

A Survey of Routing Protocols for Maximizing the Lifetime of Ad Hoc Wireless Networks

Natalia Vassileva, Francisco Barcelo-Arroyo
Universitat Politecnica de Catalunya (UPC)
natalia@entel.upc.edu, barcelo@entel.upc.edu

Abstract

The principal focus of this survey is on how to maximize the useful lifetime of ad hoc wireless networks through energy-efficient routing. Most of the studies on energy-aware routing protocols do not provide clear-cut notions about a network's lifetime and therefore there is a lack of clear objectives in the design of algorithms. Hence, first the operational lifetime of ad hoc networks is defined. Then, published works that give solutions to energy-based problems are analysed by placing emphasis on common characteristics and drawbacks. It is aimed to reveal the factors that influence the depletion of energy in ad hoc networks. This should aid the design of energy-efficient solutions. Load balancing routing protocols are also surveyed as a means for extending a network's operational lifespan, which is a technique that is overlooked in the literature. The immediate implications that load balancing has for energy consumption are indicated. Subsequently, a classification of load balancing routing protocols is provided along with a summary of load balancing methods that may be useful for efficient energy consumption.

1. Introduction

In contrast to current cellular networks, which rely on a wired structure with a wireless last hop, ad hoc wireless networks are infrastructureless. The nodes which comprise them have routing capabilities and forward traffic for other communicating parties that are not within each other's transmission range. They are characterized by lower computing and energy resources. Therefore, ad hoc routing is challenged by power and bandwidth constraints, as well as by frequent changes in topology, to which it must adapt and converge quickly. Conventional routing protocols for wired networks cannot be employed in such an environment due to the factors described above. This fact has given rise to the design of ad hoc-specific routing protocols.

Ad hoc routing protocols are usually classified as being table-driven or on-demand depending on their response to changes in the topology of a network. Table-driven routing protocols (also called proactive protocols) maintain a continuous view of the full topology of the network in each node, whereas on-demand protocols (also called reactive protocols) search for a route between a source and a destination when such a route is needed. Table-driven approaches introduce more overhead compared to reactive ones. This is because whenever there are changes in the topology of the network, control messages are flooded in order to maintain a full knowledge of the network in each node. Initially, the main criterion in these two classes of protocols was the minimum number of hops. However, the main shortcoming of this criterion in terms of energy utilization is that the selection of routes in accordance with the min-hop principle does not protect nodes from being overused. These are usually nodes in the core of the

network. When they run out of power, the network becomes partitioned and consequently some sessions are disconnected.

In order to alleviate this problem and to achieve energy-efficient consumption, many solutions have been proposed as an extension of the already existing ad hoc routing protocols. Since table-driven protocols are inherently more energy-consuming compared to on-demand ones, most of the proposals involve modifications to reactive protocols. The energy-aware algorithms referenced here are implemented in the most common on-demand protocols – AODV or DSR – or are based on their principles. Instead of searching for the shortest path as traditionally occurs, these modified algorithms use energy-sensitive metrics.

The literature consulted shows that load balancing strategies for ad hoc networks have been explored in the same context as those used for wired networks – the prevention and/or alleviation of congestion and fault tolerance. It should nevertheless be pointed out that wired networks do not present the problem of limited energy and therefore, load balancing techniques has never been considered from that perspective. However, the balanced use of a network's resources leads to more efficient energy utilization, which is essential for ad hoc networks. Hence, this work surveys load balancing techniques that can lead to energy balancing.

The protocols under review are intended for general-purpose Mobile Ad Hoc Networks (MANETs). Sensor networks are beyond the scope of this work. Sensor ad hoc networks are recognized as a prominent, compulsory part of future networks because they can be used in a wide range of applications. However, they have unique features, which differentiate them from MANETs and make the protocol's design unsuitable for the two types of network.

1.1. Goals

The main focus of this work is to maximize network lifetime by energy-efficient routing. The aim is to classify the many published solutions according to common principles and to analyse them in terms of extending operational lifetime of networks. When reviewing energy-aware routing algorithms from the above perspective, it was found that most of them did not achieve balanced energy consumption, which is a condition for maximizing the useful lifetime of networks, as explained below. It is aimed to reveal the factors that influence the depletion of energy in ad hoc networks, which should aid the design of energy-efficient solutions.

