User-centric Networking, Routing Aspects

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1 Introduction

Wireless revolutionizes local area communications permitting the general public to provide communications services as well as to become micro-providers in *User-centric Networks (UCNs)*. This emerging networking paradigm relies in the user's willingness to share connectivity and resources. In comparison to traditional Internet routing scenarios (be it based on wireless or fix line technologies), UCNs bring in forwarding challenges, due to their underlying assumptions, namely: i) end-user device nodes may behave as networking nodes, ii) nodes have a highly nomadic behavior, iii) data is exchanged based on individual user interests and expectations.

Furthermore, emerging trends such as UCNs adding to the development of faster, more reliable wireless standards, miniaturization of devices, and reduced costs of hardware and services, is leading to a fast evolution of technological as well as societal aspects in the way that people communicate. For instance, people expect to be able to send and retrieve information whenever and wherever they want. Yet, there are technological limitations which may affect this anytime-anywhere communication paradigm, e.g. gray areas (i.e., areas where the wireless signal strength is not enough to sustain connectivity); physical obstructions; limited battery devices; environmental aspects; limited resources and security issues. Related literature has been addressing aspects to mitigate wireless interference and to take advantage of cooperative diversity which may mitigate some of the problems posed by physical obstructions and coverage problems due to node mobility. However, it is imperative to say that, since information is relayed among nodes and these nodes can be highly dynamic, communication may experience delay, varying from short to long periods, as isolated areas (e.g., intermittent connected networks) may form in the case of node failure (e.g., damaged AP) or mobility (e.g., user changes position). Thus, to increase the performance of multi-hop communication, several improvements can be made, by taking advantage of transmission opportunities provided by moving nodes and accessible APs, for instance. This may occur, for instance, when a user is at a public location without Internet access. If other users are in the vicinity, and such users

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are part of a UCN, then some of them may share Internet access and data can be relayed until it reaches the closest Internet gateway. Another situation may occur when information is simply carried by users that happen to be moving towards the place where the destination is located. Nowadays, this is possible thanks to the size of devices which are making them easier to carry around, and also to the resource capabilities they have. For instance, the HAGGLE EU project [1] exploits store-carry-and-forward capabilities (i.e., devices' powerful features, user willingness, trust among users, opportunistic contacts) aiming to provide communication in scenarios with intermittent connectivity. HAGGLE considered human mobility and the power of users' devices to perform forwarding of information independently of the network layer. So it is easy to see that the way people communicate is arriving at a point where such communication must happen independently of the infrastructure available, and depending on the capabilities of intermediary devices as well as their mobility pattern, interests and social ties.

In what concerns the network layers, this new communication paradigm demands more reliable and efficient protocols, as today we have areas where spectrum abounds and creates interference - dense networks, e.g. residential households, shopping malls) as well as areas where communication is only possible through the formation of clusters of users (e.g., intermittently connected networks). Even in a metropolitan area, intermittent connected networks exist due to wireless environments, unexpected disruptions, and areas where the networking infrastructure is sparse (e.g., city parks).

Understanding human mobility and social interaction is important for the adequate operation of data transmission in the context of UCNs. Different types of models have been proposed in the last decade, from those founded on purely synthetic movements, such as the ones based on purely random movements of the nodes, to the ones aiming at reproducing the mobility patterns inside specific places. New insights and more refined and realistic models are still needed, bringing together real world measurements and mathematical characterization of node mobility. So now, besides considering the characteristics of the wireless medium and aspects that influence its functionality, other relevant characteristics as user's interests and their social interaction (resulting from the way people move) have a key role when it comes to establishing communication and managing it considering resources available and trust among users. The former has shown itself rather useful when it comes to the dissemination and retrieval of information, while levels of social interaction with family, friends, acquaintances, and total strangers dictates when and how such dissemination and retrieval is going to happen. Last but not least, a routing solution for user-centric networks must consider two basic aspects: robustness from an end-to-end perspective, and intermittent connectivity support. This last aspect is a major requirement to operate a future Internet, which means that routing systems must be able to keep graphs connected.

