</tr>
<tr>
<td>DA-AODV</td>
<td>2.62</td>
<td>0.03</td>
<td>0.49</td>
</tr>
</tbody>
</table>

AODV can not distinguish between the quality of the two paths as the hop count is the same. This negatively influences the delay. 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.

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. The jitter fluctuation for AODV and DA-AODV is however very small (less than 1 ms) for both cases due to the light network load.

C. Pareto delay scenario

To get an understanding of how AODV and DA-AODV react when the end-to-end delay on the available paths are constantly fluctuating, we considered inducing delays on nodes 2 and 3 using pareto distributions. It has been shown that end-to-end delay can be modelled with a pareto distribution [8].

1) Methodology: For the pareto delay scenario, the testbed is arranged in an equal node distance topology through MAC filtering. This yields connectivity between nodes as shown in figure 2. Path 1-2-4 and path 1-3-4 now have an induced delay with a pareto distribution with similar parameters for node 2 and node 3 \( (\mu = 30 \text{ ms}, \sigma = 10 \text{ ms}) \).

2) Analysis: A summary of the average values for the response variables are provided in table III. It can be seen that the average values for delay and jitter are close in this scenario for AODV and DA-AODV. Noteworthy is however the packet loss ratio, which is reduced by DA-AODV.

For practical purposes it can be concluded that delay and jitter are the same for AODV and DA-AODV in this scenario. A logical explanation is that path 1-2-4 and path 1-3-4 had different instantaneous delays at different times in the measurement process but both paths will have the same average delay...
TABLE III

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Delay (ms)</th>
<th>Packet loss (%)</th>
<th>Jitter (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AODV</td>
<td>31.43</td>
<td>0.38</td>
<td>8.71</td>
</tr>
<tr>
<td>DA-AODV</td>
<td>31.50</td>
<td>0.07</td>
<td>8.83</td>
</tr>
</tbody>
</table>

delay over a large enough time. This is because both paths have the same parameters for their respective pareto distributions. In the pareto scenario, one path will momentarily be better than the other, but the average over time will be the same.

Of interest however is the packet loss ratio. The packet loss ratio for AODV is higher than for DA-AODV. This can only be because AODV is still prone to route flapping. DA-AODV maintains a stable route despite the fluctuations in delay. This can be attributed to the damping factor that was employed on the routing metric of DA-AODV [5].

V. STRING SCENARIOS

AODV and DA-AODV are now tested in scenarios where the nodes are arranged in a string topology. These scenarios are performed under full network load. A best-case baseline measurement is performed. This will allow one to compare the routing protocols with the best-case baseline results.

For the baseline scenario, the effect of a routing protocol is omitted by making use of static routes. This gives a best-case scenario as no routing overhead is incurred. In reality, routing protocols strive to approach the performance of the best-case baseline.

It is expected that the first scenario, namely the MAC filtered string scenario will not highlight differences between DA-AODV and AODV due to the topological arrangement of the nodes in a string. This is because there is only one possible route for each permutation of sender/receiver pairs in the MAC filtered string scenario. AODV and DA-AODV will therefore have to discover the same route for each sender/receiver pair. This leaves no room for DA-AODV to discover a better route based on the delay metric.

In the second string scenario, the MAC filtering will be removed and hardware attenuation with transmitter power control will be used.

A. Methodology

For the string scenarios, the testbed is arranged in a string topology. This yields connectivity between nodes as shown in figure 4. The string topology is created with MAC filtering for the experiment conducted in section V-B. The transmitter power was set to 13 dBm for the above mentioned experiment.

The parameters for the wireless NICs are configured as shown in table I. 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 Transmission Control Protocol (TCP) flow is generated for each permutation of sender/receiver pairs in the testbed. This gives a total of 12 permutations ($P_4^2 = 12$) for each experiment. Each flow is regarded as a sample and lasts 10 s.

Each experiment run is repeated 12 times. The D-ITG logs are post-processed to extract TCP throughput, delay and jitter as response variables for each sample and as before node distance is used as a predictor.