A further goal is to draw attention to load balancing protocols as a means for attaining the balanced use of the battery reserves of the nodes, thus postponing network partitioning.

1.2. Structure

Most of the studies on energy-aware routing protocols do not provide a clear-cut notion about a network's lifetime and thus there is a lack of clear objectives in the design of algorithms. Therefore, first, in Section 2 the essence of the problem is explained and a comprehensive definition of the operational lifetime of MANETs is given. Then, in Section 3, a concise review of the basic principles behind energy-aware routing protocols, their shared characteristics and common drawbacks is presented. Section 4 highlights several load balancing techniques that can lead to energy balancing. Section 5 reviews the few works in the relevant literature, which overcome some of the deficiencies of the proposals reviewed in Section 3 and Section 4. The studies in Section 5 support the conclusions drawn in the aforementioned sections – they show that by exploring the synergy between energy-aware and load balance metrics more energy-efficient solutions can be designed.

2. Problem formulation

In the scientific papers reviewed, the lifetime of a network is usually defined according to the following criteria: (a) the time until the first node burns out its entire battery budget; (b) the time until a certain proportion of the nodes fails; and (c) the time until network partitioning occurs.

The problem of node failure, which results in network partitioning, is serious in ad hoc networks. In contrast, as pointed out in [3], a single node failure in sensor networks is usually unimportant if it does not lead to a loss of sensing and communication coverage. Ad hoc networks are oriented towards personal communications and the loss of connectivity to any node is significant. By way of example we consider a disaster recovery event. However, this example is equally true of most of the applications for which ad hoc networks are intended. In disaster recovery scenarios, it is of the utmost importance that firefighters or other rescuers do not lose connectivity with any of the members of their team. In order to ensure this, the connectivity between each node and the rest of the constituent nodes must be maintained at all times. It is equally important that the network be preserved in its entirety for as long as possible or at least for the duration of the rescue operation.

Network partitioning interrupts communication sessions and can be caused by node movement or by node failure due to energy depletion. Whereas the former cannot be controlled by the routing protocol, the latter can be avoided through appropriate routing decisions. Operational lifetime is therefore defined in this survey as the time until network partitioning occurs due to battery outage.

In order to achieve the objective of maintaining connectivity for as long as possible, the distribution of a network's tasks among its nodes should be equal so that they all decrease power at the same rate and eventually run out of energy at approximately the same time. From a design perspective, it is much more demanding to achieve the simultaneous failure of the nodes (due to a lack of energy), so that personal (no node powers down before the others) and network requirements (no partitioning) are met. Therefore, the operational lifetime of a network concerns network's relative rather than absolute lifetime. The useful lifetime is measured as the time until all nodes simultaneously run out of energy. When compared to the lifetime of a network that is not energy-aware (min-hop-wise, for example), it can have a lower absolute value. However, from an engineering and application perspective, the former time span is much more interesting and meaningful. For instance, a case could be envisaged in which some nodes have fully charged batteries but are unable to establish successful communications because they belong to disconnected parts of the network or must communicate with nodes that are turned off due to a lack of energy. In such a scenario, the absolute lifetime of a network will be longer compared to the useful life span, but this is not of practical interest. It should be clarified that by equal loading of the nodes, it is meant engaging them in network activities in accordance with their relative energy savings – the ratio of the current battery capacity to its full state – since the network can be heterogeneous with respect to the battery capacities of its constituent nodes.

3. Energy-aware routing

Since the majority of applications, such as conference and emergency services, are energy-dependent, this problem has gained popularity in the research community. Indeed, numerous routing algorithms have been published that address this problem. However, the research dealing with this problem shares a number of common principles. Therefore, here the review of

the literature summarizes the fundamental ideas and generic techniques used for the efficient utilization of network resources in ad hoc networks rather than covering all protocols and their extensions.