2 Related Work

With the advent of Web2.0 and the rise, both in variety and in coverage, of wireless technologies and user-friendly devices, there is a change in terms of Internet user behavior: the user is becoming more than simple consumer of services, to have roles where he/she shares or even provides networking services. Sofia and Mendes [2] describe new user-centric communication models, in which the user is not only a consumer but also a provider of communication opportunities (user empowerment) and alerts to the need to consider user-centric communications as part of an Internet of the future. Our work builds upon the models the authors describe with a specific focus on user-centric routing. Since most of the users are currently connected by means of wireless links, it is important to investigate algorithms and metrics to increase reliability and performance over multiple paths dynamic wireless networks: i) multi-path due to wireless diversity; ii) dynamic due to users' behavior.

In what concerns multihop routing, the most popular approaches such as AODV and OLSR have been engineered to sustain better *Quality of Service (QoS)* but not dynamic node movement. A line of work has addressed this need based on the definition of metrics that make a network more robust by taking into consideration link duration [5]. Chama et al. [24] has provided an extensive analysis on parameters capable of tracking a few aspects of mobility in routing protocols as a way to derive metrics that can be applied to multihop routing approaches, to make them more sensitive to node movement and hence, reduce the need for path recomputation.

A relevant aspect addressed in related literature concerns the capability to allow the network to expand based on heterogeneous and portable devices. These are often carried and transported by humans. In regards to reducing the energy consumption in mobile devices, there have been efforts in physical and data link layers as well as in the network layer related to the routing protocol as has been detailed by Oliveira Junior et al. [27]. Most of the related proposals consider energy-efficiency from an engineering perspective, i.e. extensions of the existing on-demand and link-state routing make modifications in the protocols to devise energy-awareness.

One of the major assumptions in UCN and for which routing has to be prepared is the intermittent characteristic of wireless connectivity. This intermittent behavior may occur in sparse networks such as in small villages, rural areas, or disaster areas, as well as in dense urban networks. In the latter case, intermittent connectivity may be due to wireless interference. Ad-hoc routing protocols such as AODV [3] and OLSR [4] assume that a complete path always exist between a source and a destination, and try to discover minimum cost paths. This means that such protocols are useful for networks with low to medium dynamics. While in UCNs the movement of nodes follows their owners behavior - human movement patterns -, behavior that may lead to situations where some end-to-end paths may not be temporarily suitable for communication. A family of algorithms (e.g. epidemic, gossip, greedy) [7,6,8,9,10,11] tries to make use of user mobility to route information in loose connected graphs, as the ones provided by end-users. The primary focus of this family of algorithms is to increase the likelihood of finding paths, using only information about spontaneous local connectivity. However, such algorithms are agnostic to the status of the network in terms of connectivity (potential contacts), storage and queuing capability of nodes and bandwidth capability of links. Their final goal is only to increase the probability that a message is really delivered to its destination. A more realistic scenario for user-provided networks is the one in which: i) most of the nodes have resource constraints, and ii) local connectivity may also be predictable or scheduled (e.g. connectivity provided every day while driving to work). However, routing solutions for these UCN communication scenarios have received little attention to date. The needed investigation should analyze the trade-off between delivery probability and resource usage: for instance, distributing messages to a few or large number of nodes will increase the probability of delivering a message to its destination, but in return, more resources will be used.

Balasubramanian et al. [12] propose an algorithm to replicate packets optimizing a specified routing metric in scenarios where nodes have limited resources. However, the authors do not consider node dynamics as well user behavior, such as willingness to cooperate in message forwarding. The latter limits the impact of the proposed algorithm, since nodes are autonomic in the sense that they can decide on their own whether to implement or not the rules of a routing algorithm [13]. In terms of applications support, most of the previous proposals consider only applications tolerant to changing network conditions, such as delay and losses. However, although some applications are tolerant to quality oscillations this does not mean that they would not take advantage from low delay and minimum number of expired messages. For instance minimizing delays reduces the time messages spend in the network, reducing the contention for resources.

Regarding evaluation frameworks, we highlight the most recent opportunistic routing proposals are based on *Evolving Graph (EG)* theory to design/evaluate least cost routing protocols. EG provides a formal abstraction for dynamic networks and reflects the different connectivity graphs in the time domain by considering node mobility. The result is that connectivity of links are transcribed into subgraphs for different instant in time. Thus, Newman et al. [43] take into consideration one of the formalized EG criteria (i.e., foremost) to determine journeys (i.e., future temporary connections between nodes that can form a path over time) in which data can quickly reach its destination. This evaluation framework provides designers with an algorithm that is able to reach good performance in scenarios where connectivity patterns are known beforehand. Additionally, the algorithm can be used as lower bound reference to compare opportunistic routing solutions. The work of Spyropoulos et al. [41] provides principles to help developers in designing routing solutions based on their classification of opportunistic routing, identified utility functions. The authors show that by knowing the application characteristics and requirements, the choice/design of routing solutions is eased. Still, both works lack a guideline of how performance metrics and experimental setups can be used.

