# Using Multiple Metrics with the Optimized Link State Routing Protocol for Wireless Mesh Networks

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***Abstract.*** *Wireless mesh networks (WMNs) can be used in many different applications. However, they lack standards and, as a consequence, a number of issues must still be addressed to ensure the proper functioning of these networks. Amongst these issues, routing is this paper's main concern. Thus, we propose the use of multiple metrics with the proactive Optimized Link State Routing (OLSR) protocol, in order to provide quality of service routing. Even though it has already been proved that routing with multiple metrics is an NP-complete problem, we show how the techniques of Analytic Hierarchy Process (AHP) and Pruning may be combined to perform multiple-metric routing, offering the best available routes based on the considered metrics. A study on the performance of the metrics considered for the proposal is also carried out in the NS simulator.*

## 1. Introduction

Over the years wireless mesh networks (WMNs) have shown their usefulness in different scenarios, especially those where extending already existing networking services is desired but cabling is not a feasible alternative.

As a result, these networks provide a more versatile and inexpensive solution if compared to wired, and even some other wireless, technologies. They became quite popular mainly due to their extended coverage, robustness, self-configuration, easy maintenance and low cost features [Lee et al. 2006].

Some examples of the great utility of WMNs include: to extend the coverage area of enterprises and universities; to reach areas where cabling is somehow difficult due to cost and/or physical obstacles; to provide communications in emergency situations such as earthquakes, fire fighting, and other catastrophes; to provide public Internet access; to operate intelligent transportation systems; and to help in military and rescue operations [Bruno et al. 2005].

However, even though WMNs are considered to be very useful, they still lack standards, and this has resulted in the emergence of many different solutions, proprietary or not, that are not interoperable among themselves. In fact, the IEEE 802.11 working group is investigating proposals which will specify the WMN functionalities, to be incorporated in the IEEE 802.11s standard.

Besides the standardization problem, the problem of WMN routing is also of great interest, and must be carefully addressed to guarantee the proper functioning of WMNs.

Due to these WMN characteristics (dynamic topology, lack of resources as bandwidth, security, and scalability), WMN routing protocols must display the features of self-management, self-configuration, and self-healing [Bruno et al. 2005].

Many different routing protocols have already been proposed. However, these protocols are unable to answer all the needs of this kind of network because each of them was developed to deal with a specific application [Kowalik and Davis 2006].

A number of different approaches have been considered in order to develop WMN routing protocols, including the use of heuristics, a single metric, a single compound metric, a single mixed metric, a composite metric, multiple metrics, and multidimensional metrics [Costa et al. 2002] [Badis et al. 2003] [Aslam et al. 2004] [Alkahtani et al. 2006] [Faccin et al. 2006]. Multiple metrics are of interest to this paper.

This paper's main goal is to use multiple metrics with the proactive Optimized Link State Routing (OLSR) protocol, to guarantee the selection of routes which are composed of good quality links. However, it is worth pointing out that the problem of working with multiple additive/multiplicative metrics in any combination is non-trivial, and turns out to be NP-complete [Wang and Crowcroft 1996] [Badis et al. 2003].

A solution for getting around the NP-complete problem when integrating multiple metrics may be achieved by combining the two techniques known as Analytic Hierarchy Process (AHP) and Pruning. This becomes our secondary goal which is applying these two simple techniques normally used in wired scenarios to a WMN context.

The idea is to use the AHP multi-criteria technique, a methodology of decision analysis developed by [Saaty 1980] to aid in the decision of choosing the best route between a given source and destination. [Alkahtani et al. 2006] proposed a solution which made use of this technique for wired networks with good results. Yet, this solution suffers from great complexity due to the number of matrix computations required to determine the best route. [Alkahtani et al. 2006] suggest changes to the size of the matrices being calculated, which would reduce the number of steps required to determine the best route as well as to reduce this complexity.

There is no need to say that the complexity is even greater in a WMN context, since all nodes might be able to ”sense” all, or most of, the other ones present in the network. As a result, the size of the matrices increases, and that is what we would like to avoid.

So, we introduce a second technique, called Pruning, to be applied before the first AHP step in order to improve AHP's computations. This technique simply gets rid of the paths that are not feasible, that is, those which have qualities exceeding the desired threshold. Both techniques will be detailed in Section 4.

