Link-Stability and Energy Aware Routing Protocol in Distributed Wireless Networks

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Abstract—Energy awareness for computation and protocol management is becoming a crucial factor in the design of protocols and algorithms. On the other hand, in order to support node mobility, scalable routing strategies have been designed and these protocols try to consider the path duration in order to respect some QoS constraints and to reduce the route discovery procedures. Often energy saving and path duration and stability can be two contrasting efforts and trying to satisfy both of them can be very difficult. In this paper, a novel routing strategy is proposed. This proposed approach tries to account for link stability and for minimum drain rate energy consumption. In order to verify the correctness of the proposed solution a biobjective optimization formulation has been designed and a novel routing protocol called Link-stAbility and Energy aware Routing protocols (LAER) is proposed. This novel routing scheme has been compared with other three protocols: PERRA, GPSR, and E-GPSR. The protocol performance has been evaluated in terms of Data Packet Delivery Ratio, Normalized Control Overhead, Link duration, Nodes lifetime, and Average energy consumption.

Index Terms—MANET, scalable routing, biobjective optimization, link stability, energy consumption.

1 Introduction

The aim of this contribution is the proposal of a novel routing protocol able to account for a joint metric of link stability and minimum energy drain rate in mobile ad hoc network (MANET). This protocol was enhanced by the integration of a multiobjective integer linear programming optimization model, whose solution was calculated through the LINGO tool [1].

Energy is an important resource that needs to be preserved in order to extend the lifetime of the network [2], [3], [4], [5], [6], [7], [8], [9], [10], [11]; on the other hand, the link and path stability among nodes allows the reduction of control overhead and can offer some benefits also in terms of energy saving over ad hoc networks [12], [13], [14], [15], [16], [17], [18], [19]. However, as will be shown in this contribution, the selection of more stable routes under nodes mobility can lead to the selection of shorter routes. This is not always suitable in terms of energy consumption. On the other hand, sometimes, trying to optimize the energy can lead to the selection of more fragile routes. Thus, it is evident that both the aforementioned parameters (i.e., link stability associated with the nodes mobility and energy consumption) should be considered in designing routing protocols, which allow right tradeoff between route stability and minimum energy consumption to be achieved [20], [21].

The main aim of this work is to propose an optimization routing model within a MANET. The model attempts to minimize simultaneously the energy consumption of the mobile nodes and maximize the link stability of the transmissions, when choosing paths for individual transmissions. The idea of considering, at the same time, energy consumption and link stability is motivated by the observation that most routing protocols tend to select shorter routes, in this way high efficiency in using wireless bandwidth and increase path stability are ensured. However, such routes may suffer from a higher energy consumption, since higher transmission ranges are needed.

Consequently, in order to take into account the energy consumption and link stability of mobile nodes, a biobjective integer programming (BIP) model was formulated. Moreover, a greedy approach to find the solution to the BIP model was adopted and the found suboptimal solution was previously verified in [22] by using the software package LINGO [1]. In this manuscript, on the basis of the biobjective optimization model presented in [22], a routing protocol is proposed and its validity is experimentally investigated through simulations. A comparison with other known approaches, such as Power Efficient Reliable Routing Protocol for Mobile Ad Hoc Networks (PERRA) [21] and geographic routing [2], [23], [24], [25] (in particular GPSR [25]), is also carried out.

The rest of the paper is organized as follows: the next section gives a brief overview of the existing link/path stability and energy aware metrics and routing protocols; the biobjectives optimization problem is described and formulated in Section 3; the proposed routing protocol with joint optimized metrics is presented in Section 4; finally, simulation results and conclusions are summarized, respectively, in Sections 5 and 6.

2 Related Work

The description of some works related to the link stability, energy metrics and the respective routing protocols is given in this section. In particular, after introducing some recent contributions that separately account for path or link stability and energy consumption, a few papers on joint energy-path stability metrics are summarized [20], [21], [22] and the specific contributions of this manuscript are listed.

2.1 Path Stability Aware Metrics and Routing Protocols

In the literature, many metrics focusing on the link or path stability have been defined. Among them, some have been based on the definition of the route breakage probability and some others on the link duration distribution. However, most of them have considered some parameters associated with the specific mobility model in order to estimate the stability metric.

In [12], [19] the authors make use of statistical prediction based on the node movement. In this approach, a link stability probability has been defined on the basis of the random mobility model.

A formal model to predict the lifetime of a routing path, based on the random walk mobility and on the prediction technique, was proposed in [18]. It considers a probability model derived through the subdivision into cells of the area where mobile nodes move and on the observations of node movements in these cells. Transition probabilities are calculated and a state-based model of the movement among the cells is considered. Each connection between a mobile node in a cell and the other mobile nodes among its neighbor cells is considered as the state of the wireless link. In this way, the wireless link dynamic is determined between a mobile node and its neighbors, permitting the calculation of the link lifetime. After this, through the assumption of independent link failure, the route breakage probability is derived. More details can be found in [18].

There have been many papers published over the last few years where the link stability probability is determined by considering the signal stability [26]. However, this approach cannot be suitable because it assumes that the signal strength can be affected by environmental conditions and its value can change a lot also for the same nodes distance. This determines many fluctuations in the radio signal measurement, producing erroneous considerations on the link stability.

Other techniques rely on the use of special devices, such as the Global Positioning System (GPS), to detect the exact position of the mobile nodes [23]. Each node can calculate its position and a protocol is applied, which disseminates or requests the position for the other nodes. This approach is also criticized, because in some environments, such as indoors or where the mobile nodes are greatly limited in energy, the GPS is not functional. Some enhanced versions of GPSR have been presented in literature such as [39], [40], [41], where some movement prediction is applied in order to reduce the effect of bad location information; however, these fully location-based routing schemes do not account jointly for other metrics such as energy and stability.

In [14], [15] the authors propose a novel approach to infer residual link lifetime basing the computation on the current link age and on the previous link observations. Five different metrics, for stable path selection, have been proposed in the literature: the first technique is based on the local choice of the oldest link as the most stable link; the second class of metrics concerns the selection of the youngest links, because they are considered more resilient to breakage; the third criterion is based on the selection of the link with the highest average residual lifetime value; the fourth one makes selection of the link with the highest persistence probability; finally, the fifth metric focuses on the connection failure probability. The latter approach has been shown to be robust because it is based on the monitoring of the links lifetime of the mobile nodes in the wireless network, in the past and in the present, to predict its behavior, in the future without considering directly parameters depending by underlying mobility model such as node speed or direction.

The path stability, in terms of the number of route transitions a routing protocol incurs to continue the data exchange, is considered in [20]. End-to-end delay of a source destination session is another considered performance metric, particularly for real-time applications. In this work, the idea of stability-delay tradeoff (SDT), as a measure of the efficiency of an MANET routing protocol, was introduced.

In [41], the authors propose a prediction location-based routing scheme in order to increase the delivery ratio of GPSR and select the more stable route. However, such as for the previous listed contributions, energy is not considered in the packet forwarding.

2.2 Energy Aware Metrics and Routing Protocols

Many contributions concerning energy consumption have been proposed in the literature. In this section, the focus is on the network layer because it is interesting to show some recent papers on energy aware routing protocols and on energy-based metrics. Moreover, some additional metrics have tried to consider also the battery life cycle [8], or the energy drain rate [27]. In the following, after briefly describing some energy related metrics, energy aware routing protocols paradigms are also summarized.

