Mesh Network Performance Measurements

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***Abstract*— This work is based on measurements of the ReMesh wireless mesh network deployed over the city of Niterói, Brazil. It uses a modified version of the OLSR ad hoc routing protocol. OLSR has the goal of maximizing throughput by minimizing the number of transmissions over the wireless shared medium selecting routes based on the sum of the expected transmission count (ETX) of each link from a source node towards a destination node. Because of routing instabilities and the high packet loss rates (PLR) observed with the original OLSR algorithm, this work uses an algorithm for selecting multi-hop paths based on minimum loss probability along the entire path. Test results show that the mesh network performance has been improved, leading to more stable routes, lower packet loss rates, shorter delays and in many cases a small increase in network throughput.**

***Index Terms*—Mesh Networks, Ad Hoc Wireless Networks, Ad Hoc Routing Protocols, OLSR, ETX**

I. INTRODUCTION

Over the last years, several universities and research centers around the world have been developing and deploying intra-campus wireless networks for ubiquitous communication [9]. Recently, wireless technology has been used for providing access to campus networks for users living nearby, using the concept of mesh networks. In this type of networks, wireless routers communicate with each other in ad-hoc mode using multiple hops in order to forward messages to their destinations. Mesh networks [2, 11, 12] are community networks based on cooperative routing algorithms, such as the ones found in wireless ad-hoc networks [15]. End users can connect to an access point of the mesh network using wired Ethernet or wireless 802.11. Mesh networks have several advantages over other last mile access technologies including low cost, easy and incremental deployment and fault tolerance.

This paper describes the performance of the mesh network developed by the ReMesh project [24] of the Fluminense Federal University (UFF), supported by a grant from the Brazilian NREN agency. Throughput, delay, packet loss and route stability were measured on both the indoor test-bed and the outdoor production network, and led to an improved routing metric for OLSR.

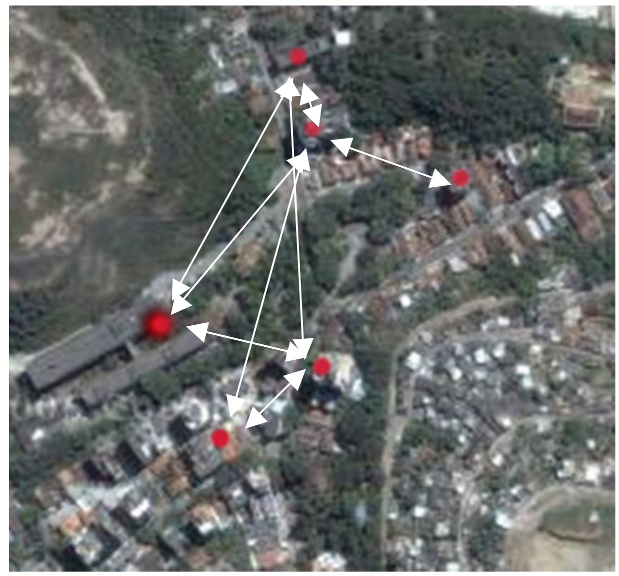

Figure 1: ReMesh outdoor network

UFF has several integrated campi distributed throughout the city of Niterói, providing an ideal scenario for the deployment of a wireless broadband access mesh network. Figure 1 shows the ReMesh network with 6 routers surrounding the Praia Vermelha campus. One of this project aims is the social and digital inclusion in Brazilian Universities. The majority of students at UFF cannot afford a traditional broadband Internet connection, such as ADSL or cable. Thus a wireless mesh network is a desirable low-cost alternative for the UFF academic community and certainly for several other Brazilian Universities, and there is an on-going proposal to replicate it at Universities in the Amazon, in the state of Pará and at the south of Brazil, in the state of Paraná.

The ReMesh wireless router is a programmable device based on the OpenWRT operating system [16]. OpenWRT is a free, open-source Linux distribution that can be customized with the installation of different routing protocols. OpenWRT needs 2MB of storage and runs in 125MHz processors with 16MB RAM. It can be installed in several commercial wireless routers [14]. The ReMesh project has been working with Linksys WRT54G and WRT54GS 802.11g wireless routers.

ReMesh uses OLSR (Optimized Link State Routing) [4, 5] as its ad-hoc routing protocol. OLSR is a pro-active routing

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protocol standardized by IETF. In order to maintain current routes available, pro-active protocols usually impose more overhead to the ad-hoc network compared to on-demand and hybrid routing approaches. However, as mesh routers do not move and do not have constraints on power usage, link-state-based routing has been broadly used in mesh solutions [2, 21, 22, 23, 25] and this lead to the choice of OLSR as our routing protocol. ReMesh routers were initially installed with OLSR version 0.4.9 [17], which uses ETX (Expected Transmission Count) as route metric [6, 8]. ETX dynamically measures link quality to find best routes, instead of using minimum hop count [5], the IETF standard metric.

