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Energy-efficient Routing in User-centric Environments

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***Abstract*—This paper is focused on the analysis of energy-aware multihop routing metrics for wireless environments which integrate heterogeneous devices that are carried or owned by Internet end-users. The paper gives our own (initial) perspective on how network energy-savings may be improved by considering not only a single (sender) node perspective, but also the perspective of its potential successors when devising energy-aware routing metrics.**

***Keywords*-Multihop routing; energy-efficiency; user-centric networks.**

I. INTRODUCTION

User-centric wireless environments integrate a highly dynamic behavior of mobile nodes, in particular of nodes that are owned or carried by humans. Examples of such environments and dynamism is the need to autonomously start a network based on end-user devices after a disaster of some nature (e.g. disaster networks) or even the need to assist emerging markets in remote areas, sometimes highly populated. Such user-centric environments attain specific requirements, of which *energy efficiency* is one of them.

Albeit being spontaneously deployed, user-centric environments rely on traditional *multihop* routing approaches. Multihop routing has been extensively analyzed and optimized in terms of resource management, but in terms of energy efficiency there is a lack of a thorough analysis in particular in what concerns user-centric environments such as *User-provided Networks (UPNs)* or *Mobile Ad-hoc Networks (MANETS)*. On the other hand, there is considerable related work in the fields of energy efficiency and energy awareness for sensor networks. Even though it is relevant to consider the results achieved in such networks, there are specific requirements of user-centric environments which make energy awareness and efficiency problems that are not trivial to be solved. Firstly, nodes in user-centric networks are expected to be heterogeneous in terms of resources such as battery capacity. Secondly, such nodes exhibit frequent movement and are also expected to frequently join and leave a network.

Our proposal has as motivation to understand the potential of current energy-aware routing metrics and whether or not they may make sense when applied to routing in user-centric environments. To meet our expectations, we consider natural ways to make multihop routing more flexible, namely, the inclusion of energy-aware routing metrics. As such, we discuss in this paper a number of existing energy-aware routing metrics based upon the perspective of a single (source) node. In addition, we discuss the potential benefits of including the energy-awareness perspective of the successors of a node, and how it may improve not only network energy savings, but also increase network robustness. It should here by emphasized that the idea behind our work is to consider at an instant in time a metric that is capable of capturing not only a source node energy-awareness, but also the same perspective but from the available successors. In other words, it is our belief that such metric should be able to capture energy-awareness from the perspective of the **routing** association between two nodes. This is different than the perspective of the link energy-awareness capability, which is today in common literature related to the signal strength perceived by a node.

This paper is organized as follows. Section II describes related work focused on multihop energy efficiency. Section III presents assumptions and requirements in terms of energy awareness and efficiency that user-centric environments need. A generic example of a user-centric networking environment is also presented. The current energy-aware routing metrics are described in section IV as well as the computational aspects of such metrics, relevant to a deeper understanding of this field. Section V is our proposal to optimize the choice of potential successor nodes (perspective of the association between two nodes), based on an energy-aware perspective. Conclusions and future work are presented in section VI.

II. RELATED WORK

A few approaches [1], [2], [3] have surveyed multihop proposals focused on energy efficiency, considering both the energy spent when nodes are engaged in active communication or inactive communication (e.g., in idle mode). Such work has as underlying scenarios heterogeneous environments, and always assume the single perspective of the sender node.

Specifically attempting to make multihop routing more flexible, some proposals [4], [5], [6] have explored new metrics having in mind different types of optimization, e.g., reduction of energy spent across a path or avoiding nodes with low residual energy, on the global network.

Attempting to understand optimal properties that multihop routing should globally consider, C. K. Toh provides a relevant overview [7] of different routing properties to consider, being one of them efficient utilization of battery capacity.

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In this work, the author also addresses the performance of power efficiency in ad-hoc mobile networks by analyzing four approaches which have as common goal to select an optimal path, being the optimum the minimization of the total power required on the network (across all nodes) and also the maximization of the lifetime of all nodes in the network. This is the work that is the closest to ours in the sense that we provide an analysis of existing energy-aware routing metrics in user-centric environments. However, our work proposes addressing energy awareness not only from a sender's perspective but from an association between two nodes, i.e., link perspective.

A few other works that relate to power awareness and which are not directly related to our work, are relevant to cite here. Lent et al. employs smart packets to take advantage of overhearing and optimizing the choice of available (closest) neighbors without incurring the associated flooding penalty [8]. We cite this work here as it is relevant to make a distinction to our work. Our proposal is not to optimize the choice of successors that are closest to our node (and then possibly indirectly improve energy savings from the source node perspective) but instead to optimize the energy-savings across a network by building paths based on a routing metric that is energy-aware and that takes into consideration the perspective of two associated nodes.

