# Energy-awareness in Multihop Routing

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**Abstract.** Recent advances in wireless technology, such as software defined radio, lead to the possibility to explore new Internet connectivity models derived from the willingness of the end-user to share some Internet services. These networking architectures are known as *User-centric Networks (UCNs)*. This chapter addresses energy-awareness in terms of multihop routing for wireless networks having the motivation to explain fundamental concepts, parameters and metrics, as well as how to address energy-awareness while keeping backward compatibility with current shortest-path routing approaches. The chapter starts by giving insight to notions concerning energy-awareness from a routing perspective, to then describe concepts that could assist in making multihop routing more efficient in terms of energy-awareness, showing the benefits in terms of performance. The chapter then describes the most recent metrics that are capable of providing some form of energy-awareness based on existing notions such as energy consumption models, energy capacity of a node, as well as based upon residual energy of a node. A section is dedicated to an analysis concerning implementation aspects.

## 1 Introduction

Nowadays, the highly nomadic lifestyle that Internet users experience, the stronger entanglement between society and technology and advances in wireless technology such as Software Defined Radio (SDR) and Wireless Fidelity (Wi-Fi), gave rise to new types of portable devices and connectivity models, e.g., *User-centric Networks (UCN)* [1,2,3]. Examples of such environments can be a network formed on-the-fly after a disaster of some nature or even a municipality network where end-user devices share Internet access, e.g. FON [4]. In contrast to traditional Internet routing scenarios (be it based on wireless or wired technologies), these new user-centric scenarios pose different forwarding and routing challenges, due to their underlying assumptions, namely: i) end-user devices may behave as networking nodes, ii) nodes have a highly nomadic behavior, iii) data is exchanged based on individual user interests and expectations iv) control and management requires decentralized and distributed solutions.

These UCN networking architectures rely on the interconnection of end-user equipment as a way to extend capillarity. Moreover, these networks rely on the development of Internet connectivity based on end-user, portable devices, thus considering heterogeneous nodes (in terms of energy consumption, for instance) and the topology exhibits high variability as nodes tend to disappear and appear in the network, based on their carriers interests and behavior. Such devices are, however, limited in terms of battery. Yet, in terms of routing, these environments rely on the most popular approaches for wireless networks, which do not consider energy-efficiency as a parameter related with Quality of Service or Quality of Experience [5].

As user-centric wireless environments rely on traditional multihop routing approaches, in order to provide energy efficiency in UCNs, this chapter discusses the potential of current energy-aware routing approaches for wireless networks, and whether or not they may make sense when applied to routing in user-centric environments having the motivation to explain fundamental concepts, parameters and metrics, as well as how to address energy-awareness while keeping backward compatibility with current shortest-path routing approaches. It also proposes concepts that could assist in making multihop routing more efficient in terms of energy awareness that consider heterogeneous devices, without necessarily having to change operational aspects of the underlying algorithms, or protocols [6].

The chapter then describes a new set of routing metrics which provide nodes with an energy-aware ranking based on existing notions such as energy consumption models, energy capacity of a node, as well as residual energy of a node. Out of such work stem two types of metrics: i) a metric that takes into consideration the perspective of a single node (father), the Energy-awareness Node Ranking (ENR); ii) a second metric that takes into consideration the perspective of both the father and son nodes - potential successors available in a path, the Energy-awareness Father-Son (EFS) metric [7,8,9].

In terms of performance, a section discusses and validates energy-aware routing metrics which can be applied to any available routing protocol. It validates the performance of the metrics based on two main branches of multihop routing, namely, link-state and distance-vector approaches. The validation is performed based upon discrete event simulations. Such metrics have been validated in the context of the Ad-Hoc on-demand Distance Vector (AODV) protocol and of the Optimized Link State Routing (OLSR) protocol, where we have proved significant improvements when applied to those protocols. The evaluation shows that the metrics significantly improve network lifetime, without incurring significant penalties in terms of network operation.

A section is dedicated to an analysis concerning implementation aspects namely a routing architecture specification for energy-aware metrics which is an Internet Draft to the ROLL working group [10]. Besides AODV and OLSR, we also discuss the applicability of the proposed metrics in Routing Protocol for Low-Power and Lossy Networks (RPL), because of its relevance in the context of the IETF as a potential standard related to the Green Internet.

## 2 State-of-the-art

This section describes the state-of-the-art of user-centric multihop routing, energy-efficient multihop routing and then focuzing on energy-aware metrics.

## 2.1 User-centric multihop routing

From a user-centric perspective and also considering short-range transmissions, Wi-Fi has become more popular than the others technologies mostly due to four factors: i) unlicensed spectrum; ii) low-cost equipment; iii) ease of deployment; iv) good adaptation to broadband access technologies.

The highly nomadic lifestyle of the XXI century is giving rise to new forms of wireless architectures which are user-centric in the sense that the end-user becomes more than a consumer of connectivity. Such user-centric wireless networks [1] range from basic functionality, for instance, the ability to provide Internet access with a simple PC (e.g., ICS functionality from Microsoft), to more elaborate cases of commercial success (e.g., FON [4]). User-centric networks are expected to grow, despite the limitations imposed by traditional operator-centric Internet communication models: the control of what to transmit in the Internet is today mostly centralized in a few players, namely, access and network providers. In contrast to traditional Internet routing scenarios (be it based on wireless or wired technologies), user-centric networks pose different forwarding and routing challenges, due to their underlying assumptions, namely: i) end-user devices may behave as networking nodes, ii) nodes have a highly nomadic behavior, iii) data is exchanged based on individual user interests and expectations, iv) control and management requires decentralized and distributed solutions.

User-centric environments are usually located within the customer premises region (where residential households, and enterprise environments reside). Out of the several possible user-centric scenarios, we summarize here a user-centric network (UCN) [2,3,5,11], a Pocket Switched Network (PSN) [12,13] and a Low power and Lossy Network (LLN) [14,15].

UCNs have been applied as complement to existing access networks: they allow expansion of infrastructure across one wireless hop. There is usually one individual or entity (the Micro Provider (MP)) which is responsible for sharing his/her connection with other users (out of a universe of users, who today belong to a single community). Moreover, a user is, in a specific community, simply identified by a virtual identifier (usually, a set of credentials username and password) which is stored by a Virtual Operator (VO) and relied upon whenever the user decides to access the Internet by means of a specific community hotspot. In these emerging architectures, the nodes that integrate the network are in fact end-user devices which may have additional storage capability and sustain networking services. Such nodes, being carried by end-users, exhibit a highly dynamic behavior. Nodes move frequently following social patterns and based on their carriers interests. The network is also expected to frequently change (and even to experience frequent partitions) due to the fact that such nodes, being portable, are limited in terms of energy resources.

