

A Discussion on Developing Multihop Routing Metrics Sensitive to Node Mobility

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Abstract—This paper is focused on a discussion of parameters and heuristics that are expected to assist multihop routing in becoming more sensitive to node mobility. We provide a discussion concerning existing and a few proposed parameters. Moreover, the work also discusses two new heuristics based on the notion of link duration. The heuristics are compared based on a meaningful set of scenarios that attain different mobility aspects.

Index Terms—multihop routing, mobility, wireless networks

I. INTRODUCTION

The most recent paradigms in wireless architectures describe environments where nodes present a somewhat dynamic behavior (e.g. *Mobile Ad-hoc Networks*, *MANETS*) or even a highly dynamic behavior (e.g., *User-provided Networks*, *UPNs*). Nodes in such environments correspond to wireless devices which are carried or controlled by humans and hence exhibit movement patterns which mimic the ones of humans - *social mobility patterns*. Moreover, in such environments, data transmission is based on multihop routing, namely, on *single-source shortest-path* approaches. In terms of routing metrics, the most popular multihop routing approaches rely on static link cost metrics such as hop count. The result is that when facing movement of nodes, multihop routing has its own shortfalls e.g., the need to recompute paths frequently if nodes exhibit high variability in movement of the nodes. In other words, current multihop approaches lack sensitivity in what concerns nodes movement. The routing metrics currently being considered cannot capture node speed variation or acceleration, node movement pattern, or even direction. Hence, a topology change is merely interpreted as a trigger to perform path re-computation. There are, however, cases where node movement may actually not represent a link break. Or, instead, a link change due to node movement may be so subtle that in fact it would not require any update to the topology, and hence, current approaches may result in useless path

re-computation, of which the cost relates to additional signaling overhead and latency.

This paper is focused on a brief analysis of mobility impact on routing and proposes a category of routing metrics related to different notions of link duration. Our expectations are that such a metric may make multihop routing more sensitive to node movement and hence, assist in improving the trade-off of node movement vs. network efficiency. Under such category, we provide several metrics and a discussion on the impact that they have, under different parameters.

The remainder sections are organized as follows. Section II goes over work that is related to ours, highlighting the relation between previous work, and our contribution. Section III gives an overview on the notion of node movement and how it impacts routing and the definition of a wireless link. Section IV gives an overview of the existing mobility tracking parameters. Section V describes our proposed routing metrics and how they improve routing sensitivity to node movement, while section VI provides an initial performance comparison of the proposed metrics. We conclude in section VII.

II. RELATED WORK

A number of approaches have been dealing with detection and measurement of accurate node mobility as well as counterbalancing mobility impact on routing.

A first category of related work considers applying signal strength measurement at the receiver as a way to estimate the distance variation between two nodes, having as ultimate goal providing a way to build more robust paths. For instance, the *Mobility Prediction Routing Protocol (MAODV)*[10] relies on the variation of the received signal strength by a particular node to predict link breaks. Dube et al. [3] have also applied signal strength measurement as a way to build more robust paths. Manoj et al. applied the notion of received signal strength to track the distance variation between two nodes, in a specific time period [8]. Their distance change tracking approach is a desirable feature as it can capture movement of nodes and the impact on links. However, and similarly to the other work in this category, it does not track movement patterns.

A second category of work that tries to make routing more sensitive to node mobility relates to throughput variation measurement as a way to determine node mobility. For instance, Suyang and Evans have used the slope

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of change of throughput in a link vs. the link load to estimate topology changes [11]. Based on history, through throughput monitoring, a decrease, according to Suyang and Evans, means that there is a true change in the physical topology. They have attributed the changes to increase in the node distance and increase in interference. Even with good attributes of avoiding interference and detecting mobility collectively, node mobility individually has attributes that have not been addressed. Nodes may exhibit movement that does not necessarily impact the route stability.

A third category of work that we cite relates to an attempt that is not directly tackling mobility impact on routing in the sense of reducing computation but instead addresses a latency reduction. In such category falls the *On-Demand Multipath Distance Vector (AOMDV)* [9] and the work of Kim et al. [6] which considers disjoint paths in AODV to counter link failure in case the alternative path shares some links with the primary one. Albeit multipath assists in reducing latency and packet loss in the event of link failure, the cost of path re-computation is still present and affects the network operation.

A fourth category of work relies on *link sensing* as a measure of improving routing in terms of mobility sensitivity. Benzaid et al. [2] have proposed the *fast Optimized Link State Routing Protocol (Fast-OLSR)* whose basic idea is to detect link changes in a quicker way, by increasing the HELLO sending rate. Albeit interesting, such rate only assists in understanding that some nodes may be on the move, but not exactly which.

All of the mentioned approaches have in common the aspect that they fail in being able to distinguish between a topology change that is long-lasting, and a topology change that is so short that in fact it should not result in route re-computation. Our belief is that by defining a multihop routing metric more sensitive to node mobility, multihop routing can become more robust and better adjusted to the current wireless dynamic scenarios.

III. NODE MOBILITY IMPACT ON ROUTING

This section provides a brief discussion on the impact of node mobility on routing. *Node mobility* here refers to a change in speed (inclusive of relative speed) and/or direction (also relative direction) for a node. Hence, *node movement* is based on three main aspects: node position; speed; direction.

The impact of mobility on routing can be measured mostly by analyzing the trade-off in robustness (e.g. the need to recompute paths more) vs. signaling overhead (more messages sent to quicker detect link breaks). Furthermore, node mobility impacts routing on a different number of ways and here we shall address the main ones, namely, relation to distance; movement pattern (and how it affects links); relative movement (link remains stable due to similar movement of the nodes that compose the link); impact on the different stages of the routing process (e.g. route discovery and maintenance phase). Intuitively, it seems that node movement can be better captured just

by sending additional signaling messages. However, it is not always the case that by increasing signaling overhead one may better prevent link breaks and reduce the cost of re-computation; on the other hand, node movement patterns affect links temporarily or permanently.