2.2.1 Minimum Drain Rate (MDR) Cost

Energy saving mechanisms based only on metrics related to the remaining energy cannot be used to establish the best route between source and destination nodes. If a node is willing to accept all route requests only because it currently has enough residual battery capacity, much traffic load will be injected through that node. In this sense, the actual drain rate of energy consumption of the node will tend to be high, resulting in a sharp reduction of battery energy. As a consequence, it could exhaust the node energy supply very quickly, causing the node soon to halt. To mitigate this problem, other metrics, based on the traffic load characteristics, could be employed. To this end, techniques to measure accurately traffic load at nodes should be devised. In particular, the *Minimum Drain Rate* will be considered and explained in Section 3.

2.3 Energy-Based Routing Protocols

In addition to energy aware metrics such as those described in the previous section, also routing strategies and different state info management through routing protocols have been proposed in the literature.

In [10], a distributed power control has been designed as a way to improve the energy efficiency of routing algorithms in ad hoc networks. Each node in the network estimates the power necessary to reach its own neighbors, and this power estimate is used for tuning the transmission power (thereby reducing interference and energy consumption).

In [28], an energy efficient Optimization Link State Routing was proposed. This approach is based on the proactive info management and on the selection of Multi-point Relay (MPR) based on energy metrics, such as MMBCR and MDR.

In [27], the authors proposed an on-demand protocol based on the MDR metric and using a route discovery mechanism and route maintenance, similar to Dynamic Source Routing (DSR).

In [19], a Life-time Prediction-based Routing (LPR), focused on the minimization of the variances of the nodes remaining energies in the network, is proposed. In this protocol, each node tries to predict the future energy expenditure, but its estimation depends on many factor such as node distances, residual power, hop count, and node mobility.

2.4 Link Stability and Energy Aware Routing Protocols

There are few multiple metrics aware routing protocols, over distributed wireless systems, in the literature. However, in the context of novel distributed wireless systems and multimedia applications, where the system complexity is increasing, the chance of controlling and evaluating more network parameters becomes an important issue.

In this context, the use of multiobjective formulation and multiple metrics plays a crucial role. To the best of our knowledge, only two published works consider simultaneously link stability and energy consumption for path selection, which is the focus of this study (i.e., [20], [21], [22]).

Specifically, a routing protocol called Power Efficient Reliable Routing protocol for mobile Ad hoc networks was proposed in [21]. This algorithm applies the following three metrics for path selection: 1) the estimated total energy to transmit and process a data packet; 2) the residual energy; 3) the path stability. Route maintenance and route discovery procedures are similar to the DSR protocol [21], but with the route selection based on the three aforementioned metrics.

In [20], [32] the authors evaluated the performance of some path stability-based routing protocols, that is the Associativity-Based Routing (ABR), Flow-Oriented Routing Protocol (FORP) and route-lifetime assessment-based routing protocol (RABR). They consider the energy consumption of the above listed protocols in order to see the best candidate from an energetic point of view. However, in the aforementioned contributions, no novel metric is proposed and the path selection is performed by considering only the route stability metric. In [22], the authors gave a first contribution on the multiobjective mathematical formulation of a routing scheme, that considers two metrics, that is stability and energy. However, in this first contribution, only the optimization problem was formulated, whereas no analysis on the protocol management and protocol performance has been carried out.

2.5 Contribution of the Proposal

In our proposal, after applying one of the metrics presented in [14], [15] a heuristic, based on the local knowledge of the neighborhood, is applied. Following this heuristic the next hop toward destination is selected among the neighbor nodes, that maximize (minimize) the joined link-stability-energy metric.

This local criterion permits a high scalability to be offered to the routing algorithm in terms of state info storage and control packets transmission sent by any underlying routing protocol to maintain the network state knowledge.

On the basis of previous considerations, the main contributions of this manuscript are the following:

1. A multiobjective mathematical formulation for the joint stability and energy problem is presented.
2. The proposed protocol is based on a geographic paradigm [23], [24], [25], different by other routing protocols accounting for joint metrics, such as PERRA.
3. Adoption of a novel stability metric based on the residual link lifetime concept. This metric is considered more robust than the metric proposed in [21] because it is independent on the transmission radius and node speed parameters, that can be affected by measurement errors.
4. A novel energy aware-metric, adopted in our previous contributions [28], has been introduced in the proposed optimization model in order to consider not only the residual energy but also its time variation associated with the traffic load.
5. The multiobjective routing algorithm is integrated in the scalable routing protocol and its performance is tested through simulations and comparison with PERRA [21], GPSR [25], and an enhanced version of GPSR [41] called Ellipsoid algorithm-based GPSR (E-GPSR).

3 Math Formulation

The problem of finding an optimal path in a MANET was formulated as a bicriteria constrained optimal path model [22], which turns out to be intractable. Indeed, the number of efficient solutions may be exponential in the problem size. Consequently, it is not possible to define efficient methods to determine all efficient paths [33], [34], [35], [36]. Symbols used for the mathematical modeling are listed below in Table 1.

Let $x_{i,j}$ denote the binary variable associated with the link $(i,j)\ \forall (i,j) \in A$ that is set to one if the link belongs to the path and zero otherwise.

Before introducing the overall math formulation of the bicriteria-based path selection, the single metric definitions are provided.

3.1 Link-Stability Aware Metric

In this paper, differently from [18], a link stability metric rather than a path stability metric is considered. This is due to the protocol scalability properties that we tried to offer to the routing scheme. As will be shown in next sections, a node with the best tradeoff between link stability and energy consumption is adopted through a local forwarding criterion. Before explaining the method adopted to estimate the link stability grade, the definition of link stability is provided in what follows:

TABLE 1
Symbols Adopted in the Math Formulation

Symbol	Meaning
N	Set of network nodes
A	Set of links in the network
$d_{i,j}$	Euclidean distance between node *i* and node *j*
$O_{i,j}$	Set of link (i,j) ages observed in the past
$P_{i,j}(t)$	Transmission power to send a packet from node *i* to node *j*.
$Q_{i,j}(t)$	Power wasted in the node reception phase
$f_{i,j}$	Rate of the data flow sent from node *i* to node *j*
$c_{i,j}$	Power consumption cost per bit associated with the link *(i, j)*
η	Path loss exponent
P	Energy dissipated to receive one bit of information
$T_{i,j}$	Time required to send a packet from node *i* to node *j* on the link *(i,j)*
E_{res}	Residual energy of a node
E_j^0	Initial energy associated with node *j*
DR_j	Energy Drain rate associated with node *j*
$e_{i,j}$	Energy coefficient associated with link *(i,j)*
$s_{i,j}$	Stability coefficient associated with link *(i,j)*
$R_{i,j}$	Stability index accounting for link duration in previous observation intervals
$a_{i,j}$	Age of a link between node *i* and node *j*
a_{max}	Maximum observed age of the links
$d[\ ]$	Array used to store the observed links age
$d[a]$	Number of links with age equal to a.
$x_{i,j}$	Binary variable associated with the link *(i,j)*

Definition 1. *A link between two nodes i and j with transmission range R is established at time instant t_{in} when the distance between both nodes is such that $d(i,j) < R$.*

Definition 2. *A link between two nodes i and j with transmission range R is broken at instant time t_{fin} when the distance between both nodes verify the condition $d(i,j) > R$.*

Definition 3. *A link age a between two nodes i and j is the duration $a(i,j) = a_{i,j} = t_{fin} - t_{in}$.*

In order to consider a robust stability estimation index, that is independent on the single calculated measure and on the adopted mobility model, the use of parameters to evaluate the stability variables such as node speeds, direction change frequency, pause time, etc., is avoided.

Moreover, a statistical-based approach has been adopted in order to discriminate among several links which are more stable, meaning they are the most likely of all to stay available for some periods of time, without exactly predicting the residual link lifetime of each link. Thus, to enable mobile devices to make smart decisions in relationship to the stability, a practical method is used, based exclusively on observations related to the link, in previous time instants. As a result, this analysis produces an evaluation of the *link residual lifetime* of the link, since the stability of a link is given by its probability of persisting for a certain time span [15]. The *link residual lifetime* represents the potential remaining time that the link can exist before breaking.