PSNs are networks based upon end-user devices which are carried. People move between connectivity islands (e.g. Wi-Fi at home and work). Outside these islands, end-to-end connectivity becomes expensive, slow, or simply unavailable. PSN is a new networking paradigm which considers human mobility and store-and-forward strategies to solve the communication problem outside the connectivity islands. In PSNs, mobile devices are still assumed to have multihop capabilities (routers), routing is taking advantage of any opportunities in the course of device mobility. One type of opportunity is found in local network connectivity (using wireless or otherwise). Whenever two PSN nodes come into contact, they must detect each other and determine what to transfer in each direction. The use of both local and global opportunities allows PSN to provide highly-robust networking for users, as it can transparently switch over to local connectivity when global connectivity is unexpectedly lost.

LLNs are typically composed of many embedded devices with limited power, memory, and processing resources interconnected by a variety of links, such as IEEE 802.15.4 or Low Power Wi-Fi. There is a wide scope of application areas for LLNs, including industrial monitoring, building automation (HVAC, lighting, access control, fire), connected home, healthcare, environmental monitoring, urban sensor networks, energy management, assets tracking and refrigeration.

Single-source shortest-path routing is the basis for today's Internet routing, independently of the type of technology. Routing is here defined as a process of computation of one or several possible paths in a network of nodes between a specific source and one or several destinations. Such paths serve the purpose to allow information transmission between source(s) and destination(s) in an optimal way, according to pre-defined optimality criteria. Routing can therefore be seen as a control plane process with the following components: topology discovery, path computation, path selection and storage, and topology maintenance [16]. Routing components belong to the control plane. Data forwarding belongs to the data plane.

The objective of single-source shortest-path computation approaches is to find the shortest path from a single source vertex to all other vertices in a graph. For the specific case of single-source shortest-path routing in Internet, there are currently two main family of algorithms applied: the Dijkstra algorithm [17] and distributed Bellman-Ford algorithm [18]. Both Dijkstra and Bellman-Ford compute solutions to single-source shortest-path problem, and both use the technique of relaxation. The Bellman-Ford can solve with some edges with negative weight, Dijkstra is only positive weight, however if there is a negative cycle there is no shortest path. The running time of Dijkstra, even in simplest implementation, is better than Bellman-Ford. The distributed Dijkstra has been widely used in routing protocols, being its protocol formulation the Link State (LS) family. Bellman-Ford is also widely implemented, being its protocol counter part the Distance Vector (DV) family. In the Internet and specially addressing IP, the most solution are either based in DV and LS family.

In link state routing the nodes diffuse (depth-first search) a set of their link-state information throughout the whole network. Such packets would contain the identity of the source node, its neighbors, and the cost of routing to them. After the initial network discovery process, all nodes converge to have a perspective of the global topology, at the expense of a higher signaling. Distance vector routing is based on Bellman-Ford shortest path search algorithm. Nodes therefore keep status concerning destination cost, and next hop towards a destination. Every node periodically broadcasts and keeps status concerning found destinations to neighbors.

Multihop ad hoc routing protocols can be classified in two groups: reactive and proactive protocols. Reactive protocols find a route on demand by flooding the network with route request packets. The main disadvantages of such algorithms are: i) high latency time in route finding; ii) excessive flooding can lead to network clogging. Proactive protocols maintain a fresh list of destinations and their routes by periodically distributing routing tables throughout the network. The main disadvantages of such algorithms are: i) respective amount of data for maintenance; ii) slow reaction on restructuring and failures.

### 2.2 Energy-efficient multihop routing

In wireless networks, there is a direct tradeoff between the amount of data an application sends and the amount of energy consumed by sending that data.

In general there are three components to energy consumption in ad hoc networks. First, energy is consumed during the transmission of individual packets. Second, energy is consumed while forwarding those packets through the network. And finally, energy is consumed by nodes that are idle and not transmitting or forwarding packets.

The basis for all communication in ad hoc networks is the point-to-point communication between two nodes. At each node, communication impacts energy consumption in two ways. First, the wireless communication device consumes some base energy when it is activated and idle. Second, the act of transmitting a packet from one node to another consumes energy at both nodes. The amount of time needed for the packet transfer determines the amount of time the card must be active, and so directly determines the energy consumed by the base card costs for both transmission and reception.

There are different approaches according to link and network layer. At the network layer, routing protocols can minimize overhead, ensure the use of minimum energy routes and use of energy-aware metrics [19,20,21,22]. At the medium access control (MAC) layer, techniques can be used to reduce the energy consumed during data transmission and reception [23,24,25,26,27,28,29]. Additionally, a MAC protocol can turn off the wireless communication device when the node is idle [30,31,32,33,34].

### 2.3 Energy-aware routing metrics

Specifically attempting to make multihop routing more flexible, several authors have explored new metrics having in mind different types of optimization, e.g. reduction of energy spent across a path, on the global network. We overview the prior-art for the last years and we find out that there are few work specifically on pure energy-aware routing metrics, i.e., which consider only energy or battery parameters to design a metric. Our work focus on pure energy-aware routing metric.

The main energy-aware routing metrics are i) transmission power, ii) residual energy, and iii) drain rate. These metrics normally are used to the problem of maximum lifetime routing, i.e. increasing the network lifetime. The *transmission power* metric aims to maximize the network lifetime by minimizing the total energy consumption per packet. The *residual energy* metric as as goal is to extend the network lifetime by extend node lifetime and balance the energy consumption per node. The *drain rate* metric aims at maximizing the network lifetime by predicting the node lifetime.

Within this context, to minimize the energy consumed using transmission power as metric, the *Minimum Total Transmission Power Routing (MTPR)* approach [35,19], was developed to minimize the total transmission energy consumption of nodes in an acquired route, for ad-hoc scenarios where nodes are static and attempt to optimize the network lifetime. We can refer as a minimum energy route. MTPR prefers routes with more hops having short transmission ranges to those with fewer hops but having long transmission ranges and increases end-to-end delay. Since MTPR does not consider the remaining energy of nodes, it may not succeed in extending the lifetime of each node. MTPR still considers a shortest path routing, homogeneous nodes in network and mainly makes decisions of routing (choose a path) under the perspective of the sender's node, i.e. using the transmission power (Tx Power) of the node.