To give a concrete example let us consider Figure 1 which illustrates a wireless topology where A and B represent nodes in movement. The figure considers three different cases. In Figure 1 i), A exhibits confined movement eventually returning to its original position. In ii) B is the node moving in a *ping-pong* pattern, i.e. B is jumping back and forth between two different positions. This stands for a case of repetitive movement, where the node exhibits some pattern and frequency of moving away/returning to origin. The final case (cf. Figure 1 iii)) corresponds to the case where B permanently moves away from its original position. Upon movement of at least one of the nodes A and B, the corresponding link quality is affected. If the nodes exhibit frequent movement, frequent path re-computation may occur. For scenarios such as the one illustrated in Figure 1, it may happen that two neighbor nodes move away from each other resulting in a link being broken and consequently, resulting in topology re-computation, to return to their original position a few milliseconds later. Were it for a protocol truly adaptive to node movement, the decision on whether or not to trigger path re-computation should be based on metrics that can capture node mobility patterns.

Node mobility impact on routing is also distance dependent, i.e., related to link *size*. For instance, a link formed by two nodes far apart (*long link*) can be affected and broken even by a small, insignificant node movement. If instead we have a *short link* (small distance between the two nodes), the movement of a node has to be significant to result in a link break. It should be noticed that link quality may degrade also due to mobility, but what we are highlighting here is that changes in distance are not sufficient to define a routing metric sensitive enough to node movement. It is also necessary to incorporate some sensitivity to a node's movement pattern and this is not a trivial task given the possible mobility patterns. For instance, a node moving between two different positions A and B can just move from A to B; move away from A to B and come back to A; or it can be ping-

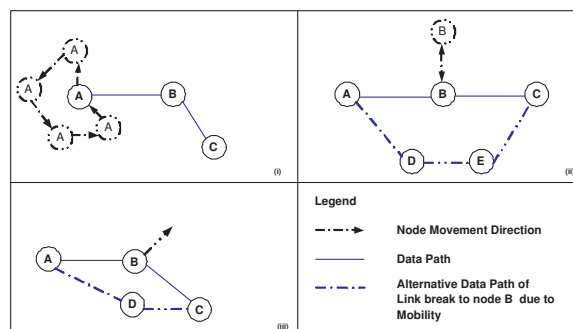


Figure 1. Examples of node mobility.

pinging between A and B. As mentioned previously, such movement pattern may be insignificant in terms of impact on a link (e.g. because the distance between the nodes is short). In contrast, a move between A and B will impact link capacity heavily, and a ping-pong movement will result in a wide wireless link capacity variation. For both the aforementioned cases, a link is not truly broken and yet, today path re-computation would occur.

Another aspect to consider in terms of impact of mobility on routing is the routing phase where movement is detected. Of utmost relevance is node mobility during the route discovery and route maintenance phases. In relation to mobility impact, the most relevant routing processes are: *route discovery*, where a route to a particular destination is not known and has to be built and computed and *route maintenance*, where routes are maintained and recomputed. For instance, if a link on an active route breaks, an alternative route to the destination is computed and this is done during the the route maintenance phase. Assuming the existence of a link considered during route discovery, where one of the nodes is moving, it may happen that the resultant path of route discovery is not available as the link would have been broken. Routing protocol under route maintenance will have to recompute an alternative path for data transfer.

To further debate on the impact of node mobility has on the routing process, we discuss, in the next sections, impact of movement during route discovery and maintenance. We start by addressing such potential impact by analyzing different parameters, to then briefly the potential impact on the two most popular multihop routing families distance vector and link state, which are represented here, by the *Ad hoc On-Demand Distance Vector (AODV)* [1] and the *Optimized Link State Routing Protocol (OLSR)*[4], respectively. The explanation provided next has as main purpose to explain in further detail the impact of node movement on routing.

A. Movement Impact during Route Discovery

Considering AODV, during the route discovery, a node (i.e. source node) upon demand broadcasts *Route Request (RREQ)* packets. An answer in the form of a *Route Reply (RREP)* will be returned as soon as a node realizes it has a route established to the destination. Assuming node movement of the source node, or movement of any of the nodes on the would be path before an answer is returned, i.e., before a path is fully established. This may result in path establishment failure, depending on the type and pattern of movement of the source node and the intermediate node. To what extent node mobility will impact the route discovery phase depends on several aspects, for instance: whether a link is short or long, the mobility pattern, frequency of motion and also the node degree. The number of nodes moving as well as the sequence of node displacement from the original positions is also relevant to address.

To assist the explanation the impact of node mobility on route discovery, Figure 2 shows a topology where a

route has to be discovered from Node S to node D, where, based on hop count, the path between S and D should be S-C-D a number of alternative paths also exist but are longer, for example paths S-A-B-D, S-A-B-C-D and S-E-F-G-D to mention a few. Let us consider that nodes A and B exhibits some form of confined movement as shown in Figure 1 i) and node S broadcasts a RREQ for route discovery. Let us also assume that only C and G know about the whereabouts of D. The RREQ sent by S may, due to such confined movement, reach C later than it reaches G. Therefore, the answer in the form of a RREP may result in a route that may be formed earlier may actually be the longest and the shortest may appear to be longer, for example, having a path of S-A-B-C-D instead of S-C-D.

The impact of movement in this phase is therefore related to the type of movement but also related to the type (short or long) link. If the links affected by confined movement are long, then the node movement will affect more significantly the path recomputation and adequate route discovery. If links are short, then movement of nodes in a confined area may not even be noticeable from a routing process perspective. However, if we consider some movement pattern which exhibits some regularity, such as the one in Figure 1 ii), then the frequency of regular movements significantly affects the route discovery independently of links being short or long.

We have discussed the impact of confined node mobility on route discovery, now let us debate on the frequency of regular node movement and how, in our opinion, it impacts the routing process in terms of route discovery. The three cases of node movement presented in Figure 1 may exhibit some frequency which implies that the node crosses its original position at some instant in time. By *low frequency* of movement is here meant that the node crosses its original position seldom; by *high frequency* it is meant that the node crosses its original position often.

