Performance Analysis of the B.A.T.M.A.N. Wireless Ad-Hoc Network Routing Protocol with Mobility and Directional Antennas[1]

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Abstract—In this paper we show how the network routing protocol B.A.T.M.A.N. can be augmented by a simple hysteresis mechanism called Batrytis in order to provide a more stable routing table with no decrease in performance. This leads to an improved operating environment for various networked applications. We conduct various indoor and outdoor experiments showing the operation of Batrytis. We also demonstrate its operation with directional antennas and propose various improvements both at the network and MAC layer.

Index terms—IEEE 802.11b, ad hoc networks, routing protocols, wireless networks, directional antennas, MANET, B.A.T.M.A.N. routing protocol.

1. INTRODUCTION

Wireless networks have become ubiquitous in today's society with the advent of, for example, mobile phones, WiFi (802.11) and WiMAX networks. Most of these systems use existing infrastructure such as base stations or access points for communicating. However in some military and civilian areas it would be advantageous to have the ability to deploy networks quickly without existing infrastructure. Networks of this type in which each node can be used to route traffic have the greatest flexibility. These *Mobile Ad-hoc NETworks* (MANETs) may be rolled out in military tactical situations, in emergency relief operations or in areas where existing fixed telecommunications infrastructure does not exist. Additionally, using directional antennas can in many cases improve transmission range, increase link data rates, decrease interference and improve security, depending on particular requirements.

Various routing protocols have been proposed for MANETs. One of the most recent and interesting of these protocols is The Better Approach To Mobile Ad-hoc Networking (B.A.T.M.A.N.) protocol, currently being developed by the Freifunk Community in Germany [01]. It is a proactive distributed protocol that quickly creates stable routes with low network overheads, by only considering the first hop choice towards a destination. Each WiFi node is linked together using the B.A.T.M.A.N. routing protocol, which finds the optimal paths between nodes within this network. The B.A.T.M.A.N. code is stable and works well for networks with high and varying link losses.

In this paper we present a technique for improving the efficacy of the B.A.T.M.A.N. routing protocol by implementing a simple hysteresis mechanism when choosing routes in the network, which we call "Batrytis." The name Batrytis is derived from *Botrytis*, a mold used in the production of sweet, or sticky, wines. Batrytis is "sticky" B.A.T.M.A.N. in that it "sticks" to routes more closely than standard B.A.T.M.A.N. This hysteresis mechanism reduces the prevalence of rapid routing changes which for a variety of reasons can lead to application instability. A WiFi network has been created and the improved technique has been demonstrated using this network. We examine the WiFi network using directional transmission and reception.

In Section 2 we look at related work in this field and provide our motivation for the current work. In Section 3 the software and the hardware used in our network is described. A simple indoor experiment to demonstrate our improved technique is shown in Section 4, followed by an outdoor experiment in Section 5. In Section 6 we show results from a more complex experiment. In Section 7 we examine alternative methods for route selection. We then discuss the research and look at future directions in Section 8.

2. MOTIVATION AND RELATED WORK

2.1 Ad-Hoc Network Routing Protocols

There are many papers that investigate ad-hoc networks using simulation. These look at many different aspects of MANETs, including routing protocols and algorithms for optimising traffic flow. The building and analysis of wireless networks using WiFi devices has become quite popular recently due to the ubiquity and low cost of these devices. A good review of the research laboratories around the world in 2007 is given in [02]. Some networks have been designed to look at how the B.A.T.M.A.N. routing protocol works in large networks. For example in [03] a 49 node network was set up to compare B.A.T.M.A.N. with the OLSR routing protocol, and in [04] an eight node network was set up to compare B.A.T.M.A.N. with OLSR and BABEL. In [05] a small 5 node network was set up with two of the nodes mobile to show how B.A.T.M.A.N. and OLSR work with mobility. In these works B.A.T.M.A.N. has been shown to be an efficient and stable routing algorithm. In [06] the authors demonstrated how a cross-layer design can be used to improve the end-to-end performance of MANET, by adjusting a routing

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protocol dynamically based on both the Signal-to-Noise Radio and Received Power along the end-to-end routing path. In [07] the authors modified the AODV protocol for use in a WiFi environment.

2.2 Ad-Hoc Networks with Directional Antennas

Directionality in ad-hoc networks can provide a number of advantages through spatial diversity. These include improving transmission range, increased data rates, decreasing interference and improving security by reducing the chance of interception or jamming.