B. MAC filtering scenario analysis

A summary of the experiment results are provided in table IV. The average values for the response variables as well as the percentage of samples for which no link could be established are provided.

The TCP throughput is calculated over all samples that were measured during the experiment, including samples where no link could be established. The TCP throughput is taken as zero for samples that could not establish a link. The other response variables are calculated over all samples that were able to establish a link during the sample period.

In table IV, the overhead incurred due to the use of a routing protocol is clearly visible from the average values for the response variables. The effects of overhead is particularly noted when comparing TCP throughput and delay between experiments.

Table IV shows that delay and jitter for AODV is lower than for DA-AODV. However, take into account that 17.5% of the links for AODV failed. On average, AODV delivers better QoS for successful links, but this is negated by a lower percentage of links that are successful.

Table IV shows that delay and jitter for AODV is lower than for DA-AODV. However, take into account that 17.5% of the links for AODV failed. On average, AODV delivers better QoS for successful links, but this is negated by a lower percentage of links that are successful.

TABLE IV

<table>
<thead>
<tr>
<th>Experiment</th>
<th>TCP throughput (kbps)</th>
<th>Delay (ms)</th>
<th>Jitter (ms)</th>
<th>No link (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>3954.59</td>
<td>390.17</td>
<td>6.28</td>
<td>0</td>
</tr>
<tr>
<td>AODV</td>
<td>3460.90</td>
<td>532.54</td>
<td>6.03</td>
<td>17.5</td>
</tr>
<tr>
<td>DA-AODV</td>
<td>3712.21</td>
<td>552.48</td>
<td>8.19</td>
<td>0</td>
</tr>
</tbody>
</table>

In table V it can be seen that 100% of the links with a node distance of 3 failed for AODV. Consider that for this scenario node distance is equal to hop count. It follows that all the samples for a node distance of 3 or a hop count of 3, failed for AODV.

TABLE V

<table>
<thead>
<tr>
<th>Node distance</th>
<th>1 (%)</th>
<th>2 (%)</th>
<th>3 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AODV</td>
<td>0</td>
<td>5</td>
<td>100</td>
</tr>
<tr>
<td>DA-AODV</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

DA-AODV managed to find a route for every sample flow that was taken. It is argued that this is however not directly due
to the metric changes. The ability of DA-AODV to discover 3 hop routes whilst AODV fails, lies in the requirement of the DA-AODV design that only the destination node may reply to a Route REQuest (RREQ). This is enforced by setting the Destination only flag in the RREQ and ensures that the latest delay values for the total path is computed in the route discovery process.

Figure 3a shows the mean plots for TCP Throughput versus node distance. The 95% confidence intervals are also shown. It can be seen that at a node distance of 1, performance of the routing protocols are on par with the baseline scenario. At a node distance of 2 the difference in throughput becomes more pronounced. The throughput for AODV is shown to be lower than DA-AODV for a node distance of 2. AODV could not establish a link for any of the samples with a node distance of 3. DA-AODV is shown to achieve throughput at a node distance of 3.

Figure 3b shows the mean plots for delay versus node distance. The large range for the confidence intervals suggest that delay varies considerably for all 3 experiments. This is because the nodes are under full load.

For a node distance of 1, delay is roughly the same for the baseline and routing protocol experiments. The overhead of the routing protocols become more pronounced on a node distance of 2. The routing protocol delay is almost double the baseline delay for a node distance of 2. As with throughput, a plot for AODV at a node distance of 3 is not possible due to all links failing.

Figure 3c shows the mean plots for jitter versus node distance. The jitter for the baseline and routing protocols are seen to be the same for a node distance of 1. At a node distance of 2 it can be seen that AODV and DA-AODV have similar values for jitter. At a node distance of 3 the jitter is considerably more for DA-AODV than the baseline.

C. Hardware attenuation scenario analysis

AODV and DA-AODV are now evaluated for the scenario where the string topology is formed via hardware attenuation and transmitter power control. The transmitter power was set
to 6 dBm as this gives a good balance between good 1-hop neighbour signal strength whilst still allowing a multi-hop string topology to form. The link budget calculations for the transmitter power values are detailed in [5].