Initial tests of the ReMesh network were performed in an indoor environment to validate our hardware and software choices before deployment. The indoor test-bed consists of mesh routers and workstations placed on two adjacent floors of the same university building, where the Computer Science and Telecommunications Engineering Departments are located. In those floors, there are several other WiFi networks with 802.11b/g access points. Thus, the ReMesh indoor test-bed suffers severe external interference. During the initial tests, throughput, packet-loss rate and round-trip delay were measured and the results showed great instability and poor performance of the OLSR algorithm. We experienced high loss rates and long delays, and the routing tables oscillated so much that broken routes were very frequent. After this initial test phase, we used a different metric for calculating multi-hop link quality targeting the selection of minimum loss paths. Additional tests demonstrated that the mesh network performance was improved under those conditions, leading to stabler routes, lower loss rates, shorter delays and in many cases higher network throughput. After this test phase, the ReMesh routers have been incrementally installed on the top of buildings surrounding the Praia Vermelha campus, as shown in Figure 1, using the new metric.

This paper shows results of performance measurements collected both in the indoor test-bed and outdoor production network. It is organized as follows. Section II presents related work. Section III gives a brief explanation of the original link quality extension, available in the OLSR distribution. Section IV explains our change to OLSR, using multiplicative link quality metric for multi-hop paths. Section V presents our indoor test-bed and the outdoor network, and shows test results comparing the original OLSR implementation to the new one. Section VI presents our conclusions and future work.

II. Related Work

There are several other pilot projects of mesh networks around the world. Examples are RoofNet at MIT [1, 6], VMesh in Greece [25], MeshNet at UCSB [10, 20], CUWiN in Urbana [14], Microsoft Mesh [7, 8], Google Mesh [28], among others [26].

Besides academic projects, commercial solutions are already on the market, offered by enterprises such as Nortel [21] and Cisco [3] and several other smaller companies [2]. Several governments are investing on building digital cities using wireless mesh networks, such as Dublin [26], and Taipei where Nortel equipments are used and recently in the historical city of Tiradentes in Brazil, which uses Cisco equipments. One disadvantage of commercial mesh routers is their cost, which is higher than locally built solutions. Our project, similar to those in [1, 10, 14, 25], is linux-based, open-source and uses a low-cost wireless router.

Some solutions, including those from Microsoft [7], Nortel [21] and Cisco [3], use two different frequencies, usually 802.11a 5GHz for the backbone (links between wireless routers) and 802.11b/g 2.4GHz for access links (links between end users and access points). Since in Brazil the 5GHz band in not regulated yet, ReMesh uses only the 2.4GHz band. In ReMesh most end users are connected to mesh access points through wired Ethernet, in the same way of RoofNet and VMesh, but users may also use wireless 802.11b/g access.

VMesh and ReMesh use OLSR [4, 5], a standard pro-active routing protocol. Microsoft Mesh uses an on demand reactive source routing protocol derived from DSR (Dynamic Source Routing) [13], called MR-LQSR (Multi-Radio Link-Quality Source Routing) [7]. RoofNet developed a hybrid approach, combining link state and DSR-style on-demand querying, named Srcr [1]. The work presented in [20] from UCSB uses AODV (Ad Hoc On-Demand Distance Vector) [18, 19], a standard reactive routing protocol. Cisco´s solution uses a proprietary routing protocol named AWP (Adaptive Wireless Path) [3] and Nortel uses the traditional OSPF (Open Shortest Path First) wired routing protocol [21]. The CUWin project is developing a link state routing protocol that minimizes the cost of maintaining a consistent view of the network, called HSLS (Hazy Sighted Link State) routing [2, 22, 23].

Generally, link costs can be calculated using traditional hop-count [5, 22], per-hop round trip time, packet pair delay [7], ETX [6] or similarly derived metrics such as ETT (Expected Transmission Time) [1] and WCETT (Weighted Cumulative Expected Transmission Time) [7]. ETT predicts the total amount of time to send a data packet along a route, considering each link's highest-throughput transmission rate and its delivery probability at that bit-rate. WCETT takes into account the interference among links that use the same channel. A discussion on link quality metrics can be found in [7, 8]. Most work on mesh networks calculates the multi-hop path cost as the sum of the cost of each link in the path. Some authors [1, 6] state that it is better to select shorter paths with wireless links that have significant loss rates than to favor longer paths made of low loss links, because throughput decreases with hop count due to contention. Our initial metric chose shorter paths, but network performance was not satisfactory. The test results showed that choosing links with minimum loss rates lead to higher throughput, with the added benefit of exhibiting more stable routes and fewer lost packets.

