Multicriteria QoS-aware Solution in Wireless Multi-hop Networks

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***Abstract*—Ad-hoc Wireless Networks provide a major base for ubiquitous computing development. In such networks, the communication occurs by multiple hops in a shared medium. In order to meet the different requirements of the applications, routing solutions aware of Quality of Service (QoS) have been developing. However, single-criterion strategies are unable to cope with conflicting objectives that commonly appear in these networks. This work proposes a multicriteria approach that considers End-to-End Delay (E2ED) and Packet Delivery Probability (PDP) as vital criteria in the route discovery process. For this purpose, Optimized Link State Routing Protocol (OLSR) with a modified Dijkstra algorithm is applied, wherein the bi-objective problem is transformed into a mono-objective problem through the epsilon-constraint technique. Extensive simulations have demonstrated that the multicriteria method can provide efficient routing in mobile environments, and it has outperformed the best results of single-criterion methods in terms of Packet Loss Ratio (PLR) by nearly 5 - 35 %. The results also have shown the potential of the model in finding a proper trade-off in relation to the number of hops and End-to-End Delay.**

***Keywords*–Multicriteria optimization; Mobile Ad-Hoc Networks; Quality of Service.**

I. Introduction

The spread of mobile services has boosted the advance of wireless networks. Such growth has demanded endeavors to provide Quality of Service (QoS) and to ensure that the network resources are spent as fairly as possible. In fact, the proper provision of quality enables the wireless technology to be used when limited or no infrastructure is available [1]. In this context, Mobile Ad-Hoc Networks (MANETs) are representative as they have particularly worthwhile features. First, mobile wireless devices are able to communicate each other without relying on a fixed infrastructure. Second, messages can be exchanged collaboratively provided that devices are able to operate as both router and host. Third, the varying mobility patterns and the low deployment cost are factors that can promote the emergence of new applications [2].

Among several relevant problems in MANETs, routing issue is one of the most challenging. In recent years, efforts have been directed at proposing new or reformed protocols to address varied scenarios, from mesh networks to underwater networks [1]. Up to now, there is no routing protocol that provides a proper performance in any scenario [3].

Furthermore, applications can have conflicting quality requirements, which indicates the need to optimize opposing objectives. For example, elastic applications, as file transfer programs, demand reliable and stable links. On the other hand, real-time applications, as voice over IP, are extremely sensitive to delay. As a glimpse, regarding the elastic applications, it would make sense to minimize the Packet Loss Ratio (PLR), while for real-time applications, it would be fitting to minimize the End-to-End Delay (E2ED) [3][4]. Future standardized routing mechanisms will possibly follow the trend towards more flexible support to the multiple QoS requirements [3]. Hence, it becomes vital to take into account the performance trade-offs in the route discovery process [5][6][7][8].

The aim of this paper is twofold. First, the need to take decisions bearing in mind multiple criteria in ad-hoc networks is demonstrated. For that, two traditional QoS-aware metrics were considered, wherein one is applied to minimize E2ED and the other one is utilized to maximize the reliability of packet delivery. Second, in order to arrange both metrics in the route discovery process, the employment of the well-known scalar epsilon-constraint method [9][10][11] is proposed. The idea is to turn one of the metrics into a constraint in the optimization model. As such, the route discovery problem was modeled as a Constrained Shortest Path Problem (CSPP) [12]. A modified Dijkstra's algorithm was used as the solver. The routing protocol utilized was the OLSR [13]. In addition, the selection process of the MultiPoint Relays (MPR) was adjusted in order to consider both metrics. The hypothesis is that the multicriteria approach can achieve better results when recognizing the trade-off between E2ED and PLR.

The proposal was compared to single-criterion solutions in a Wireless Multi-hop Network with different node speeds via OMNET++ simulator. Summarily, our solution has reached consistent reductions in PLR. Moreover, when comparing to the single-criterion Minimum Packet Loss (MPL) metric, our solution has obtained routes with a lower average number of hops, which also has promoted a decrease in E2ED. Accordingly, our proposal improves the link reliability, without generating prohibitive delays.

The remainder of this paper is organized as follows. Section II presents the related works and the motivation. Section III introduces the multicriteria optimization problem and presents the suggested mathematical model. Section IV provides the simulation parameters and investigates the results by comparing the single-criterion OLSR implementation with the multicriteria one. Section VI shows the conclusions and future works.