Addressing energy conservation, considering the remaining battery capacity the *Maximum Residual Energy Routing with Reverse Energy Cost (MREP)* proposal [36] attempts to keep residual energy at a maximum after a packet is sent. Their approach is applicable when delay is a lesser concern than global network lifetime and has as main performance parameter energy conservation.

Attempting to understand optimal properties that multihop routing should globally consider, C. K. Toh provides a relevant overview [37] of different routing properties to consider, being one of them efficient utilization of battery capacity. 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. The author analyzes MTPR against the *Minimum Battery Cost Routing (MBCR)* and the *Min-Max Battery Cost Routing (MMBCR)* [22] approaches. The author shows that the three approaches fall short in terms of guarantees that the minimum total transmission power paths will be selected under all circumstances. Hence, as workaround the author proposes a *Conditional Max-Min Battery Capacity Routing (CMMBCR)* which considers battery capacity as a route selection metric. When all nodes in some possible routes have remaining battery capacity above a threshold, a route with minimum total transmission energy is chosen among these routes. The CMMBCR does not guarantee that the nodes with high residual energy will survive without energy breakage even when heavy traffic is passing through the node.

A more relevant metric to consider assuming that scenarios may involve heterogeneous nodes (in terms of battery) is the *Drain Rate (DR)* of a node [38].

DR is a metric that measures the energy dissipation rate (speed of energy consumption) in a given node. Each node monitors its energy consumption caused by the transmission, reception, and overhearing activities (in number of bits) and computes the energy drain rate. This metric is then used to predict the lifetime of nodes according to the current traffic conditions. Combined with the value of residual energy, the authors derived the *Minimum Drain Rate (MDR) approach,* which extends both node battery life as well as the connections lifetime by evenly distributing energy expenditure across all nodes. As a follow-up of this work, the authors propose the *Conditional Minimum Drain Rate (CMDR)* [39] which adds up to the previous work the minimization of the total transmission energy consumed per packet.

The most recent work on this topic in which the IETF WG ROLL recently proposed as standard is the RFC 6551 [40] which describes a set of link and node routing metrics and constraints, from which the node energy issue is one of them, being suitable for improving routing protocols for LLNs. In this context, Karkazis et. al. [41] design a set of primary and composite metrics for RPL protocol which a energy-aware metric is one of them. The energy metric is expressed as the ratio between the maximum initial energy and the current energy value of a node, i.e., the remaining energy percentage. Still in this context, in January 2013 the authors of [42] have discussed the energy-based routing metric to apply in RPL. They have used the node residual energy estimation on a scale of 255 (full) to 0 (empty) in order to represent the node energy level. For path computation, a cost as the minimum node energy level captures the energy-based path weight.

Moreover, the metrics are mostly used as node selection metric and incorporated into the specific protocol operation.

## 3 Energy-awareness in User-centric Networks

These are environments that can be considered a sub-set of MANETs, but where two fundamental aspects require energy efficiency: self-organization, and a highly dynamic roaming behavior of the nodes that compose the network. UCNs integrate the end-user connected to the Internet by means of a variety of broadband access technologies, which the final segment is provided by a number of short-range technologies, among which Wi-Fi is a solution [1,11]. UCNs are also in the context of Low Power and Lossy Networks (LLNs). In those environments, the majority of devices are multimedia capable with strong limitations in terms of energy capabilities.

Hence, energy efficiency is a key aspect since those Wi-Fi enabled mobile devices are heterogeneous in terms of battery capacity and energy consumption. By devising routing metrics to assist multihop routing protocols in becoming more efficient without adding too much operational complexity, one is improving the overall notion of energy aware networks.

Multihop protocols choosing paths based on optimal network lifetime is an aspect that introduces more flexibility in multihop routing approaches and makes them better suited for user-centric environments. Hence, the idea behind our work is to consider energy-aware routing metrics that can provide stability in terms of network lifetime to shortest-path based routing, improving the overall network lifetime without penalizing the network performance. The impact of such inclusion of energy-aware metrics should be some minor changes in the control messages of the protocols which can be validate under experimental evaluation.

We emphasize that the architecture and also the energy-awareness requirements of wireless sensor networks are different than the ones in user-centric environments. Sensor nodes are normally considered to be homogeneous in terms of energy capability and normally placed to get information and send it to a manager sensor node. In contrast, in user-centric networks, nodes are expected to be heterogeneous in terms of energy and to follow a human behavior as social networking. Those aspects do not allow the energy-efficient and energy-aware solutions of sensor networks to be reusable in user-centric environments.

The WG ROLL is currently discussing energy-aware multihop metrics tailored for energy efficiency for routing protocols. The WG recently proposed as standard the RFC 6551 [40] which describes a set of link and node routing metrics and constraints, from which the node energy issue is one of them, being suitable for improving routing protocols for LLNs.

### 3.1 Energy parameters and power consumption model

Energy awareness for a network can be obtained from a single node perspective, from a link perspective, or from a 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 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 IEEE 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 communications are possible but there is still a low-power consumption.

Power consumption values are usually provided in the respective Network Interface Card (NIC) manuals or available on manufacturer websites. There are studies on measurements such as reported in [43] by Feeney and Nilson which provide detailed power consumption data in an ad-hoc network for two WLAN NICs (Lucent WaveLan 802.11 PCMCIA ”Silver” and ”Bronze”) in different operational modes (Sleep, Idle, Receive and Transmit) and for 2 Mbps and 11 Mbps data rates. However, those NICs are old which does not reflect the current network interface cards. There are some recents work on power consumption measurements either for laptops and smartphones such as [44,45,46].

Table 1 shows some power consumption values of actual NICs with multimode (802.11 a/b/g/n) support provided by the vendors. Power consumption data collected from vendors manuals often appears to be very heterogeneous and thus difficult to find a common values. Usually, there is not enough information about how the power consumption measurements is performed by the manufacturer, the kind of load conditions is assumed for active (Tx, Rx, Idle) and inactive (Sleep) mode power consumption.

We highlight that the most used Wi-Fi chipset for smartphone is the Broadcom BCM 4329, which is used in several popular smartphones from manufacturers like Samsung, Apple, HTC, Motorola and Google Nexus S.