Assuming a confined movement scenario for a node with low frequency of movement route discovery is barely affected with such node mobility whether long link or short links, while high frequency of confined movement impacts more on long links than short links. However, if we consider a movement pattern such as a ping-pong movement, then the impact of such frequency may in fact severely affect the route discovery phase, leading to route that are not shortest-path based or even delaying such

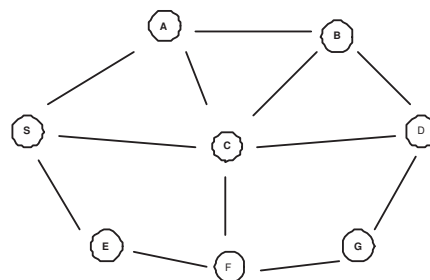


Figure 2. Node Topology Example.

phase in a significant way as both short and long links are affected.

Such delay is highly related to the network composition and node degree, in particular on the degree of the nodes exhibiting movement. Moreover it is also highly related to the relation of the movement that a node exhibits in regards to its neighbors. Therefore, it is not always the case that links formed with a node that exhibit high frequency of movement will significantly impact the route discovery phase. Such impact also depends on the relativeness of movement between nodes that form links. To give an illustration, we refer to Figure 2. If all nodes in this topology were moving with high frequency of ping pong with minimal relative movements among the nodes, delay in route discovery will be minimal. On the other hand, high variability of such movement at high frequency will introduce high delays in the route discovery stage.

In terms of relation to distance-vector and during the route discovery phase, the main impact of node movement is delay which in our opinion may, in specific cases and due to node frequency as well as topology composition, result in such variability that mainly jeopardize the whole routing process, as the route discovery phase may be delayed significantly for a distance-vector approach.

Were it for the case of a link-state protocol such as OLSR, then route discovery is performed in a proactive way based upon the Hello control messages and also based on the notion of *Multipoint Relay (MPR)*, i.e., a successor of a node chosen to forward packets on behalf of the node. This assists in reducing flooding on the network, in contrast to the original link-state routing approaches. OLSR is better suited for large, dense environments. Moreover, OLSR can tune the frequency of information exchange and thus provides, in principle, better support for node movement.

In terms of the route discovery phase, the impact that node movement again relates to the parameters already discussed, namely: correlation of movement pattern to time (frequency and type of movement) as well as to node degree and network density. The main difference in comparison to AODV during this phase relates to the proactive behavior, which provides more stability when nodes move. Let us again consider Figure 2 and the provided (potential) paths. Again assuming that nodes A and B exhibit some type of movement, the expected delay would most likely be less but the result would be the same in the sense that again the selected route would be the longest one independently of the fact that the movement type and frequency could imply that after a small delay the best route could indeed be the shortest one. In other words: none of these families currently includes a natural (metric-based) way to detect such minor variations and to ignore them.

In terms of different multihop approaches, while with AODV the result may be a significant delay while with OLSR the delay may be smaller but the signaling overhead may significantly increase, depending on the type of movement, frequency of movement, as well as related to

the position of the node(s) moving from and end-to-end path perspective.

B. Movement Impact during Route Maintenance

Again considering the AODV perspective, let us now debate the potential impact that node movement has during the route maintenance phase. A topology change may occur due to a temporary link break, or due to a permanent link break. For instance, if one node moves from a specific position to another and hence there is a link break but the node returns to its original position in a few milliseconds, this corresponds to a *temporary* link break. A temporary link break does not always imply discontinuity from a routing perspective and this is highly related to the type and pattern of movement. For instance, if a node exhibits confined movement as discussed the frequency of movement dictates whether or not such movement may result into a temporary link break, or a permanent link break. Being on-demand (reactive), upon even a temporary link break AODV triggers signaling in order to deal with topology changes. It may even happen that upon the detection of a temporary break, AODV triggers path recomputation and the result may simply be the path that was already established. This will increase the signaling overhead in a way that could be prevented, if the applied routing metric would be capable of "isolating" these situations, i.e., by making the routing protocol understand when a change is temporary, or permanent, or simply react for cases where changes are permanent.

Assuming that the type of movement implies some frequency of returning to the original position, then in addition to the signaling overhead there is delay which is highly dependent on such frequency.

In regards to the impact on a link-state approach (e.g. OLSR) during the route maintenance phase, due to its proactive nature, OLSR will detect quicker the location of a topology change and due to the flooding nature, it will, most likely, heal such failure quick. However, for the case of a temporary failure there is no detection capability. Both temporary and permanent topology changes will be dealt with as a change and hence require recomputation. Signaling overhead is associated with this. The corresponding delay will be less for OLSR than for AODV. However, both families treat temporary and permanent topology changes as changes, thus requiring path recomputation. Despite the fact that such changes may be insignificant, the relative cost (be it in terms of delay or in terms of signaling overhead) seems to impact both protocol families the same way. This has, of course, to be corroborated with experimentation which we leave as future work.

Therefore, one main aspect to tackle in order to make routing more sensitive to node mobility is to consider metrics that are capable of capturing some properties of such movement. In the next section, we describe a number of parameters and of metrics that can be used to achieve such goals.

IV. MOBILITY TRACKING PARAMETERS

In this section, we describe several parameters related to the routing process which provide some support in terms of sensitivity to node mobility, explaining their advantages, as well as weaknesses.

A number of parameters affect the performance of routing protocols differently. They will affect the routing protocol on the routing discovery and route maintenance procedures. The parameters under study in this section are: *link duration* or *lifetime*; *node degree stability*; *ratio of static nodes vs. moving nodes*; *average number of link breaks*; *pause time*.

A. Link Duration

Link duration (LD) or *lifetime* is a parameter that is tightly related to the movement of nodes and is also as of today one of the parameters that is most popular in terms of tracking node mobility. By definition, link duration is associated to the period of time where two nodes are within the transmission range of each other. In other words, it is the time period that starts when two nodes move to the transmission range of each other and that ends when the signal strength perceived by the receiver node goes under a specific threshold [7][14] [12]. Some authors then provide a variation of this definition by working the threshold value.