II. Related work and motivation

A MANET network is composed of self-organized and self-manageable devices distributed in a given area [1]. In addition, messages can be transmitted by multiple hops, that is, the nodes provide support to the network, playing the role of relays. Therefore, whenever nodes want to "talk" each other, routes must be established. Routing protocols are in charge of defining rules and procedures to provide such routes [2]. However, because of shared medium, interferences and mobility, links can be constantly broken and frequently rebuilt. Due to these instabilities, typical from a wireless environment, it has been a challenge to make feasible the use of applications which are sensitive to high delay, limited bandwidth, and recurrent packet losses [3]. In order to address these issues and, furthermore, meeting the requirements of new applications and kinds of MANET networks, QoS-aware routing solutions have emerged [4].

Table I shows distinct quality requirements related to the main applications that can be made available in a network. Indeed, forthcoming MANETs will have to deal with a particular set of constraints in view of the current exigencies of performance. Therefore, providing QoS guarantees for different services is essential to the development and deployment of future wireless multi-hop networks [4][14].

TABLE I. QOS REQUIREMENTS OF MAIN APPLICATIONS. ADAPTED FROM [14]

Applications	*Bandwidth*	*Sensibility to Delay*	*Packet Delivery Ratio*
Elastic (FTP, Email)	Low	Low	High
Voice over IP	Low	High	Medium
Videoconference	High	High	Medium
Streaming audio	Low	Medium	Medium
Streaming VoD	High	Medium	Medium

Standardized protocols, such as OLSR (Optimized Link State Routing) and AODV (Ad-hoc On-demand Distance Vector), do not resort to any QoS parameter when building the routes. Both work with an elementary *hop-count* metric. While OLSR uses *hop-count* to evaluate the shortest path [13], AODV verifies *hop-count* to update routing table entries [15]. Given the need, there is a move in the direction of proposing new and reformed protocols that are QoS-aware [2][4].

Nevertheless, just including a single QoS metric in the routing protocol is not enough to offer solutions that cover each scenario, precisely because the QoS provision changes according to the application or the network status. Furthermore, one application may need the guarantee of several metrics simultaneously. If these metrics are conflicting, it is necessary to yield solutions that reach a trade-off between them [3].

The authors in [16] identify a diversity of possible requirements to be addressed in a MANET, such as: minimizing hop-count, minimizing delay, maximizing data delivery, minimizing energy consumption, minimizing computational overhead, maximizing route stability, balancing traffic load, among others. The work also relates these requirements to the main link evaluation metrics and points out the associated performance trade-offs. In [17], the authors advance in the analysis by demonstrating the conflicting performances between some QoS-aware metrics as: Minimum Delay (MD) and Minimum Packet Loss (MPL). However, in both works, multiple metrics are not employed.

The reason of satisfying conflicting requirements has been deeply studied in fields as decision theory and operations research. The goal is to make effective decisions by pondering the criteria through an optimization process [11]. Recently, multicriteria optimization on ad-hoc networks has been drawing attention as a tool to design routing protocols that deal with more than one QoS parameter. Although it is still an open-field, multicriteria optimization can be a valuable alternative in search for robust and adaptive solutions that fit in distinct scenarios [4].

In spite of the diverse multicriteria optimization techniques available, varying from sophisticated evolutionary algorithms to outranking methods, the applicability in ad-hoc networks is restricted to simple approaches [11]. Indeed, since mobile devices have limited processing and power resources, the method needs to run as fast as possible [9].

Considering an opportunistic route discovery process in Mobile Ad-hoc Networks, the authors in [18] propose to incorporate some context criteria, such as signal quality, geographic progress, and node residual energy, when evaluating the link quality. A weight is assigned to each criterion, composing the measure called Dynamic Forwarding Delay (DFD). In [19], the weighted sum method is used in order to minimize the delay and maximize the throughput in Static Wireless Mesh Networks.

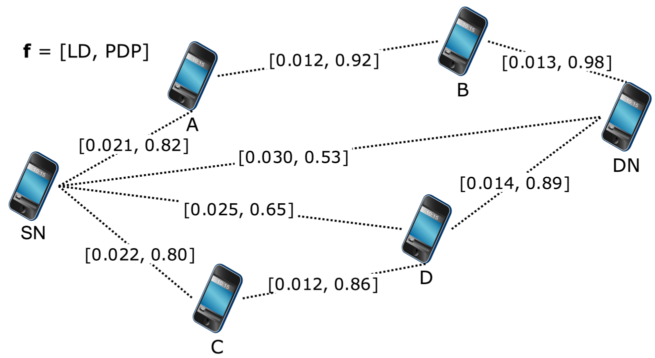
The research presented in [5] proposes, for proactive routing in MANETs, a composite-additive utility function that employs normalized weights for two metrics: delay and energy. Likewise, in [6] is introduced a solution driven by battery and queue metrics, taking a normalized weighted additive utility function as QoS metric. Both solutions utilize OLSR as the base protocol.