The remainder of this paper is organized as follows. Section 2 presents related work. Section 3 gives a general overview on WMNs, routing protocols, and link quality metrics. Section 4 presents the AHP and Pruning techniques. A case study using simulation is presented in Section 5. Finally, Section 6 presents the conclusions and current work.

## 2. Related Work

This section presents previously published work on matters related to this paper. The following publications provide relevant information on WMNs, defining these networks, showing their applicability, and pointing out important issues currently being investigated.

[Akyildiz et al. 2005] present a detailed study on advances and open research issues related to all protocol layers in WMNs highlighting system architectures, applications, testbeds, commercial practices and related standards activities. Case studies, technical issues and solutions for developing WMNs, as well as an overview on standardization of mesh technology, are presented by [Faccin et al. 2006]. [Held 2005] explores some WMN applications and protocol operations, analyzing problems affecting these networks as well as suggesting solutions for each of them.

An overview on mesh technology is provided by [Bruno et al. 2005] using examples of proprietary and commercial solutions, concepts on which WMNs must be based, and challenges faced by WMN design. Another overview on mesh technology, pointing out some standards which are applicable to the concept of multihop techniques in different wireless networking technologies, is presented in [Lee et al. 2006].

[Nandiraju et al. 2007] discuss challenges slowing down the development of WMNs, showing how each layer of the network could be improved to address such challenges. Finally, [Zhang et al. 2007] point out problems and challenges in designing WMNs, considering a number of important issues, and detailing techniques to improve WMN performance.

Regarding routing, [Clausen and Jacquet 2003] provide important information on the protocol considered in this paper, OLSR. Reasons for the existence of so many different WMN routing protocols are presented in [Kowalik and Davis 2006].

A number of different approaches have been proposed for improving WMN routing, which may simply combine different metrics with OLSR, or create new routing protocols. [Costa et al. 2002] evaluate the use of a single mixed metric and heuristics, compared with the multiple individual metric approach, to speed up routing computations, with the former presenting outstanding results. [Badis et al. 2003] propose a single metric solution to achieve QoS routing. The use of a composite metric for routing improvement is explored in [Aslam et al. 2004]. A new protocol is proposed by [Alkahtani et al. 2006] using a multiple metric approach, while [Faccin et al. 2006] discuss how multidimensional metrics can be used for QoS routing.

The metrics we study in this paper for integration are Expected Transmission Count, Minimum Loss, and Minimum Delay, and these are described in [DeCouto et al. 2003], [Passos et al. 2006], and [Cordeiro et al. 2007], respectively. However, the use of multiple metrics is non-trivial, and [Wang and Crowcroft 1996] prove it turns out to be NP-complete problem. [Saaty 1980] presents one of the techniques considered in this paper to solve the NP-completeness problem, and [Alkahtani et al. 2006] present a routing protocol based on this technique known as Analytic Hierarchy Process (AHP).

A second technique, Pruning, can be used to improve routing computations, when more than one additive/multiplicative metric is considered, and [Costa et al. 2002] describe its use with excellent outcomes.

## 3. Wireless Mesh Networks

WMNs have self-organizing, self-configuring, and self-healing features with easy deployment/maintenance at a very reasonable cost providing high scalability and reliable services as well as improving capacity, connectivity, and resiliency of the already existing network. Due to these characteristics, WMNs have been recognized as a promising technology, which will play an important role in future generations of wireless networks.

These networks are an extension of wireless ad hoc networks [Bruno et al. 2005]. However, protocols and architectures developed for ad hoc networks have a weak performance when applied to WMNs. This is explained by the differences between these two kinds of networks, regarding their applicability, deployment goals and the resource limitations to which they are subjected [Held 2005].

### 3.1. Routing metrics in WMNs

WMNs are a combination of mobile and fixed nodes which communicate through wireless links forming a multi-hop network.

In most cases, WMN nodes are fixed and not battery operated. Thus WMN routing protocols must focus on reliability and performance improvement rather than dealing with mobility or minimizing energy consumption.

Giving the characteristics of the WMN scenario under consideration (fixed nodes and small number of nodes), proactive protocols are more suitable for it [Zhang et al. 2007]. Amongst the proactive protocols, Optimized Link State Routing (OLSR) protocol [Clausen and Jacquet 2003] has been widely used in mesh solutions [Passos et al. 2006].