Our initial experiments showed that this scenario poses a greater challenge to the routing protocols than any of the previous scenarios. The initial experiments were performed for this scenario as described in the methodology in section V-A. However, this produced unusable results as most sample flows for AODV and DA-AODV were not able to establish links beyond a node distance of 1. To provide usable results it was decided to wait up to 60 seconds for a 10 second flow sample to finish. This approach affords extra time for the routing protocols to discover the route and the data transfer for the flow sample to complete. This ensured that more flows could establish a link.

The resulting values for delay and jitter are therefore very high for this scenario. Sample flows for which the routing protocol is able to discover a route and transfer data in the normal sample time of 10 seconds, would not be penalised by the extra time.

Due to the high delay and jitter values, it is impractical to plot the results on a graph, as the scale of the values makes it difficult to read. The results will therefore only be shown in tables.

A summary of the experiment results for AODV and DA-AODV are provided in table VI. The average values for the response variables as well as the percentage of samples for which no link could be established are provided. Of note is the amount of flows which could not establish a link during the 60 second waiting period. AODV could not establish 45% of the sample flows, whilst DA-AODV could not establish 24.2% of the sample flows in the given time.

<table>
<thead>
<tr>
<th>Protocol</th>
<th>TCP throughput (kbps)</th>
<th>Delay (ms)</th>
<th>Jitter (ms)</th>
<th>No link (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AODV</td>
<td>2115.99</td>
<td>1577.19</td>
<td>949.33</td>
<td>45</td>
</tr>
<tr>
<td>DA-AODV</td>
<td>2278.37</td>
<td>2638.28</td>
<td>1111.02</td>
<td>24.2</td>
</tr>
</tbody>
</table>

In table VII it can be seen that 100% of the links with a node distance of 3 failed for AODV. AODV also failed to establish 85% of the the links with a node distance of 2. DA-AODV failed to establish 65% of the links with a node distance of 3, whilst 40% of links failed for a node distance of 2.

<table>
<thead>
<tr>
<th>Node distance</th>
<th>Protocol 1 (%)</th>
<th>Protocol 2 (%)</th>
<th>Protocol 3 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AODV</td>
<td>0</td>
<td>85</td>
<td>100</td>
</tr>
<tr>
<td>DA-AODV</td>
<td>1.7</td>
<td>40</td>
<td>65</td>
</tr>
</tbody>
</table>

From table VI it can be seen that delay and jitter for AODV is lower than for DA-AODV. However, take into account that 45% of the links for AODV failed. These failed links were not included in the delay and jitter calculations.

Figure 3d shows the mean plots for TCP throughput versus node distance. The baseline results from the previous scenario are also plotted for comparison in figure 3d. DA-AODV achieves usable throughput for all node distances, but throughput is less than 20% of the baseline at a node distance of 2 and 3. When comparing figure 3d with figure 3a it can be seen that the throughput is much lower in all cases when compared to the baseline and the previous scenario.

The average values for delay and jitter are shown in table VIII and IX respectively. It can be seen from the delay values that communication is only practically feasible for a node distance of 1 for AODV and DA-AODV. The jitter values also indicate that communication is only practically feasible for a node distance of 1.

<table>
<thead>
<tr>
<th>TABLE VIII HARDWARE ATTENUATION: DELAY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node distance</td>
</tr>
<tr>
<td>--------------</td>
</tr>
<tr>
<td>Baseline</td>
</tr>
<tr>
<td>AODV</td>
</tr>
<tr>
<td>DA-AODV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE IX HARDWARE ATTENUATION: JITTER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node Distance</td>
</tr>
<tr>
<td>---------------</td>
</tr>
<tr>
<td>Baseline</td>
</tr>
<tr>
<td>AODV</td>
</tr>
<tr>
<td>DA-AODV</td>
</tr>
</tbody>
</table>

It follows from the results of the hardware attenuation scenario that network performance degrades severely with the use of AODV and DA-AODV, though DA-AODV still shows better performance than AODV. However, both routing protocols show unsatisfactory performance when compared to the baseline scenario.