III. ENERGY AWARENESS IN USER-CENTRIC ENVIRONMENTS

This section covers notions, assumptions and requirements related to energy awareness in user-centric environments. We start by providing a few notions that will assist the reader throughout the next sections.

A *node* represents a wireless heterogeneous device with a single or with multiple network interfaces. Edges interconnecting nodes are represented as *links* with a cost which is a measure of energy expenditure. Such energy expenditure can be obtained from a single node, a link, or network utilization perspective. From a single node perspective, there are three main modes of operation which depend on the node status. A node is in *Transmit mode* when transmitting information. Hence, *Transmit Power (Tx Power)* for a node corresponds to the amount of energy (in Watts) spent when the node transmits a unit (bit) of information. A node is in *Receive mode* if it is receiving data. Hence, *Reception Power (Rx Power)* for a node corresponds to the amount of energy (in Watts) spent when the node receives a unit (bit) of information. Particularly for the case of 802.11, there are two additional states a node may be at. When not receiving or transmitting, the node is still listening to the shared medium (*overhearing*) and is said to be in *Idle mode*. When the node is not overhearing, then it is said to be in *Sleep mode*. In this mode, no communication is possible but there is still a low-power consumption.

The way a node spends energy relates to an *energy consumption model*, which dictates how much energy (how many units) are spent for each mode per unit of data (transmitted, received, overheard). Then, different node metrics can capture such energy spendings or savings, and thus can make a node energy aware up to some point. Feeney et al., for instance, provide a general model [9] for per packet energy consumption, i.e., energy spent by a node when it sends, receives, or discards a packet.

As previously addressed [10], user-centric routing has to take into consideration some aspects which are intrinsic to the way that humans move and establish social contact, given that this behavior is today the basis for user-centric wireless networks. We provide an example of a generic scenario that can capture this in Figure 1, where the notion of group is depicted by a dotted line around a few nodes - mobile nodes. Groups have a spatial-temporal correlation, e.g., a group at an instant in time may dissolve on another instant in time and space. The illustrated nodes can be either *static* or *mobile*. In addition, nodes may behave as a *regular* node, or a *micro-provider* node. A micro-provider node is basically a node that provides Internet access to other nodes. It should be noticed that in contrast to the notion of *gateway* in MANETs, a micro-provider may simply *relay* Internet access from a gateway to a group of nodes. Furthermore, a micro-provider node may be completely mobile. Therefore, the topology presented in Figure 1 shows a highly dynamic behavior, where not only links are bound to frequently change, but also where the nodes that provide Internet access can also change on-the-fly, e.g., due to congestion of the micro-provider(s) in the group, due to better network conditions.

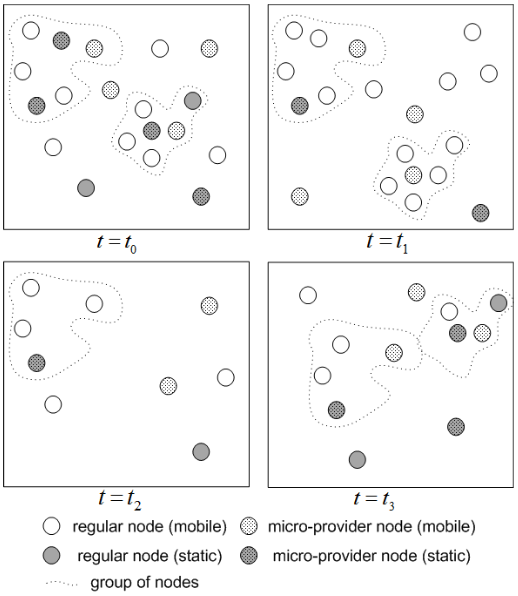


Figure 1: User-centric networking environment example.

Under the scenario illustrated in Figure 1, there are varying features which are relevant in terms of routing. To exemplify some potential changes, Figure 1 illustrates these changes in different instants in time. For instance, in time $t = t_0$ there are two groups of nodes and some isolated nodes. In time $t = t_1$, there are less static nodes, i.e., some nodes changed their behavior according to the network conditions and one group moves to another position. In time $t = t_2$, one group dissolved and some micro-provider mobile nodes changed their status becoming regular nodes. In time $t = t_3$, another group is created and changes the position. There are then more static nodes and micro-provider nodes.