However, the original OLSR is not quite suitable for WMNs since it does not take into account the link quality while computing routing tables. Instead, it considers the minimum hop count to determine the best path to reach a given destination. This metric, hop count, has been shown not to be at all useful in multi-hop networks [DeCouto et al. 2003]. As a result, researchers started to propose metrics based on what constitutes a good quality link. That is, these metrics reflect the quality of each link, and the routing protocol considers this information when computing its routing tables.

Many proposals have been made to improve WMN routing. The use of heuristics, a single metric, a single compound metric, a single mixed metric, a composite metric and multiple metrics are some of the solutions which have been proposed to create new routing protocols, or simply to be combined with OLSR in order to improve its performance [Costa et al. 2002] [Badis et al. 2003] [Aslam et al. 2004] [Alkahtani et al. 2006].

This paper focuses mainly on the combination of two metrics with OLSR, and evaluates the performance of the ones presented as follows.

#### 3.1.1. Expected transmission count (ETX) [DeCouto et al. 2003]

The goal here is to choose routes with the minimum expected number of transmissions (including retransmissions) a packet will need to be delivered and have its receipt acknowledged. Consequently, the selected routes have high throughput. The main advantage is that probe packets are broadcast, which results in reduced probing overhead. The main disadvantage resides in the fact that the probe packets are small and are sent at the lowest data rate possible, and tend not to suffer the same loss rate as larger data packets sent at higher data rates.

#### 3.1.2. Minimum loss (ML) [Passos et al. 2006]

This is based on ETX, with the aim of selecting the path with the minimum loss probability. It uses the probability of successful transmissions, and not the inverse probability, as in ETX. Another difference is related to a route composed of two or more links. The route probability is given by the product of the link probabilities instead of the sum of their inverse probabilities. It has the advantage of eliminating high loss rate routes, and the disadvantage that some low quality links may still be taken into account in choosing a given route, since the metric considers only the total probability product.

#### 3.1.3. Minimum Delay (MD) [Cordeiro et al. 2007]

The routing table computation is based on the total minimum transmission delay. The transmission delay measurements come from a variant of a link capacity estimation technique, known as Adhoc Probe. The use of the Adhoc Probe technique is a great advantage, because it takes into account differences in clock synchronization, thus providing a more reliable measurement. A disadvantage is that this metric considers routes which have nodes sharing a collision domain with many others, and this tends to degrade the communication on such routes.

It is worth pointing out that, for this proposal, we only considered metrics that are frequently discussed on the available related researches such as ETX. Since we have proposed another metric, MD, we decided to simulate it along with ETX and ML in order to determine the two metrics to be considered for the proposal.

## 4. Techniques for Combining Multiple Metrics with OLSR

It has been proved that the selection of routes based on the combination of additive and/or multiplicative metrics is NP-complete [Wang and Crowcroft 1996] [Badis et al. 2003].

However, there is a technique which can be used to get around the NP-completeness of the use of multiple metrics, known as Analytic Hierarchy Process. Thus, a secondary goal of this proposal is to combine another technique, called Pruning, to AHP in order to reduce its complexity still offering routes based on the best link qualities available at the moment.

This section is intended to present what these techniques are and how they work.

### 4.1. Analytic Hierarchy Process (AHP) [Saaty 1980]

AHP is widely known in the field of decision making, when different qualitative and/or quantitative criteria must be applied. A number of applications already make use of this methodology, in fields such as telecommunications and the provision of health services.

By making small changes to the methodology, [Alkahtani et al. 2006] proposed a routing protocol which takes different metrics into account, when deciding the best route to a given destination. The goal was to provide support for multimedia applications which are characterized by multiple Quality of Service (QoS) requirements.

To illustrate the approach proposed by [Alkahtani et al. 2006], we apply it to the network in Figure 1 shown below. It is worth pointing out that this network is a small WMN where every node may have a link to every other one unless they are too far apart. Every link has two metrics: ETX and MD, for this example. Finally, we assume we wish to set up a connection between nodes 1 and 4.