By following the strategy outlined in [15], in the proposed mathematical model, the expected residual lifetime $R_{i,j}(a_{i,j})$ of a link (i,j) of age a_{ij} is determined from the collected statistical data as follows:

$$R_{i,j}(a_{i,j}) = \frac{\sum_{a=a_{ij}}^{A_{\max}} a \cdot d[a]}{\sum_{a=a_{ij}}^{A_{\max}} d[a]} - a_{i,\,j} \ \forall (i,j) \in A, \tag{1}$$

where a_{max} represents the maximum observed age of the links and d is an array of length $a_{max} + 1$ used to store the observed data.

In particular, d is determined through a sampling of the link ages every fixed time interval and its generic component $d[a]$ represents the number of links with age equal to a.

The coefficient $R_{i,j}(a_{i,j})$ (see (1)) is defined as the ratio between the sum, on all links with age equal or greater than $a_{i,j}$, of the products of the age a and the number of links with age equal to a (that is *d[a]*), over the total number of links with age greater or equal to a_{ij}. The main disadvantage of using the coefficient $R_{i,j}(a_{i,j})$ for path selection is related to the fact that it does not allow discrimination among links of the same age.

In order to overcome this drawback, the average traveled distance $d_{i,j}^{avg}$ should be taken into account. It represents the average among the movement distances of each node under the Random Way Point (RWP) mobility model. Each node selects a target position to reach with a randomly selected speed and after reaching this position it selects a new one. In our approach we store the crossed distances and we determine the average. The rationale is that if two links have the same residual lifetime, a shorter average distance is preferable to a longer distance in terms of link stability [22].

Indeed, the transmission and reception operations, associated with data and control packets, are more computational expensive in comparison with the operations associated with the links ordering. This is particularly true in the case of MANETs, where the node density, defined as the number of neighbor nodes, is very limited (i.e., ranging between 5 and 10) even in the case of very high-density networks [37]. For this reason, this work does not take into account the number of reordering operations of links with different expected residual lifetimes.

On the basis of the previous considerations, the stability of the link $(i,j)\ \forall (i,j) \in A$, at time t, has been represented by the coefficient $s_{i,j}(t)$, defined as follows:

$$s_{i,j} = \frac{d_{i,j}^{avg}}{R_{i,j}(a_{i,j}) \cdot k} \quad \forall (i,j) \in A, \tag{2}$$

where k is a scaling factor, defined in such a way that the link stability can be compared to the energy consumption. The coefficient $s_{i,j}(t)$ defined in (2) can be interpreted as a reciprocal measure of the stability. It has been defined in this way for the following reasons: first of all, it is assumed that the second objective function of the proposed mathematical model has to be minimized; in addition, the higher the residual lifetime of a link, the higher the reliability of the link. Finally, the higher the average traveled distance between two nodes, the higher the likelihood that their distance exceeds the transmission radius with a consequent the link breaks up.

3.2 Energy-Aware Metric

In this study, it is assumed that each wireless node has the capability of forwarding an incoming packet to one of its neighboring nodes and to receive information from a transmitting node. In addition, each node is able to identify all its neighbors through protocol messages (this issue will be explained in Section 4). It is assumed that each node does not enter in standby mode and each node can overhear the packet inside its transmission range and it is not addressed to itself.

The energy needed to transmit a packet p from node i is: $E_{tx}(p,i) = I \cdot v \cdot t_b$ Joules, where I is the current (in Ampere), v the voltage (in Volt), and t_b the time taken to transmit the packet p (in seconds).

The energy *E(p, i)* spent to transmit a packet from node i to node j is given by

$$E(p,i) = E_{tx}(p,i) + E_{rx}(p,j), \tag{3}$$

where E_{tx} and E_{rx} denote, respectively, the amount of energy spent to transmit the packet from node i to node j and to receive the packet at node j; to the energy spent to overhear the packet has been avoided in this context such as referred in [28]. The power dissipated by mobile nodes to exchange beacowning messages and/or to remain always in active modality is also considered.

In the proposed model, the power dissipation is determined by considering both the power consumption at a transmitter $P_{i,j}(t)$ and the power consumption at a receiver $Q_{i,j}(t)$.

In particular, the transmission power is modeled as follows [3], [4], [32]:

$$P_{i,j}(t) = c_{i,j} \cdot f_{i,j}, \tag{4}$$

where $P_{i,j}(t)$ represents the power dissipated to transmit at a given instant of time t and $f_{i,j}$ is the rate of the data stream sent from node i to j.

The coefficient $c_{i,j}$ represents the power consumption cost per bit associated with the link *(i, j)* and it is modeled as follows:

$$c_{i,j} = b \cdot \tilde{\beta} \cdot d_{i,j}^{\eta}, \tag{5}$$

where b is a distance-independent parameter accounting for the network characteristics; η represents the path loss index and $2 \leq \eta \leq 4$ [3], [4], [32]; $d_{i,j}$ denotes the last observation of the distance between node i and node j; $\tilde{\beta}$ is a coefficient associated with the distance-dependent term, which has been defined in such a way as to take into account the reciprocal movement among nodes.

In particular, $\tilde{\beta}$ is modeled as follows:

$$\tilde{\beta} = \beta \cdot \frac{d_{i,j}^{avg}}{d_{i,j}^{0}}, \tag{6}$$

where $d_{i,j}^{(0)}$ represents the distance between node i and node j observed at the time t_0, when the link is formed for the first time, $d_{i,j}^{avg}$ is the average traveled distance between nodes i and j at time t, whereas β is the parameter traditionally associated with the physical distance between nodes in static networks [3], [4], [32]. The power wasted in the reception is movement and time independent and it is modeled in the following way:

$$Q_{i,j} = \rho \cdot f_{i,j}, \tag{7}$$

where ρ represents the energy dissipated to receive one bit of information. In our model, it is assumed that ρ is constant and the same for every node. $f_{i,j}$ is the data rate from node i to node j.

It is important to point out that, starting from node i, the generic nondestination neighboring node j can be selected if and only if both the following conditions are satisfied:

1. j has enough energy to receive the information sent from node i,
2. j is able (in terms of energy) to transmit the information toward another relay node.

In order to guarantee that conditions *(a)* and *(b)* are fulfilled, two constraints have been introduced in the proposed model.

Let $T_{i,j}$ be the time required to send a packet of information from node i to node j and let E_{res_i} denote the residual energy of the node i $\forall i \in N$; the first constraint is stated as follows:

$$T_{i,j} \cdot Q_{i,j} \leq \delta \cdot E_{res_j} \qquad \forall (i,j) \in A, j \neq D, \tag{8}$$

where δ is a parameter between 0 and 1 (i.e., $0 < \delta < 1$), that has been introduced to avoid the selection of a node for which the energy required to receive a message is equal to its residual energy.

It is also important to guarantee that node i is able to send the information toward a neighbor j without going down. Indeed, the following constraint has to be fulfilled:

$$T_{i,j} \cdot P_{i,j}(t) \leq E_{res_i} \qquad \forall (i,j) \in A. \tag{9}$$

Constraint (9) means that the energy to transmit the information from node i toward node j should be lower or equal to the residual energy of node i. It is assumed that each node is able to estimate its residual energy.

The Minimum Drain Rate, such as in [27] has been applied with a cost function that takes into account the drain rate index (DR) and the residual energy (E_{res}) to measure the energy dissipation rate in a given node.