In such dynamic environment and since the nodes are not only battery operated but also limited in terms of resources, the routing needs to adjust well in terms of energy resources of nodes.

IV. CURRENT ENERGY-AWARE ROUTING METRICS

Energy-aware routing metrics are normally associated to the perspective of a node and hence are known as *energy-aware node metrics*. The main energy-aware node metrics are i) transmission power, ii) residual energy, and iii) drain rate. Table I provides a summary of current energy-aware node metrics. These metrics are normally used to the problem of maximum lifetime routing, i.e., increasing the network lifetime.

The *transmission power* metric aims at maximizing the network lifetime by minimizing the total energy consumption per packet. The *residual energy* metric goal is to extend the network lifetime by extending node lifetime and balancing the energy consumption per node. The *drain rate* metric aims at maximizing the network lifetime by predicting the node lifetime.

The transmission power is commonly applied as a link cost (even though it is a metric that provides only a node perspective) in shortest-path computation. The residual energy and drain rate metrics are normally considered to be applied in min-max algorithms, which explicitly avoids the minimum energy problem by selecting the route that maximizes the minimum residual energy of any node on the route. Routes selected using min-max algorithms may be longer or have greater total energy consumption than the minimum energy route. This increases per packet energy consumption, but it generally performs better than minimum energy routing.

There are common drawbacks for these metrics. A first negative aspect relates to the fact that all of them consider scenarios with homogeneous devices in terms of energy parameters. They are mostly used as selection metrics which are included in energy-aware routing mechanisms, so the routing decision (choosing a best path) is always provided from the perspective of the route request originator. In other words, the nodes requesting specific routes only consider their own perspective about their energy resources.

As described, what the metrics shown in Table I have in common is that they have as underlying aspect network scenarios composed of homogeneous nodes in terms of energy awareness. Such nodes normally use the same parameters of energy (e.g., Tx Power, Rx Power, Idle Power, and Sleep Power). All of them also make decisions of routing under the perspective of the sender's node. The shortest path algorithms are still used but with other carefully designed power-aware cost metrics instead of simple hop count metric.

In some approaches, the min-max cost function is applied, and thus optimizes the time until a first node exhausts on the network. However, this scheme can set up the route with an excessive hop count and then consume a lot of the total transmission energy. In terms of network lifetime and energy consumption, the problem still persists. Moreover, approaches that estimate the node lifetime have problems with the selection time to update energy values of a node. When a node that has several interfaces and several routes is forwarding packets generated from different sources, it is hard to measures the accurate values.

Out of the metrics mentioned, the most relevant to consider in our work are the drain rate and residual energy metrics, which are described in the next section.

A. Drain Rate and Residual Energy Computation Aspects

The *Residual Energy (RE)* of a node i (also known as *residual battery capacity* of node i), $RE(i)$ [11], is defined as the amount of energy units that the battery of node i has at an instant in time. The cost function used in routing is provided in equation 1.

$$R(i) = \frac{1}{RE(i)}, \tag{1}$$

where $R(i)$ is the battery cost function of node i at an instant in time. $RE(i)$ is, however, not an instantaneous metric. Instead, it requires observation through time due to the energy fluctuation level. $RE(i)$ could be updated each time a packet is sent, received but still, this would imply too much overhead in terms of computation. Hence, $RE(i)$ is normally computed based on a time window T.

The *Drain Rate (DR)* of a node i [12], $DR(i)$, is defined as the amount of energy being spent by node i through time due to the activities the node is performing (e.g., sending or receiving; overhearing). $DR(i)$, can be computed by applying an *Exponential Weighted Moving Average (EWMA)* as shown in equation 2.

$$DR(i) = \alpha \times DR(i)_{t-1} + (1-\alpha) \times DR(i)_t, \tag{2}$$

where $DR(i)_{t-1}$ and $DR(i)_t$ represent the previous and the newly calculated values, respectively. For the original definition, node i computes $DR(i)$ every T seconds, i.e., based on a time window T.

The DR alone simply provides a way to measure energy being spent by nodes. However, it cannot capture the nature of a node. For instance, both a PDA and a Laptop may hold the same level of DR at an instant in time and yet, it is likely that the PDA will exhaust resources sooner. It should be noticed that DR was developed having in mind homogeneous nodes.