Table 1: Power consumption of NICs for multimode IEEE 802.11(a/b/g/n) standards.

| Device (NIC) | Power (mW) | | | |
|---|---|---|---|---|
| | Transmit | Receive | Idle | Sleep |
| Intel Wi-Fi Link 5300 801.11n (MIMO 3 antennas) [46] | 2100 | 1600 | 1450 | 100 |
| Intel Wi-Fi Link 5300 801.11n (MIMO 2 antennas) [46] | 1990 | 1270 | 1130 | 100 |
| Intel Wi-Fi Link 5300 801.11n (1 antenna) [46] | 1280 | 940 | 820 | 100 |
| Intel PROset/Wireless Wi-Fi Link 4965AGN [47] | 1450 | 850 | 800 | 60 |
| Cisco Aironet Wireless PCI Adapter AIR-PI21AG-E-K9 [48] | 1828 | 1049 | 669 | 20 |
| D-Link Wireless G PCI Adapter DWA-510 [49] | 1485 | 858 | 786 | 49 |
| Agilent Current Drain Analysis WLAN Network Card Test [50] | 1188 | 1138 | 1108 | 70 |
| Sparklan 802.11n draft Mini-PCI Module WMIR- 215GN [51] | 1221 | 990 | 627 | unspecified |
| PCIe mini card wireless LAN module WMPCIE- V01-R20 [52] | 2013 | 1112 | 730 | unspecified |
| Broadcom BCM4329 802.11a/b/g/n [53] | 1240 | 810 | 697 | unspecified |
| | | | | |

Energy is a node and network resource that is similar in nature to capacity of a node. A node spends, as explained, energy when performing an action, namely, when transmitting or receiving but also when in idle or sleeping mode. The way a node spends energy relates to an energy consumption model, which dictates how many energy units are spent in each mode per unit of data (transmitted, received, overhearing). Then, different node metrics can capture such energy spendings or saving, and thus can make a node energy-aware up to some point.

An energy consumption model refers to the energy consumed by a node. In this document we consider the model provided by Feeney and Nilson [43] which presents a general model for per packet energy consumption, i.e., energy spent by a node when it sends, receives, or discards a packet. The model considers the energy cost associated with each packet from a single node perspective and can be described using the linear equation 1:

$$Energy = m * size + b \tag{1}$$

where $m$ and $b$ are linear coefficients that must be experimentally derived and that vary depending on the type of operation, and where size is measured in bits. It should be noticed that Equation 1 is a particular equation based upon the experimental result by the authors and may not be applicable to all wireless interfaces available. We consider it due to its simplicity and during our research we realized that this model is the most complete during the development of our implementation.

However, a recent work [54] provides an experimental investigation of the per-frame energy consumption in IEEE 802.11 devices. The authors also proposes a new energy consumption model claiming that traditional models either neglect or amortize energy costs component in a fixed baseline cost. This model can be analyzed for considerations in future work. Gomez and Riggio [55,56,57] recentely have been worked in power consumption measurements and energy savings for IEEE 802.11 standard.

### 3.2 Categorization of current energy-efficient approaches

This section provides an overview of different attempts to provide routing with energy efficiency, which we have categorized in terms of the goals that each work attempts to tackle and which are: i) network utilization perspective; ii) path optimization perspective. Furthermore, we provide an overview also on energy awareness applied as a networking metric, to improve routing.

### 3.3 Network Utilization Perspective

Energy metrics have been classified by [58] which focuses on designing protocols to reduce energy consumption and to increase the lifetime of each mobile node, increasing network lifetime as well. Such metrics are:

1. *Energy consumed per packet*: if energy consumed per packet is minimized then the total energy consumed is also minimized.
2. *Time to network partition*: the routing algorithm should divide the work among these mobiles in such a way that the mobiles drain their power at equal rates, avoiding network partition.
3. *Variance in power levels across mobiles*: the idea is that all mobiles in a network operate at the same priority level. This metric ensures that all mobiles in the network remain powered-on together for as long as possible.
4. *Cost per packet*: routes should be created such that mobiles nodes with depleted energy reserves do not lie on many routes. The cost of a packet needs to be minimized to maximize the life of all mobiles nodes in the network.
5. *Maximum node cost*: attempts to minimize the cost experienced by a mobile node when routing a packet through it.

In the context of network utilization perspective, the main goal is to maximize the network lifetime. This objective can be done by reducing the energy consumption of the nodes, minimize the energy consumed per packet, energy consumed of control packets and avoid retransmissions. Energy conservation of nodes considering the residual energy is important to extend the network lifetime. In this context, a important trade off to be considered is the end-to-end delay. When using the energy metrics and mechanisms to reduce the energy consumption, e.g. avoid nodes with low battery capacity, normally increase the delay.

### 3.4 Path Optimization Perspective

The current multihop routing approaches consider hop count as a metric to apply when choosing shortest-paths. Other metrics today consider the link quality by applying in addition energy metrics to path computation, one can assist in improving network lifetime, or even in computing more robust paths.

Considering the residual energy of a node, the selection path can be visiting the nodes with the highest residual energy. Each flow is ensured to have enough energy on the selected path, and depleted nodes are avoided. A cost energy of node can be used selecting the path with the minimum cost, where the cost takes into account the residual energy of each visited node (and possibly its neighbors) and the energy consumption of a packet on this path.

However, these selection path normally increase the end-to-end delay. It is important to define an optimization path that can reduce the delay maximizing the network lifetime.

### 3.5 Node-based Metrics

Node metrics can be either static or dynamic, depending on the underlying scenario. There are scenarios that have highly heterogeneous nodes in terms of energy consumption and support. More capable and stable nodes may assist the most constrained ones for routing packets, which results in extension of network lifetime and hopefully more efficient network operations.

The main node-based metrics that are energy aware are i) transmission power, ii) residual energy, and iii) drain rate. These metrics normally are used to the problem of maximum lifetime routing, i.e. increasing the network lifetime. The *transmission power* metric aims to maximize the network lifetime by minimizing the total energy consumption per packet. The *residual energy* metric has as goal 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 uses a fixed transmit power of the sender node. It is commonly applied as a link cost (even though it is a metric that considers only 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 avoid the minimum energy problem by selecting the route which 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 perpacket energy consumption, but it generally performs better than minimum energy routing. These metrics can also use minimum cost routing, which minimizes the total cost of forwarding the packet at each node. In case of residual energy, it selects the route that considers the sum of the battery of node along the path avoiding node with low battery. In case of drain rate, it selects the route that uses maximum path lifetime by minimum drain rate of nodes along the path.