3 Use-Cases, Assumptions and Requirements

This section provides a characterization of a UCN scenario, including a set of assumption and requirements, to assist in the debate concerning user-centric routing. To clarify main differences against other autonomic networks, the section also provides a comparison of connectivity features for UCN against ad-hoc and other forms of multihop networking.

Fig. 1 provides a high-level perspective on potential cases of UCNs, to assist in the description of two potential applicability cases which are described next, namely, a scenario based on dense networks, and the other based on challenged communications. The intent is to assist in explaining routing assumptions and requirements that are today already present for UCN environments.

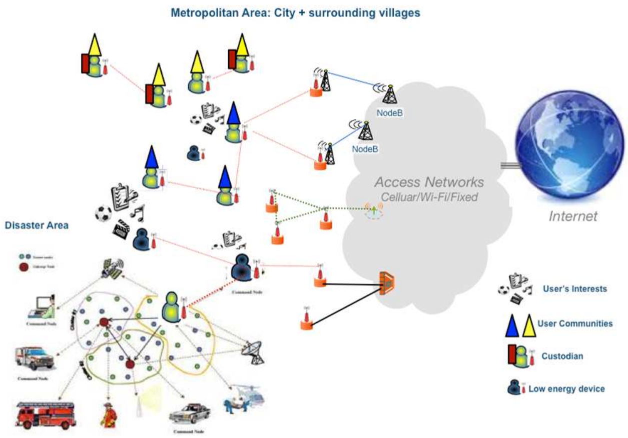

Fig. 1. High-level perspective on potential UCN infrastructures.

3.1 The CityRoam Scenario

CityRoam stands for an example of an applicability scenario based on community services. The citizens registered in the system have the right incentive [14,15,16] to forward data to other registered users via *Wireless Local Area Networks (WLANs)*. The users may also agree to share their subscribed Internet connection (mobile, fixed, or wireless) [17]. Here, UCNs exhibit the usual spontaneous growth based on the idea that the dissemination of information is expected to improve the citizen's daily life. For instance, by means of such spontaneous settings, citizens can get local information concerning e.g. traffic or up-to-date situations. They can also exchange messages independently of their location and terminal. This is therefore a context-based applicability scenario where there is a backbone provided by the city eventually in agreement with several operators.

Then, User Equipment (UE) shares services based on specific policies and local trust/security management, thus giving users the opportunity to connect even in gray areas. Consequently, CityRoam is partially based upon end-users willingness to forward data and share their Internet access and results in increased coverage (capillarity) from the provider perspective.

Description Maria is a professional in a highly demanding job. As her day is packed with meetings starting early in the morning, she would like to make sure she has all the necessary items with her before leaving her house. This includes her mobile, keys, glasses, wallet, and electronic company identification card. These devices exchange information, creating an opportunistic network. When leaving her apartment door, the door key initiates a check to see that she has everything. She has left her ID card on the counter, which causes an alarm, sending a notification to her mobile. Maria leaves home very early to go to the airport for a business trip. While walking to the bus stop the street lights shift on in a coordinated manner when she is passing by, due to a system of moving detection sensors, allowing her to walk safely to the bus stop while saving energy. At the bus station, Maria has access to the first news of the day by a city service that distribute news to bus stops. News are mostly about local activities in Maria's neighbor (provided by citizens). Maria's device interacts with the bus stop allowing the upload of news of interest to Maria. When entering the bus, Maria keeps reading the news previously downloaded, while some of them are forwarded to the device of another passenger with similar interests. As soon as Maria returns from her trip her mobile device offloads to the residential WLAN. Her phone attempts to locate her suitcase, also UCN enabled, but alas the suitcase last reported position was being loaded onto a flight to another city. Since the phone is aware of the description of the suitcase, it automatically notifies the lost luggage office of the airline with the description and a photo. The lost luggage office acknowledges receipt of the report, and thus avoiding a fruitless wait for her luggage to appear on the belt, Maria leaves to find the taxi from the company's that she always use.