For heterogeneous environments, a combination of the DR with the RE of a node is significant to capture both the expenditure and the resources still available. Such combination can be provided in several ways. The authors of the drain rate provide such a definition by considering the ratio between the RE and the DR of a node i as shown in equation 3.

$$C(i) = \frac{RE(i)}{DR(i)}, \tag{3}$$

where $C(i)$ provides a measure of when the battery of a node may be exhausted, based on the expenditure rate (DR) that the

Table I: Overview on current node metrics.

	Transmission power	**Residual energy**	**Drain rate**
Main goal	- Extends network lifetime - Minimizes the total energy consumption	- Extends network lifetime - Extends node lifetime - Balances energy consumption	- Extends network lifetime - Extends node lifetime
Cost function	- Shortest path - Tx power	- Shortest path - Battery capacity	- Shortest path - Residual energy and past activities (drainage)
Path optimization	- Minimum total transmission power of path	- Min-max algorithm - Sum of battery life along the path - Avoids nodes with low battery	- Min-max algorithm - Minimum drain rate - Maximum path lifetime - Predicts lifetime of nodes
Network utilization	- Energy consumed per: packet, flow, path, bit	- Time to network partition	- Time to network partition - Maximum node cost
On demand routing	- Route discovery process	- Route discovery process - Update mechanism: rediscovery	- Route discovery process - Update mechanism: rediscovery
Link state routing	- Update routing table	- Update mechanism: energy status to neighbors	- Update mechanism: energy status to neighbor
Advantages	- Tx power of sender node	- Considers battery capacity	- Node lifetime of heterogeneous nodes - Traffic conditions in a node
Node perspective	- Homogeneous	- Homogeneous	- Heterogeneous
Node energy parameters	- Homogeneous devices	- Homogeneous devices	- Homogeneous devices
Routing decision	- Sender node	- Sender node	- Sender node
Reliability	- No	- No	- No
Robustness	- No	- No	- No
Adaptability	- No	- No	- No
Drawbacks	- More hops path: end-to-end delay - Does not consider battery capacity - Shortest path: fast node depletion - Does not extend the network lifetime	- Overhead of control packets - Does not measures the real battery status - Time window based	- Overhead of control packets - Does not ensure the least energy path - Drain rate update mechanism - Time window based

node has at an instant in time. For routing, $C(i)$ is a better measure to understand how long can a node cope with routing operations, i.e., node lifetime.

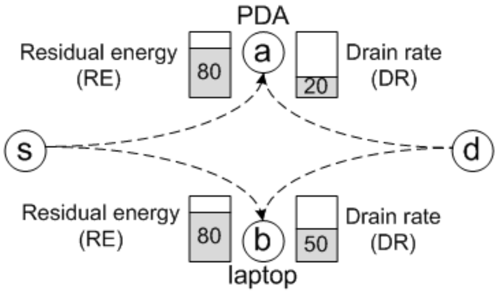


Figure 2: Simple scenario to explain differences from a routing perspective in applying $DR(i)$, $RE(i)$, and $C(i)$.

Let us provide an example to show the difference of applying $RE(i)$ and $DR(i)$ in combination or in isolation. Figure 2 represents 4 nodes, s, d, a, and b. Node s is the sender and node d is the destination. Let us start by applying only $RE(i)$ to obtain a shortest-path between s and d. If only $RE(i)$ is considered, then both nodes a and b are valid successors since they have the same residual energy values. Instead, if $DR(i)$ is applied in isolation, then node a would be chosen as successor. However, node a is more likely to be quickly left out without energy unless powered, given that it is a PDA. By applying $C(i)$, we get better accuracy in terms of not only the potential level of battery, but also of the energy drainage rate. That means node a would be selected since its lifetime is greater than node b's.

B. *User-centric Issues*

Out of the analysis on current metrics, and having as underlying scenario the dynamic, user-centric, and heterogeneous scenario described in section III, we here define some identified gaps. The current energy-aware metrics were devised for homogeneous scenarios and the ones that are the most significant to consider in heterogeneous scenarios are $DR(i)$, $RE(i)$, and the ratio between these two, i.e., $C(i)$. All of these metrics relate to a node perspective only and such perspective may affect path robustness.

In terms of energy awareness in routing, energy-aware metrics are normally based on fixed time window updates. This may result in lack of synchronization due to the fact that paths are computed based on requests which carry a specific metric as link cost. The resulting routing trade-off in terms of path robustness vs. network lifetime improvement could be optimized by adequately adjusting the time intervals to specific conditions. Current energy-aware approaches either attempt to minimize the cost of the forwarding path(s), or to maximize network lifetime. This is an aspect that results of such approaches applying energy-aware node metrics.