There are common drawbacks for these metrics. All of them consider scenarios with homogeneous nodes in terms of battery and 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 under the perspective of the sender's node, which does not consider the successors of the nodes. In other words, the nodes requesting a specific route only consider their own perspective about their energy resources.

### 3.6 Novel energy-aware multihop routing metrics

This section provides an overview on our metrics published in [8]. In previous section we have proposed energy-aware heuristics considering the single node perspective. In this section, we build on top of this node-based cost, but consider a father/successor approach.

***Energy-awareness Node Ranking (ENR)*** Based on the notion that in UCNs nodes are heterogeneous in terms of energy capacity ENR 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 2. The estimated lifetime $C(i)$ provided by Garcia-Luna-Aceves et. al. [39] have considered the ratio between residual energy and drain rate which can capture the heterogeneous energy capability of nodes.

$$ENR(i) = \frac{T - t_{idle}}{T \times C(i)} \qquad (2)$$

$ENR$ 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.

***Energy-awareness Father-Son (EFS)*** Based on ENR, we consider in this work the *Energy-awareness Father-Son (EFS)* metric, which considers a composition of the ENRs of both a father and successor nodes (c.f. Figure 1), as specified in equation 3.

$$EFS(i,j) = ENR(i) \times ENR(j) \tag{3}$$

$EFS$ provides a ranking which we believe is useful to assist the routing algorithm to converge quickly in particular in multipath 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.

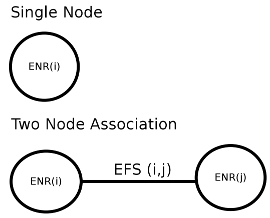



Fig. 1: Perspectives of the metrics.

Next section, we improved our metrics considering history of past activities.

***Improved iENR and iEFS*** The time instant when the route is selected could not better represent the right behavior of the metric in that time. Due to those characteristics of the metric, which can oscillate when the instant in time to select the path, we have considered a improvement of the metrics using history.

Hence, we have considered the EMA (Exponential Moving Average) which gives more weight to the most recent calculated energy-aware cost provided by both metrics ENR and EFS.

For that, equation 4 is the new iENR metric.

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

And equation 5 is the new iEFS metric.

$$iEFS(i,j) = (1-\alpha) \times iEFS(i,j)_t + \alpha \times iEFS(i,j)_{t-1} \tag{5}$$

The coefficient $\alpha$ represents the degree of weighting, which we are using 0.3 in order to gives 70 percent of priority to the new calculated values.

We believe that such improvement provide stable values of the metric in order to calculate the iENR and iEFS ranking.

# 4 Performance Aspects

We have evaluated both the main link-state (OLSR) and distance-vector (AODV) routing protocols running our ENR and EFS metrics against their versions with plain hop count on NS-2.34 simulations. We have considered two scenarios: a controlled random topology and a scenario derived from real data traces collected in North Carolina State University (NCSU) which comprises human mobility trace data of students enrolled on the computer science department who share common interests.

We also have evaluated our improved iENR and iEFS metrics considering history for the AODV and OLSR protocols against the ENR, EFS and hop count approaches. We have considered a study [59] of how mobile users interact with batteries to define the energy parameters. Our motivation was to ensure that validation is as realistic as possible.

We have considered the UM-OLSR implementation for NS-2 provided by [60] and default AODV modules. These modules have been changed to reflect the required changes detailed in next sections, being the code publicly available here [61].

## 4.1 Performance Metrics

The results analyze the benefits in terms of *network lifetime*. We define network lifetime as the time period since a topology becomes active up to the moment it becomes disconnected, from the perspective of destination nodes. In other words, such time period is counted since the topology becomes active, until a destination cannot be reached by any of the available sources in the topology.

Even though we analyze benefits in terms of network lifetime, we also want to understand the impact of the metrics on the overall network performance. For that, we consider additional aspects depending on the employed case: i) *average estimated node lifetime*, i.e., the estimated node lifetime, $C(i)$, across all nodes in the network; ii) *average end-to-end delay*, the time a packet takes between source and destination, comprising propagation and queuing delay. The end-to-end delay is computed per destination and then averaged across all destinations; (iii) *average throughput*, the average number of bytes reaching destination nodes, measured in Kbps. The results presented correspond to the average throughput in the network, which is computed first per destination and then averaged across all destinations in the network; iv) *average packet loss*, the percentage of packets that does not reach the destination. Average packet loss corresponds to the number of packets dropped between source and destination, averaged across all of the destinations.

To generate sound statistical results we relied on the Akaroa2 [62] tool. All results have been computed within a 95% confidence interval.

## 4.2 Implementation Aspects

We have used the reserved field of the control messages to include the energy-aware cost and then use it to determine the shortest path instead of hop count as in both AODV and OLSR (here referenced as *AODV-native* and *OLSR-native*). We have called *AODV-ENR* and *OLSR-ENR* the protocols running the ENR metric, and for the EFS metric, we referenced them as *AODV-EFS* and *OLSR-EFS*. For the improved metrics, we have called *AODV-iENR* and *OLSR-iENR* the protocols running the improved iENR metric, and for the improved iEFS metric, we referenced them as *AODV-iEFS* and *OLSR-iEFS*. All approaches exchange HELLO messages every two seconds.

We have implemented the energy consumption model provided by [43] on the networking nodes which consider the energy expenditure of the transmission, reception, and idle modes.

### 4.3 Experimental Environment

We have considered the NS-2.34 default physical layer parameters with TwoRayGround propagation model. The scenarios are Wi-Fi based with 802.11g parameters.

We have then considered two scenarios. The first scenario is a controlled random topology, where we consider the parameters described in Table 2 (Scenario I). The second scenario considered is derived from real data traces collected in North Carolina State University (NCSU) [63], where the parameters have been set as provided in Table 2 (Scenario II), from the traces. The NCSU comprises human mobility trace data of students enrolled on the computer science department who share common interests.

The rationale for those scenarios, as previously described, is to understand the behavior of the proposed metrics considering a controlled random topologies in different square area (i.e. dense and sparse scenarios), and a traces based topology as an example of user-centric environment closest to reality as possible.

Table 2: Scenario parameters.