Not having had a chance to buy groceries, her refrigerator, which is aware of her schedule and hence her return, knowing her meal preferences, orders the necessary grocery items and schedules the delivery for that evening when she will be home. A notification of this transaction is also sent to her mobile with an option of modifying the delivery time. Meanwhile, her luggage has arrived and based on the same schedule, her mobile arranges for the delivery of that the same evening. Following a busy day of meetings, she returns home in good time for the delivery of her groceries, and luggage. After dinner, while relaxing watching TV, her device, which is registered to the local UCN, receives a notification that some friends have decided to go to a movie in the local cinema. The device notifies the TV, which displays the information. By clicking OK in her remote, she notifies the others that she will join them.

3.2 Emergency Network

A second applicability scenario concerning UCNs and where routing is required relates with critical networking infrastructures. In such situations it is assumed that most of the available communication infrastructure in damage, which makes is difficult to setup communication in a reasonable and useful time-frame. UCN can, in this situation, assist devices in self-organizing to quickly establish a local infrastructure across UEs; wireless APs; vehicles equipped with Internet access (e.g. rescue teams). In such scenario, the plain application of current multihop routing approaches may not be enough to route data with some certainty due to the unpredictable availability of communicating devices. For instance, devices available may not be enough to sustain communication. Hence, in such situation, routing solutions need to take advantage of any transmission opportunity (*opportunistic communication*).

Description John is on a business trip to Lisbon, carrying a UCN enabled device which integrates a routing solution that allows the establishment of opportunistic communications, to route information on the fly. While driving from Lisbon to Sintra, a minor earthquake occurs near the coast and isolated fire situations spread out of control turning into a major wildfire and a major communication infrastructure is damaged. Devices of people running out of the affected areas collect sensory information (e.g. temperature) and sonic information (e.g. number and amplitude of human voices and wireless communications). This information is sent outside the affected area by any means available (e.g. undamaged cellular links, moving vehicles). Analysis of mobility patterns and available transmission opportunities gives indication about the best devices to consider in the communication process. The reception of spread information impacts the moving direction of rescue teams. While moving, these teams send rescue information towards each affected area, in order to allow people on the field to start providing first help. This dissemination is based on nodes that are moving as fast as possible towards the affected areas, and have good battery conditions. Social data provides information about spontaneously created helping groups, which can provide a more efficient dissemination of information.

3.3 User-centric Routing: Assumptions and Requirements

Based on the two examples provided in section 2, this section provides a set of assumptions and requirements for routing solutions to consider in UCN.

The primary focus of routing in the context of UCNs - *User-centric Routing (UCR)* - is to be capable of transmitting information in environments where the communication upstream (from user to the backbone network) becomes as relevant, if not more relevant, than the communication downstream (from the network to the user). UCN equipment is based on current networking technology (routers and switches) as well as on UE (relayers). Moreover, UCN equipment operation is highly dependent on social aspects, as the citizen controls part of that equipment. The operation relates with the citizen environment (e.g. urban or rural landscapes); social communities; roaming habits of the citizen.

Routing in UCNs requires networked devices to have embedded functionality that can make use of several environmental and communication interfaces, sustaining communications among an unlimited number of devices that are able to collect and process information without a constant human intervention. This is a reasonable assumption, as today any end-user device, mobile or not, integrates such features.

Assumptions In terms of communication capabilities, many of today's networks able to transmit environmental information (wireless sensor networks) are evolving toward a protocol-translation gateway model, similar to what happened before with computer networks. However, protocol gateways are inherently complex to design, manage, and deploy. The network fragmentation leads to non-efficient networks because of inconsistent routing, for instance. Moreover, the Internet today is more and more IP-based, being TCP/IP widely accepted as a flexible alternative to design scalable and efficient networks involving large numbers of communicating devices, as advocated by the *IP for Smart Objects (IPSO) alliance*, and as suggested by the action Plan for the deployment of the *Internet Protocol version 6 (IPv6)* in Europe [42].

A key assumption for routing in UCNs is that wireless devices are IP enabled, independently of their size and battery capacity. This is a key starting point although there is not a strong requirement for UCN technology to be based on IP.