To the best of our knowledge there are very few analyses, experiments or systems using directional antennas with specifically designed ah-hoc network routing protocols. The majority of current research considers changes at the physical and access layers to enable operation with directional transmission. Directionality introduces a number potential problem with standard MAC- and network-layer protocols, including problems with medium access, neighbour discovery and routing. In [08] it was shown by simulation that by integrating directional and non-directional links into the same network, and using shortest path algorithms, a better result can be achieved than if separate sub-nets were used for the directional and non-directional links. In [09] simulation was used to show the improvement in throughput and delay using steering and beam-forming techniques with power control. A key assumption was that high-power omni-directional neighbour discovery was possible, allowing directional traffic to flow efficiently. In [10] the same authors claim to have produced the first system implementation of MAC- and network-layer protocols ("UDAAN") specifically designed for MANETs with directional antennas. UDAAN uses a slightly adapted version of the Hazy-Sighted Link State (HSLS) protocol, beam-forming, a novel Carrier-Sense Multiple Access scheme with Collision Avoidance (D-MAC), directional neighbour discovery and power control. A test suite using ground vehicles was built as part of this research programme. D-MAC frame headers include information on transmitter location, angle of transmission and power level, and the back-off mechanism adapts to a variety of channel access conditions. The test results showed a significant improvement in delay and throughput against an omni-directional system. In [11] the DSR routing protocol was augmented to support antenna directionality.

Directional antennas can also be adopted to make the detection or jamming of transmissions more difficult. This is of great importance when a platform is both trying to communicate with other platforms, whilst simultaneously hiding its existence from or limiting its interference to other platforms. This also increases the network's data rate since the spatial diversity increases the ability of simultaneous data transmission taking place. This is shown to be the case in networks in [12], with the probability of being detected reduced considerably, with the probability of detection being highly dependent on the antennas' characteristics.

2.3 Research Motivation

Whilst looking at the use of ad-hoc mobile networks with directional antennas, we observed that rapid changes in the routing table (*route-flipping*) regularly occurred using B.A.T.M.A.N. with very small changes in the perceived quality of routes. The effect was first observed when using B.A.T.M.A.N. on a small ah-hoc network was the seemingly unnecessary interruption of SSH sessions between nodes in the network due to routing changes during that session.

Route-flipping, also called *fluttering* or *flapping,* is known to cause a variety of problems [13][14], including:

- Introducing asymmetry—if route-flipping occurs in one direction, leading to (for example) problems with synchronising network clocks;
- Difficulties in constructing reliable path estimates such as round-trip time and
- Packet re-ordering, leading to (for example) TCP generating duplicate acknowledgements due to its Fast Transmission algorithm.

In addition to apparent SSH session problems, we observed problems with MPEG-2/UDP video streams. In particular, we observed that video quality seemed to degrade when routes changed. We also observed occasional problems unrelated to route changes, perhaps from reordering of packets due to MAC-layer retransmissions. Our assumption, therefore, is that decreasing the frequency of route-flipping is generally good for a variety of networked applications, and we leave the following open question to the research community: what are the exact mechanisms which cause the problems in networked applications by excessive route-flipping?

We hypothesised that a simple hysteresis mechanism (Batrytis) would in some circumstances improve the execution of various applications across the network.

We build here upon our previous published work on routing in MANETs with directional antennas in [15] and we refer the reader to this paper if a greater understanding of these issues is needed.

2.4 Motivating Scenarios

A scenario which we use to test Batrytis is shown in Figure 1. An emergency ground vehicle (A) wishes to transfer real-time videos to a remote location via a satellite (E). The ground vehicle (A) moves from left to right, with connectivity to only a subset of airborne relays (B, C and D) at any one time. The information is routed eventually to the satellite (E) via relay (D). Relays (B) and (C) cannot communicate directly with the satellite. For example, at position 2 the ground unit can only communicate with relays (B) and (C). Directionality of antennas is found necessary in this situation in order for the data rate to be sufficient to get a real time video stream. This sectionalises the emergency vehicle's route. As the vehicle traverses each section it is desirable that the route changes the minimum amount of times that is necessary for the application to be successful. We performed outdoor experiments to examine the performance of B.A.T.M.A.N. where we replicate key features of this scenario, which we describe below in Section 5. Due to time limitations we did not examine Batrytis in an omni-directional network or standard B.A.T.M.A.N. in a directional network.