Additionally, considering that nodes are chosen based on the lowest DR at a given moment, such DR value does not reflect the real energy expenditure e.g., if the node experiences abrupt traffic variation. We believe that energy-aware link metrics may address the aforementioned issues, as detailed next.

V. OUR PROPOSAL: ENERGY-AWARENESS FROM A LINK PERSPECTIVE

As shown in Figure 3, an energy-link metric consider not only a perspective of a node (node metric) but also the perspective of potential successors at the same instant in time. In other words, when nodes perform a request for specific routes, they would consider not only their own perspective about their energy resources, but also the perspective sent by successors in the meanwhile about their own resources. Hence, what we are arguing is that a link-based metric may be better suited for multihop routing approaches than a pure node-based metric. As basis for the discussion provided, we consider $C(i)$ as the most relevant node-based metric, for the reasons already mentioned in section IV. Our proposal is two-fold. First, to consider how such link perspective can be provided. Second, to assist in devising an adequate computation for the metric, by providing a way to dynamically adjust the related time-window. We explain these two aspects in the next sections.

A. *Optimizing the Choice of Successor Node(s)*

Let us consider Figure 3, where s, the originator node, is looking for a suitable path to node d. Potential successors of s are node a, a cell phone, and node c, a laptop. In this example, both possible paths $s-a-b-d$ or $s-c-e-d$ have a corresponding cost of 200 units. Moreover, the choice of a successor depends on the protocol applied but is heavily dependent on the perspective of node s. Hence, when s opts for a it is simply having into consideration the amount of units that node a has left. It is not, however, considering the perspective of the association between node a and b. The path $s-a-b-d$ is clearly weaker in the sense that if traffic in nodes a or b increases then the change in cost may be more abrupt in path $s-a-b-d$ than in path $s-c-e-d$. Therefore, if s would have a way to opt for node c as successor instead of a, the resulting path would in fact be more stable and the result would be an increased network lifetime. What we are arguing is that by providing each node with the perspective not only of itself but in fact based upon an association between the node and each of its successors, one will achieve more robust paths and ultimately have as consequence an increased network lifetime. For the example provided in Figure 3 and for the path $s-c-e-d$, this means that s would be aware of some link cost related both to $C(s)$ and $C(c)$.

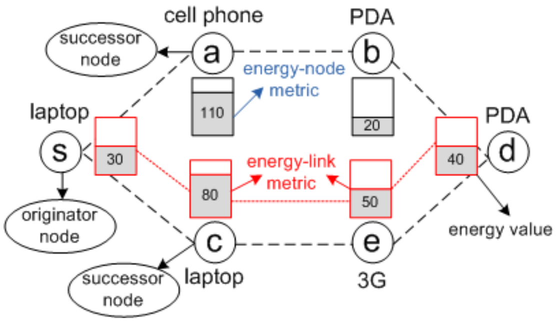


Figure 3: Scenario showing how information on energy awareness on the association of two nodes may be beneficial in comparison to a node-based perspective.

Let us provide an example related to how such a link perspective can be defined. Figure 4a nodes a, b, c, s, correspond to heterogeneous wireless devices (e.g., laptop, PDA, cell phone, etc). Instant t_0 and instant t_4 represent the instants when $C(i)$ is computed, based on $DR(i)$ and $RE(i)$ samples. The values provided in the circles correspond to the node lifetime based on its $C(i)$ computation. For instance, in instant t_0 the originator node s computes $C(s)$. In instant $t = t_1$ and upon the reception of an answer from each successor, node s chooses node a as successor. In $t = t_2$ node s keeps node a since the node lifetime is higher than the lifetime of c. But then in $t = t_3$, node a sees its energy level quickly decreased and in $t = t_4$ the link between s and a disappears given that a exhausted its battery. Hence, path re-computation is triggered at instant $t = t_4$ only, given that at that instant and before the detection of the link break there is a re-computation for the cost of the link.