Today's definition of LD only assimilates node mobility in regards to its relation to signal strength. It fails, however, in terms of sensitivity to movement patterns. For instance, the current LD does not capture the case where a node jumps between its original position and a second position with a frequency that is not significant in terms of the potential delay it causes. Such movement will trigger repeated recomputation, which brings in more delay than if such frequent hopping would simply be disregarded. In as far as mobility patterns are concerned, LD captures link stability of nodes that do not reach their link break threshold. However, cannot distinguish between a temporal and permanent link break.

B. Node Degree Stability/Rate of Changing Neighbors

The *node degree* N_i of a node i corresponds to the number of neighbors i has at a particular instant in time. From a mobility perspective, an increase in node degree either means that other nodes moved towards node i , or that node i moved towards other nodes. It should be noticed that from our mobility analysis perspective, having nodes moving towards others is the same as having static nodes simply joining or leaving a network. Hence ND_i per se is not an adequate mobility tracking parameter. However, if one considers the variation of the node degree through time one may be able to infer some mobility properties. We define *Node Degree Stability* (NDS_i) for node i as a parameter that tracks the rate of ND changes. For the sake of clarity we provide a simplistic and initial embodiment of NDS_i in (1) which corresponds to the

difference between the ND at a previous instant $t-1$ and the ND at the current instant t .

$$NDS_i = ND_{i_{t-1}} - ND_{i_t} \quad (1)$$

Let us consider the case where node i is moving through clusters of other nodes. NDS_i captures, through time, the fluctuation of neighborhood variation from the perspective of node i . Per se, it does not suffice to truly track mobility, given that i may be moving or instead, i may actually be static and its neighbors may move. As far as mobility patterns are concerned, because rate change of neighbor is not expected to change in a topology where most node movements are confined, it is expected that that in itself will allow the parameter to capture stability in the links of confined topology. Worthy of mention is that the parameter in the confined node mobility is not affected by frequency of confined motion and caters for both long and short links as there is generally constant neighboring nodes. However, the performance in non confined node mobility is dependent on the gradient of change of neighbor topology and how fast the node is moving relative to other nodes whether it is the same set of neighbors or not. For example, a node with circular motion response to mobility depends on the how fast it is moving relative to other nodes, when it can be moving within the same set of nodes. It is only in confined mobility that the types of links do not matter. In case of ping pong and free movements, long links are affected more than short links as long links are close to changing neighbor hood than short links with minimal displacement. Also relative node speed, frequency and node density plays a part and an increase of any brings about more neighbor change signaling high mobility. With this, rate of change of neighbors does not distinguish between temporal breaks and permanent.

C. Ratio of Static vs. Moving Nodes

The ratio of static vs. moving nodes (or a ratio between them) in a network estimated through time and for the perspective of a single node i is here defined to be an evolution of NDS_i and a parameter that can be considered in order to partially capture mobility dynamics of a network. Through time, if the percentage of nodes moving is low in comparison to the static nodes, it is more likely to have more stable links. Relevant also is to be able to capture the dispersion (and not only the percentage) of such nodes on the network.

D. Average Number of Link Breaks

Another parameter that assists in tracking mobility dynamics is the *Average Number of Link Breaks* estimated in a specific interval for a node i , ALB_i [7]. If node i experiences a high ALB, then through time it may be a node to avoid, if the goal is to provide robust paths. This implies that it Albeit interesting due to the easy computation of such parameter, ALB can only assist in terms of the route discovery phase, given that it may assist

in setting up more robust paths. However, and for the case of repetitive movement patterns, ALB cannot capture such mobility dynamics and will result in route re-computation. This is a parameter that captures the stability of short links but not on long links in any mobility pattern. It fails to capture even spatial correlation of long links with confined mobility pattern. It is affected by high frequency of repetitive node motion.

E. Pause Time

Pause time is the period of time that the node is *stationary* (e.g. its speed is zero) [13]. Khamayseh et al. [5] have used pause time to determine mobility levels, by assuming that nodes with long pause times are less mobile than nodes with small pause times, and hence assist in developing more stable links. Their notion of pause time is based on an aggregate perspective and relative to the global time of a simulation. In real-time, nodes exhibiting short-pause times may or may not prevent the development of more robust links, but this is related not only to being static, but also to the movement pattern they exhibit.

F. Summary

Most of the mobility parameters previously discussed in this section are able to partially capture mobility dynamics of a node. Out of the ones described, LD seems to be the most relevant to consider in regards to attempting to develop routing metrics that can assist in tracking mobility dynamics in particular regarding node movement with patterns that exhibit some recurrent behavior (e.g. ping-pong movement). The remainder parameters are relevant and may be applied to assist parameters such as LD, in building more robust metrics.

It is, however, our belief, that LD requires a more thorough characterization to be able to integrate routing metrics that are more sensitive to movement.

V. MAKING ROUTING MOBILITY AWARE, LINK DURATION HEURISTICS

In this section, we provide our proposal concerning heuristics that augment the current definition of LD in a way that optimizes the routing process, by being able to better capture when route re-computation is truly required.

A. Link Duration based on Signal-to-Noise Ratio Threshold

Today's LD definition simply relates to the receiver's perceived signal strength, as mentioned in section IV. As long as two nodes are within each other transmission range, then the LD keeps increasing [7]. If two nodes i and j share a short link and exhibit a synchronous mobility pattern thus keeping the same average distance while moving, then LD also increases. Let us now consider the same type of movement pattern between two nodes that are at a larger distance. Because of displacements nodes

in the long link will lead to reach the breaking threshold. The resultant link duration will be much smaller than in a short link. Hence, micro-movement of nodes will impact longer links more than shorter links in what concerns route re-computation. However, metrics that just consider LD cannot capture this behavior.

The current definition of LD relates to applying a threshold for SNR, so that LD becomes dependent of a "good" SNR level, that can assist in reaching a better trade-off in terms of route re-computation vs. signaling overhead. In other words, LD would become the instant in time that starts when two nodes encounter each other with SNR above the required threshold and which ends when the perceived SNR at the receiver is lower than a pre-defined threshold. This definition is evidently highly dependent on the choice of the SNR threshold.