Yarvis et al. [27] worked with a 100-node sensor network and DSDV (*Destination-Sequenced Distance-Vector*) routing protocol [15]. They used a link quality metric based on the number of lost packets similar to the one we are proposing, and suggested that using the product of the costs, when calculating multi-hop route costs, was better than adding the link costs together. However, due to limitations in the hardware platform used in the sensor network experiment, they converted link metrics to the log domain and added them to find multi-hop total costs (which basically amounts to a product). Besides monitoring link losses, [27] also applied passive acknowledgements in the CSMA/CA medium access control and stated that using both techniques could improve real network performance. The ReMesh project decided not to modify the medium access layer to maintain compatibility to the IEEE 802.11 standard, but monitoring link losses and using a multiplicative metric were enough to improve mesh network performance in our project, as will be seen in the following sections.

III. Original OLSR Link Quality Extension

Minimum hop-count is the metric most commonly used by existing ad-hoc routing protocols to calculate optimal routes, including the standard OLSR specification [5]. Minimizing hop count is not enough in a wireless environment, because when the network is dense, there may be several routes with the same minimum hop count and very different link qualities. An arbitrary decision made by minimum hop-count algorithms may not select the best available route. The OLSR implementation in [17] uses a link quality extension, called ETX (Expected Transmission Count) metric [6]. This extension aims at finding paths with the lowest number of required transmissions to deliver a packet to its final destination.

The ETX of a link is calculated using forward and reverse link delivery ratios. The delivery ratio is the probability that a data packet successfully arrives at the next hop. The expected probability that a transmission is successfully received and acknowledged is the product of the forward delivery ratio (d_f) and the reverse delivery ratio (d_r) of a link. Thus, the expected number of transmissions is given by:

$$ETX = 1 / (d_f \times d_r).$$

The delivery ratios (d) are measured using modified OLSR HELLO packets sent every t seconds (t=2, by default). Each node calculates the number of HELLOs received in a w-second period (w=20, by default) and divides it by the number of HELLOs that should have been received in the same period (10, by default). Each modified HELLO packet informs the number of HELLOs received by the neighbor during the last w seconds, in order to allow each neighbor to calculate the reverse delivery ratio. The worse the link quality is, the greater the ETX link value becomes. The ETX value is 1 for a perfect link that loses no packets. If no HELLO packet is received during a w-second period, ETX is set to 0 and the link is not considered for routing. Otherwise, ETX is greater than 1.

In the case of a multi-hop path, the ETX value of the complete route is given by the sum of the ETX of each hop. Thus in a route from A to C, passing through B, the final ETX value is given by:

$$ETX_{AC} = ETX_{AB} + ETX_{BC}..$$

OLSR selects the best route from one source to a specific destination as the one with smallest ETX value.

However, in this work we observed that the use of ETX may result in (1) route instabilities and (2) high packet loss rate (PLR), though smaller than they would be if a minimum hop-count metric were used.

In order to illustrate one potential source of instability, we define a window *w* of 22 seconds (11 HELLO packets) and consider the window state for three links as shown in Table 1. Table 1 is an abstraction of the ETX window and considers that the links between nodes N1-N2 and between nodes N2-N3 are perfect links. The direct link between nodes N1-N3 has a 50% loss probability and, at each other interval, one HELLO packet is lost. When selecting a route between nodes N1-N3, The ETX of the path N1-N2-N3 is always equal to 2, since each of the links N1-N2 and N2-N3 has an ETX of 1. On the other hand the ETX of the direct link N1-N3 varies between 1.83 and 2.20, depending on the state of the ETX window of this link.

Table 1: ETX Window Example: Instability and High PLR

N1-N2	1	1	1	1	1	1	1	1	1	1	1
N2-N3	1	1	1	1	1	1	1	1	1	1	1
N1-N3	1	0	1	0	1	0	1	0	1	0	1

In this artificial example, routes between N1 and N3 would change every 2 seconds, flipping between the lossy direct link and the perfect 2-hop path. Even though this is an artificial example, it was not uncommon to see this unstable behavior in our test-bed, as it will be shown in Section V.

Even though ETX is based on the success probability over a single link, it aims at minimizing the number of transmissions along a given path and not minimizing the loss probability along the path. The example shown on Table 1 illustrates that OLSR-ETX would often select a route with almost 50% of packet losses over an alternative path with no losses. In fact, with a window *w* of 20 seconds, the ETX of the direct link N1-N3 would be exactly 2, and this link with 50% PLR would be the selected route between N1-N3, since the criteria is to select the path with the minimum number of hops among the paths with the smallest ETX. Thus, the lossy direct link would be chosen in that case.