3.1. Residual energy

The fundamental idea behind energy-aware routing is to apply the remaining battery capacity of each node as a prime metric in the route selection process. Several cost functions have been designed to reflect the energy status of a node in the many energy proposals. Here, we review the fundamental ones, whose basic principles can be found in more recent solutions. Toh et al. [22] follow the idea of [20], who first discussed power-aware routing. This consisted in applying a reciprocal function to the remaining energy RE_i^t of a node i at time t in order to compute the cost C_i of the node:

$$C_i(RE_i^t) = \frac{1}{RE_i^t}. \quad (1)$$

Three approaches for determining the cost function of a route are proposed in [22]. The cost of a route R_j can be defined by the total sum of the cost functions $C_i(RE_i^t)$ of the nodes along the route:

$$C_j = \sum C_i(RE_i^t) \quad (2)$$

The minimum cost route is selected from among all those discovered:

$$C_i = \min\{C_j | j \in A\}, \quad (3)$$

that is, the route with the maximum total energy is chosen. However, since only total energy is considered, the route can be constructed by nodes with highly varying battery levels. This may result in the battery supply of the energy-starving nodes along the path becoming exhausted. In order to guarantee that the nodes with little energy are excluded from routing and forwarding tasks, the authors [22] propose another approach – the battery cost R_j for a route j is defined by the node with least power on route j :

$$R_j = \max C_i(RE_i^t). \quad (4)$$

The minimum cost route according to [3] is selected from among all discovered routes. The algorithm is called Min-Max Battery Capacity (MMBC) routing. The principle of min-max has been frequently utilized in many recent approaches in order to exclude nodes with highest cost (least power).

Min-max algorithms consist in determining the cost of a path based on the cost of the node with the least resources, that is, the node with the highest cost. Subsequently, all the routes discovered during the selection phase are compared and the one with minimum cost is chosen.

3.2. Energy drain rate

Numerous studies base their metrics on a node's residual battery for designing energy-efficient routing algorithms. However, as pointed out by Kim et al. in [8], this metric is not sufficient to guarantee that no node will completely exhaust its battery capacity. The algorithms

that use the residual battery do not usually implement monitoring functions. Therefore, they do not exercise control over the battery level of the nodes. If the same route is utilized for forwarding a great number of packets, the energy level of its constituent nodes will soon drop and many of them may run out of supplies. To overcome this problem, the authors [8] introduce an energy drain rate metric, which represents the speed of energy consumption. It estimates the lifetime of a node; therefore, if the estimated value is below a threshold, the traffic passing through it can be diverted in order to avoid node failure due to battery outage. The cost function of a node i is defined as the ratio between the Residual Battery Power (RBP) and the Drain Rate (DR):

$$C = \frac{RBP}{DR}. \quad (5)$$

The drain rate is computed by the exponential weighted moving average method and gives the estimated energy dissipation per second:

$$DR_i = \alpha DR_{old} + (1 - \alpha) DR_{sample}. \quad (6)$$

The metric is implemented in the Minimum Drain Rate (MDR) [9] algorithm. The idea of estimating node lifetime and utilizing it as a metric in the cost function of routes can be found in other works such as [47-50].

3.3. Local routing

In generic (denoted as global in the work of Woo et al. [28]) on-demand ad hoc algorithms, all nodes participate in the phase of path searching, while the final decision is made in the source or destination node. The Woo et al. [28] algorithm grants each node in the network permission to decide whether to participate in route searching, which thus spreads the decision-making process among all nodes. The Local Energy-Aware Routing (LEAR) algorithm has as a main criterion the energy profile of the nodes. The residual energy defines the reluctance or willingness of intermediate nodes to respond to route requests and forward data traffic. When energy E_i in a node i is lower than a predefined threshold level Th :

$$E_i < Th, \quad (7)$$

the node does not forward the route request control message, but simply drops it. Thus, it does not participate in the selection and forwarding phase.

The technique of shifting the responsibility for reacting to changes in the energy budget of the nodes from the source-destination nodes to the intermediate nodes avoids the need for the periodic exchange of control information, which exchange translates into bandwidth and energy consumption. It has been commonly used for improving the performance of the routing protocols in many more recent approaches. This mechanism is inventive but depends on the way it is implemented. In [6], for example, the proposed SEADSR protocol is biased towards highly powered routes as it does not execute a monitoring function and a great deal of traffic can be forwarded by nodes, which at the time the route was selected were highly powered.