In [7], two metrics for route selection in Multi-hop Wireless Ad-hoc Networks are derived, namely, Secrecy Outage Probability (SOP) and Connection Outage Probability (COP). The former is concerned with to meet security requirements and the latter seeks to address the different QoS requirements. The route selection algorithm uses a control parameter β to adjust the weights in terms of priority of each metric.

The authors in [8] investigate the trade-off between energy consumption and end-to-end delay when selecting clusterheads in Wireless Sensor Networks. The choice of clusterhead is made by means of a weighted metric where the weights α and β indicate the importance of energy consumption and end-to-end delay, respectively. In addition, a Depth-First Search (DFS) algorithm is proposed to calculate the number of probable routes from clusterhead nodes to the sink node considering an end-to-end delay constraint Δ.

As one can see, the weighted sum method is the most used approach for dealing with more than one criteria in the optimization process related to Wireless Multi-hop Ad-hoc Networks. Although it is easy to implement, this method has some drawbacks. First, fine-tuning of weights is by itself an optimization problem that implies generating and evaluating several weight distributions in order to model each scenario. It means that when one does not have *a priori* preferences, an excessive computational processing can be required to obtain a representative weights distribution [9][11]. Second, distributed uniformly weights do not ensure a uniform distribution of points on the Pareto front. Third, these methods are unable to reach points in non-convex regions of the Pareto front [3].

In [20] is proposed a hybrid routing algorithm which combines Cellular Automata (CA) with Genetic Algorithm (GA) in Mobile Ad-Hoc Networks, wherein energy and delay are considered restrictions in the model rather than metrics to be weighted. Although the deployment of metaheuristics for



	Route	E2ED (s) $\sum$	PDP (%) $\prod$
1	SN -> A -> B -> DN	0.046	75
2	SN -> DN	0.027	53
3	SN -> D -> DN	0.039	58
4	SN -> C -> D -> DN	0.041	61

Figure 1. Multicriteria ad-hoc wireless network

solving the MANET routing problem has gained remarkable relevance in the last years [21][22], its viability is still unclear when applying in very dynamic environments. That is because such stochastic methods can spend much time to reach a satisfactory solution since the optimization process depends on an iterative search which involves repeated execution of the algorithm [3]. Hence, research works have given preference to scalar techniques.

This paper develops a mathematical model that applies the epsilon-constraint scalar technique in order to minimize the E2ED, transforming the PDP into a link constraint. This strategy, besides being able to reach non-convex regions of the Pareto front, can generate points in specific regions that meet the demand of underlying network [9][10][11]. That is, when we have a reasonable clarity about the level of quality to be reached regarding a given metric, this technique can be more effective in achieving such point. Even though the model foresees more than two metrics, one can work with a single metric as the objective function and the remaining ones as restrictions. However, these constraints need to be defined accurately, otherwise, there is the risk of rendering the model unfeasible. In fact, when this is uncertain, finding proper constraint for one metric can be as difficult as to find well-suited weights for several path selection metrics. In this case, one can resort to the underlying layers to define such constraints [3], as summarized in Table I.

Apart from demonstrating the associated trade-off between the two QoS-aware metrics, our proposal presents a feasible alternative to achieve a better compromise related to conflicting metrics in a mobile network.

III. QoS MULTICRITERIA SUPPORT IN MANETs WITH THE EPSILON-CONSTRAINT METHOD

In this section, the mathematical formulation and the description of the proposed multicriteria routing optimization method are presented.