Therefore, OLSR-ETX may choose a route in which the PLR is so high that degrades network throughput, causing it to miss its main target, namely, minimizing retransmissions. This can be inferred by noticing that with a window of length *w* packets, the ETX increment for each packet lost as a function of *r* packets received in the window is given by:

$$\delta = \frac{w}{r(r-1)}.$$

This increment of δ is typically very small on good quality links and only becomes closer to 1 when packet losses get closer to half of the window. As already mentioned, for a perfect link, the ETX value is 1, so the additive increment of selecting a route with one more hop is at least 1. OLSR-ETX ends up selecting shorter paths with higher packet loss rates over longer paths with smaller packet loss rates.

IV. Using Multiplicative Metrics with OLSR

Using the original OLSR link quality extension, we experienced route instability and high packet loss rates in our mesh network, as it will be shown in Section V. In order to improve network performance, we used an alternative way to calculate the link quality of a given path in order to select the path with the minimum loss probability.

Interpreting link delivery ratios as probabilities, as they were originally defined, the probability of a successful transmission from A to B is:

$$P_{AB} = (d_f \times d_r).$$

In a multi-hop path, the probability of successful transmission over the complete path should be the product of the probabilities of each path. Thus, in a route from A to C, passing through B, the total probability of successful transmission is given by:

$$P_{AC} = P_{AB} \times P_{BC}.$$

Therefore, in our approach, a multi-hop path link quality value is given by the product (and not the sum) of each link quality. As we are using the probabilities P and not its inverse value (ETX), the best route from one source to a specific destination is the one with the highest probability (P) of successful transmission, i.e., the one with minimum loss probability.

Using this approach, one could argue that if all link qualities were 1 in a given network, then the probability of successful transmission over a multi-hop path between two nodes would be same as the probability over a direct link between them. This is true, but the regular OLSR implementation already has a solution for this scenario. When multiple routes with the same link quality are present, the one with the minimum number of hops is chosen. Thus the direct link would be chosen in that case.

On the other hand, if a multi-hop route has a higher successful transmission probability (or a smaller packet loss probability) than a single-hop route, the multi-hop route is chosen. Measurements described in Section V indicate that this alternative improved mesh network performance regarding network stability, packet loss rates, round trip delays and even throughput in many cases.

The proponents of ETX [6] argue that maximum throughput is achieved by minimizing the number of transmissions per packet over the shared medium, and they have demonstrated a two-fold improvement in throughput compared to the minimum hop-count metric. In this paper, we extend this argument by suggesting that paths with minimum loss rates (or higher probabilities of successful transmissions) also lead to high throughput, with the added benefit of more stable routes and lower packet loss rates.

V. Mesh Network Performance Analysis

This section presents performance measurements collected in two mesh networks, the indoor test-bed and the outdoor ReMesh network deployed over the city of Niterói, in the state of Rio de Janeiro, Brazil. The experiments in the indoor test-bed showed that minimum loss paths improve mesh network performance when comparing to the ETX metric, leading to more stable routes, lower packet loss rates, shorter delays and, in many cases, a small increase in network throughput.

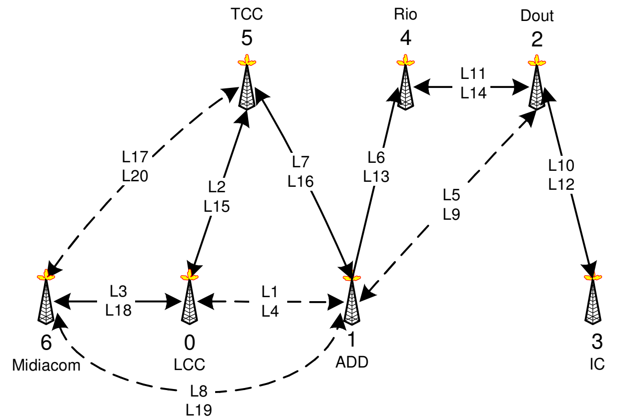


Figure 2: The ReMesh indoor test-bed

A. *Indoor Experiments*

Performance tests of the indoor ReMesh network were made among seven laboratories within one of UFF campi. User workstations are connected to ReMesh access points through wired Ethernet. The indoor test-bed consists of seven routers and a number of workstations placed on two adjacent floors of the same building. The 802.11g ReMesh routers in the indoor test-bed use their original small 2dB gain omni-directional antennas.

Figure 2 illustrates the ReMesh indoor test-bed. Nodes are numbered 0 through 6 and labeled with the respective lab location. Node 6 is located on the fourth floor. All other nodes are on the third floor. Links numbered L1 through L20 were identified by monitoring the topology built by OLSR within each router, using a plug-in of the OLSR daemon. Dashed lines indicate noisy low quality links while continuous lines indicate better quality links. Using this test-bed, we observed routing instabilities and high packet loss rates when using the standard OLSR routing algorithm. This motivated the research on routing metric. In the remainder of this section the original OLSR implementation will be labeled OLSR-ETX and the modified version of OLSR used in our project will be labeled OLSR-ML (minimum loss).