We summarize the major assumptions to be observed when devising or adjusting routing solutions to UCNs as:

- UCN nodes must incorporate solutions (software or hardware based) that allow then to collect environmental and/or contextual data.
- Some devices are UCN gateways, i.e., they are capable of providing Internet access and/or routing data to controllers that can provide Internet access.
- UCN nodes may or may not have intermittent wireless connectivity.
- UCN nodes may or may not be limited in terms of battery, storage, as well as bandwidth capacity.
- Users involved in UCNs are willing to forward data to other users, passively, or actively.
- Some UCN nodes can relay data to others.

Requirements Routing in UCN aims to extend communication across the Internet assuming a humongous number of mobile devices as well as assuming that there is a relevant portion of data generated by and focused on the individual citizen.

A continuous exchange of information across such infrastructure, that has a high topological variability due to the self-organizing properties of UCNs, requires a paradigm shift in the way that routing is devised. Relevant aspects to consider relate with the need to assist data to be forwarded based on the interests expressed by objects and not instead by the reachability of a specific object, as occurs today.

Destination reachability based solutions, based on globally routable identifiers, as used today in the Internet, limits any effort to devise UCNs. Hence, one of the technological roles of routing when applied to UCNs should be to devise an information-centric routing framework that considers information based on: the user's roaming patterns (*mobility awareness*); the limited battery capacity of nodes (*energy awareness*); some aspects of social behavior, such as shared interests and the opportunities to disseminate such interests (*opportunistic data transmission awareness*).

These aspects can be summarized as the following requirements:

- Routing must be able to distribute information based on interests manifested by nodes and taking into consideration context-awareness.
- Routing must interface with or encompass some system to identify/track information blocks rather than objects.
- Routing must be able to forward information even in the presence of intermittent connectivity.
- Routing should support secure and private communications, whenever required.
- Routing performance must be ensured, independently of the number of nodes.
- Routing must be based on connectivity among peer objects, avoiding dependencies upon network devices with specific roles, in particular, dependencies on centralized gatekeepers.
- Routing must be aware of the intrinsic characteristics of nodes, such as battery, storage capacity, environmental capture capacities, processing power, and connectivity degree, in order to achieve an efficient control of available communication resources.

4 User-centric Routing

Multihop routing approaches are usually considered in any wireless scenarios. In UCNs, as explained these approaches fall short due to the variable topological UCN behavior, where formed routes will be subject to more frequent breaking due to the fact that nodes in the network are now part of the *Customer Premises (CP)* as well as limited in terms of energy capacity. A routing protocol or framework will provide or compute a route when there is need to transmit data for nodes that are not in each other transmission range. Also, when a route incurs a break on one of the links on the route, the routing protocol will recompute an alternative path for data transmission to commence. It is imperative that a discovered route be a stable as frequent path re-computations weigh down the performance of routing in terms of control overhead, increased delay, lowered throughput and in some cases packet loss will also occur.

This section gives insight into how to make current multihop approaches more adaptable to UCNs, by going over the three dimensions mentioned in section 3, namely: mobility awareness; energy awareness; opportunistic transmission awareness.

4.1 Mobility Awareness

Node movement and its impact on the network operation is often left to be taken care of by mobility management solutions (control plane). While such solutions assist in handing over data sessions, on the network layer the routing process will always experience link breaks independently of being temporary or permanent. In other words, current mobility management solutions assist in making applications agnostic to node movement up to some extent. However, the underlying layers experience such impact which will then have repercussion in the network performance.

Concerning routing, a potential way to overcome such impact is to investigate mobility metrics that assist routing in becoming more sensitive (more adaptive) to node movement patterns.

Prior work [**?**,24] has addressed potential mobility tracking parameters that can be used to derive adaptive routing metrics. Some of such mobility tracking parameters are *pause time*, *link duration* and *average number of link breaks.* From the mobility parameters that were reviewed (e.g. node degree, number of link breaks, link duration), link duration is a parameter that possesses some ability to capture properties that may assist in distinguishing between permanent and temporal link breaks. Another category of parameters that we have researched demonstrating some relevancy in terms of mobility awareness relates with the definition of the movement relation of a node towards its neighborhood, aspect which we identify as the *node's neighborhood mobility correlation*[25,20,24].

Link Time Stability *Link duration (LD)* is a parameter that is tightly related to the movement of nodes; it 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. Some authors then provide a variation of this definition by working the threshold value.

In order to assist in developing a cost associated to link stability, we have considered two different metrics associated to the notion of link break and duration, and to the relation of these two elements.