A. Mathematical modeling

An Ad-hoc Wireless Network can be defined as a directed graph $G(V, E)$, where the vertices $V = \{v_1, v_2, \ldots, v_n\}$ describe a finite set of nodes, and the edges $E = \{e_1, e_2, \ldots, e_m\}$ yield a finite set of links that connect these nodes. A node subset $N_{(v_i)} \subset V$ is established within the coverage area of each node v_i, producing a neighborhood that draws the network topology. In transmission context, there is also a destination node $DN \subset V$ and a source node $SN \subset V$. Each link e_k, $k = [1, \ldots, m]$, has an associated cost of packet transmission w_{e_k} from v_i to v_j. If necessary, a subset F of relay nodes are elected from the neighborhood based on the cost, in order to build a route $R_{SN,DN} = (SN, F_1, \ldots, F_n, DN) \subset V$ that connects SN to DN. Figure 1 can be considered a handy and simple example of a Wireless Multi-hop Ad-hoc Network drawn by means of the OLSR protocol.

In this paper, the cost is not composed of only one value. Thereby, as a multiobjective problem, it must be represented by a vector $\mathbf{f} : \mathbb{B}^m \rightarrow \mathbb{R}^k$, wherein each item denotes a function to be optimized. In general, a minimization problem with multiple objectives can be defined as

$$\begin{aligned} \min_{\mathbf{x}} \quad & [f_1(\mathbf{x}), f_2(\mathbf{x}), ..., f_k(\mathbf{x})] \\ \text{s.t.} \quad & \mathbf{x} \in S, \end{aligned} \tag{1}$$

where k is the number of objectives, S is the feasible decision space, $\mathbf{x}$ is the decision variable vector, and $f_i(\mathbf{x})$ describes the scalar value of the i-th objective. A decision vector $\hat{\mathbf{x}} \in S$ belongs to the Pareto-optimal set if there is no other decision vector $\mathbf{x} \in S$ such that $f_i(\mathbf{x}) \leq f_i(\hat{\mathbf{x}})$, for all i; and $f_i(\mathbf{x}) \neq f_i(\hat{\mathbf{x}})$ for at least one $i = \{1, \ldots, k\}$ [11].

As can be seen in Figure 1, two criteria are pondered to optimize the path considering the following objectives: I) minimize the E2ED and, II) maximize the reliability of packet delivery. The latter can be seen as: minimize the PLR. Thus, link QoS is represented by a vector $\mathbf{f}$ containing two metrics: Link Delay (LD) and Packet Delivery Probability (PDP). The objective functions are given as follow:

$$\begin{aligned} f_1 = f_{E2ED} &= \sum_{(v_i,v_j) \in E} LD_{(i,j)} \times x_{i,j} \\ f_2 = f_{PDP} &= \prod_{(v_i,v_j) \in E} PDP_{(i,j)} \times x_{i,j} \end{aligned} \tag{2}$$

The decision variable $x_{i,j}$ is 1 when the node $j \in N(v_i)$ belongs to the route. Otherwise, $x_{i,j}$ is 0. The Link Delay measurement is estimated using the AdHoc Probe algorithm [23]. This algorithm uses a pair of packets to measure the dispersion between them. Thus, in a route from SN to DN, having D as the relay node, f_{E2ED} is given by:

$$E2ED_{(SN \rightarrow DN)} = LD_{(SN \rightarrow D)} + LD_{(D \rightarrow DN)} \tag{3}$$

Details of calculating the LD metric can be found in [17][23][24]. In Figure 1, if only LD was employed in the optimization, the route 2 ($SN \rightarrow DN$) would be chosen, in spite of lower PDP.

The second function aims to maximize reliability in packet delivery and, consequently, reducing the PLR. This function is given below

$$PDP_{AB} = d_f \times d_r \quad (4)$$

where d_f and d_r are the forward and the reverse delivery ratios, respectively. The product between them is the probability of successful transmission from A to B. In a route from SN to DN, having D as relay node, the end-to-end f_{PDP} is the product of probabilities related to each link, as follow:

$$PDP_{(SN \rightarrow DN)} = PDP_{(SN \rightarrow D)} \times PDP_{(D \rightarrow DN)} \quad (5)$$

In a time window w, each node computes the delivery ratio by dividing the number of OLSR HELLO messages that should have been received by the number of OLSR HELLO messages actually received. Every t seconds, HELLO packets are sent. Delivery ratio of 100% means all messages were fully received in period w. More details of calculating the PDP metric can be found in [17][23][25]. In Figure 1, if only PDP metric was employed, the route 1 ($SN \rightarrow A \rightarrow B \rightarrow DN$) would be chosen, in spite of the larger E2ED and number of hops.