1) *ETX Variability*

Table 2 shows the measurements of the ETX metric for the ReMesh indoor test-bed depicted in Figure 2. We monitored the average, minimum, maximum and standard deviation of all 20 links over a period of 24 hours. Lines in boldface in Table 2 indicate links with good quality and an average ETX lower than 1.20. However, notice that even good quality links, such as links L3 and L18, between nodes 0 and 6, occasionally experience high loss intervals and have registered a maximum ETX value of 141.67. Similar phenomenon is observed in links L7, L14, L15 and L16. Interestingly, low quality links with an average ETX greater than 6.10, such as links L4, L5, L9 and L17, occasionally experience no loss and report a minimum ETX value of 1. The standard deviation (σ) indicates the variability of the ETX of each link.

TABLE 2: ETX MEASUREMENTS

L	S	D	Avg	Min	Max	σ
L1	0	1	9.40	1.05	71.30	7.03
L2	**0**	**5**	**1.06**	**1.00**	**1.97**	**0.07**
L3	**0**	**6**	**1.12**	**1.00**	**51.00**	**2.07**
L4	1	0	10.09	1.00	53.12	8.02
L5	1	2	90.91	1.00	451.56	72.11
L6	**1**	**4**	**1.07**	**1.00**	**2.21**	**0.09**
L7	**1**	**5**	**1.13**	**1.00**	**13.42**	**0.17**
L8	1	6	2.40	1.00	104.04	4.08
L9	2	1	199.60	1.00	451.56	180.58
L10	**2**	**3**	**1.02**	**1.00**	**1.32**	**0.03**
L11	**2**	**4**	**1.07**	**1.00**	**1.39**	**0.06**
L12	**3**	**2**	**1.01**	**1.00**	**1.24**	**0.03**
L13	**4**	**1**	**1.06**	**1.00**	**2.28**	**0.09**
L14	**4**	**2**	**1.05**	**1.00**	**68.45**	**0.42**
L15	**5**	**0**	**1.04**	**1.00**	**30.44**	**0.19**
L16	**5**	**1**	**1.20**	**1.00**	**451.56**	**4.19**
L17	5	6	6.10	1.00	51.00	3.54
L18	**6**	**0**	**1.10**	**1.00**	**141.67**	**2.16**
L19	6	1	2.25	1.00	106.25	2.17
L20	6	5	8.21	1.05	425.00	6.58

The ETX link quality variability resulted in frequent route changes in the ReMesh indoor test-bed. Consider a data exchange between nodes 1 and 6. There is a direct link L8 with an average ETX metric of 2.40. There is also an alternative path through 3 links, L7, L15 and L3, (or through nodes 1-5-0-6) with an average ETX metric of 3.29 (= 1.13 + 1.04 + 1.12). Small fluctuations of the quality of link L8 may result on a route change to the alternative path above. Notice that links L7, L15 and L3 are more stable than link L8. Notice also that the loss probability of link L8 is 58.3% while the loss probability along the path L7-L15-L3 is 24%.

2) Routing Stability

In this experiment 18,000 ping packets, registering the traversed route, were sent between nodes 3 and 6, over a 5-hour period between 10am and 15pm of a normal work day. We observed 426 route changes using the original OLSR-ETX. When OLSR-ML was deployed, no route changes were observed over the same period of another regular workday.

3) Packet loss rate

This experiment was performed during a 12-hour period transmitting 43,200 packets between nodes 3 and 6 with the goal of comparing the packet loss rates of OLSR-ML and OLSR-ETX. The experiments were run during the same hours of the day, but in different workdays for each routing algorithm. As expected, Figure 3 shows a significant drop on PLR with OLSR-ML, with reductions varying between 59.8% and 97.0%.

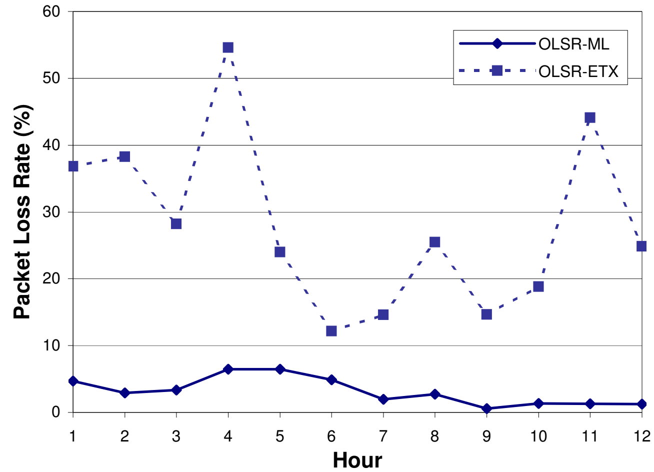


Figure 3: The ReMesh packet loss rate for communications between nodes 3 and 6.