In the scenario, the real-time video stream requires a moderate level of route stability as key video timing frames must be received regularly; whilst some packet loss can be tolerated. In video over IP, for example MPEG-4, temporal dependencies are an important feature as they increase compression ratios significantly. However, this means that if key video frames are lost the video stream can be affected for an extended period of time. There are many other examples of temporal dependency in networked applications.

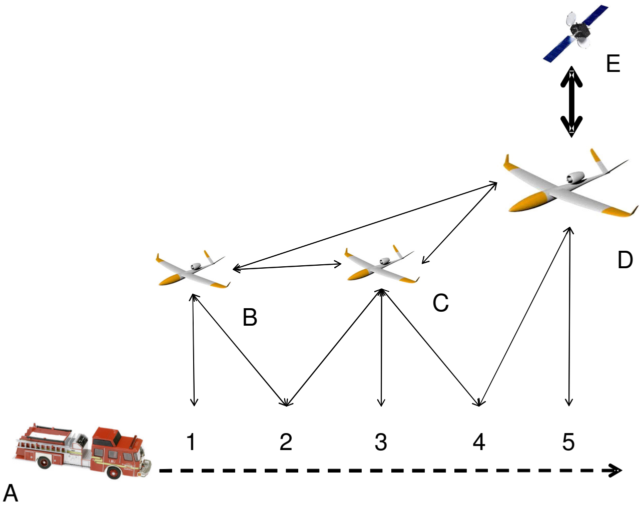


Figure 1. Likely emergency scenario, showing a mobile node's intermittent connectivity to airborne nodes.

In Section 4 below, we examine a simple indoor experiment where route-flipping occurs and the effect that hysteresis has on the behaviour of B.A.T.M.A.N. Firstly, we look at the experimental setup.

3. THE EXPERIMENTAL NETWORK AND ALGORITHM

The hardware used in these experiments comprised a laptop running Ubuntu Linux version 10.10 ("Maverick Meerkat") and either three or five (depending on the experiment) Ubiquiti Nanostation 2 Locos (NS2Ls) each running OpenWrt Linux version 8.09.02 ("Kamikaze"). All nodes in the network operated at 1 Mbit/s with 802.11b on Channel 6 (2.437 MHz) in ad-hoc mode. Various additional hardware parameters are shown in Table 1 below.

Specification	NS2L	Laptop
Processor	Atheros MIPS 4KC 180 MHz	Intel Core2 Duo T660 2.2GHz
Antenna	Dual-polarization (set to vertical)	Asus WL-167G (PCB strip)
Antenna transmit power	0dBm (1mW)	20dBm (100mW)
Antenna gain	8dBi (directional in the horizontal plane)	1.77dBi (omni-directional in the horizontal plane)
Transceiver sensitivity	-95 dBm	*Unspecified, presumed < -84dBm*

Table 1. Specification of the hardware devices used in the experiments.

We used B.A.T.M.A.N. version IV, as part of the 0.3.2 distribution. In B.A.T.M.A.N., originator messages (OGMs) are exchanged between link-local (first-hop) neighbours and are also re-broadcast. The tally of re-broadcast replies ("echoes", the *EQ* value) together with the tally of OGMs originating from link-local neighbours (the *RQ* value) are used to calculate the quality of routes, called Transmit Quality or the *TQ* value. By this method, the B.A.T.M.A.N. protocol finds for every possible route from one node to another the *TQ* value. The *TQ* for each route is calculated over a sliding window, which ensures that transient better routes are not needlessly adopted. However it has been found that even with this in place the B.A.T.M.A.N. protocol may change routes unnecessarily when two or more routes have consistently similar *TQ* values. It is to minimise this effect that the hysteresis adaptation to B.A.T.M.A.N. (Batrytis) has been introduced.

Batrytis enables a good route to be chosen even though a better route (in the sense of a higher *TQ* value) may be available. Only when the better route's quality is better by a significant margin (the tolerance *H*) will this new route be adapted. This ensures that when two routes have very similar *TQ* values the routes do not keep switching as one is marginally better than the other and vice-versa. The hysteresis tolerance should not be set too large to ensure that B.A.T.M.A.N. does change to better routes when one is available. The Batrytis algorithm is summarised below:

1. Set hysteresis tolerance = H.

2. Set TQ to be the TQ observed in incoming OGM. If first value recorded then

    a. set TQc ("TQ current") = TQ.