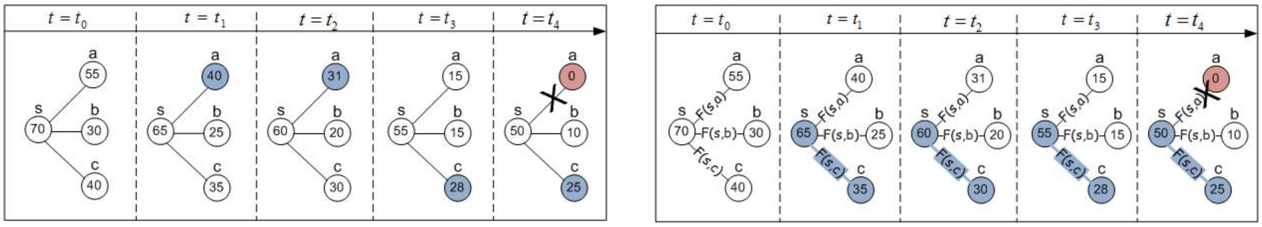
Figure 4b provides an illustration of the benefits introduced if one considers a link perspective. In instant $t = t_0$, the energy values of each node are measured and sent to node s. Then node s estimates the lifetime for itself and its successor nodes. Based on prediction model, such estimation makes node s select node c as a successor despite the fact that at instant $t = t_1$ node a holds a higher value than c. The reason for the choice of s relates to the fact that what is being considered now is both s and its successors perspective. Such perspective gives a prediction that the node a will quickly exhaust its battery during the time line, i.e., is going to die in instant $t = t_4$. The result of this is lesser path re-computation due to a better choice of the successor node before the link break due to energy drainage of the node.

The function that gives the link cost is $F(i, j)$, where i and j are adjacent nodes, $F(i, j)$ is simply a combination of both the perspective of the originator and each of its successors at an instant in time and may take several parameters which are to be defined in future work. For instance, $F(i, j)$ could be equal to the minimum value provided by the originator and its successors. The full definition and description of F is left out of this paper, to be defined in future work.

B. *Automatically Adjusting the $C(i)$ Computational Time Window*

As briefly discussed, a link-based perspective assists in providing more robust paths. However, it is also necessary (both for the node-based and link-based perspectives) to consider a mechanism that is able to automatically adjust the computational time window. In other words, what we are proposing is to consider a learning time window mechanism that is dependent on the slope variation of the energy-aware metric, e.g., $C(i)$. It should be noticed that for the specific case of the time window proposed adjustment mechanism, $C(i)$ can be based upon a node perspective (and hence i corresponds to a node) or from a link perspective (and hence i is a link).

Considering the adjustment of the time window and again relying on the previous section example (cf. section V-A, Figure 4b), the time window is defined as $T = t_4 - t_0$. This is a fixed time window. Now, let us imagine that $C(i)$ is in fact stable for the duration of $10 \times T$. If the time window were to be adjusted to become longer, then lesser path re-computation would occur. Thinking of the opposite case, where $C(i)$ actually experiences abrupt changes within e.g., a $2 \times T$ period then a shorter time window may also assist



(a) Example based on a node perspective.

(b) Example using link-based perspective.

Figure 4: Example for the choice of successors based on energy-aware metric.

in preventing path re-computation, by allowing to understand quicker potential variations of $C(i)$ and hence provide a better choice of successors quicker.

An automatic time window adjustment function is defined in equation 4.

$$\triangle C(i) = \alpha(C(i)_{t-1} - C(i)_t)_{t-1} + (1-\alpha)(C(i)_{t-1} - C(i)_t)_t \tag{4}$$

Based on such formula, T can easily be adjusted as described in table II which summarizes the impact of $\triangle C(i)$ on the time window T.

Table II: Variation of the time interval.

$\triangle C(i)$	Time Window Adjustment
- Large, positive value - Indicates abrupt decrease in $C(i)$ slope	- Reduce time window significantly
- Large, negative value - Indicates abrupt increase in slope	- Reduce time window
- Small, positive value - Indicates a small difference	- No change required
- Small, negative value - Indicate small difference	- No change required
- Zero	- Increase time window

As explained, if $\triangle C(i)$ is large then there is a strong impact on the time window. If instead $\triangle C(i)$ is small then no change to the time window is required. If $\triangle C(i)$ is zero for a few rounds then we can increase T.

VI. CONCLUSIONS AND FUTURE WORK

Energy efficiency is a key aspect to consider in user-centric routing environments and in order to better assess how to integrate such awareness into current multihop routing protocols we have discussed energy awareness aspects and metrics in regards to routing. We then make a proposal in regards to the way that energy awareness is transmitted in routing and also in regards to the time window computational aspects.

We believe that our proposal can improve the network lifetime. Both a link-based perspective and an automatic time window update will result in: i) less path re-computation thus resulting in a signaling reduction and less latency; ii) more reliability and accuracy due to the automatic time window adjustment; iii) more robust paths given that adequate successor nodes shall be chosen earlier in the routing process. As future work, we intend to validate our proposal by means of discrete event simulations.

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