4) Network delay

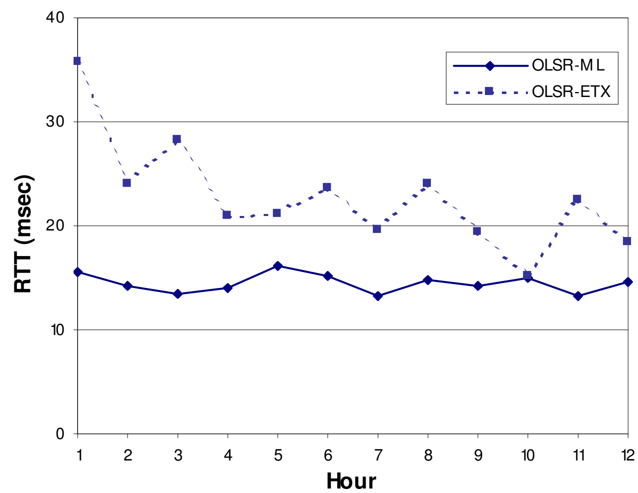


Figure 4: The ReMesh round trip times for communications between nodes 3 and 6.

In order to select paths with lower packet loss rates, OLSR-ML usually selects paths with a larger number of hops compared to OLSR-ETX. This increase in hop count could result in longer delays. Interestingly, Figure 4 shows that OLSR-ML also performs better in terms of delay. The result is again for a 12-hour period.

In order to understand how paths with larger number of hops have shorter round trip times (RTT) than paths with a smaller number of hops, the layer-2 statistics were investigated and initial results indicate fewer layer-2 retransmissions along the path with smaller PLR selected by OLSR-ML compared to the number of layer-2 retransmissions along the path selected by OLSR-ETX. The maximum number of transmission attempts for each packet at layer-2 is set to 7 in accordance with the 802.11 standard. The reduction on RTT using OLSR-ML varied between 1.34% and 56.3%.

5) Network Throughput

OLSR-ML typically chooses paths with lower PLRs and higher number of hops when compared to OLSR-ETX. Each additional hop in multi-hop transmissions over the shared medium increase contention and collision probability, and can have a significant negative impact on the overall network throughput. In order to measure the ReMesh throughput, a sender connected to node 3 running IPERF [29] was configured to send packets to each node of the ReMesh test-bed. A total of 300 IPERF measurements per destination node were performed. Figure 5 shows a slight increase in throughput using OLSR-ML for the communications with 3, 4 and 5 hops.

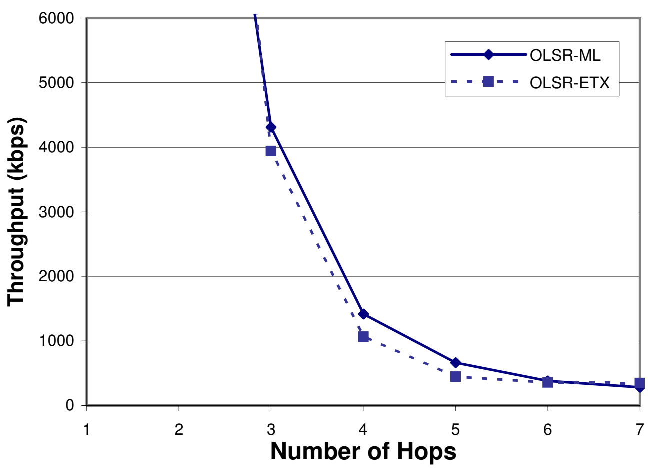


Figure 5: The ReMesh throughput measured with IPERF for communications starting at node 3.

The exponential decrease in throughput, as the number of hops increases, shown in Figures 5 and 6 is consistent with the behavior of other mesh and multi-hop ad hoc networks [1, 7]. RoofNet [1] exhibits a similar behavior in terms of throughput, reporting values from 2.45 Mbps for 1-hop communications dropping to 181 Kbps with 7-hop communications. ReMesh throughput is higher than RoofNet's because we use 802.11g while RoofNet used 802.11b. Moreover RoofNet's routing protocol chooses the route with the lowest ETT [1].