3. If (($TQ + H$) > TQc) or (($TQ - H$) < TQc) then

    a. set $TQc = TQ$ and

    b. set $TQ = TQc$.

4. Go to Step 2.

The datasets analysed throughout this report are freely available—please contact the authors for more information.

4. STATIC INDOOR EXPERIMENT

We initially conducted an indoor experiment to examine route-flipping in B.A.T.M.A.N. All results in this section are from the dataset "2011-02-25-160004". We used four nodes with IP addresses 192.168.6.x. Nodes 122, 61 and 63 formed a full-mesh sub-network, with Node 65 hidden from Node 122 by an obstruction. Node 65 had an equally strong signal to Nodes 61 and 63. The result of this topology is that Node 65 route-flips between 61 and 63.

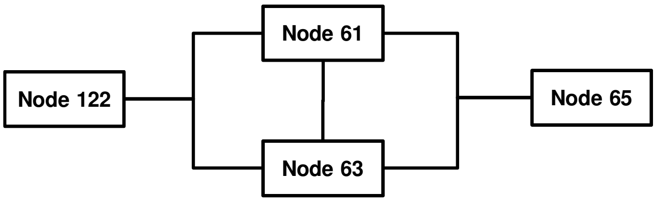


Figure 2. Indoor experimental network, showing wireless connectivity.

Firstly, we simply examined the *TQ* values as observed by Node 122 for 15 hours. The maximum *TQ* value was set to

255 for all nodes, and the originator message (OGMs) transmit rate was set at one per second. Whilst we conducted these initial topological results, we also simulated traffic by using the *iperf* tool set to transmit UDP traffic from Node 122 to the remaining nodes at 100 kbit/s; well below the maximum capacity of the channel. We conducted this test to examine the anticipated effect of delaying route-flips (due to Batrytis) on the overall throughput.

The total count of all next best-hop neighbour choices from Node 122 was collated. As can be seen in Table 2 below, Node 65 spent roughly equal times routing through the Node 61 (46% of total time) and Node 63 (54%). Node 122 nominated Node 61 as the best next-hop route to Node 61 87% the time, with Node 63 nominated as the best next-hop for Node 63 97% of the time. Neither Node 61 nor 63 used Node 65 as its best next-hop at any time; verifying the topology in Figure 2.

Each *iperf* experiment comprised the following steps, where Node 122 conducted the test between itself and each of the NS2L nodes 61, 63 and 65:

1. Set the Batrytis hysteresis tolerance *H*
2. Conduct a 60 second *iperf* test to each of the three NS2L nodes

Destination Node	Next-best hop		
	61	**63**	**65**
61	64,608 (87%)	9,780 (13%)	0 (0%)
63	1,878 (3%)	71,395 (97%)	0 (0%)
65	33,980 (46%)	40,412 (54%)	0 (0%)

Table 2. Total count of next-best hop neighbour choices for Node 122 and percentage time spent in each state for each node during indoor experiment using *iperf* at 100 kbit/s.

For the test we repeated the experiment described above 720 times, cycling through Batrytis' hysteresis tolerance values then repeating the same tests, giving 120 results per hysteresis tolerance. We used hysteresis tolerances *H* of 0 (no hysteresis), 1, 2, 5, 10 and 20. We kept tests short and repeated the tests in order to negate the effect any short term interference or multipath effects.

As can be seen in Table 3 below, even the lowest hysteresis tolerance (1) significantly reduced the number of route-flips.

Destination Node	Hysteresis Tolerance					
	0	**1**	**2**	**5**	**10**	**20**
	Number of Route Flips (% reduction)					
61	190	157 (17%)	111 (42%)	62 (67%)	40 (79%)	12 (94%)
63	144	60 (58%)	26 (82%)	27 (81%)	10 (93%)	1 (99%)
65	460	345 (25%)	236 (49%)	141 (69%)	96 (79%)	47 (90%)