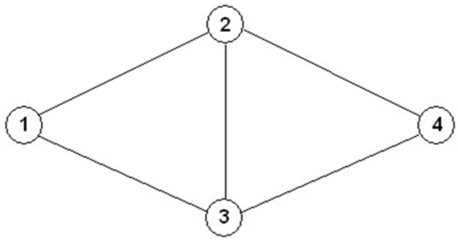



**Figure 1. Example of a small network**

Step 1: First, we need to find all possible routes between nodes 1 and 4. Table 1 shows each possible path along with its respective overall values of ETX and MD. Further information for these metrics can be found in [DeCouto et al. 2003] and [Cordeiro et al. 2007], respectively.

**Table 1. Possible paths**

| Paths | A | B | C | D |
|---|---|---|---|---|
| Links | 124 | 134 | 1234 | 1324 |
| ETX | 2.19 | 2.25 | 3.23 | 3.45 |
| MD | 1.01 | 0.20 | 0.51 | 1.40 |

Step 2: The computation of the path-path pair-wise comparison matrix (ppcm) for each metric is carried out to determine how well each path is scored for each metric compared to the other paths. [Alkahtani et al. 2006] define three criteria: *min* - metrics to be minimized (i.e. delay), *max* - metrics to be maximized (i.e. bandwidth), and *bin* - binary nature metrics (i.e. link security - 1: secure, 0: insecure). Since ETX and MD are quantitative metrics which need to be minimized, the matrix calculation is based on the following equations. Here *i* and *j* are paths, and $m_j$ is the overall value of the metric for path$_j$:

- $ppcm(i, i) = 1$, when comparing the same path;
- $ppcm(j, i) = 1/ppcm(i, j)$, for reciprocal paths; and
- $ppcm(i, j) = m_j/m_i$, for *min* criterion.

As an example, the ppcm for ETX is given by:

$$ppcm(ETX) = \begin{bmatrix} 1 & 1.027 & 1.475 & 1.575 \\ 0.973 & 1 & 1.436 & 1.533 \\ 0.678 & 0.697 & 1 & 1.068 \\ 0.635 & 0.652 & 0.936 & 1 \end{bmatrix}$$

Step 3: The normalized path-path pair-wise comparison matrix (nppcm) is calculated, based on the following equation with *i* and *j* = 1, .., *P*, where *P* is the number of paths (four in this example):

$$nppcm(i, j) = ppcm(i, j)/\Sigma ppcm\_column(j)$$

As a result:

$$nppcm(ETX) = \begin{bmatrix} 0.3043 & 0.3043 & 0.3043 & 0.3043 \\ 0.2962 & 0.2962 & 0.2962 & 0.2962 \\ 0.2063 & 0.2063 & 0.2063 & 0.2063 \\ 0.1932 & 0.1932 & 0.1932 & 0.1932 \end{bmatrix}$$

Step 4: The average normalized path-path pair-wise comparison matrix (anppcm) is calculated, based on the following equation:

$$anppcm(i) = \Sigma nppcm\_row(i)/P$$

The anppcm matrix is [*n* x *P*] where *n* is the number of metrics and *P* is the number of paths. The anppcm for ETX is:

$$anppcm(ETX) = \begin{bmatrix} 0.3043 & 0.2962 & 0.2063 & 0.1932 \end{bmatrix}$$

Steps 2 - 4 must be carried out for every metric. And as result, the complete anppcm is showed below. It is worth mentioning that each line of this matrix refer to the metrics ETX and MD, respectively.

$$anppcm = \begin{bmatrix} 0.3043 & 0.2962 & 0.2063 & 0.1932 \\ 0.1143 & 0.5770 & 0.2263 & 0.0824 \end{bmatrix}$$

Step 5: The average normalized priority pair-wise comparison matrix (anprpcm) is calculated to determine the relative importance of each metric compared with the other metrics. For the original AHP, an absolute number is given to each metric, based on the decision maker's feelings. Then Steps 2 - 4 are performed to find the anprpcm. Another modification proposed by [Alkahtani et al. 2006] is that these metrics are assigned weights directly in the range [0, 1] where the sum of all weights is equal to one, as presented in the matrix below.

$$anprpcm = \begin{bmatrix} 0.5 & 0.5 \end{bmatrix}$$

Step 6: Select the required priority of metrics, if more than one priority is set. In this example, the priority set is 0.5 for both ETX and MD, since priority is not considered for this paper.