Each node i monitors its energy consumption caused by the transmission, reception and overhearing activities and computes the energy drain rate, denoted by DR_i, for every

T seconds sampling interval by averaging the amount of energy consumption and estimating the energy dissipation per second during the past T seconds. The actual value of DR_i is calculated by utilizing the well-known *exponential weighted moving average* method applied to the drain rate values $DR_i(t-1)$ and DR_{curr}, i, which represent the previous and the newly calculated values

$$DR_{curr,i} = DR_i(t), \tag{10}$$

$$DR_i(t) = \alpha \cdot DR_i(t-1) + (1-\alpha) \cdot DR_{curr,i}. \tag{11}$$

In addition to drain rate DR_i, also another parameter called *Propensity* (PR) is applied. The PR_i term expresses the propensity of a node i to receive information from another node. Given a generic instant of time t, the coefficient $PR_j(t)\ \forall j \in N_i$, is defined as follows:

$$PR_j(t) = \frac{E_{res_j}}{E_j^0}, \tag{12}$$

where E_j^0 represent the initial energy of node j.

The propensity $PR_j(t)$ is used, in conjunction with the power transmission $P_{i,j}(t)$ and drain rate DR_j to define the coefficient $e_{i,j}(t)$ that is used in the first objective function of the proposed model, to characterize a node from an energetic point of view.

More specifically, $e_{i,j}(t)$ can be represented as follows:

$$e_{i,j}(t) = \frac{P_{i,j}(t)}{PR_j(t)} \cdot \frac{DR_j(t)}{E_j^0} \cdot T_{i,j}. \tag{13}$$

For each link $(i,j) \in A$ and for each instant of time t, the coefficient $e_{i,j}(t)$ is defined as the ratio between the power $P_{i,j}(t)$ dissipated to send information from node i toward to node j and the propensity $PR_j(t)$ of node j.

The rationale of defining the coefficient $e_{i,j}(t)$ as in (13) is that the objective function has to be minimized. In addition, the higher the value of $PR_j(t)$, the higher the propensity of node j to receive information, whereas the higher the value of $P_{i,j}(t)$, the lower the advantage of selecting node j. Moreover, the higher is the energy drain rate DR_i associated with node i, the higher is the consumption in the time of energy and, consequently, the higher is the link cost $e_{i,j}$.

3.3 Multiobjective Problem Formulation

The problem of selecting the best path (in the Pareto sense [33], [34], [35], [36]) connecting node s to node d, accounting for energy consumption and link stability can be mathematically stated as follows:

$$\min f_1 = \sum_{(i,j)\in A} e_{i,j}(t) \cdot x_{i,j}, \tag{14}$$

$$\min f_2 = \sum_{(i,j)\in A} s_{i,j}(t) \cdot x_{i,j}, \tag{15}$$

subject to

$$x_{i,j} \cdot T_{i,j} \cdot P_{i,j}(t) \le E_{res_i} \quad \forall (i,j) \in A, \tag{16}$$

$$x_{i,j} \cdot T_{i,j} \cdot Q_{i,j}(t) \le E_{res_j} \quad \forall (i,j) \in A, \tag{17}$$

$$\sum_{(i,j)\in A} x_{i,j} - \sum_{(i,j)\in A} x_{j,i} = \begin{cases} 1 & \text{if } i = S, \\ 0 & \text{if } i \in N \backslash \{S, D\}, \\ -1 & \text{if } i = D, \end{cases} \tag{18}$$

$$x_{i,j} \in \{0,1\}\ \forall (i,j) \in A,$$

where

$$e_{i,j}(t) = \frac{P_{i,j}(t)}{PR_j(t)} \cdot \frac{DR_j(t)}{E_j^0} \cdot T_{i,j} \qquad \forall (i,j) \in A, \tag{19}$$

$$d_{i,j}^{avg} = \frac{\sum_{k=1}^{|O_{i,j}|}}{d_{i,j}^{(k)}} |O_{i,j}| \qquad \forall (i,j) \in A, \tag{20}$$

$$s_{i,j} = \frac{d_{i,j}^{avg}}{R_{i,j}(a_{i,j}) \cdot k}, a_{i,j} \in \{0, \dots, A_{\max}\} \quad \forall (i,j) \in A, \tag{21}$$

where conditions (18) represent the flow conservation constraints, that are used to ensure that each feasible solution of the proposed model is a path from S to D. By following a popular approach used to deal with multi-objective optimization problems [30], [31], [32], [33], the model (14)-(21) has been transformed into a single objective one, using arbitrary importance factors for each criterion (i.e., p_1 and p_2) and combining the objectives into a single function to be minimized.

The resulting single-objective problem, in which a positively weighted convex sum of the objectives has to be minimized, can be represented as follows:

$$\begin{aligned} f_{tot} &= p_1 f_1 + p_2 f_2 \\ &= p_1 \sum_{(i,j)\in A} e_{i,j}(t) x_{i,j} + p_2 \sum_{(i,j)\in A} s_{i,j}(t) x_{i,j}. \end{aligned}$$

Consequently, the single objective optimization model assumes the following form:

$$\min f_{tot} = \sum_{(i,j)\in A} (p_1 \cdot e_{i,j}(t) + p_2 \cdot s_{i,j}(t)) \cdot x_{i,j}, \tag{22}$$

subject to the constraints (16-21). Parameters p_1 and p_2 are chosen such that the condition $p_1 + p_2 = 1$ is satisfied.

It is easy to prove that the optimal solution of the model introduced above is Pareto optimal [33]. The user should choose appropriate values for the parameters p_1 and p_2. Indeed, by minimizing the convex sum of the objectives for various settings of the convex weights, it is possible to determine various points in the Pareto set. This approach gives an idea about the shape of the Pareto surface and allows information to be obtained about the tradeoff among the various objectives [33], [34], [35], [36].

It is important to note that the proposed single-objective model can be used to address many applications, with different QoS constraints. For example, for applications in which more relevance is given to energy saving, more importance could be given to the energy weight p_1 (i.e., $p_1 >> p_2$), whereas for applications, where it is important to reduce the link breakage and the queuing delay, more importance could be given to the stability weight p_2 (i.e., $p_2 > p_1$). Moreover, all metrics are calculated on a local basis each Δt time interval. This permits to update the parameters' model in order to capture the network dynamics. More details about this sampling procedure are given in [21].

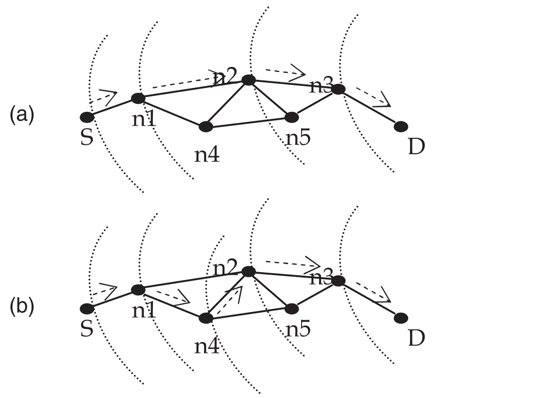

Fig. 1. Greedy forwarding (a) *GPSR* greedy approach based on the euclidean distance; (b) *LAER* greedy based on the joint metric f_{tot}.

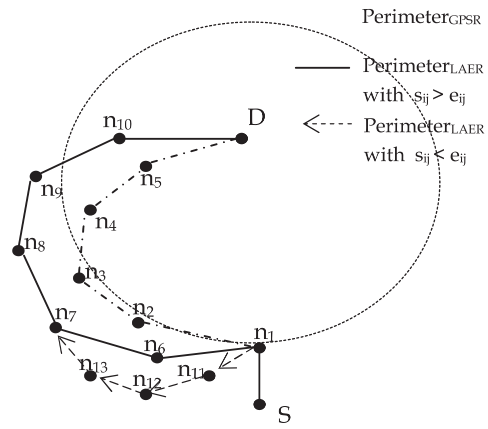

Fig. 2. Perimeter forwarding in GPSR and LAER protocols.