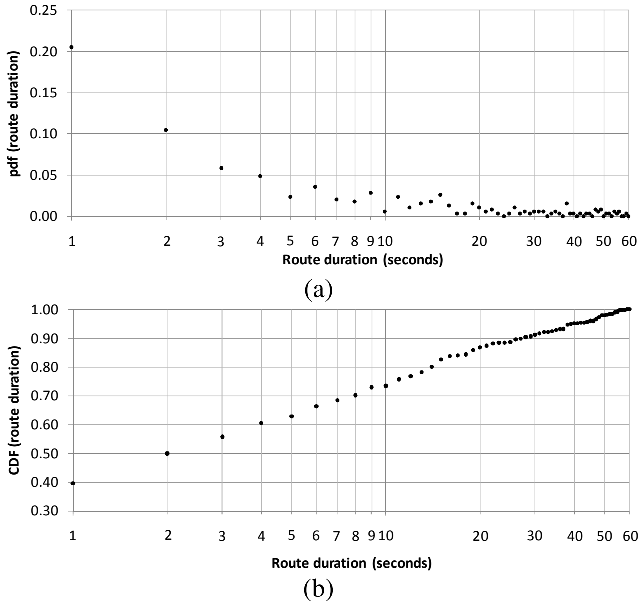
Table 3. Total number of route flips and percent reduction due to hysteresis for Node 122 for each neighbouring node and hysteresis tolerance during indoor experiment, using *iperf* at 100 kbit/s.

Whilst the average rate of route-flips is not high (around one every 20 seconds), in practice there are long periods of stability and short periods of rapid route-flapping at a rate on the order of one route change every few seconds. This can be seen in

Figure **3**, where we show the probability density function (pdf) and cumulative distribution function (CDF) of the persistence of the routes.

A limitation of our analysis is that as each test was 60s in duration, we are restricted to route persistence below 60s. B.A.T.M.A.N. also produced routes with zero duration, where a routing change was instantly followed by another routing change. This was presumably because at the time of route analysis OGMs arrived from different neighbours, and recalculations were performed based on the order of OGM packet arrival. In the case shown below, roughly 19% of all route changes had zero duration. The most important feature demonstrated by this analysis is the prevalence of extremely short duration routes. Roughly 20% of all routes are 1 second in duration, and around 50% of all route durations were 0, 1 or 2 seconds in duration. This infers that small hysteresis values may be sufficient to eliminate a large proportion of the route changes.

For each of the 720 tests we recorded 100 kbit/s throughout, indicating that even using a large hysteresis tolerance of 20 did not prevent B.A.T.M.A.N. from using an optimal (in the sense of achieving maximum throughput) route during any *iperf* test. In other words, most of the routing changes proposed by standard B.A.T.M.A.N. were not necessary.



(a)

(b)

Figure 3. Probability density function (a) and cumulative distribution function (b) of route durations for best-hop neighbour of Node 122 for Node 65 during first indoor experiment.

We then repeated the experiment with *iperf* transmitting UDP packets at 700 kbit/s. The results shown below from dataset "2011-02-24-170502" in Table 4 indicated again that hysteresis had no appreciable effect on throughput. We suspect that more samples need to taken for any meaningful result; however we consider these results indicative for this simple static scenario.

		Hysteresis Tolerance					
Destination Node	**Samples**	**0**	**1**	**2**	**5**	**10**	**20**
61	6	645	572	604	627	622	613
63	29	635	619	638	631	650	664
65	5	404	375	431	353	416	433

Table 4. Average throughput (in kbits/s) from Node 122 during indoor experiment using *iperf* at 700 kbit/s.

In order to introduce mobility, and as there were also concerns about conducting experiments in a noisy radio frequency environment, we then conducted a series of mobile outdoor tests as described below in Section 5.

5. MOBILE OUTDOOR EXPERIMENT

In our outdoor experiment, we sought to replicate the key features of the scenario shown in Figure 1. The three NS2L nodes represented the airborne relays, whilst the ground unit was represented by a user walking with a laptop. We positioned the nodes as shown in Figure 4, where Node 61 transmitted to the left of the figure, Node 65 transmitted directly downwards and Node 63 transmitted to the right.

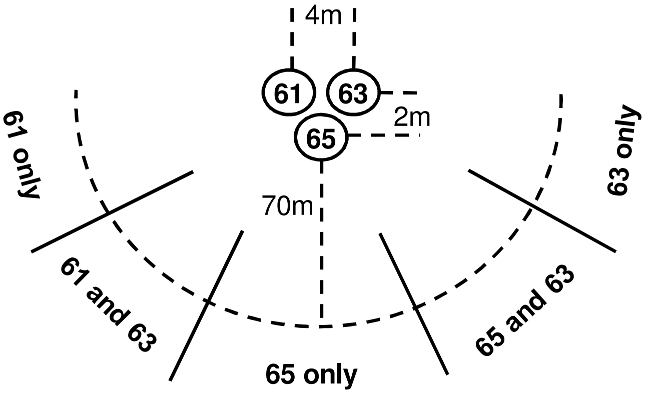


Figure 4. Outdoor experimental network, showing node locations, orientation and transmission sectors due to antenna directivity at 70m range.