B. Outdoor Experiments

The ReMesh outdoor network is being gradually installed, and during the time the measurements were made it consisted of six routers placed on the top of buildings surrounding the Praia Vermelha campus, as shown in Figure 1. Figure 7 illustrates another view of the outdoor topology. ReMesh outdoor routers use 18dB omni-directional external antennas and the gateway uses a 24dB directional antenna. This section focuses on the outdoor network measurements.

The outdoor environment was harsher than we expected. Because of the many interfering sources we had in our indoor test-bed, we expected the same level of interference or even less interference in the outdoor test-bed than indoors. Unfortunately, the higher gain antennas installed in the routers to cover longer distances made the interference area greater. Another problem was related to the different heights among user building, which lead to worse link qualities among wireless routers. Moreover, the popularity of WiFi conspired to make conditions more challenging. Wardriving in the neighborhood of the University discovered 37 active access points. Although all channels were populated, there was a predominance of access points using channel 6, probably due to channel 6 being the pre-configured default channel in most wireless routers. Currently, we use different, non-interfering channels on the outdoor and indoor networks (the latter is still operational to test software changes before updating the production network).

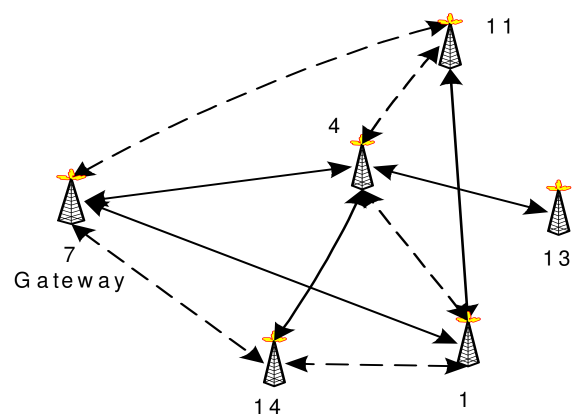


Figure 6: The ReMesh outdoor network

Performance tests were also run in our production network. To minimize service disruption, only tests that required no intervening traffic, such as throughput, were run with no users in the network. Other tests were run with normal user traffic, which certainly made results noisier. The chosen routing protocol was OLSR-ML due to its better results over the indoor network.

1) ETX Variability

Table 3 shows the average, the minimum, the maximum and the standard deviation for the most frequent links between nodes of the external network as shown in Figure 6. The information was collected over a 24-hour period.

TABLE 3: OUTDOOR NETWORK ETX MEASUREMENTS

L	S	D	Avg	Min	Max	σ
L1	7	11	1.55	1.00	12.75	0.59
L2	7	4	1.69	1.00	6.39	0.41
L3	7	1	1.41	1.00	4.72	0.31
L4	7	14	38.65	2.02	425	55.97
L5	14	1	6.70	1.00	106.25	8.92
L6	4	14	33.17	2.81	451.56	31.74
L7	4	1	13.88	1.32	71.3	13.51
L8	1	11	1.30	1.00	7.92	0.28
L9	4	11	1.70	1.05	13.62	0.50
L10	4	13	1.50	1.00	3.58	0.28

The measurements show six links with average ETX quality metrics between 1.3 and 1.7 and with low standard deviation (links L1, L2, L3, L8, L9 and L10). Even though these average ETX values are reasonably good, the fact that they are all close and frequent variations in link qualities shown by their standard deviation results in a potentially frequent route changes. Table 4 shows the frequency that a path is taken given a source-destination pair.

TABLE 4: OUTDOOR NETWORK ROUTE STABILITY

S	D	Path	Route Frequency
7	13	L2-L10	91.51%
7	4	L2	63.69%
7	4	L3-L7	19.05%
7	1	L3	56.45%
7	1	L2-L7	13.62%
7	11	L3-L8	52.48%
7	11	L2-L7-L8	21.30%
7	14	L3-L5	24.25%
7	14	L2-L6	13.47%

2) Packet loss rate

Figure 7 shows packet loss rate, in two days of measurements, using 86,400 ping packets in each run, sending one ping packet per second from a machine in the same Ethernet LAN as the gateway router to each other mesh node. We expected to see fewer losses, as our metric favors minimum loss paths, but the frequent route changes had a negative impact on the PLR because of the time needed for the nodes to update their routing tables.

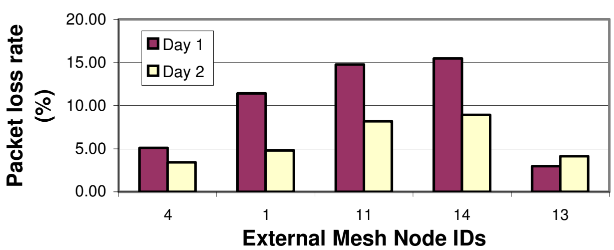


Figure 7: Percentage of lost ping packets in the outdoor network.