4 Link Stability and Energy Aware Routing (LAER) Protocol

The LAER algorithm requires each node i to advertise its location (x_i, y_i, z_i), rate of energy consumption (MDR_i), and link stability index for each link outgoing by node i. We will insert the information mentioned above in LAER *HELLO* packet.

Each node broadcasts HELLO packets to all its neighbors that are in its communication range; each node in LAER maintains the table of its direct neighbors.

When a node receives the HELLO packet, it updates the information of the neighbor, if neighbor ID is already present in table or adds a neighbor information, if it is a new neighbor.

4.1 Forwarding Strategy

The data forwarding strategy of LAER is based on a greedy technique such as GPSR. However, differently by GPSR, the next hop selection tries to minimize the joint energy-stability metric. LAER packet forwarding presents high scalability property because only the neighborhood and destination knowledge are necessary for the greedy technique. The flexibility of energy-stability-based greedy forwarding is offered through the capability to weight the stability and the energy consumption on the basis of the interest of the application layer. This means that if an application is more sensitive to the path stability and, consequently, the link stability, it is possible to give more importance to the $s_{i,j}$ index. On the other hand, an application that needs to prolong the network lifetime and to reduce the energy consumption also selecting longer route with higher data packet end-to-end delay, the $\mathrm{e_{i,j}}$ terms is more considered, as underlined in (10).

In Fig. 1, it is shown the packet forwarding under the greedy technique based on the euclidean distance (see GPSR) and the forwarding scheme with the joint stability and energy aware metric. In particular, in the figure the following situation is depicted: S falls in the transmission range of node $\mathrm{n_1}$ (and vice versa), $\mathrm{n_1}$ in the transmission range of nodes $\mathrm{n_2}$ and $\mathrm{n_4}$, $\mathrm{n_2}$ in that of $\mathrm{n_3}$ and $\mathrm{n_5}$, and $\mathrm{n_3}$ in that of node D. It is possible to observe as the selected path can be different depending on the metric considered and on the weights used when the joint metric is applied. In particular, the GPSR scheme selects the path S-n1-n2-n3-D because all neighbor nodes that minimize the distance toward the destination D are selected (maximum progress), whereas the LEAR forwarding scheme selects $\mathrm{S - n1 - n4 - n2 - n3 - D}$ path. This means that LAER selects a longer path but with higher residual energy.

In order to avoid either routing loop or long packet detour and to offer always a progress direction, a combined euclidean distance-based forwarding and a joint stability-energy metric for the next hop selection are adopted. In particular, it is selected as next hop the neighbor node j of current node i with the highest f_{tot}, and a distance from destination equal or lower than the current node i.

This approach guarantees, as GPSR, a progress direction in the application of greedy technique but, differently from GPSR, it permits also to select the best candidate for the joint metric rather than the node with only the highest euclidean progress direction. In the following, it is shown the pseudocode of modified *LAER Greedy-Forward* from node i at the arrival of packet p.

LAER GREEDY-FORWARD (p, i)

$j_{best} = n_{curr}$;
$\mathrm{s_{min}} = \max(\mathrm{s_{i,j}}); \forall j \in N_i$
$d_{best} = Distance(j_{best}, p.d)$;
For each $j \in N_i$
  Calculate $f_{tot}(i, j)$;
  $distance = Distance(j, p.d)$;
if $distance < d_{best}$ then {for each $j' \in N_i$
    if $s_{i,j} < s_{\min}$ then {
    $s_{min} = s_{i,j}; j_{best} = j'$;}
}
if $j_{best} = n_{curr}$ then return LAER Greedy *failure*;
else{forward p to j_{best}; return LAER Greedy *success*;
}

where N_i is the set of neighbors of the node i.

The LAER algorithm fails when no neighbors with progress direction in the euclidean sense is found and the LAER greedy failure is returned such as expressed in the pseudocode above. This is the case when for the current node n_1 where the *euclidean* distance of all its neighbors from D is greater than distance $\overline{n_1 D}$ such as shown in Fig. 2. Like in greedy routing, at this point node n_1 thinks that there is a *hole* (or local maximum) in the geographical distribution of nodes and a recovery procedure is applied such as will be explained below. On the other hand, if also the recovery procedure fails the data packet is dropped.

In our implementation of LAER, we recovered from this situation by applying Karp and Tung solution (GPSR) [25] that uses a planar subgraph of the wireless networks graph to route around holes. More details about this recovery technique are provided in the next section.

4.2 Local Maximum Recovery Strategy

During the greedy technique, it is possible to meet a *void* or *local maximum* in the GPSR. Local maximum represents a point in the network where it is not possible to find any neighbor node that leads to the minimization of the distance toward the destination in comparison with the current node (see Fig. 2). In this case, the protocol assumes to use a recovery mode called *Perimeter Forwarding*. This technique permits the go out from local maximum selecting other neighbor nodes among the perimeter of the polygon face such as explained also in [24], [25], [39]. In LAER, this situation can happen due to greedy routing strategy based on the minimization of the joint metric f_{tot} associated with each link *(i,j)*. In our case it is met a *local maximum* if a node i cannot find any neighbor node $j\ \forall j \in N_i$, that minimizes f_{tot}, where N_i is the set of i's neighbors. In this case, LAER uses an approach similar to GPSR but the joint metric is used to select the set of neighbor candidates for the perimeter mode. An example is shown in Fig. 2 where a node n_1 is in a local maximum and it has to select a neighbor on the basis of the perimeter forwarding. A set of possible candidates is $\{n_2, n_6, n_{11}\}$ that represents n_1's neighbors on distinct faces of the polygons obtained after the graph planarization. In our approach, the Gabriel planarization is applied according with [25] to avoid loop in the *perimeter mode* and also the *right hand rule*. However, differently from authors in [25], it is not selected the node on the face with the minimum angle formed by the direction followed by the data packet entering in n_1 (from s to n_1) and the line connecting s and a specific neighbor on the planarised graph. In our case, we applied the joint metric with just one metric to discriminate the neighbor node to select in the *perimeter forwarding* mode. It is important to observe that it is assumed that a local maximum is a network point that does not allow progress to be made in terms of the joint f_{tot} metric. However, this condition can be avoided if the single metrics are applied. Thus, in LAER recovery mode, first of all a n_1' neighbor node with the lowest $\mathrm{s}_{i,j}$ metric is selected. If no neighbor is found, the other metric is considered $e_{i,j}$ and in the last case the approach of the original GPSR is applied. The motivation to select *in primis* the link stability aware metric in the recovery mode is to promote the selection of shorter and more stable routes to reduce the long packet detour determined by the classical perimeter forwarding [37].

Let us consider now a node i with a list of its neighbors indicated with N_i and their relative positions. Let α^i_{in} be the ingress angle calculated on the basis of the direction of the data packet arriving on the node i (it is possible to calculate it through the knowledge of position of node sending the packet and the node i receiving the packet); α^i_{out} is the angle formed by two lines: the first one connecting node i and its predecessor and the second connecting node i and $j \in N_i$. The GPSR *right-hand-rule* selects the node on the polygon face that minimizes the difference $\Delta\alpha^i = \alpha^i_{out} - \alpha^i_{in}\ \forall j \in N_i$. In order to determine α^i_{in} and α^i_{out} it is necessary to calculate the ATAN ($\tan^{-1}$) of the angle formed by the lines, as expressed above. The information about the coordinates contained in the packet arriving on the node (*self.l.x*, *self.l.y*), the coordinates of the node i sending the packet (*i.x*, *i.y*), and the coordinates of neighbor node j with $j \in N_i$ permit to calculate these two angles through a simple inverse trigonometric formula.