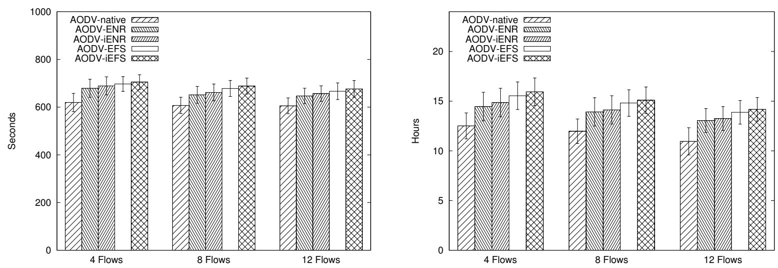
| Scenario | I | II |
|---|---|---|
| Area | 600m x 600m | 2587m x 2347m |
| Number of nodes | 25 | 20 |
| Movement | static | human behavior |
| Node speed | — | 1 m/s |
| Simulation time | 1000 sec | 24 h |
| Energy parameters | heterogeneous | heterogeneous |
| Traffic model | Poisson (VBR) | Poisson (VBR) |
| Average packet size | 512 bytes | 512 bytes |
| Sending rate | 128 Kbps | 128 Kbps |
| Number of flows | 4, 8 and 12 | 4, 8 and 12 |

### 4.4 Network Lifetime

There are some studies on how mobile users interact with batteries such as described in [64,59,65,66,67]. The main goal is to understand how users deal with limited battery lifetime on mobile devices according to the human habits.

Banerjee et.al. [59] have conducted a systematic user study on battery use and recharge behavior on both laptop computers and mobile smartphones. This study has concluded that (i) most users recharges their devices when the battery has a large percentage of energy left, (ii) most recharges are driven by user context such as location, and by battery levels usually occur when the battery level is much higher than an empty battery, and (ii) there are significant variations among users patterns and mobile systems.

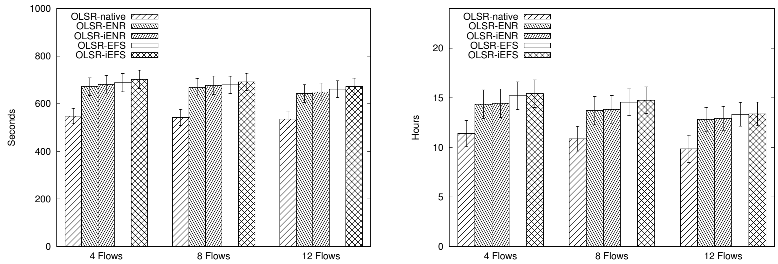
We have followed the Banerjee et.al. findings to define the energy parameters of mobile devices. The rationale for this choice is to better represent the wireless heterogeneous user-centric environment across different scenarios based on previously studies.




(a) Scenario I. (b) Scenario II.

Fig. 2: Network Lifetime for AODV.

As study suggest, there are significant differences between laptop and mobile phone charging patterns. Laptop users tend to use a larger portion of their energy and they encounter low battery scenarios more commonly than mobile phone users. Hence, we have divided all nodes into two groups, in order to represent for instance the mobile smartphones and laptops. All of the nodes of the described topologies have been set with initial energy levels picked up randomly but, for group 1 considering circa of 50% of nodes having more than 70% of energy level, and for group 2 considering circa of 50% of nodes having between 20% and 70% of energy level. In order to represent the behavior of users shutdown the device and/or the battery is empty, we have also randomly picked up on and off periods of nodes, but ensuring that circa 15%-30% of nodes go down and then come up after 20%-30% of simulation time. The on and off periods repeats after 70%-80% of simulation time. The line of thought considered was to create a more real scenario, where there is more variability in




(a) Scenario I. (b) Scenario II.

Fig. 3: Network Lifetime for OLSR.

terms of devices, energy levels, recharging, energy consumption (due to traffic fluctuation), and also due to path availability.

Table 3: Network lifetime improvement.

| Scenario | I | | | II | | |
|---|---|---|---|---|---|---|
| Flows | 4 | 8 | 12 | 4 | 8 | 12 |
| Against native hop count approaches | | | | | | |
| *OLSR-iENR* | 26.4% | 26.9% | 23.3% | 29.3% | 29.3% | 33.2% |
| *OLSR-iEFS* | 30.2% | 29.7% | 27.6% | 38.4% | 37.9% | 37.6% |
| *AODV-iENR* | 13.3% | 11.0% | 10.5% | 19.5% | 20.1% | 22.8% |
| *AODV-iEFS* | 15.9% | 16.4% | 13.7% | 28.6% | 27.8% | 30.6% |
| Against ENR and EFS metrics | | | | | | |
| *OLSR-iENR* | 3.9% | 3.8% | 3.3% | 3.5% | 3.1% | 3.0% |
| *OLSR-iEFS* | 4.3% | 5.2% | 3.9% | 5.0% | 4.8% | 4.3% |
| *AODV-iENR* | 3.6% | 3.5% | 3.6% | 4.0% | 3.8% | 3.7% |
| *AODV-iEFS* | 3.4% | 3.6% | 3.5% | 4.4% | 4.1% | 4.0% |

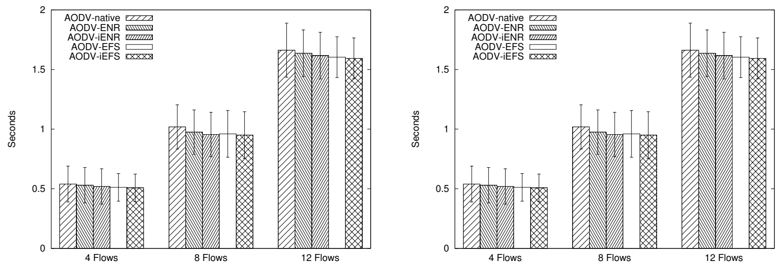
Figure 2 and Figure 3 show the average network lifetime for the different approaches regarding scenario I and II. Concerning scenario I (Figures 2a and 3a), we show results for the metrics applied to both AODV and OLSR routing protocols. Consistently, and independently of the number of flows, both iENR and iEFS result in a slight better performance than ENR and EFS, in what concerns network lifetime. However, all metrics outperforms the native hop count approaches around 15% for AODV and around 30% for the OLSR. When looking at Scenario II (Figures 2b and 3b), despite the change of network lifetime unit (seconds to hours), the results still hold, thus corroborating that the improved iENR and iEFS metrics result in significant benefits in what concerns network lifetime.

To better understand the magnitude of the improvement, Table 3 shows the relative improvement of network lifetime, which the improved iENR and iEFS metrics archive 3%-5% of gain comparing to ENR and EFS metrics. We believe this is due to the stable computed values by the metrics using history selecting a robust path.