An overhead view of the actual experimental area is shown in Figure 5. Each experiment lasted around 3.5 minutes. Note as the experiment was brief we increased the rate of originator message transmissions from one per second to ten per second. This allowed us to observe the B.A.T.M.A.N. analysis of route changes at a higher rate. The laptop had a transmit power of 20dBm (omni-directional with 2dBi gain in the horizontal plane), whereas the UNS2L nodes had a transmit power of 0dBm (directional with 8dBi gain).

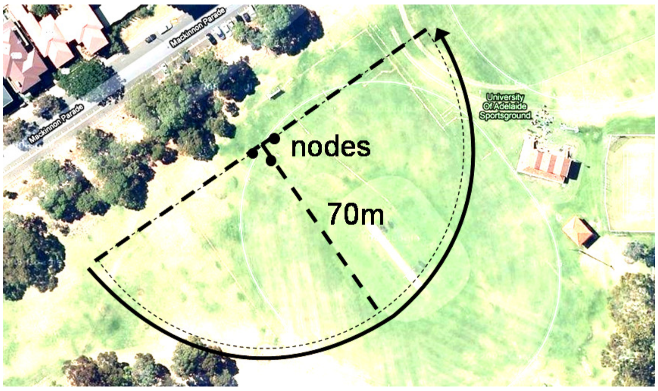
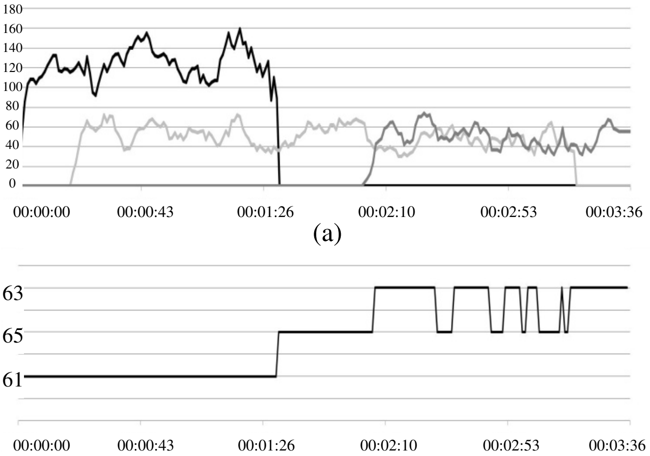


Figure 5. Satellite view of experiment location, showing path taken by mobile node.

Results from this experiment are shown in Figure 6. These show that Node 122 initiates a clean "hand-over" from Node 61 to Node 65 when the signal from Node 61 drops. However, the handover from Node 65 to Node 63 involves considerable route-flapping, due to the *TQ* values of Nodes 65 and 63 being similar yet variable. There are 12 route-flaps in total. Not counting the 2 required under ideal conditions, we note that there are 10 potentially unnecessary route-flaps.



(a)

(b)

Figure 6. Changing *TQ* values for Node 61 using standard B.A.T.M.A.N.: (a) for direct link (black), via Node 65 (light grey) and via Node 63 (dark grey) and (b) best first-hop neighbour.

We then repeated the experiment with a hysteresis tolerance of 10. These results are shown below in Figure 7. Note in this experiment the mobile node followed a reverse trajectory, explaining why a Node 61 direct hop occurred at the end of the experimental run. The results show that a total of 4 route-flaps occurred. Counting the two necessary route-flaps, then unnecessary route-flaps have been reduced by 80%. Even with few samples, this is roughly in line with the laboratory results shown in Table 3.