Our proposal aims to minimize E2ED and maintain the PDP of link equal or above an acceptable threshold. This threshold will depend on the application requirements or even network current condition. For this purpose, the bi-objective problem was modeled as a mono-objective problem applying the epsilon-constraint method, where the PDP of link was turned in a constraint into [9]. Therefore, the routes are created based on a Constrained Shortest Path Problem model (CSPP). Herein, instead of treating the PDP as an end-to-end metric, it is evaluated locally along the route. The model is proposed as follow,

$$\text{minimize} \quad f_{E2ED} = \sum_{(v_i,v_j)\in E} LD_{(i,j)} \times x_{i,j}$$

s.t.

$$PDP_{(i,k)} \times x_{i,k} > \epsilon_b, \quad k \in N(v_i),$$

$$\sum_{(v_i,v_j)\in E} x_{i,j} - \sum_{(v_j,v_i)\in E} x_{j,i} = 0, \quad \forall v_i \in V\backslash\{SN, DN\},$$

$$\sum_{(SN,v_j)} x_{SN,j} = 1,$$

$$\sum_{(v_j,DN)} x_{j,DN} = 1,$$

$$x_{i,j} \in \{0,1\}, \quad \forall (v_i, v_j) \in E$$

where ϵ_b is the minimum PDP that a link must guarantee to be part of the route. Thus, ϵ_b represents the link reliability, whose value can be defined *a priori* or it can be changed iteratively during network operation. The former option is employed in this paper, while the latter is an improvement that relies on probabilistic models, which will be studied in future researches.

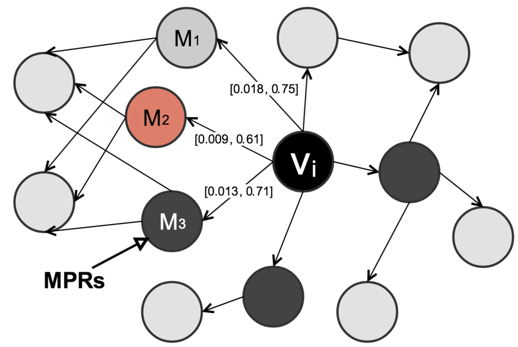


Figure 2. MPRs selection with reliability constraint

The remaining constraints ensure flow conservation and establish that the first node will be the source (SN) and the last node will be the destination (DN). Finally, decision variables must have binary values, which describes whether or not a link belongs to the route.

In Figure 1, if $\epsilon_b = 0.6$ (60%), the route 3 ($SN \rightarrow D \rightarrow DN$) would be chosen since it presents the lowest delay among routes that do not violate the PDP constraint. If $\epsilon_b = 0.7$ (70%), the route 4 ($SN \rightarrow C \rightarrow D \rightarrow DN$) would be created. Note that these promising solutions would be lost in the case of a single-criterion optimization problem.

As a step towards bi-objective optimization in routing, a modified Dijkstra's algorithm was employed to solve the CSPP model. The goal is to find lower delay paths while simultaneously bounding the PDP of link for a lower limit. In short, after comparing the cumulative delay in deciding between paths, as in common Dijkstra's algorithm, the PDP of link is compared to the ϵ constraint. If the PDP is lower than ϵ, this path is pruned off.

Furthermore, a change in the OLSR protocol was proposed to bear the desired minimum reliability constraint when building the Multipoint Relay (MPR) set of a node. When there are more than one 1-hop neighbors covering the same number of uncovered 2-hop neighbors, the one with the lowest link delay and that does not violate the reliability constraint ϵ to the current node is selected as MPR. Figure 2 illustrates such procedure. Let us consider ϵ equal to 0.7. Note that the node M_2 has the lowest delay (0.009s), however, the PDP (0.61) violates the constraint ϵ. Since both $M1$ and $M3$ do not violate ϵ, the one with the lowest delay is selected to be part of the MPR set.

IV. SIMULATION RESULTS

Extensive simulations were conducted in OMNET++ 5.0 simulation tool. A sample size of 10 topologies was defined for each method in order to obtain a confidence level of 95%. The comparison between the methods was performed using Analysis of Variance (ANOVA) test and Honestly Significant Difference (HSD) test [26]. All the assumptions required to carry out the ANOVA test were analyzed and the results are provided in a support information file [27].