Our belief is that by working the LD definition, one can provide a routing metric that is more adequate to environments where nodes are expected to frequently move and hence, where there is a high variability in terms of topology reconfiguration. In the next sections we propose a few LD variations and explain how they may assist routing in providing more sensitivity to node movement.

B. Relaxing the Link Duration Definition: LD with a Tolerance Interval

One way to assist routing in becoming more tolerant to frequent and temporary movement, the LD definition can be relaxed in regards to time. Hence we propose the *Relaxed Link Duration (RLD)* heuristic. Let us assume that a link has been stable since instant t_0 and breaks at an instant t_1 and that at instant t_2 the node that originated such break returns to its original position. With the current LD definition, the link would be considered broken at instant t_1 thus originating a route re-computation. In such case, $LD = t_1 - t_0$. At instant t_2 , the route would again have to be recomputed. Following the same example provided, at instant t_1 , the node detecting the link break would wait Δt time units before issuing a route re-computation. Assuming that Δt is large enough (for our example, larger than $t_2 - t_1$), then the node would return, on instant t_2 , to its original position and the routing process would disregard the temporary link break. The key aspect here is the choice of an adequate Δt . If Δt is too large, then for nodes that may cross frequently their original position, link breaks will not be detected and hence signaling is reduced. The flip-side to this is that for nodes that exhibit movement that result in a permanent link break, there is an additional delay added.

C. Spatial Stability-based Link Duration

In section IV we have introduced NDS_i and ALB_i . The combination of NDS_i and of ALB_i assists in capturing some properties of node mobility. To provide an example of how this can be achieved, we define *Spatial Stability-based Link Duration (SSLD)* as an extension of

LD based on a correlation between ALB_i and NDS_i . It should be noticed that the work here provided is intended to be initial and hence we do not provide a concrete instantiation of a formula that may represent SSLD. Instead, we explain the rationale for this heuristic.

Let us consider a node i that has a high NDS and a high ALB. In terms of node mobility and its impact on routing, links related to such node are expected to be less robust, given that there is a strong movement associated to the perspective of such node. Hence what SSLD can provide is a way to, at an early instant in time, discard successors of a node because they exhibit some mobility variability. As mentioned before, the node may be static and yet, the result are less stable paths (because most neighbors may be moving). For a more detailed explanation we provide in Table I the full set of NDS vs. ALB, by considering a high and low value. For each combination we provide examples of scenarios that may result in such values. Moreover, we also explain what the correlation may provide for each combination.

Scenarios where a node i holds both a low NDS (be it negative or positive) and low ALB imply that despite the reduction on the number of neighbors, the rate of link breaks is low. Potential cases for such result are scenarios where i is static and has a few nodes around it moving, or the node and its neighbors exhibit a group movement pattern. In both cases, the correlation between NDS_i and ALB_i can capture that mobility is not having particular impact on routing, for links associated to i .

Let us now consider a scenario with a low NDS and a high ALB value. This means that despite the fact that i has stability in terms of neighbors (i.e. it keeps a steady rate between neighbors leaving and joining), it can be captured that the neighborhood of i shows high variability. In contrast, if only NDS would be considered, then it would be assumed that i was a node stable in terms of links and hence a robust choice for a successor on a path. Also, if only ALB would be considered on such a scenario, then it would be immediately assumed that i was a node to rule out.

As example of scenarios which result in a high value for NDS and low value for ALB we provide cases 5 and 6. For both cases i sees an increase in neighbors (new nodes are joining); yet, such change has no impact in terms of links already established. If i is a static node (cf. case 5) then this means that its neighborhood is mobile in its majority. If instead i is moving, there is a clear group movement pattern, given that there is no increase in terms of link breaks.

The final discussion here provided relates to having both a high NDS and a high ALB. Potential examples of scenarios where this occurs are cases 7 and 8 are where node i is respectively experiencing a sudden and significant change in terms of neighborhood or moving through a dense region.

In the next section we provide a brief analysis related to the performance comparison for the heuristics described in this section.

VI. PERFORMANCE COMPARISON ANALYSIS

This section provides an analysis on the performance comparison for the heuristics proposed on section V. We consider a specific set of scenarios and evaluate the different heuristics in terms of route re-computation in the form of signaling overhead reduction, delay reduction, as well as improved throughput. Also looked into is the expected outcome as far as different routing families will be affected by the different heuristics in their respective routing phases (i.e. routing discovery and routing maintenance). As underlying scenario for this comparison we consider Figure 1 main cases: i) confined movement to a specific region where node a is making confined movements; ii) ping-pong movement as a result of periodic node mobility of node b ; iii) free movement in a large region. The confined movement example stands for a case where the node exhibits some features that may be captured, as happens in social mobility models, but its mobility is confined to a specific region and hence there may be some probability of returning to origin. In this case it is also likely that most of the node's movements do not truly impact the links it is part of severely. In other words, movement does not always imply a link break. The second case stands for an example of movement of a node which returns to the original position frequently. The third case represents an example of movement where the node will not return to origin.

In addition to the movement patterns based on Figure 1, we also consider other parameters in our analysis. From a topology perspective we shall analyze the different cases assuming different distances for links, namely, short and long links, given that as explained, movement of nodes impacts differently the network depending on the distance of nodes to neighbors. We also consider *network density*, namely, low or high density. A third parameter that we take into consideration is *movement frequency* in the form of *low frequency* (the node moves seldom thus exhibits long pause times) and *high frequency* (the node is highly dynamic; pause time is short). We have also analyzed the impact of routing based on the routing family; Link State or Distance Vector highlighting the difference in impact of mobility on routing based on different LD heuristics, covering also the impact on the routing processes (i.e. route discovery and route maintenance).

In Table II, we provide a summarized comparison of the performance of each heuristic, namely, LD based on today's definition (benchmark), and the two proposed heuristics: LD with a tolerance interval, as well as LD based on Spatial Stability.