TABLE 2
Fields Adopted in LAER HELLO Packet

Field	Function
Node ID	Node identification
Node location	Geo-coordinates
E_{res}	Residual energy
s_{ij}	Stability index

***Right-Hand-Forward* (*p, i*)**
$\alpha^i_{in} = NORM(ATAN(self.l.y - i.y, self.l.x - i.x))$
$\delta_{\min} = 3\pi$; $s_{\min} = \max(s_{i,j}); e_{\min} = \max(e_{i,j});\ \forall j \in N_i$
For each $j \in N_i$ If $s_{i,j} < s_{\min}$ then $\{s_{\min} = s_{i,j}$; $j_{\min} = j$
$\}$ else if $(s_{i,j} = s_{\min} \&\& e_{i,j} < e_{\min})$ then $\{$
$e_{\min} = e_{i,j}$; $j_{\min} = j$
$\}$ else $\{$
$\alpha^j_{out} = NORM(ATAN(self.l.y - j.y, self.l.x - j.x))$
$\delta_{curr} = NORM(\alpha^j_{out} - \alpha^j_{in})$
If $\delta_{curr} < \delta_{\min}$ then $\delta_{curr} = \delta_{\min}$; $j_{min} = j\}$
return j_{min};

4.3 Packet Formats

Concerning the data packets and HELLO packets adopted by LAER, it is necessary a packet modification and extension because we need to update the info related to energy index and stability index of neighbor nodes and because also the weights p_1 and p_2 can be determined by application layer on the basis of the importance given to the energy consumption or to link stability. For this reason, a modified version of HELLO and DATA packet formats was adopted such as presented below. In particular, LAER HELLO packet information is shown in Table 2.

The data packet format, instead, is presented in Table 3. In this case also the weights info is carried by data packets.

It is observed that L_p is important to establish when to switch from *perimeter* to *greedy* mode. When, in the *perimeter* mode, a node with distance from destination lower than L_p is reached, it is possible to switch in *greedy forwarding*. Concerning e_0, it represents that location of the first edge on the new face of the polygon traversed. This last variable is important to apply the right-hand-rule according with a criterion similar to that adopted in [25].

TABLE 3
Fields Adopted in LAER Data Packet

Field	Function
S	Source Address
D	Destination Address
L	Destination node location (x,y)
M	Forwarding mode (greedy or perimeter)
L_p	Location of first node entered in perimeter mode
e_0	First edge of the new face traversed in perimeter mode
$e_{i,j}$	Energy based index
$s_{i,j}$	Stability based index

5 Performance Evaluation

It is assumed that all mobile nodes are equipped with IEEE 802.11a network interface card, with data rates of 11 Mbps. In our simulations, the voltage V is chosen as 5 V and it is assumed that the packet transmission time t_p is calculated by $(\frac{p_h}{6\cdot 10^6}+\frac{p_d}{54\cdot 10^6})(p_h/(6.10^6)+p_d/(54.10^6))$ seconds, where p_h is the packet header size in bits and p_d the payload size.

In order to validate the effectiveness of the LAER protocol, some simulations and comparisons with other energy aware protocols have been assessed. In the following, it will be shown how LAER represents a good tradeoff in terms of protocol overhead, data packet delivery ratio (DPDR), and average energy consumption in comparison with the other protocols.

5.1 Protocols Considered for Comparison

Protocols adopted for comparison purpose are, respectively, PERRA as representative of on-demand routing protocols accounting multiple metrics and E-GPSR and GPSR as representative of scalable- and location-based routing.

5.1.1 PERRA

PERRA is an on-demand routing protocol that provides new features achieving power efficiency and reliable data transmission. Some basic functions are listed below:

1. PERRA uses a route discovery procedure through the RREQs propagation that involves just nodes that meet the source's energy requirements before transmitting data packets.
2. Data packets are transmitted through the optimum path on the basis of the minimum residual energy, path stability, and total estimated energy to transmit and process a data packet.
3. Alternative routes are prepared in case of link break and used before an actual break occurs.

The objective function in PERRA is the following:

$$f_{tot} = w_1 \times E_t - w_2 \times \min[E_{res}] - w_3 \min[LL], \qquad (23)$$

where E_t is the energy spent in the transmission and in the processing of a packet, E_{res} is the residual energy, and LL is the link lifetime. This approach selects the minimum E_{res} and LL among nodes belonging to the path from source to destination.

The main differences with our proposal are the application of an on-demand strategy, the flooding of the route request for the path discovery, and the different definition of the metric. However, because this protocol is an example of a routing protocol using multiple metrics in the path establishment, it has been considered a good candidate for comparison with LAER.

5.1.2 Ellipsoid Algorithm-Based GPSR

In order to compare LAER protocol with a novel GPSR version, we considered an enhanced GPSR proposed in [41] called E-GPSR. The main features of E-GPSR are briefly listed below:

1. Calculation of future position of neighbor nodes on the basis of a prediction technique based on the Least Squares Lattice filter and time series.
2. Selection of the next node to reach the destination based on the ellipsoid algorithm. Through this approach is selected the neighbor node that minimizes the difference distance between current total distance d and the future total distance d' from current node to destination node. In particular considering a source node S, an intermediate node R, and a destination node D the ellipsoid algorithm selects the node that minimizes $\Delta = d + d'$, where $d = d_{SR} + d_{RD}$ and $d' = d'_{SR} + d'_{RD}$.

For more details about this approach, please refer to [41].

5.2 Simulation Parameters

To evaluate the LAER protocol, the ns-2 network simulator was used [38]. A wireless network is simulated, with 50 nodes moving in a 870×870 m^2 area. Each node moves randomly in this area, with a speed selected in a range [0, v_{max}] with no pause time. Between mobile hosts there are 8 and 16 CBR/UDP sources generating 8 packets/s (with a packet size of 512 bytes). The duration of each simulation is 700 seconds. To extract average values, we simulated each scenario five times.

Simulation output variables that have been considered in our simulator are:

- Data packet delivery ratio: it is the number of packets received at destination on data packets sent by source.
- Protocol overhead: it is calculated as the number of HELLO packets sent in the LAER and GPSR protocols and the number of RREQ, RREP, and RERR in the PERRA protocol.

To have detailed energy-related information over a simulation, the ns-2 code was modified to obtain the amount of energy consumed (energy spent in transmitting, receiving) over time. In this way, accurate information was obtained about energy at every simulation time. We used these data to evaluate the protocols from the energetic point of view.

Simulation output variables considered in the evaluation of the energy and link stability metrics are the following:

TABLE 4
Common Parameters Adopted in the Simulations

Area	870mx870m
Nodes	50
Nodes speed	0.1-20m/s
Simulation time	700s
Traffic sources	8,16
Traffic type	CBR
Packet size	512bytes
Start of Traffic	30s
End of traffic	600s
Transmission power	1.4 W
Reception power	1.0 W

TABLE 5
PERRA Parameters Adopted in the Simulations

Hello time interval **s**	*1 s*
w_1	0.4
w_2	0.4
w_3	0.2
T_{wait_PCREP}	0.3s
RREQ time interval	10s

- Average link stability: this parameter is adopted rather than path stability because for protocols such as GPSR, E-GPSR, and LAER the path stability cannot be considered due to the absence of a path establishment phase;
- Average energy consumption: this parameter allows to make considerations about energy wastage associated with the route maintenance and route discovery and it accounts for energy consumption during transmission and reception of control and data packets;
- Average node residual energy: it can be useful to evaluate the remaining energy in order to have an idea of the network lifetime;
- Variance of node residual energy: this parameter is considered to evaluate the distribution of energy among nodes. The greater is the dispersion around the average residual node energy, the higher is the unfairness in the node usage and in the energy dissipation among nodes.