Independently of the results, a slight improved of iENR and iEFS can be considered since it does not requires additional implementation aspects.

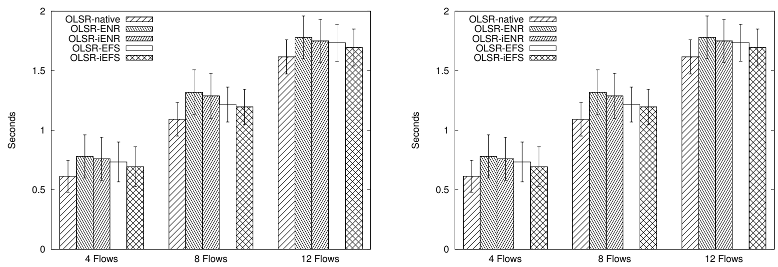
### 4.5 End-to-end Delay

As our main goal is to extend network lifetime without penalizing the network operation, Figure 4 and Figure 5 show the average end-to-end delay of the iENR and iEFS metrics for the different approaches.




(a) Scenario I. (b) Scenario II.

Fig. 4: End-to-end delay for AODV.

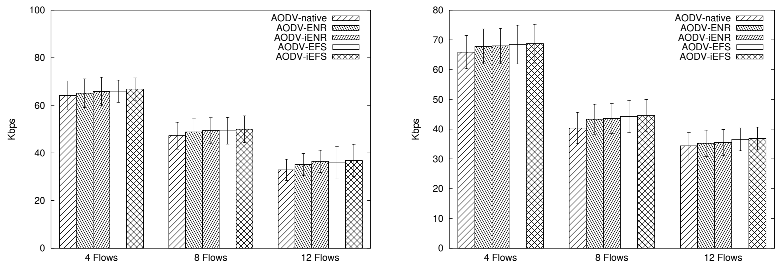



(a) Scenario I. (b) Scenario II.

Fig. 5: End-to-end delay for OLSR.

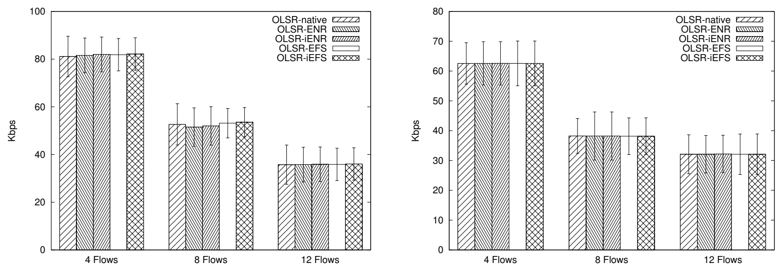
In scenario I, the end-to-end delay, even though low across all scenarios experimented, increases (as expected) for higher traffic load. Moreover, as in previous performance evaluations, while for AODV, iENR and iEFS result consistently in a lower end-to-end delay, with OLSR, the metrics achieve a slightly higher end-to-end delay.

### 4.6 Throughput




(a) Scenario I. (b) Scenario II.

Fig. 6: Throughput Results for AODV.




(a) Scenario I. (b) Scenario II.

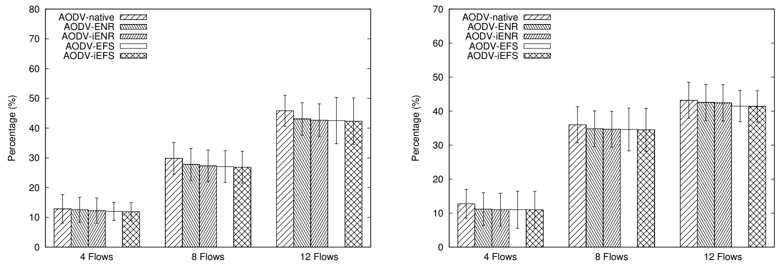
Fig. 7: Throughput Results for OLSR.

Figure 6 and Figure 7 show throughput results (Kbps) for different number of flows, again for scenario I and II. The first observation is that when the number of flows increases, the load in the network seems to decrease. This is due to the higher packet loss (refer results on packet loss) - congested network.

In what concerns AODV results, iENR and iEFS slightly improve throughput across all scenarios in comparison to ENR and EFS metrics which we believe due the stability of the improved metrics considering history. For OLSR, the improved metrics slightly improve the ENR and EFS metrics performance. As mentioned, the intention of the metrics were to provide a more robust path selection in order to improve network lifetime, without jeopardizing the overall network operation.

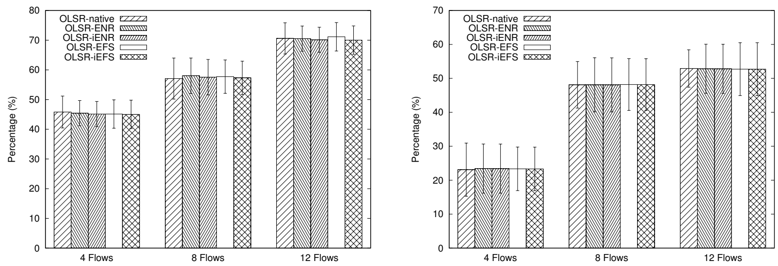
These results show that the metrics are at least as stable as the native versions of the protocols tested, and for AODV, they in fact indirectly improve the network operation.

### 4.7 Packet Loss




(a) Scenario I. (b) Scenario II.

Fig. 8: Packet loss for AODV.




(a) Scenario I. (b) Scenario II.

Fig. 9: Packet loss for OLSR.

Figure 8 and Figure 9 provide results concerning packet loss. The results show our iENR and iEFS metrics slightly improve packet loss comparing to all approaches, which means our improved metrics selects more robust paths when considering history.

## 5 Operational Aspects

The most popular multihop routing protocols stem from two distinct routing families: *link-state*, and *distance-vector* routing. Out of such families, the most popular protocols in use today are AODV (actually working progress AODVv2 [68]) and OLSR (actually working progress OLSRv2 [69]).

In this section we are going to explain main differences concerning these two protocols, as the intent is to assess whether or not we can truly provide metrics that can be applied to any multihop routing approach - the ones mentioned, and others arising now, or in the future. The purpose of any multihop routing protocol is to dynamically find paths to reach a destination and to select the best path, where best is connoted to the notion of *shortest path*.