The table contemplates the three scenarios (confined movement category, ping-pong movement, free movement) where we have considered the combination of network density and movement frequency by relying on the two extreme values *low* and *high*. For each scenario, we also consider what may happen if the topology is mostly based on short or long links.

Table I
NDS AND ALB CORRELATION FOR NODE i .

| NDS_i | Low | Low | High | High |
|---|--|--|---|--|
| ALB_i | Low | High | Low | High |
| Examples resulting in such parameter values | <p><u>Case 1</u> A static node i has only a few mobile neighbors.</p> <p><u>Case 2</u> Node and its neighbors are moving exhibiting a group movement pattern.</p> | <p><u>Case 3</u> A static node i has a few mobile nodes which either exhibit ping-pong behavior or which are on the move.</p> <p><u>Case4:</u> A node i keeps a stable rate of change of neighbors based on different neighbors (and hence different links).</p> | <p><u>Case 5</u> Node i is static and experiences a significant change in terms of neighborhood.</p> <p><u>Case 6</u> Node i is mobile and experiences an increase in its neighbor degree, thus implying that there is a group movement pattern - old links are kept.</p> | <p><u>Case 7</u> A node moves towards a more dense region.</p> <p><u>Case 8</u> A node experiences a significant change in its dense neighborhood.</p> |
| What the correlation assists in capturing | <ul style="list-style-type: none"> - Realizes that there is low mobility impact - - Ensures robustness of node as potential successor | <ul style="list-style-type: none"> - Realizes that there is significant mobility impact. - Node may be ruled out as potential successor. | <ul style="list-style-type: none"> - Indication of group movement pattern; - Stability in the neighborhood independently of having the node static or moving. | <ul style="list-style-type: none"> - High variability in terms of movement and of neighborhood. |

A. Confined Movement Scenario

We start by discussing the performance of the heuristics in confined movement scenarios where the majority of links are short. Being a confined movement scenario, the nodes involved move in a specific personal space revolving around their initial position and hence are expected to return or to pass on its original position with some frequency. Such frequency is strongly related to the link stability.

Because confined movements of nodes result in few permanent link breaks for short links, if any, confined movement has almost no impact on routing performance. Such mobility, even though, will result short links elongating to long ones, no notable link breaks will occur, if any, then few. With few links breaks and absence of major change in the node neighborhood, the three heuristics will give almost the same result.

For the long links, because a slight node displacement cause links to reach the breaking threshold, varied performance is expected under the three heuristics. We look into the distance vector family and the respective heuristics at the different stages of routing. In a low node topology region with low node mobility frequency, the route discovery of distance vector under LD will record few link breaks and it is expected that node mobility will be at its minimal. As such, route discovery will barely be affected as it takes a short period. However, there exist a possibility of having unutilised paths as nodes may be resting at some places resulting in discovery of long paths. In the route maintenance phase, because few links are expected to break, a slight increase in path recomputation will occur under LD. As far as RLD and

SSLD are concerned, route discovery latency is expected to be the same as LD due to few breaking links and nodes resting in same positions for long periods. In the route maintenance phase, RLD and SSLD will slightly outperform LD, due to the few path recomputations that will occur. With increase in node mobility frequency and in a low density topology, more long links in the face of confined node mobility will be reaching the breaking threshold. Compared to the static and nodes with spatial correlation, Distance vector routing, using LD heuristic, will be challenged even at a routing discovery level. This is due to the fact that propagation of the control messages will not be effective resulting in high latency due to link breaks. The control messages, as a result of failed discovery and quests to discover new paths, will contribute to the delay also. As far as route maintenance is concerned, there will be more path recomputation compared to low mobility frequency and in short links. The control overhead will weigh down the throughput and increase the delay. If RLD is used on the other hand, route discovery latency will be low as route discovery control messages will propagate in the “tentative” links also. An improved performance is expected in the route maintenance also, as less path recomputations will occur. With SSLD, the avoidance of nodes with high mobility will bring a slight improvement in route discovery and maintenance phase of the distance vector.

A topology with high node degree gives a different perspective of mobility impact different from the low topology. Still looking at long links, low confined node mobility will not impact routing discovery in that more alternative paths exist and that possibility of having good

routes is high. The challenge is that periodic neighbor control messages will increase and route discovery will record the increase in delay. Because the delay is not as a result of change in topology, the three heuristic performance will be the same as far as route discovery in distance vector will be the same. Routing maintenance performance will be the same, with LD giving slightly more delay to due few link breaks. When long links in a high node topology are subjected to high frequency confined node mobility, a number of factors come into play, MAC contention and link breaks become common. With this, the different heuristics will render the distance vector routing protocol different performance levels. Route discovery using LD heuristic will be affected due to MAC contentions and failed route discoveries as a result of link breaks increasing the delay. Under RLD, the delay will only be due to MAC contentions as control messages will propagate the tentative links too. SSLD will have better performance as LD in that the stable nodes will be fished out. In as far as routing maintenance is concerned, RLD will have a good improvement as some temporal link breaks will not cause path recomputations and SSLD will capture stable nodes for its routing purposes.

We now look into how confined node mobility will affect a link state routing protocol. Because of the proactive nature of the routing family, paths are computed with change in topology (i.e. link state, neighbor list). As such, the impact mobility of such a protocol, in as far as routing data is concerned, will be in the maintenance phase. We use the same parameters as in distance vector to analyze the impact on link state. These being; short or long links, low or high node mobility frequency and low or high node degree. As mentioned above on short links, confined node mobility will lead to almost no link breaks and the three heuristics will behave the same, with expected increase in delay in high node degree topologies. Because no extra control packets are generated, routing degradation due to mobility may be due to different reasons at some instances when compared to distance vector.