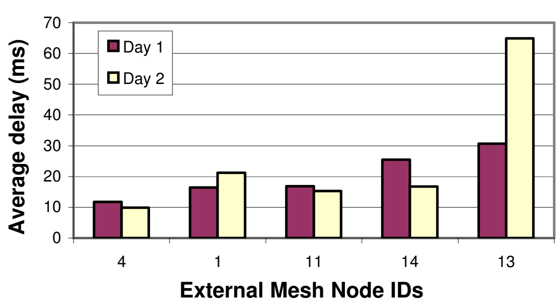


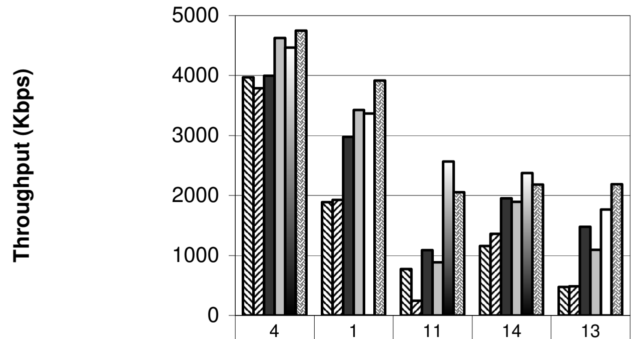
Figure 8: Average delay in the outdoor network.

3) Average delay

Figure 8 illustrates delay measurements in the outdoor network. The average delay can also be explained by topology. Node 13 is two hops away from the gateway, so its path is longer and experiences more contention delay then other nodes. The high variance found may also raise the average.

4) Throughput

Using IPerf, three types of bandwidth measurements were made, one in each direction to or from the gateway: (1) throughput with two simultaneous bidirectional TCP flows, (2) the same measurements, but with one flow at a time and (3) the same measurements with stressing UDP loads of 10Mbps.



	4	1	11	14	13
Downlink bidirect	3970	1890	773	1157	476
Uplink bidirectional	3789	1925	247	1363	484
Downlink unidirect	3996	2979	1086	1952	1480
Uplink unidirectional	4629	3428	886	1896	1093
Downlink uni UDP	4467	3365	2569	2373	1767
Uplink uni with UDP	4751	3919	2053	2182	2187

Figure 9: Outdoor throughput measured with IPERF.

We can see that simultaneous flows interfere with each other, and their added throughput is always smaller than a single unidirectional flow (although TCP sends acks, which create a secondary backwards flow). UDP flows achieved on average 20% higher throughputs, and in case of node 11, UDP flows achieved more than twice the TCP flows throughput.

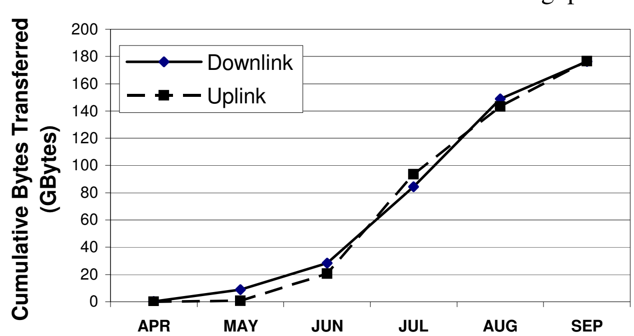


Figure 10: Usage Statistics for the outdoor network.

5) Usage Statistics

The ReMesh outdoor network is being used by student volunteers that get free Internet access. Figure 10 shows the usage statistics reflecting the growth of the network, from the original node installed on top of the UFF's building to the six nodes when the tests were run.

CONCLUSIONS

Community wireless mesh networks are becoming an attractive solution to provide affordable broadband Internet access and services such as ubiquitous computing and VoIP over wireless.

The ReMesh project is meant to be a model that can be replicated throughout Brazil, for the digital inclusion of students and also because it is a low cost alternative for providing Internet access to the underprivileged population. ReMesh has been under test since January 2006. Initial tests with the original OLSR-ETX routing algorithm exhibited high packet loss rates, long delays and frequent route changes. Latter tests with OLSR-ML improved network performance.

This work presented several test results in both an indoor test-bed and an outdoor production wireless mesh network. Performance results over the ReMesh indoor test-bed using the metric developed for this work achieved a reduction of up to 97% in packet loss rate, a decrease of up to 56% in network delay and throughput slightly higher than OLSR-ETX in the indoor test-bed. Further outdoor measurements to gather data on the performance of ETX metric will be made, but require careful planning not to disrupt the production network. Also for future work, we intend to provide QoS (quality of service) provisioning in the ReMesh network. QoS is crucial for offering VoIP services and supporting other multimedia applications over mesh networks.

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