Step 7: Calculation of the total score for each path, Table 2, through the equation:

$$Path_j\ score = \sum_{i=1}^{n}(anprpcm[i] \times anppcm[i,j]),\ j = 1, ..., P$$

**Table 2. Total scores for each path**

| Paths | A | B | C | D |
|---|---|---|---|---|
| Total Score | 0.2093 | 0.4366 | 0.2163 | 0.1378 |

Step 8: Select the path with the maximum total score to be used in the communication between nodes 1 and 4. As it can be seen, path B is the one that has the best link quality overall.

To reduce the number of matrix computations, it would be enough to make ppcm and nppcm be P x 1 matrices instead of P x P, since the columns of the P x P nppcm have the same values. Thus, Step 5 would be eliminated.

This technique is a very interesting approach to get around the NP-completeness problem of using multiple metrics for routing.

However, if the WMN is quite large, there may be a large number of possible paths between a source and destination, due to the fact that each node may ”hear” a major part of, if not all, the surrounding nodes. This situation will result in a large number of calculations in order to obtain just ppcm and nppcm. To combat this, we adopt another technique, Pruning.

### 4.2. Pruning

This technique has been applied to many different applications in order to improve their performance [Costa et al. 2002].

It consists of eliminating links which have quality values greater than or equal to a given threshold. To determine this threshold, we need to know both the network and the functioning of the metrics used in this scenario. For this proposal, we calculate the threshold through the median of ETX values of the links, discarding links with values above this threshold since ETX is to be minimized.

In the previous example, path D in Table 1 would not even be determined since one of its links has the highest values for the ETX and MD metrics. By doing this, the number of possible paths calculated between the source and destination can be reduced, improving even more the performance of the AHP technique.

## 5. Case Study

In this section we present the scenario used in carrying out simulations, and how the routing metrics were chosen.

### 5.1. Scenario

The simulations attempted to reproduce the behavior of the metrics to be used in the routing protocol for a WMN backbone at the main campus of the Federal University of Pará, in Belém, Pará state, Brazil. This campus is located by the Guamá river within a large wooded area, and and contains many buildings separated by parking areas. Figure 2 shows the WMN scenario under consideration.


**Figure 2. Federal University of Pará Campus**

Since this scenario happens to be in a tropical region, deploying an outdoor wireless network is rather challenging due to sometimes heavy rain and the number of trees present in the area.

### 5.2. Metrics used

To decide which metrics were to be used for routing, simulations were run to determine the metrics' performance in the aforementioned scenario. These simulations were carried out on Network Simulator 2.31 [NS 2007] using different seeds for the random number generator. A confidence interval of 95% was considered for the calculations according to [Jain 1991]. Each simulation was run for 50 seconds and repeated 10 times.

The two metrics with the best overall performance would be considered for the routing protocol. To show that the real scenario and equipments were closely represented in the simulation, some variables were chosen, as shown in Table 3.

It is worth pointing out that the values of Path Loss Exponent and Shadowing Deviation could have been obtained directly from the NS manual [NS 2007]. However, the values used here were obtained from field measurements carried out at each of the ten points as shown in Figure 2. Using a notebook computer running the NetStumbler[1]

[1] http://www.netstumbler.com/

**Table 3. Simulation Parameters**

| Parameters | Values |
|---|---|
| IEEE Standard | 802.11b |
| Propagation Model | Shadowing |
| Antennas | Omnidirectional, 18dB gain |
| Router's Carrier Sense Threshold | -76dBm [IEEE 1999] |
| Router's Receiver Sensitivity | -80dBm [IEEE 1999] |
| Router's Transmit Power | 17dBm (WRT54G) |
| Frequency | 2.422GHz (Channel 3) |
| Path Loss Exponent | 1.59 |
| Shadowing Deviation | 5.4dB |

software with a GPS device attached to it, measurements took place at each point, as illustrated in Figure 3 for the Capacit point and discussed below.

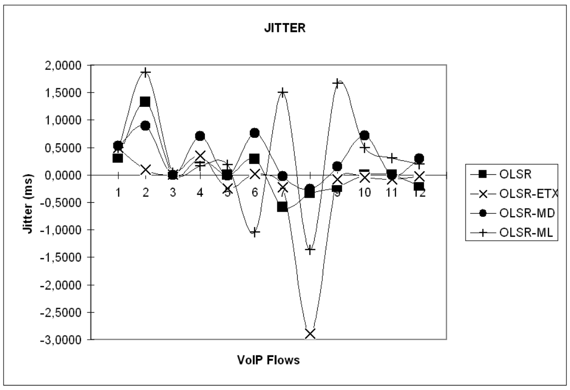

**Figure 3. Paths taken for data gathering**

At each point, data was collected in eight different ways starting close to the point and moving away from it until a signal level of -85 dB was reached. The directions of measurement took into account the position of the point in regards to other neighboring points. Once the measurements had been carried out, a final value was attributed to each variable by calculating the average based on the data collected at each point.