A. Experimental design

The physical layer is implemented using the log-distance path loss model, where the path loss $P_l = P_t - P_r$ in dB over a distance d is simply defined $P_l = 10log(c/4\pi f)^2 + 10log(1/d^{\lambda})$, where c is the speed of light, f is the carrier frequency of 802.11g (2.4 GHz), d is the distance between the transmitter and receiver and $\lambda = 2$ is the path loss exponent. The interference is modeled using the SNIR (Signal-to-interference-plus-noise ratio), where the power of other transmissions is considered as interference for the signal power. There is a MAC protocol which deals with the media contention and ensures that, among the neighbors, only the addressed receiver will retain the message, while the other neighbors will discard it. Table II summarizes the remaining parameters.

TABLE II. SIMULATION PARAMETERS

Parameter	*Configuration*
Simulation area	1500 m x 300 m
Simulation duration	500 seconds
Traffic flow	Constant bit rate with UDP transport
Number of flows	10 IP unidirectional flows
Connection rate	5 packets/s
Packet size	1000 bytes
Number of nodes	50 nodes
Mobility pattern	Random Waypoint Mobility
Moving speeds	2, 5 and 10 mps
Pause time between node movements	10 seconds

In addition to the static scenario, moving speeds of 2, 5, and 10 mps were tried. All the hosts communicate on the same shared wireless channel and each node has a unique identifier with at least one transmitter and one receiver. It is assumed that the effective transmission distance between every node is equal. Nodes are neighbors when they are in the transmission range of one another. The OLSR protocol is in charge of discovering neighborhood. The fixed specific parameters for OLSR include: HELLO message interval of 2 seconds, TC message interval of 5 seconds and time window for PDP calculation of 20 seconds.

The Mobile Ad-hoc Network has 50 mobile wireless devices distributed in a given geographic region with two-dimensional (2D). Routing performances are measured in terms of PLR, average E2ED, average number of hops, and Packet Error Ratio (PER).

B. Trade-off analysis

At the beginning, the associated trade-off between E2ED and PLR was evaluated. The method that applies the LD metric is called Minimum Delay (MD) [24]. Herein, the method that applies the PDP metric is called Minimum Packet Loss (MPL) [25]. In an independent batch of 10 simulations of each method configured according to Table II, a straightforward compromise between the quality measures in all mobility scenarios was identified. Figure 3 highlights the non-dominated points.

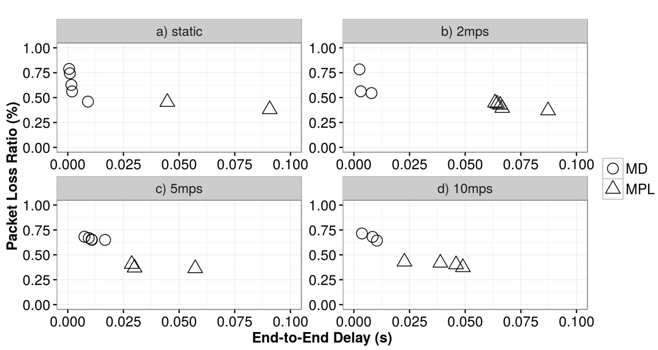


Figure 3. Packet Loss Ratio and End-to-End Delay trade-off

The MD generates straighter routes, which minimizes the E2ED. However, packet drops can overly enlarge due to the increased probability of choosing slower links. On the other hand, the MPL generates routes with more hops, regardless of the latency. That decreases the PLR but provokes larger E2ED. As can be seen in Figure 3, the trade-off is sharp. Furthermore, as mobility increases, this compromise narrows.

C. Comparison of multicriteria and single-criterion methods

Our method is labeled of EC (Epsilon-constraint) plus the corresponding minimum PDP constraint. Thereby, four settings were simulated according to such constraints: $\epsilon_b = (50\%, 60\%, 70\%, 80\%)$.

1) Minimum Delay (MD): MD remarkably achieves less E2ED than MPL and ECs methods, which is depicted in Figure 4. In fact, the source node usually sends packets directly to the destination node, if they are in the range area from one another. Figure 6 indicates such reality when displaying the average number of hops equal to 1 for all the node speed set. MD measures the one-way delay through ad-hoc probe packets. Thus, paths with less Round Trip Time (RTT) are selected. On the one hand, this reduces the latency in transmission, but on the other hand, increases the probability of handling poor quality links. Figures 4a. and 4b. show that the reduced mobility favors the stability of E2ED. Figures 4c. and

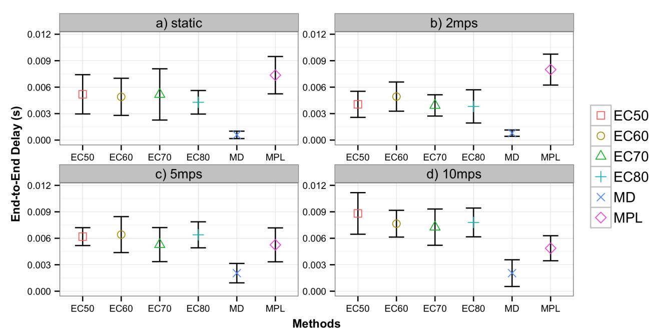


Figure 4. End-to-End Delay to such mobility scenarios: a) static, b) 2mps, c) 5mps, and d) 10mps.