The first embodiment of link stability for link l, $s1_l$, comprises the ratio between the time a link is down (link break duration), lb, and the link lifetime lf for the duration that elapses between two consecutive breaks, as expressed in equation 1:

$$s1_l = \frac{lb}{lb + lf} \tag{1}$$

Such ratio gives a measure of stability in the sense that the more prone is a link to break, the lesser is its stability. It is a simple metric which should assist in prioritizing links over time, and in choosing the ones that have a lower $s1_l$. The ratio will avoid short-lived links, since the duration in which the link is in broken state (lb) will be large. As nodes move, new links are formed and others are broken, meaning that link stability can change with time. A good link metric is one that captures the change in link stability. A link break means that there is a change in link stability. In our metric, link cost depends on the time the link has been down: links that incur long breaks will not participate in routing in the presence of links that are stable. Link stability depends on the time the link has been down and up. Implicitly, the metric captures nodes that are in group mobility. It can differentiate links that are formed between two mobile groups whose propagation path differ. It can also capture stable nodes that are static.

In a second embodiment of link stability based on LD, we introduce an additional parameter: the *number of link breaks*, nb_l.We refer to this embodiment as $s2_l$, provided by equation 2.

$$s2_l = \frac{lb * nb_l}{lb + lf} \tag{2}$$

$s2_l$ takes into consideration the time period that a link is active, and also the number of breaks incurred with respect to a specific time-window. In comparison to $s1_l$, $s2_l$ not only considers the percentage of time a link is active, but also the frequency of breaks during that period.

To provide a concrete example, let us consider two links i and j, with the same duration: $lf_i = lf_j = 10$ seconds and also with the same link break duration, $lb_i = lb_j = 2$ seconds. However, while in i such inactive time is derived from one single, longer break, for link j that has been the product of 2 link breaks.

The routing metrics were implemented in AODV where it was found out that that our metrics, and in particular the s2 metric assists AODV in a better path selection - paths that are more steady, thus reducing the need to have path recomputation. Observed was that mobility-aware routing metrics actually improved routing performance, in both protocols, although higher improvements were noted in AODV compared to OLSR.

Node to Neighborhood Mobility Correlation A node to neighborhood mobility correlation relates with the stability that a node can provide in a path and which is dependent not only of the node's individual mobility pattern, as well as of the neighbors individual patterns towards the node - the group mobility pattern. A routing solution must therefore take into consideration not only the own perspective of a node concerning movement, but also the group relation. To capture this neighborhood movement variability, we have address the notion of node degree stability as well as the notion of link breaks in the context of group movement. The relation between the node degree at an instant in time as well as the integration of new nodes in the neighborhood are parameters, that when combined, assist in understanding the mobility variability surrounding a node.

4.2 Energy-efficiency Awareness

Multi-hop 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 wireless environments. 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 UCNs which make energy awareness and efficiency problems that are not trivial to be solved. Firstly, UCN nodes are 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.

Routing in UCNs can be adjusted to be energy-aware. In our work we have considered organic ways to make multi-hop routing more flexible, namely, the inclusion of energy-aware routing metrics in current multihop solutions.

Energy Awareness Routing Notions A UCN node is expected to be interconnected via one or more networking interfaces. In the context of energy-awareness one can consider the edges that interconnect nodes to have an *energy-efficiency cost* which is a measure of energy expenditure of the nodes involved in the connection. Such cost can be computed based on the perspective of the source node - the node transmitting -, or based on the perspective of both nodes involved in a potential transmission - the *source/father* node, and the potential *successor* node.

Concerning the source node perspective, there are three main modes of energy expenditure. 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 is based on 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 spending or savings, and thus can make a node energy aware up to some point. Feeney et al., for instance, provide a general model [21] for packet-based energy consumption, i.e., energy spent by a node when it sends, receives, or discards a packet.

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 [44], ii) *Residual Energy (RE) [45]* , and iii) *Drain Rate (DR)* [22]. 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.

Out of the metrics mentioned, the most relevant to consider in the context of routing applied to UCNs are the drain rate and residual energy metrics, as explained in previous work [27,28]. Still, in the context of UCN such metrics cannot be applied in isolation to provide energy awareness, in the context of multihop proposals. We would also like to emphasize that the *Internet Engineering Task Force (IETF)* is currently discussing energy-aware multihop metrics tailored for energy efficiency for routing protocols in the context of the working group ROLL.