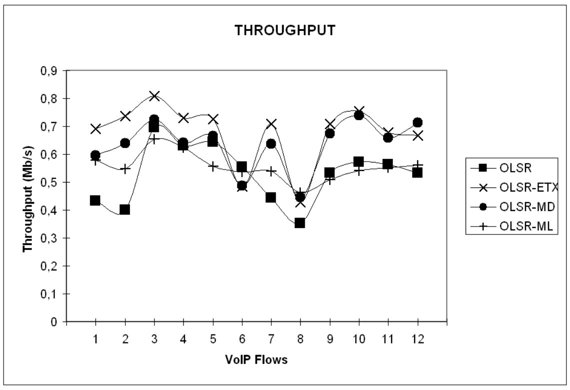
In the simulator, a total of six Voice over Internet Protocol (VoIP) calls and three background Paretto traffic flows were simulated. These calls involved the following points: Capacit/Graduação Profissional, Reitoria/Capacit, Reitoria/CT, DI/CT, Secom/Laboratório, and DI/Secom, and the points with background traffic were: DI/Laboratórios, Graduação Básico/CT, e Secom/Graduação Profissional. For each of the metrics, jitter, delay, blocking probability and throughput were calculated, and are shown in Figure 4. Since a VoIP call is bidirectional, each call is represented by two flows. The same indicators were also calculated for the original OLSR, which uses hop count as a metric. These points were selected so that the communication between them happened through three hops at most and nodes really competed for the wireless medium.

For jitter, OLSR-ML had the highest variation amongst the metrics, as can be seen in Figure 4a. OLSR-ETX and OLSR-MD had the best performance in regards to throughput as shown in Figure 4b.

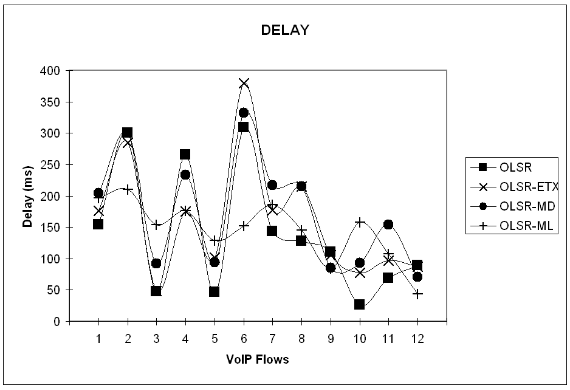
In Figure 4c, OLSR-ML had the best performance amongst the metrics, but its values still are not considered appropriate for VoIP calls. This high-delay behavior is explained by the number of different flows attempting to use wireless medium in the simulations. It is important to mention that, during the calls, the protocol was still computing its routing tables during the beginning of the VoIP calls. This was done on purpose, in order to determine the performance of each metric in the worst-case scenario. As for the blocking probability, Figure 4d, OLSR-ML also had the highest values.



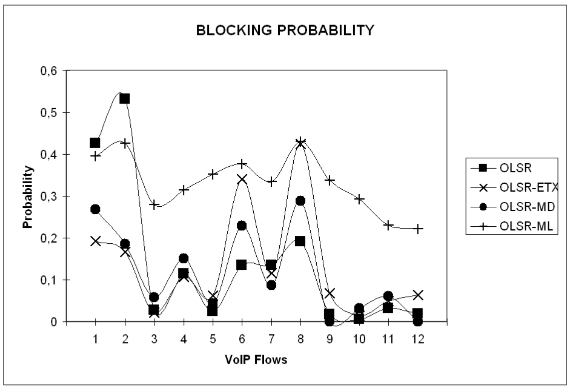

(a) Jitter per VoIP flow




(b) Throughput per VoIP flow




(c) Delay per VoIP flow




(d) Block Probability per VoIP flow

**Figure 4. Results obtained from the simulations**

It is important to remember that the main goal here is to choose the metrics with the best performances in the scenario under consideration to be used in the proposal. Original OLSR was simulated only for comparison purposes. Even having performed better for some flows than the other metrics, it was not considered for use in WMN routing, since it is widely known that it does not take into account the quality of a given link. Instead, it uses the shortest path approach, that is, the minimum number of hops between a given source and destination. And that is not useful in a mesh network context [Faccin et al. 2006].