Simulation parameters adopted in the performance evaluation campaigns are listed in Tables 4, 5, and 6. Table 4 lists the common parameters adopted in the simulator regardless the specific considered protocols. Tables 5 and 6 present simulation parameters adopted, respectively, for the PERRA and LAER protocols. PERRA's parameters are fixed as in [21].

TABLE 6
GPSR, E-GPSR, and LAER Parameters
Adopted in the Simulations

p_1	0.1, 0.3, 0.5, 0.7, 0.9
p_2	0.1, 0.3, 0.5, 0.7, 0.9
Δt	5s
Hello interval	2s
α	0.3
Idle power	0.0 W

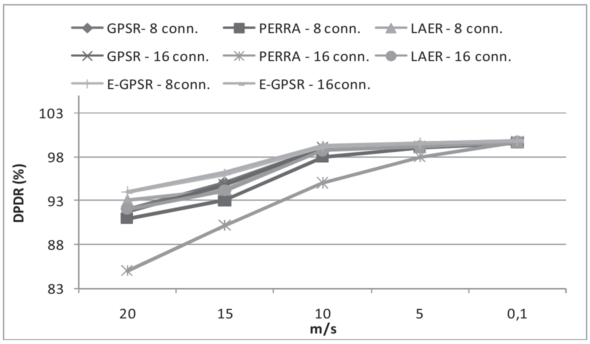

Fig. 3. Data packet delivery ratio for different maximum node speed and number of connections.

5.3 Simulation Results

Two simulation campaigns are shown in the following sections. The first one exploits the performance of the proposed protocol against PERRA, GPSR, and E-GPSR considering the standard statistics such as DPDR and control overhead. The second campaign focuses on the link stability and energy consumption.

5.3.1 Data Packet Delivery Ratio and Control Overhead Evaluation

The DPDR for different number of connections is shown in Fig. 3. GPSR, E-GPSR, PERRA, and LAER present similar performance when the traffic load is not heavy with percentage value about 99 percent for very low mobility. However, for higher traffic load and high mobility (10-20 m/s) the low scalability of PERRA is visible and LAER, GPSR, and E-GPSR perform better. PERRA wastes bandwidth for control overhead and the reactive management of the protocol leads to a degradation of performance reducing the DPDR to 85-90 percent. The curve depicted in Fig. 4 testifies the increase in the normalized control overhead for higher speed. It is possible to observe the good scalability of protocol based on the local topology knowledge such as LAER, GPSR, and E-GPSR. The greedy technique applied to both protocols and the only local control packets exchange (HELLO pkts) determines a similar performance of LAER, GPSR, and E-GPSR, differently by PERRA that is forced to start new route discovery procedure that increases the control overhead.

Obviously, the changing of p_1 and p_2 parameters, as shown in Fig. 5, do not affect the performance of PERRA, GPSR, and E-GPSR. However, it is interesting to observe as

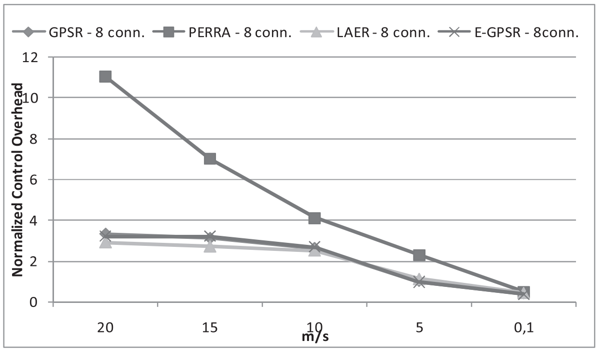

Fig. 4. Normalized control overhead versus maximum node speed.

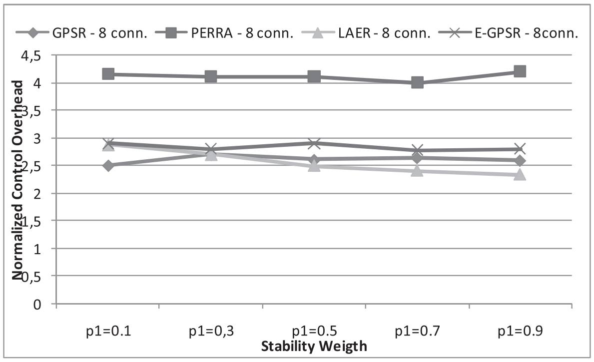

Fig. 5. Normalized control overhead versus stability weights.

TABLE 7
Average Link Duration for Decreasing Nodes Speed

	20m/s	15 m/s	10 m/s	5 m/s	0,1 m/s
GPSR	10	12,5	15,2	18	80
E-GPSR	12,1	15,2	19,3	21,6	120
PERRA	11,5	14	18	22,2	100
LAER	13,3	17	22	27	150

the coefficients associated with stability and energy metrics do not affect also the performance of LAER. This is due to the specific scenario where the initial node energy is so high to not see any node energy exhaustion. The different performance associated with the different metrics weight are more evident in the next section.

5.3.2 Link Stability and Energy Evaluation

In Table 7, it is possible to observe the increasing link duration trend for decreasing node mobility such as expected. The higher node mobility determines more link breakage reducing the average link duration.

Both PERRA, E-GPSR and LAER increase the link duration because specific link aware metrics permit to select the most appropriate nodes. However, it is possible to see that LAER can increase the average link duration for fixed p_1 and p_2 values (they are fixed both to 0.5 in the graphics where the nodes speed changes). This means that the link stability aware metric can better discriminate the neighbor nodes through the adoption of the history of the link lifetime and the statistical behavior to infer consideration on the residual link duration, whereas PERRA through consideration of only node speed is not always able to discriminate the longer link from a lifetime point of view.

TABLE 8
Average Link Duration for Different Stability Weights

	p1=0.1	p1=0,3	p1=0.5	p1=0.7	p1=0.9
GPSR	15,2	15,2	15,2	15,2	15,2
E-GPSR	19,3	19,3	19,3	19,3	19,3
PERRA	18	18	18	18	18
LAER	16,4	18,2	21	22	24

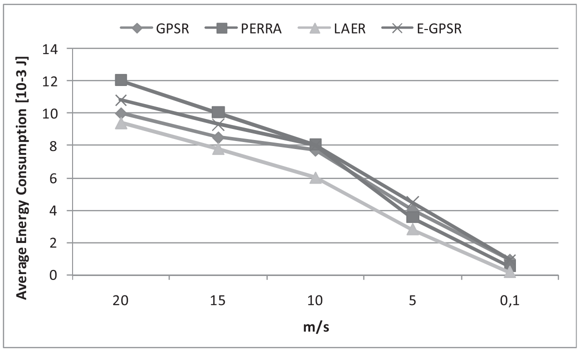

Fig. 6. Average energy consumption versus maximum node speeds.

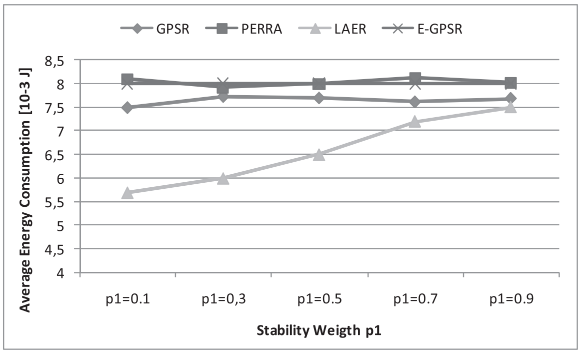

Fig. 7. Average energy consumption versus stability weights.