Novel Metrics for Energy-awareness Based on the notion that in UCNs nodes are heterogeneous in terms of energy capacity we have discussed and validated several metrics, summarizing the most relevant ones in this section. Initially, we have proposed heuristics which consider an energy-awareness ranking of node based on idle times, which a node provides a ranking in terms of the node robustness to optimize the node lifetime as well as the global network lifetime. Then, a second heuristic we have considered the impact of node degree history for ranking the node to extend the lifetime.

The *Energy-awareness Node Ranking (ENR)* metric [29,28][30] explores the fact that nodes that have been in idle mode for the majority of their lifetime, and that still exhibit a good estimate for their future energy level are the most adequate candidates to constitute a shortest-path. In ENR we estimate how much of its lifetime has node i been in idle mode, to then provide an estimate towards the node's future energy expenditure, as this will for sure impact the node's lifetime. Such periods are the ones that are expensive to i in terms of energy. Hence, we consider the total period in idle time, t_{idle} over the full lifetime expected for a specific node, which is given by the sum of the elapsed time period T with the estimated lifetime of the node, as provided in equation 3. The estimated lifetime $C(i)$ was first provided by Garcia-Luna-Aceves et. al [22].

$$ENR(i) = \frac{T - t_{idle}}{T \times C(i)} \tag{3}$$

ENR is therefore a node weight which provides a ranking in terms of the node robustness, from an energy perspective, and having as goal to optimize the network lifetime. The smaller $ENR(i)$ is, the more likelihood a node has to be part of a path.

Based on ENR, we have developed the *Energy-awareness Father-Son (EFS)* metric, which considers a composition of the ENRs of both a father and successor nodes as specified in equation 4[32].

$$EFS(i,j) = ENR(i) \times ENR(j) \tag{4}$$

EFS provides a ranking which we believe is useful to assist the routing algorithm to converge quickly in particular in multi-path environments, as the selection on which successor to consider shall be made up from, by the father node. The goal is, similarly to ENR, to improve the network lifetime without disrupting the overall network operation. Hence, the smaller $EFS(i,j)$ is, the more likelihood a link has to become part of a path.

These two sets of metrics and variations have been validated via discrete event simulations in the context of both AODV and OLSR. Operationally, these two protocols have a very different behavior, and applying global metrics to them independently of the protocol behavior is not trivial. However, from an energy-aware perspective, it is possible to do so, by considering that both families rely on shortest-path computation.

Hence, the line of thought considered in the development of our energy-aware metrics is that the principle of shortest-path computation must be kept. Instead of hop-count, a metric that can provide an energy expenditure cost to a node is considered. The main caveat related with this change is that in order to keep accuracy, one must ensure that the protocol synchronizes path status adequately. This implies considering either a time-window mechanism, or updates to a node's cost each time a change occurs. These are regular techniques, where it is essential to find an adequate commitment between accuracy and low overhead due to the required signaling.

In terms of the behavior of EFS vs. ENR there seems to be an improvement in particular when scenarios have larger distances, and when the network load is higher [32]. This implies that EFS seems to provide more robustness when scenarios have more variability (e.g. more nodes moving, and several successors at disposal). In terms of network lifetime and for the scenarios evaluated, ENR results in a small improvement. The greater advantage of applying EFS instead of ENR seems to relate with an improvement in throughput and a significant improvement concerning packet loss. Our belief for this gain relates to the fact that EFS allows nodes to react quicker to energy changes on a path - resulting paths will be more robust earlier in time, assuming that nodes have a reasonable out-degree (several successors available).

Thinking on real implementation, we have discussing the impact of energy awareness and operational aspects of the link-state and distance-vector routing families. Then, we have described and discussed the routing architecture specification for energy awareness submitted to the IETF working group ROLL[31]. The specification can be applied in any available multihop routing protocols, such as AODV, OLSR and RPL.

4.3 Opportunistic Communication Awareness

Related work concerning opportunistic routing aim to investigate the use of node contact metrics (e.g., frequency of encounters), resulting from node mobility, to reach a good trade-off between cost and rate of message delivery. These proposals started by investigating schemes based on which nodes send unique copies of messages (replicate once) until destination is found (e.g., single copy forwarding) aiming to reduce transmission costs (i.e., number of message replicas in the network) and schemes based on which nodes keep replicating messages to any encountered node (e.g., Epidemic) aiming to increase delivery probability and to reduce delay.