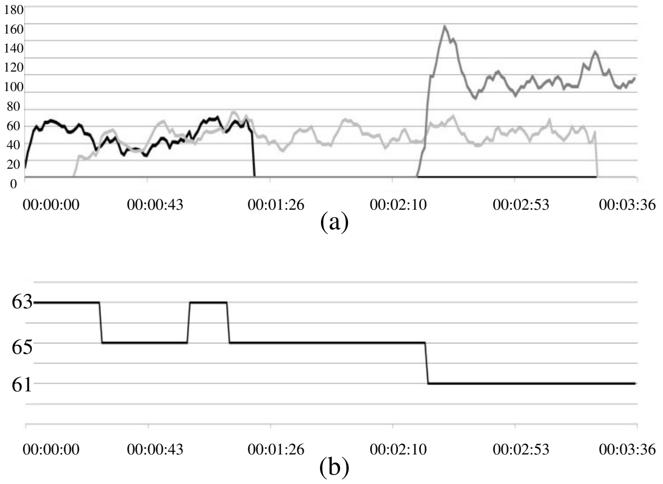


Figure 7. Changing *TQ* values for Node 61 using Batrytis: (a) via Node 63 (black), via Node 65 (light grey) and for direct link (dark grey) and (b) best first-hop neighbour.

6. 6-NODE INDOOR TEST

We repeated the indoor test with 6 nodes, introducing marginal links with short-term multi-path interference. This has a similar effect to mobility, in that the choice between routes truly reflects changing conditions. As in previous experiments, we examined the *TQ* values as observed by Node 122. In this case (dataset "2001-03-11-13308") we observed traffic for 48 hours. The topology is shown below in Figure 8.

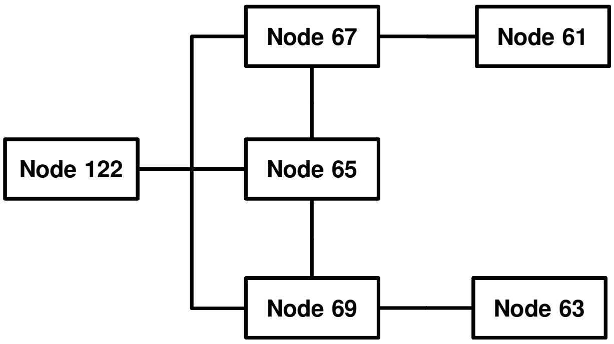


Figure 8. 6-node indoor experimental network, showing wireless connectivity.

The total count of all next best-hop neighbour choices was collated from Node 122: this is shown below in Table 5.

Destination Node	Next-best hop				
	61	63	65	67	69
61	4,986 (8.0%)	18 (0.0%)	10.367 (16.6%)	45,055 (71.9%)	2,201 (3.5%)
63	48 (0.1%)	1,985 (3.2%)	2,678 (4.3%)	1,370 (2.2%)	56,539 (90.3%)
65	85 (0.1%)	0 (0.0%)	61,652 (98.4%)	635 (1.0%)	294 (0.5%)
67	296 (0.5%)	0 (0.0%)	4,948 (7.9%)	57,176 (91.3%)	202 (0.3%)
69	95 (0.2%)	703 (1.1%)	1,284 (2.1%)	322 (0.5%)	60,228 (96.2%)

Table 5. Total count of next-best hop neighbour choices from Node 122 and percentage time spent in each state for each node during 6-node indoor experiment using *iperf* at 700 kbit/s.

As can be seen in Table 6, Batrytis greatly reduces route-flipping, as with the 4-node case.

Dest. node	Hysteresis Tolerance					
	0	1	2	5	10	20
61	471	422 (10.4%)	309 (34.4%)	185 (60.7%)	101 (78.6%)	54 (88.5%)
63	226	177 (21.7%)	116 (48.7%)	71 (68.6%)	42 (81.4%)	24 (89.4%)
65	53	48 (9.4%)	30 (90.7%)	21 (90.7%)	18 (92.0%)	9 (96.0%)
67	303	165 (45.5%)	125 (44.7%)	71 (68.6%)	40 (82.3%)	8 (96.5%)
69	78	44 (43.6%)	21 (90.7%)	28 (87.6%)	15 (93.4%)	15 (93.4%)

Table 6. Total number of route flips for Node 122 and percent reduction for each node and hysteresis tolerance during 6-node indoor experiment using *iperf* at 700 kbit/s.

We then repeated *iperf* throughput tests. The results are shown below in Table 7. The results again show no obvious trend in throughout with increasing levels of hysteresis *H*, meaning again that most of the routing changes proposed by standard B.A.T.M.A.N. were not necessary.

Dest. Node	Samples	Hysteresis Tolerance					
		0	1	2	5	10	20
61	29	638	593	624	538	614	557
63	29	283	278	295	285	285	287
65	32	700	700	700	700	700	700
67	48	668	669	669	672	669	669
69	29	667	668	668	668	670	667

Table 7. Average throughput (in kbits/s) for Node 122 during 6-node indoor experiment using *iperf* at 700 kbit/s.