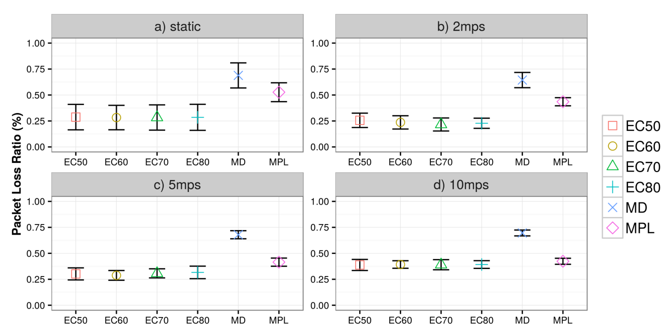


Figure 5. Packet Loss Ratio to such mobility scenarios: a) static, b) 2mps, c) 5mps, and d) 10mps.

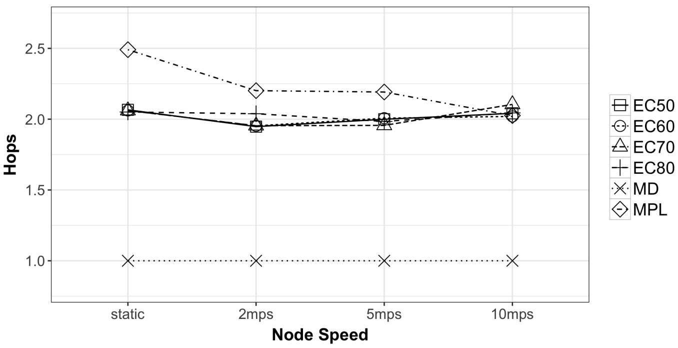


Figure 6. Average number of hops

4d. present larger variations, precisely because of additional mobility.

Figure 5 shows that PLR always has values above 50% in all mobility scenarios. Such poor performance can be justified by the distance between nodes of the route, which promotes the formation of slow and direct links. As nodes speed increases, drops are even more constant, since the source and destination are distancing and approaching speedily, which generates nonstop packet loss due to disconnections, collisions, and interferences.

If a delay-sensitive traffic is being transmitted, delay-aware routing protocols can be useful. However, in the simulated scenarios, E2ED as a single criterion does not reach a proper trade-off, as the small delay is followed by excessive loss rate.

2) Minimum Packet Loss: MPL selects paths with less PLR, i.e., those routes with high successful delivery are preferred, even though it means longer paths, as shown in Figure 6. Meanwhile, Figure 4 displays that longer routes augment the E2ED compared to MD. In terms of PLR, Figure 5 reveals that MPL overcomes MD in all mobility scenarios, having mean values below 50%. The high loss rate identified in Figures 5a. and 5b. is due to the fact that in a dense environment, MPL selects closer nodes, which implies routes with an additional number of hops, as shown in Figure 6. This fact naturally contributes to a higher incidence of packet drops and interferences in the shared medium. Interestingly, more mobility may shorten the length of path, since a given relay node can be moving closer to the destination. Note that, in Figures 5c. and 5d., there was some reduction in drops.

Reliability-aware routing protocols are well-suited to provide QoS when the application is delay-tolerant, but requires high delivery rate. Likewise, they may also be feasible for multimedia applications as long as the delay requirements are met.

3) Epsilon-Constraints: As shown in Figure 1, in terms of PLR, the EC multicriteria methods get better results than single-criterion methods. This is because our model seeks to minimize the E2ED as long as the PDP requirement is satisfied. Such result is corroborated by the constant average number of hops displayed in Figure 6. The variability in Figure 5a. (static scenario) is because of fixed density, which leads to a high need for contention. In Figure 5d., ECs and MPL obtained equivalent results. Actually, the high mobility impacts on the efficiency of the Dijkstra's algorithm when dealing with the imposed constraint. Upon constant and strong mobility, it is difficult to find links that do not violate the reliability requirement. This condition further generates an increase in the E2ED, as displayed in Figure 4d. In addition, it is relevant to record that the OLSR protocol is not suitable for highly mobile networks due to its proactive characteristic. In this context, the routes become outdated quickly and the protocol is not able to rebuild them timely.