The imprecision in the link stability metric of PERRA is accentuated when more independent movements are made by a mobile node and the RREP message of PERRA is not able to predict these fast variations. On the other hand, a statistical characterization of the link duration can avoid to send often control packets on the built path in order to refresh the previously discovered info. Moreover, in the second table (Table 8) the effect of the coefficients p_1 and p_2 is also evaluated. As expected, a higher p_1 value determines the selection of more stable nodes and consequently link with a longer lifetime. It is interesting to observe as the advantage of link stability metric of LAER is more evident for lower speed. This is due to the fact that when the most stable node is selected and discriminated among other neighbor nodes its link lasts more times due to the lower node mobility and this increases a lot the average link duration. Moreover, it is interesting also to see the improvement of E-GPSR over GPSR on the basis of the mobility prediction and ellipsoid algorithm implementation. However, also LAER is able to perform well in terms of link duration with the addition of reduced energy consumption as it is possible to see later.

The average energy consumption for decreasing nodes speed and different stability weight values are shown, respectively, in Figs. 6 and 7. It is interesting to observe

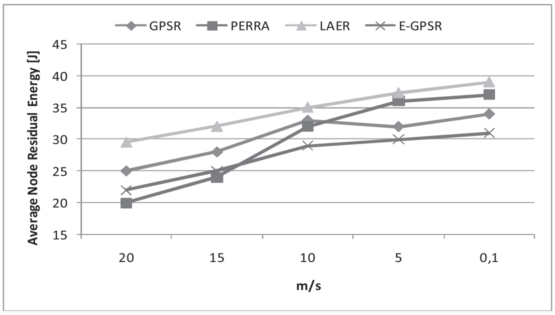

Fig. 8. Average node residual energy versus maximum node speeds.

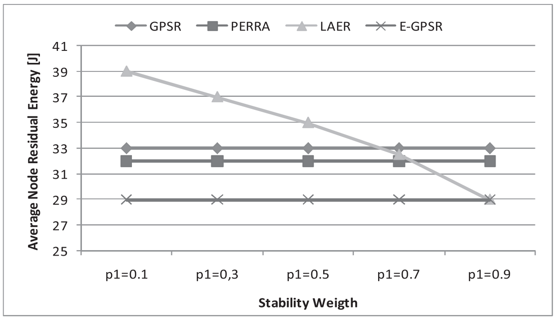

Fig. 9. Average node residual energy versus stability weights.

how both GPSR, E-GPSR and LAER consume lower energy: this is due to the simplest topology management and to the absence of route discovery procedures that are energy consuming. Moreover, LAER improves further the performance reducing the energy consumption about 15-20 percent in comparison with GPSR for 0.1-10 m/s and about 30 percent in comparison with PERRA.

When coefficients p_1 and p_2 are changed it is possible to improve even more the performance of LAER in comparison with GPSR, E-GPSR, and LAER. Increasing the stability weights leads to the selection of shorter and more stable routes such as testified also in [22] and this increases the energy consumption of nodes. On the other hand, the increase of the stability weight and the decrease of the coefficient associated with the energy aware metric reduce the remaining residual energy on nodes such as highlighted in Fig. 9. It is interesting to observe how in Fig. 8 the GPSR and E-GPSR perform better than PERRA for higher node speeds. This can seem to be strange, but it is important to observe as for higher speed (15-20 m/s) the mobility offers a natural load balancing effect and this means that also even if GPSR is not conscious of the residual energy, different nodes are selected due to the link breakage and local topology change. However, for medium and low speed the capability to discriminate node with higher residual energy can become important and PERRA and LAER are more effective and outperform E-GPSR and GPSR.

Moreover, LAER presents better performance prolonging more the network lifetime because the local topology management is less energy consuming than route discovery procedure of PERRA. E-GPSR and GPSR show performance similar to that achieved with LAER, when node mobility is high, but the better next hop selection criterion of LAER is still visible.

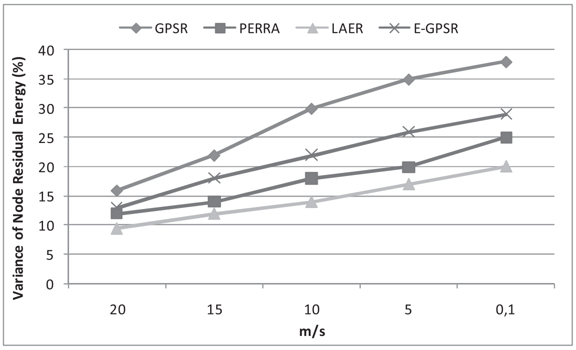

Fig. 10. Variance of node residual energy versus maximum node speeds.

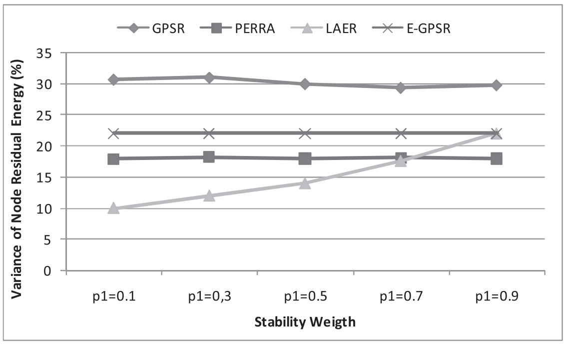

Fig. 11. Variance of node residual energy versus stability weights.

The last evaluated parameter is the variance of residual node energy such as depicted in Figs. 10 and 11. This parameter has been adopted to consider the load balancing capacity of the three protocols. It is interesting to see how GPSR is the worst in terms of load balancing because it selects the node on the basis on the only minimum euclidean distance from destination without considering other parameters. On the other hand, PERRA, E-GPSR, and LAER present a similar trend due to usage of the residual energy metrics (PERRA and LAER) and to the use of the link stability of E-GPSR. However, LAER reduces the variance permitting a lower dispersion of node energy around the average, because the use of an energy aware metric is able to consider not only the residual energy but also the drain rate trend and the traffic load on each single node. A higher traffic load on a specific node implies a higher drain rate and faster energy consumption. This means that also the energy metric of LAER is better than PERRA permitting to discriminate between nodes with the same residual energy but with different traffic load. Moreover, to confirm our previous assertion the GPSR and E-GPSR energy variance are close to the PERRA and LAER energy variance when the nodes mobility is high to testify the benefic advantage of mobility that determines a natural traffic load balancing. It is important to notice also as the energy variance of E-GPSR is better than GPSR for lower node mobility because a criterion based on the stability (node position prediction) is more effective than only a topological criterion such as maximum progress (minimum distance from destination).

6 Conclusions

A scalable routing protocol called LAER, based on the joint metric of *link stability* and *energy drain rate*, has been proposed. It is based on the local topology knowledge and it makes use of a greedy technique based on a joint metric and a modified *perimeter forwarding* strategy for the recovery from *local maximum*. Its performances have been compared with other three protocols proposed in literature such as GPSR, E-GPSR, and PERRA. LAER protocol inherits the scalability of GPSR and E-GPSR, improving the performance in terms of node selection with higher link duration when a higher weight is given to the stability index and a higher residual energy is given to energy aware index. LAER outperforms PERRA in terms of control overhead and in terms of a higher capability to balance traffic load due to the minimum drain rate metric included in the joint metric. Moreover, also the average link duration can be longer in comparison with PERRA and E-GPSR, due to the capability to better discriminate the node behavior associated not only with the current node condition but also with the history of link lifetime.

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