In a low node degree topology, low confined node movement frequency will cause the few links to break and this will cause path recomputations when LD is used, but because these are few link breaks, few packets will be delayed and it will have less bearing on routing in a link state. When the mobility frequency increases, more link breaks occur and path recomputations will occur within a limited number of nodes. The result will be increased delay as packets are buffered as they await the link break to be detected and path to be recomputed. When RLD is used, expected is that temporal link breaks will be detected and the packets will propagate "tentative" links, hence, less packets will be buffered and improvement is expected compared to LD. Because there is a larger number of link breaks, the only benefit SSLD will bring is to detect the few stable links amid highly mobile nodes and the improvement is slight. An increase in neighbor degree will cause more control packets, with highly mobile nodes, a good number of links will reach the breaking threshold

and path recomputation will be common with LD as a heuristic. The extra control overhead will weigh down the performance. Unlike in low density topology where few available paths break, a number of paths will be available but they are short lived. RLD will also be weighed down due to control overhead. Slight improvement is expected in SSLD. Low node mobility in a high node density topology will introduce overhead to routing and all heuristics will be affected with RLD and SSLD with better delay than LD as few path recomputations do not occur.

In summary, a low density network where most nodes are static (movement frequency is low), as shown in the first line of table II, then the expected result when relying on LD is that the path re-computation is normally triggered due to permanent link breaks. With the increase of movement frequency (cf. Table II second and fourth row) , path re-computation occurs due to link breaks. A first aspect to highlight is that the LD performance in terms of routing degradation is heavily dependent on movement frequency, and pattern. A second aspect relates to the fact that LD behavior will impact routing more heavily for dense networks. Overall, LD performance is dependent on the link distance and hence the impact on routing is expected to be more significant for topologies where links are in their majority long.

Looking into the first proposed heuristic, RLD (cf. Table II rows 5 to 8), for the case of confined movement. At a first glance and in what concerns simpler topologies (low density, mostly static nodes) RLD seems to have a similar performance at the cost of a slight increase in delay, which depends on the choice of the tolerance interval. It should be noticed that RLD will experience an additional delay, but when LD is applied, there is also a delay increase due to path re-computation. Therefore, even though there is potentially an increase in delay depending on the choice of the tolerance interval, we expect RLD to behave better given that it reduces the need to recompute paths and hence improves throughput and reduces the delay associated to path re-computation. Such improvement is not so significant in simpler topologies but becomes significant when the movement frequency increases, given that the RLD is less sensitive than LD to movement frequency.

In regards to SSLD, for simpler topologies the expected performance is similar to LD, for this scenario. The reason for this is that SSLD does not incur particular delay (in contrast to RLD) and the variability in terms of ND and of link breaks is low. When the movement frequency increases, then this heuristic works better by being able to more quickly track that there is variability in terms of movement affecting the link.

B. Ping-Pong Scenario

Ping pong effect, unlike confined node mobility where impact on routing highly depends on the link length, affect both short and long links. This is in a situation where relative node displacement can be so large such

that short links will elongate and even reach the link break threshold. We discuss the impact the ping pong effect will have in routing, extending the analysis to the routing processes under varied conditions of node degree and mobility frequency.

Ping pong effect, as mentioned earlier, can result in short links becoming long with the worst case having links reaching their breaking threshold. In a low node density topologies with minimal node mobility, expected is that few links will break both short and long links with short links being tolerant to displacement. As such, route discovery will barely be impact in that node will rest in their respective positions for some time. The three different heuristics are expected to perform the same as there is barely changes in link breaks and node neighborhood with LD with slight delay as there is a probability of picking on the node that is in motion for route establishment. As for route maintenance phase, expected is that LD and SSLD will perform the same, while RLD will introduce slight delay as the few links that have broken maybe held on to in the tolerance interval. On the other hand, during the routing maintenance phase, RLD is expected to give the best performance due to reduced path recomputation even though they are already few. An increase in mobility frequency, increases the number of link reaching threshold and Routing maintenance best performance is expected to be from RLD as there are less control overhead. SSLD will record a slight improvements due to selection of stable links. LD, on the other hand, will be affected due to increased routing overhead in a sparsely populated topology with few alternative paths for routing. The route discovery using the RLD will have less latency as links picked are bound to successfully deliver the route discovery control messages even in their "tentative" state. LD and SSLD will have the same performance. Increased node density have pros and cons. Increased or high node density provides a number of alternative paths in case of link breaks but bring along also control overhead. With increased mobility, RLD, once more will give the best performance in both routing maintenance and discovery. When node mobility frequency is low, the performance of the heuristics will almost be the same as few links will break. Compared to low node density and low mobility frequency, in high node density and low mobility nodes, the heuristics are expected to give a scaled down performance with increase in node degree due to MAC contention.

In summary, ping pong effect is a scenario where LD does not suffice to provide routing with adequate stability in the face of movement routing. The ping-pong frequency is highly related to the link stability. If it is too short (e.g. a few milliseconds) it will originate frequent link breaks. If it is long, then it affects routing less, when considering LD. Hence, when LD is considered this type of movement results in significant throughput reduction and increase in delay, as well as additional signaling due to the route re-computation.

By considering RLD it is possible to decrease the

impact of mobility on routing, if the tolerance interval is adequately tuned. The result is an increase in performance due to lesser path re-computation. Another aspect that seems interesting to be further explored in RLD is that it is an heuristic that seems to be less sensitive than LD to movement frequency.

SSLD is also expected to offer a good improvement in comparison to LD, for this scenario. The correlation between NDS and ALB gives the means to detect that there is some repetition in terms of neighborhood. When combined to the linear ALB, it is feasible to realize that the node is moving in a repetitive pattern and hence to take a more intelligence action in terms of the decision to recompute.

When comparing the three heuristics in this scenario for short links vs. long links, we believe that the behavior is similar to the previous scenario: there is an overall performance degradation for the case of long links, given that distance increases the need for MAC contention.

C. Free Movement Scenario

In the free movement scenario, we consider the case where a node is moving away from its original position and not expected to return. The way it moves away (pattern) also impacts the movement. In this type of situation, LD suffices to ensure that path re-computation is only triggered when a permanent link break occurs. When we consider RLD, then the expected performance is similar to the one of LD if the topology is mostly static but when the movement frequency increases and with the increase in network density then the behavior of RLD becomes worse as it adds delay to the moment when a link breaks. It should be noticed that such delay, albeit always expected to be present, can be tuned through time to become less significant. An exception to this may be the situation where a node moves with a slow motion and stopping on the way for long pause times. In some cases, LD may result in path re-computation that can be avoided an instant later in time (due to a slow motion node, pausing also for long times).