From the results, the metrics ETX and MD had the best overall performance for the considered scenario, and thus they were chosen for use with OLSR to improve its routing table computations.

## 5.3. A Practical Example

For the following practical example, consider the scenario presented in Figure 2. As the mesh network simulated high-gain antennas, every node is able to "sense" all the other nodes despite the distance between them. It is important to point out that this is not a problem since every routing decision is made considering the link qualities, ETX and MD.

Table 4 shows the routing table of each node in the network with the metrics' values for every link towards all other nodes at a given time.

**Table 4. Nodes and their respective routing tables**

| Node 0 | | | Node 1 | | | Node 2 | | | Node 3 | | | Node 4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Dest | ETX | MD | Dest | ETX | MD | Dest | ETX | MD | Dest | ETX | MD | Dest | ETX | MD |
| 1 | 1.5873 | 0.658136 | 0 | 1,5873 | 0,018508 | 0 | 1,7857 | 0.647492 | 0 | 2.0408 | 0.016017 | 0 | ***2.7778*** | *0.015599* |
| 2 | 1.7857 | 0.658136 | 2 | 1.1111 | 0.016834 | 1 | 1.1111 | 0.647492 | 1 | 1.2500 | 0.016017 | 1 | 1.8519 | 0.015599 |
| 3 | 2.0408 | 0.268625 | 3 | 1.2500 | 0.018508 | 3 | 1.3889 | 0.264523 | 2 | 1.3889 | 0.016017 | 2 | 1.3889 | 0.015599 |
| 4 | 2.7778 | 0.268625 | 4 | 1.8519 | 0.018508 | 4 | 1.3889 | 0.647492 | 4 | 1.7857 | 0.016017 | 3 | 1.7857 | 0.015599 |
| 5 | ***2.8571*** | *0.658136* | 5 | ***2.7778*** | *0.018508* | 5 | ***2.2222*** | *1.605214* | 5 | ***2.7778*** | *0.016017* | 5 | 2.2222 | 0.015599 |
| 6 | *3.1250* | *0.268625* | 6 | *2.8571* | *0.018508* | 6 | *2.5000* | *0.647492* | 6 | *2.8571* | *10.000000* | 6 | *2.8571* | *0.015599* |
| 7 | *3.3300* | *0.268625* | 7 | *3.1250* | *0.018508* | 7 | *2.7778* | *0.647492* | 7 | *3.7037* | *10.000000* | 7 | *3.7037* | *0.015599* |
| 8 | *4.1667* | *1.605298* | 8 | *3.3300* | *4.007866* | 8 | *2.8571* | *1.605214* | 8 | *4.7619* | *0.016017* | 8 | *4.7619* | *0.015599* |
| 9 | *4.7619* | *0.268625* | 9 | *3.3300* | *10.000000* | 9 | *4.7619* | *0.647492* | 9 | *4.1667* | *0.016017* | 9 | *8.3333* | *10.000000* |