Comparison of the hardware attenuation scenario and the MAC filtering scenario results suggest that something is fundamentally flawed with AODV and the AODV derived DA-AODV. Inspection of the routing table logs revealed that in numerous cases routes would be expired whilst being used by a data flow.

This is caused by the AODV neighbour sensing mechanism that keeps track when a HELLO was last received. Under full network load conditions, HELLO messages don’t always reach the intended neighbours. HELLO messages are not positively acknowledged since HELLO messages are broadcast messages. The sender therefore has no guarantee that the neighbours received the HELLO. According to RFC3561 [2], when more than 2 HELLO messages are missed, the neighbours assume that the link is down and delete the corresponding routing entry.

Another problem is spurious control messages. This only affects the hardware attenuation scenario and will not affect...
local connectivity management is done in AODV. From these
performance is due to a fundamental problem in the way that
hardware attenuation results suggest that the poor protocol
Comparison of the MAC filtering scenario results and the
performance is still unsatisfactory.

In many cases transmission will fail, and a new route will
need to be discovered. Alternatively a spurious message may
suggest a better route, to which neighbours update their routing
tables. AODV will be more sensitive to the route updating
problem than DA-AODV. DA-AODV uses a damped end-to-
end delay metric that was shown to combat route flapping in
previous scenarios.

In both cases, if spurious messages arise often enough,
communication becomes disrupted and unreliable. Spurious
messages have the same effect on on-demand routing protocols
as the communication grey zone problem [9]. These effects
have a big impact on the performance of wireless ad hoc
routing protocols in the real world. The hardware attenuation
scenario pointed out that local connectivity management in
AODV needs refinement.

VI. ANALYSIS REMARKS

The previous section presented the experimental results of
four scenarios that were constructed to evaluate DA-AODV
versus AODV. Some remarks can be made about the delay
and the string scenarios for AODV and DA-AODV.

An equal hop count, but different static delay scenario
showed that DA-AODV shows improved results for delay and
packet loss ratio when compared to AODV. The pareto
delay scenario showed similar performance for DA-AODV
and AODV in terms of delay and jitter. However, DA-AODV
showed improved packet loss ratio for the pareto delay sce-
nario.

In the string topology with MAC filtering, DA-AODV
managed to establish links for all samples, whilst AODV was
not able to establish a single flow for a node distance of 3.
It was shown that the Destination only flag on RREQ
messages are the cause for the improvement in performance.
DA-AODV showed improved performance for TCP throughput
and similar performance to AODV for delay and jitter.

The string topology with hardware attenuation scenario
showed that DA-AODV and AODV perform poorly in a
scenario which is close to real world operation. DA-AODV
showed better performance than AODV in terms of through-
put. The delay and jitter values suggest that the DA-AODV
performed better than AODV, but compared to the baseline
performance is still unsatisfactory.

The packet loss ratio for DA-AODV and AODV were high.
Comparison of the MAC filtering scenario results and the
hardware attenuation results suggest that the poor protocol
performance is due to a fundamental problem in the way that
local connectivity management is done in AODV. From these
scenarios it is also suggested that AODV and DA-AODV are
not suited for congested networks.

VII. CONCLUSION

In this paper the evaluation of DA-AODV and AODV in the
wireless prototype testbed was presented. Four scenarios were
constructed to gain insight into routing protocol behaviour and
performance. The statistical analysis performed on the first two
scenarios suggest that the delay metric exhibits improved QoS
properties.

However, the benefit of using DA-AODV seems to be
outweighed by factors influencing both routing protocols when
more than 3 nodes are traversed and the network load is high.
Experimental results suggest that AODV and DA-AODV are
not suited for congested networks. However, when network
traffic is bounded, DA-AODV shows an improvement to
AODV in terms of delay, jitter and packet loss ratio.

Initial results obtained in the prototype testbed show room
for improvement and warrants further investigation to get to
the core of the problem. To this end future work include ex-
perimenatial evaluation of AODV and DA-AODV in a wireless
grid testbed with more nodes.

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