In link state routing the nodes diffuse (depth-first search) a set of their link-state information throughout the whole network. Such packets would contain the identity of the source node, its neighbors, and the cost of routing to them. After the initial network discovery process, all nodes converge to have a perspective of the global topology, at the expense of a higher signaling. Distance vector routing is based on Bellman-Ford shortest path search algorithm. Nodes therefore keep status concerning destination cost, and next hop towards a destination. Every node periodically broadcasts and kept status concerning found destinations to neighbors.

Operationally, as explained, these two families of 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.

### 5.1 Specification aspects for distance-vector approaches

To analyze the behavior of the proposed metrics in distance-vector approaches we have considered AODV. This section describes the operational procedures we have considered so far, to ensure that the protocol can cope with the new metrics.

AODV is distance-vector protocol that works on-demand determining a route to a destination only when a node wants to send a packet to that destination. Routes are maintained as long as there is active traffic to the specific destination. Sequence numbers ensure the freshness of routes and are a way to mitigate transient loops and of avoiding counting-to-infinity. AODV nodes use four types of messages to communicate among each other. In the route discovery process are used *Route Request (RREQ)* and *Route Reply (RREP)* messages. Moreover, *Route Error (RERR)* messages are used for route maintenance; HELLOs are used to keep status concerning links (between neighbors).

The AODV protocol uses a hop count as metric to determine the shortest path between source and destination nodes. The routing information is only exchanged between directly connected neighbors. In order to accommodate our metrics, we have used the reserved field of the control messages to include the energy-aware cost and then use it to determine the shortest path instead of hop count as in native approach. For the node-based perspective, i.e., ENR metric, the protocol uses the node cost to compute the path. For the successor-based perspective, i.e., EFS metric, we have used the HELLO control messages to exchange the node cost and then define a binding cost between two nodes to compute the shortest path. The node cost sent from a node to its neighbors which its neighbors will have this information in advance to improve robustness.

### 5.2 Specification aspects for link-state approaches

For the case of link-state we have considered OLSR. As a proactive link-state protocol, OLSR relies on flooding techniques to assist in a quick synchronization of the global topology perspective. OLSR is, however, optimized to the wireless media by relying on HELLO exchange which is capable of performing a 2-hop neighbor information discovery and then performing a distributed election of a set of *Multipoint Relay (MPR)* nodes. MPRs assist in decreasing control traffic overhead, since only those nodes are allowed to broadcast topology changes. Nodes use the topology information to compute next hop paths regarding to all nodes in the network by using shortest path hop count metric.

We also have used the reserved field of the control messages to accommodate our metrics allowing a node to send to its neighbors its energy level information. Based on that information, each node can have the perception of the energy level to the link towards the neighbors nodes. In order to allow OLSR to cope with the new metrics, we had to change the MPR selection mechanism. Instead of considering a selection based on shortest-path with a hop-count metric, we consider a selection based on our metrics. For that, when there are more than one 1-hop neighbors covering the same number of uncovered 2-hop neighbors, the one with the better energy cost to the current node is selected as MPR.

Hence, we emphasize that we made minor changes as possible to accommodate our metric in the two main routing families focused on improve energy efficiency without significant operational changes.

### 5.3 Applicability guidelines for the RPL approach

In order to use the metrics described in this chapter on the Routing Protocol for Low-Power and Lossy Networks (RPL) [70], no changes or adaptation to the protocol are needed. By separating the packet processing and forwarding processes from the routing path selection, RPL provides a very flexible way of using and incorporating different metrics.

RPL operates upon the concept of Destination-Oriented Directed Acyclic Graph (DODAG), where routes are calculated from all nodes to a single destination in the topology (root node). Each node in the topology has a Rank, that is basically a value that represents its distance to the topology root.

According to specific LLN applications, such routes are calculated in order to achieve different objectives that may be desired (e.g. minimize delay, maximize throughput, minimize energy usage), so different Objective Functions (OF) may be defined. An OF defines how routing metrics, constraints and related functions are used, in order to define the route between the nodes towards a single destination in the topology. That is, an OF, in conjunction with routing metrics and constraints, allows for the selection of a DODAG to join (if there is more than one), and a number of peers in that DODAG as parents (that is, an ordered list of parents). The OF is also responsible to compute the Rank of the node.

The RFC6551 [40] defines a very flexible mechanism for the advertisement of routing metrics and constraints used by RPL, even though no OF is presented. A high degree of flexibility is offered by that mechanism, and a set of routing metrics and constraints are also described in the document.

**Impact on *<object>*** In order to use the metrics described in this document, the Node Energy object (NE), as defined in RFC6551, can be used without the need for any changes or adaptation. Figure 10 shows the NE structure is composed by a set of flags (8 bits), and an 8-bits field (E_E) used for carrying the value of the estimated energy.

```
0                   1
0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| Flags |I| T |E|  Energy Cost  |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Fig. 10: Node Energy object structure

To use the NE object with the metrics described in this document, the value of ENR or EFS metrics should be placed in the E_E field, and the flag 'E' (Estimation) should be set, indicating that a value for the estimated energy is provided in the E_E field. The other flags of the NE should be filled as defined in the standard.

## 6 Conclusions

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 the chapter have discussed energy awareness aspects and metrics in regards to routing. Out of the possible energy-efficiency aspects, choosing paths having in mind optimal network lifetime is an aspect that introduces more flexibility in multihop routing approaches and makes then better suited for user-centric environments.

Then, the chapter have evaluated the energy-aware routing metrics, being the intent to show that such metrics can improve multihop routing globally and independently of the protocol flavor. For such purpose, we have considered the two main popular families of multihop routing: link-state, and distance-vector. In terms of experimentation (based on simulations), we have considered the two most popular examples of each family, respectively: OLSR and AODV. The evaluation that has been carried out show that the metrics significantly improve network lifetime, without incurring significant penalties in terms of network operation. Moreover, and concerning the proposed metrics, one consistently achieved better results: EFS and iEFS. We believe that because EFS is based on the ranking (energy-awareness cost) of both a father node and its successor(s), it assists protocols in more quickly selecting stable paths. In other words, our belief for this gain relates to the fact that EFS allows nodes to react quicker to energy changes on a path, which will be more robust earlier in time, assuming that nodes have several successors available. The iEFS metric slight outperforms all approaches due to considering history, which provide stability in path selection.

Thinking on real implementation, a section was dedicated to 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 IETF ROLL WG as Internet-draft. The specification can be applied in any available multihop routing protocols, such as AODV, OLSR and RPL which can be used in UCNs and LLNs.

## Acknowledgments

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