In a second stage, several proposals started to investigate methods to mitigate the cost of replication mechanisms, aiming to achieve the delivery probability and delay of epidemic approaches with the low network cost of single-copy ones. These replication-based approaches tried to exploit more elaborated networking aspects such as node encounter, resource usage, and social similarity, which is the latest trend identified in the last couple of years.

Then, we have further investigate the different opportunistic routing solutions, with particular emphasis on the social-aware approaches [37]. Another important aspect that we could observe while covering the state-of-the-art in opportunistic routing is related to the way proposals are evaluated: there no guidelines with respect how such proposals should be compared in order to provide a fair performance assessment. This led us to come up with a Universal Evaluation Framework [38,39], which aids networks to evaluate new opportunistic routing solutions to already existing ones in way to have their assessment done respecting the limitation of each of the proposals involved.

In what concerns solutions based on social similarities, it is important to achieve a correct mapping between real node interaction and the social graph that aids routing. Hossmann et al. [33] show that the key for successful forwarding is related to the ability of mapping social interaction (resulting from the mobility process) into a clean social representation (i.e., that best reflects the mobility structure), which should capture the daily life routine of nodes. Eagle and Pentland [34] show that people have routines that can be used to identify future behavior as well as interaction with people with whom they share similar behavior and potentially the same community. In what concerns the latest argument, the identification of social structures encompasses the challenge of detecting and adjusting communities on-the-fly in a useful time frame. Current research efforts show the difficulty of constructing and adjusting social structures in short periods of time.

In UCNs, the user daily routine is an essential aspect and hence, our choice concerning opportunistic communication awareness falls the social approaches.

In this context, in previous work we have proposed two utility functions [35] that take into consideration the daily routines of users and the intensity of their social interactions to take forwarding decisions: the *Time-Evolving Contact Duration (TECD)* that weights social interactions among nodes considering the duration of contacts; and *TECD Importance (TECDi)* which estimates the importance of nodes according to the weight of the links to its neighbors and their importance. Experiments carried out to evaluate the two utility functions showed that routine has a positive effect on opportunistic routing, when compared against contact and social-based benchmarks.

This work evolved to become a new routing algorithm, dLife [40] which captures the dynamics of the network represented by time-evolving social ties between pair of nodes.

Another part of this work refers to point-to-multipoint communication, which is a desirable feature in opportunistic routing since it increases reachability of nodes interested in the content of the messages. Such feature has been shown to lead opportunistic routing to have better performance and wise use of resources [46].

dLife has been implemented in the context of the ONE simulator, as well as in the context of a realistic Delay Tolerant Networking testbed set in the Amazon region [1] holding 10 devices (3 personal computers with Ubuntu 10.10 Maverick, 3 smartphones Android 2.3.6 Gingerbread, 4 wireless routers with OpenWrt 10.03.1) with the purpose to exploit physical proximity, a key aspect of dLife to determine different levels of social interaction among devices.

5 Summary and Future Work

This paper addresses assumptions and requirements of routing in the context of UCNs, alerting to the need to revisit multihop approaches making them aware to node movement, to the limited battery capacity of the nodes, as well as to the potential value of opportunistic communications.

The line of thought followed is that in order to allow end-to-end routing on the Internet to adequate work in future Internet architectures, it is required to consider new metrics that incorporate properties that allow nodes to choose other-than-shortest-path solutions, while at the same time ensuring backward compatibility with the current solutions.

[1] A DTN testbed was created in collaboration between COPELABS and the University Federal of Pará (UFPA) in order to test the performance of dLife in the extreme conditions of the Amazon region, in the context of the joint project UCR: User-centric Routing, 2010-2013, project funded by Fundação para a Ciência e Tecnologia (FCT).

The work described has addressed ways to integrate metrics capable of providing such sensitivity to current shortest-path based approaches showing that it is feasible to improve the network lifetime as well as to reduce path recomputation, by integrating simple metrics into existing approaches, derived from parameters that are, in their majority, passively captured by nodes. In other words, these metrics do not require active probing of the network.

A conclusion to draw is that the metrics proposed have shown good improvements of different network properties (e.g. lifetime, path recomputation). Such improvements were possible without adding any significant overhead be it to a node or network operation, as described in the different IETF specifications proposed.

Research work in this field should address ways to combine the three dimensions mentioned, as well as to validate the metrics proposed in the context of other multihop solutions.

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