In Figure 4, although not achieving the best latency results, the multicriteria method can be suited to multimedia traffic, since there was a significant decrease in the PLR and the E2ED remained at a reasonable threshold. In summary, as speed increases, the delay also increases. However, the PLR remains stable.

Looking at the underlying layer, the errors caused by collisions and interferences were analyzed. Packet Error Rate (PER) is the number of incorrectly received data packets divided by the total number of packets received. A packet is declared incorrect if at least one bit is corrupted. Figure 7 demonstrates that delay-aware methods (MD and ECs) have higher estimated PER. This is due to some factors. In general, the delay calculation is made through the ad-hoc probes, which increases the overhead, causing more collisions. In MPL, this addition of packets is not necessary since, as aforementioned, the metric calculation is done using short HELLO messages. Specifically, MD obtains routes with few hops, generating less reliable connections, whereas EC methods obtain routes with more hops than MD, generating additional need of contention, which adds errors by interferences and collisions. In short, it is possible to correlate the number of hops to the PER. Mostly, the PER values of the EC methods are slightly larger compared to the MD because of the additional hops. This condition is also evident for the MPL, since, inasmuch as the number of hops decreases, the PER also decreases.

In terms of PLR compared to the best result of single-criterion methods, our multicriteria model obtained, in each scenario, better results of about: 34% in static, 28% in 2mps, 18% in 5mps, and 6% in 10mps. Such results show that multicriteria optimization in ad-hoc networks can be a valuable strategy since it encourages the design of intelligent, adaptive and robust protocols that fit into the dynamic nature of MANETs.

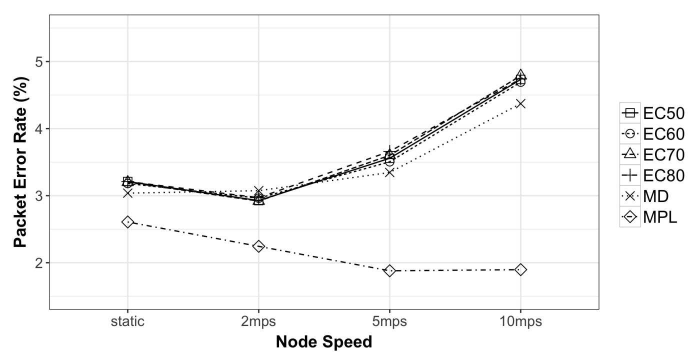


Figure 7. Average Packet Error Rate

V. CONCLUSION

Routing plays a key role in the development and spread of mobile ad-hoc networking. The multi-hop wireless network technology has gained commercial attention and new applications have emerged. However, in this context, there exists a crescent demand by QoS levels that are compatible with these new applications. As MANETs are dynamic networks, such expectations are difficult to achieve. Now, it is not only necessary to provide properly and timely routes, but also manage the scarce resources available. That means conflicting requirements can be found when trying to satisfy such demands, which implies in need to find a trade-off solution. The compromise between delay and reliability exemplifies such challenge.

This work has demonstrated such a trade-off through two link quality metrics. While MD metric seeks to minimize the E2ED, MPL metric aims to maximize the reliability of packet delivery. The introductory contribution of this paper was to present a multicriteria mathematical model that copes with both metrics in route optimization process. From our results, it was concluded that by dealing with the reliability metric as a constraint, an expressive decrease in PLR can be achieved. Besides, a handy trade-off can be earned.

In future works, new criteria that consider node residual energy and link stability will be added. Other mobility models, such as Gauss-markov, and different network density will be applied as well. Moreover, it is intended to compare the proposal to the weighted sum and existing works that take into account more than one QoS metric. The main target is to create a flexible and robust model where QoS constraints can be dynamically adapted to the network conditions and the type of application, for example. For this purpose, probabilistic models should be proposed and implemented in an optimization and decision-making support module that can be used by different routing protocols. Another relevant challenge is to eliminate or at least reduce the need for probes to compute the delay. Time series forecasting methods can be tested, therefore.

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