Considering SSLD, our analysis tells us that when considering simpler topologies, this heuristic seems to behave in a similar way to LD. But when there is an increase in the movement frequency then SSLD may assist in providing an action on the right instant. Moreover and in comparison to RLD, there is no significant delay added when applying SSLD. As for the three types of scenarios, SSLD seems to be the better suited for the confined movement scenario.

VII. CONCLUSIONS AND FUTURE WORK

This paper addresses ways to make multihop routing more sensitive to movement. We introduce the problem space of impact of mobility on routing and discuss a few existing parameters and also some novel parameters that may be considered to track mobility in routing. Based on the analysis and discussion of such parameters, we propose heuristics based on the notion of link duration to

attempt to make routing more sensitive to node mobility. Such heuristics are then compared against the current definition of link duration for a meaningful set of scenarios.

Albeit being initial work that requires further delving, the provided comparison hints that the two heuristics being proposed, namely, the RLD and the SSLD, are relevant enough to be considered as potential candidates to assist multihop routing in terms of mobility sensitivity. While the RLD seems to be more relevant for scenarios that exhibit some repetitive motion pattern, SSLD seems to provide an overall good performance, in particular for confined movement scenarios.

As future work we intend to further detail the two proposed heuristics, and to provide an evaluation of them against LD for the most popular forms of multihop routing (distance vector and link-state approaches).

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Table II
COMPARISON OF THE LD HEURISTICS.

| Heuristic | Network density | Movement frequency | CONFINED MOVEMENT | | PING-PONG | | FREE MOVEMENT | |
|-------------|-----------------|--------------------|---|--|--|---|---|---|
| | | | Short links | Long links | Short links | Long links | Short links | Long links |
| LD | Low | Low | - Path re-computation hardly triggered without need | - Path re-computation hardly triggered without need but error probability higher than with short-links | -Some path re-computation -Some throughput reduction and delay increase. - only affects parts of the network | -Some path re-computation -Some throughput reduction and delay increase - Worse performance overall than in short-link | - Path re-computation triggered without need if node speed is low. | - Path re-computation triggered without need if node speed is low. |
| | Low | High | - Path re-computation triggered without need - Movement frequency dictates performance degradation | - Path re-computation triggered without need - Movement frequency dictates performance degradation | - Path re-computation triggered without need - Movement frequency dictates performance degradation - only affects parts of the network | - Path re-computation triggered without need - Movement frequency dictates performance degradation - Worse performance overall than in short-link | - Path re-computation triggered without need if node speed is low. - Link break hard to predict/anticipate | - Path re-computation triggered without need if node speed is low. - Link break hard to predict/anticipate |
| | High | Low | - Path re-computation hardly triggered without need | -Path re-computation hardly triggered without need - Slightly worse performance overall than in short-link | -Some path re-computation | -Some path re-computation - Worse performance overall than in short-link | - Path re-computation triggered without need if node speed is low. - Plenty of alternative paths | - Path re-computation triggered without need if node speed is low. - Link break hard to predict/anticipate |
| | High | High | - Path re-computation hardly triggered without need -Throughput reduction and delay increase due to MAC contention | -Heavy path re-computation -Heavy throughput reduction and delay increase due to MAC contention - Worse performance overall than in short-link | -Heavy path re-computation -Heavy throughput reduction and delay increase due to MAC contention | -Heavy path re-computation -Heavy throughput reduction and delay increase due to MAC contention - Worse performance overall than in short-link | - Path re-computation triggered without need if node speed is low. -Plenty of alternative paths | - Path re-computation triggered without need if node speed is low. - Link break hard to predict/anticipate |
| RLD | Low | Low | - Similar performance to LD but slight increase in delay | - Similar performance to LD but slight increase in delay | - slight improvement when compared to LD | - slight improvement when compared to LD | - Slightly worse performance than LD | - Slightly worse performance than LD |
| | Low | High | - Good improvement compared to LD - Less sensitivity to movement frequency | - Good improvement compared to LD - Less sensitivity to movement frequency | - Good improvement compared to LD | - Good improvement compared to LD - Worse performance overall than in short-link | -Good improvement to LD if node speed low and node pause time is high and frequent | -Good improvement to LD if node speed low and node pause time is high and frequent |
| | High | Low | - Good improvement compared to LD but slight increase in delay | - Good improvement compared to LD but slight increase in delay | - Good improvement compared to LD | - Good improvement compared to LD - Worse performance overall than in short-link | - Similar to LD | - Similar to LD |
| | High | High | - Good improvement compared to LD - Less sensitivity to movement frequency | - Good improvement compared to LD - Better sensitivity to movement frequency | - Good improvement compared to LD | - Good improvement compared to LD - Worse performance overall than in short-link | -Good improvement to LD if node speed low and node pause time is high and frequent | -Good improvement to LD if node speed low and node pause time is high and frequent |
| SSLD | Low | Low | - Similar performance to LD | - Similar performance to LD | - Similar performance to LD | - Similar performance to LD | - Similar performance to LD | - Similar performance to LD |
| | Low | High | - Slight improvement compared to LD - No delay added | - Slight improvement compared to LD -No delay added | - Good improvement compared to LD | - Good improvement compared to LD | - Slightly better performance than LD | - Slightly better performance than LD |
| | High | Low | - Slight improvement compared to LD - No delay added | - Slight improvement compared to LD - No delay added | - Slight improvement compared to LD - No delay added | - Slight improvement compared to LD - No delay added | - Slightly better performance than LD | - Slightly better performance than LD |
| | High | High | - Good improvement compared to LD - No delay added | - Good improvement compared to LD - No delay added | Slight improvement compared to LD - No delay added | - Slight improvement compared to LD - No delay added | - Slightly better performance than LD | - Slightly better performance than LD |