7. ALTERNATIVE METHODS FOR ROUTE SELECTION

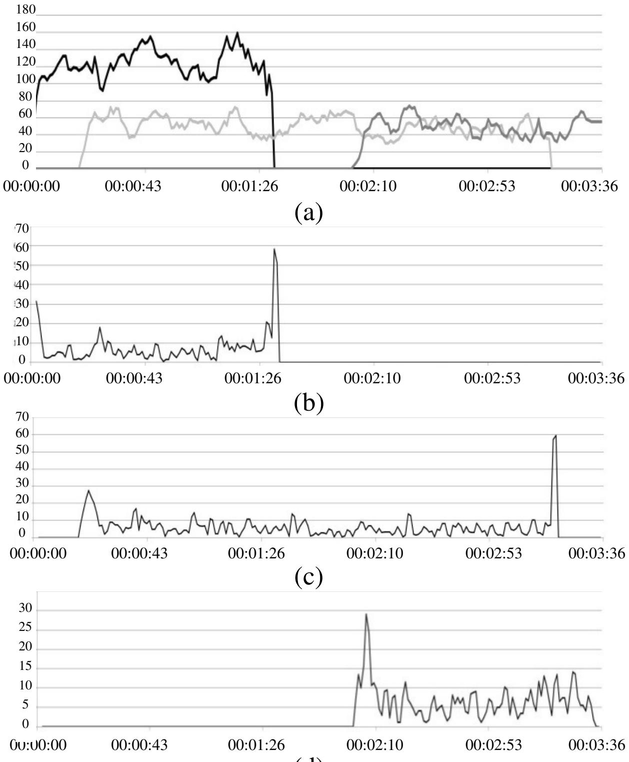
As an alternative to a hysteresis algorithm, we also considered whether a time-series analysis of *TQ* values could detect changing route conditions. Our hypothesis is that changing route conditions should affect the rate of change of *TQ* values. Our objective is to design an algorithm to react faster than Batrytis, and to make a quick decision to hand-over.

As a simple example we took the standard deviation of 3 consecutive samples of *TQ* values. In Figure 9 we show the standard deviation values. The results show standard deviation "events" occurring at each of the three significant points in the trial; when (i) Node 61's transmission is lost, (ii) Node 63's transmission appears and (iii) Node 65's transmission is lost. If we had set a threshold for detection a smooth hand-over would have been achieved. Note that zero value standard deviation values were observed due to *TQ* values being zero at certain times, for example during a period of no transmission from a particular node.

This suggests that a time-series analysis can be used to initiate a hand-over; or at least to provide extra information to another algorithm that conditions may be changing.

8. DISCUSSION AND FUTURE WORK

An observation we made whilst examining the data was that *TQ* values often dropped significantly for all nodes with only moderate levels of traffic. In one case we determined that the problem was a wireless card which delayed the echo OGMs by over a second. With OGMs transmitted at a rate of one per second, B.A.T.M.A.N. regarded these OGM echoes as out of order, leading to *EQ* and *TQ* values decreasing: *RQ* values remained the same. With moderate levels of traffic in other experiments we were unable to isolate the cause with our limited time. We suspect that the broadcast nature of OGMs (that is, with no retransmissions) prevents reliable transport, which is not the case for unicast traffic such as used in *iperf*. These results highlight the need to protect control traffic (OGMs) even in the presence of high traffic to ensure they are representative of real traffic conditions. A technique using cross-layer design [06] or data-driven metrics may be more effective than network-layer OGMs, whereby *TQ* value information could be stored inside headers of the lower layer of the OSI stack. We would be interested so see whether problems also occur using B.A.T.M.A.N. Advanced as this operates at a lower layer.



(a)

(b)

(c)

(d)

Figure 9. Experimental results for Node 61: (a) *TQ* values and standard deviation of 3 consecutive *TQ* values for (b) direct link, (c) via Node 65 and (d) Node 63.

When using directional antennas, it is clear that standard MAC and network-layer protocols are not sufficient. For example, a node can be interfering with another node and not be aware of the problem. This may have been occurring during our tests. Some of the techniques previously discussion in Section 2 could be employed, for example with omni-directional neighbour discovery and power-control.

In future work we plan to more closely quantify how directionality can improve the operation of a MANET, and what networking layer designs are required on top of existing MAC-layer mechanisms in order to achieve this.

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