| Node 5 | | | Node 6 | | | Node 7 | | | Node 8 | | | Node 9 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Dest | ETX | MD | Dest | ETX | MD | Dest | ETX | MD | Dest | ETX | MD | Dest | ETX | MD |
| 0 | *2.8571* | *0.647470* | 0 | *3.1250* | *0.010764* | 0 | *3.3300* | *10.000000* | 0 | *4.1667* | *0.029616* | 0 | *4.7619* | *1.607991* |
| 1 | *2.7778* | *0.647470* | 1 | *2.8571* | *0.010764* | 1 | *3.1250* | *0.016015* | 1 | *3.3300* | *4.007866* | 1 | ***3.3300*** | *0.050315* |
| 2 | ***2.2222*** | *0.647470* | 2 | ***2.5000*** | *0.010764* | 2 | ***2.7778*** | *0.016015* | 2 | ***2.8571*** | *0.029616* | 2 | *4.7619* | *10.000000* |
| 3 | *2.7778* | *0.647470* | 3 | *2.8571* | *0.011802* | 3 | *3.7037* | *10.000000* | 3 | *4.7619* | *4.007866* | 3 | *4.1667* | *0.050315* |
| 4 | *2.2222* | *0.647470* | 4 | *2.8571* | *0.013005* | 4 | *3.7037* | *0.016015* | 4 | *4.7619* | *0.029616* | 4 | *8.3333* | *4.010439* |
| 6 | 1.1111 | 0.647470 | 5 | 1.1111 | 0.010764 | 5 | 1.3889 | 0.016015 | 5 | 1.8519 | 0.029616 | 5 | 2.0833 | 0.026158 |
| 7 | 1.3889 | 0.647470 | 7 | 1.2500 | 0.013005 | 6 | 1.2500 | 0.016015 | 6 | 1.7857 | 0.029616 | 6 | 1.8519 | 0.050315 |
| 8 | 1.8519 | 1.605250 | 8 | 1.7857 | 0.010764 | 8 | 1.2346 | 0.016015 | 7 | 1.2346 | 0.029616 | 7 | 1.3889 | 0.050315 |
| 9 | 2.0833 | 0.647470 | 9 | 1.8519 | 0.010764 | 9 | 1.3889 | 0.016015 | 9 | 1.1111 | 0.018973 | 8 | 1.1111 | 0.026158 |

Firstly, Pruning is applied to get rid of links of unsatisfactory quality, and the metric considered was ETX. To do this, the median is calculated and links with ETX values equal to or greater than the median are pruned since this metric is to be minimized. We could also consider MD for pruning threshold calculation since we are not prioritizing any of these metrics as in [Saaty 1980]. In Table 4, the median is in bold digits and the pruned links' values are in italics.

As the first step of the AHP solution requires all possible routes to be found, Pruning becomes very important. Dijkstra's algorithm [Cormen et al. 2001] can be run to find all these paths. Without Pruning, a total of 48.929 possible paths were found, whilst with this technique the number of paths was reduced to 256. Thus, the goal of reducing the computational complexity mentioned earlier is achieved.

Both metrics, ETX and MD, make use of Dijkstra's algorithm to determine the best route, that is, the one with the least cost among the possible routes found. For this example, we wish to determine to best route between nodes 0 and 9. The best route, through nodes 0 - 4 - 5 - 9, ended up to be the same for both ETX (7.0833) and MD (0.931694).

Since this proposal aims to select routes which combine the best quality values of the considered metrics, after the application of AHP and Pruning the best selected route should be the same as for ETX/MD or another one even better. It is important to point out that even though ETX was considered for Pruning, priority of metrics was not taken into account and anprpcm in Step 5 remained unchanged. So, applying the remaining steps of the solution in [Alkahtani et al. 2006], the route obtained was also through nodes 0 - 4 - 5 - 9 with a maximum total score of 0.0066343. Hence, we also attain the goal of combining multiple metrics with OLSR in order to provide selection of the best route.

## 6. Conclusions and Current Work

The main goal of this paper was to provide QoS routing for Wireless Mesh Networks through the application two simple techniques, Analytic Hierarchy Process and Pruning, normally used in wired scenarios, and that together may improve OLSR's performance through the usage of multiple metrics.

Although the solution presented by [Alkahtani et al. 2006] was proposed for a wired scenario, it does have great potential for application in a wireless network context. However, the complexity of this solution may be high, due to the many matrix computations which are a result of the number of possible paths between a source and destination. In WMNs, this complexity may become even greater, since most, or even all, of the nodes are able to "sense" the other ones present in the network.

With that in mind, the Pruning technique comes into play to lessen the number of matrix computations, and thus reducing even more the complexity of the solution presented in [Alkahtani et al. 2006]. By applying Pruning, links with metric values that are greater than or equal to a certain threshold will not be taken into account, and as a result less computation will be needed. [Costa et al. 2002] successfully applied this technique, which really improved their results.

Unlike only having improvements either on throughput or transmission delay, when only a single metric is used for routing, this proposal guarantees improvements based on both metrics at the same time, using the already known techniques of AHP and Pruning, which together enhance OLSR's route selection.

Currently, efforts are being undertaken to conclude the NS-module implementation of the proposal presented here, which will make it possible to really evaluate its performance.

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