3.4. Expected energy consumption

The proposals for energy-saving protocols that use transmission energy aim to reduce the total energy for transmitting a packet from the source to the destination. As a rule, they do not extend the operational lifetime of networks because these algorithms do not consider the current energy state of the nodes. The Conditional MMBC algorithm in [22] is proposed to maximize the lifetime of the nodes. It also uses transmission energy as a metric but the route is chosen on the minimum transmission energy basis until the residual energy of the constituent nodes in a network is above a predefined threshold. If there are any nodes on the discovered routes whose energy is below the threshold, the MMBC is applied. Other works, see [49], for example, take both transmission power and residual energy into account in the cost function of the algorithms. Here, the focus is on the work presented by Misra and Banjeree in [13] since it accounts not only for residual energy and transmission power but also for possible retransmissions. Similarly to the energy drain rate metric, it brings an important aspect to light in the design of energy-efficient routing algorithms: the estimation of future energy consumption. The authors estimate the energy that is expected to be used in order to successfully send a packet across a given link. The cost metric ($C_{i,j}$) thus comprises a node-specific parameter (battery power B_i of node i) and a link-specific parameter (packet transmission energy $E_{i,j}$) for reliable communication across the link (between nodes i and j):

$$C_{i,j} = \frac{B_i}{E_{i,j}}, \quad (8)$$

where the expected transmission energy is defined by the power to transmit a packet over the link between nodes i and j ($T_{i,j}$) and the link's packet error probability ($p_{i,j}$):

$$E_{i,j} = \frac{T_{i,j}}{(1 - p_{i,j})^L}. \quad (9)$$

The main reason for adopting the above is that link characteristics can significantly affect energy consumption and can lead to excessive retransmissions of packets. The cost of choosing a particular link is defined as the maximum number of packets that can be transmitted by the transmitting node over that specific link. It is also assumed that there is complete absence of any other cross traffic at that node [13]. The maximum lifetime of a given path is determined by the weakest intermediate node, which is that with the lowest cost.

3.5. Battery-sensitive routing

A completely different approach is presented in [5] by Chiasserini and Rao, and subsequently by Ma and Yang [30]. Their solutions make use of the available battery capacity by means of battery-sensitive routing. Both works [5 and 30] study the lifetime of the battery and the algorithms proposed by their authors are based on two processes, namely, recovery (reimbursement) and discharging loss (over-consumed power). These processes are experienced when either no traffic or new traffic is transmitted. This line of study led to the design of a cost function that penalises the discharging loss event and prioritises routes with "well recovered" [30] nodes. Thus, battery recovery can take place and a node's maximum battery capacity can be attained. The selection function in [5] is a minimum function over the cost functions of all routes.

3.6. Performance evaluation

Although the energy-saving problem – to which there are many proposals – has drawn a great deal of attention, almost all of the works that evaluate new energy-efficient proposals compare them to their energy-unaware counterparts. Furthermore, almost all of the performance studies on ad hoc routing protocols that were found in the literature evaluate them in terms of packet delivery fraction, overhead and end-to-end delay [31–39 and 43]. Only two studies, [41 and 42], evaluate energy consumption in ad hoc networks. Ref. [41 and 42] give useful insight into the energy performance of AODV and DSR protocols (note, however, that these protocols are investigated for the case when the min-hop criterion is applied).

Three works compare energy-aware routing protocols: [4, 44 and 46]. They evaluate the revised MMBC, CMMBC and MTPR algorithms, the latter of which uses transmission power as a selection criterion. The results of [4] support the conclusions drawn on energy-efficient methods in Section 3.7.

3.7. Common characteristics and deficiencies

When the ultimate goal is to extend the time until network partitioning, often under consideration is the efficient use of battery capacity of nodes, that is, maximizing the life of a node. However, it should be noted that extending nodes' lifetime could be a way of making the connectivity between all of the nodes last longer rather than an objective.

A common characteristic of the methods examined in the preceding subsections is the fact that a min-max cost function is applied. The min-max algorithms are implemented in order to overcome the problem that arises when the total energy cost of routes is used as an argument for the selection of a route, that is, nodes with low energy reserves are excluded. However, if these protocols are analysed in terms of a network's operational lifetime, the problem of extending the network's lifespan for as long as possible persists. The simulation results in [4], which is the most recent and comprehensive study that evaluates the performance of some of the energy-aware routing protocols, show that protocols that implement min-max algorithms or the energy drain rate have lower values for the standard deviation of the remaining energy in comparison with algorithms that use transmission power as a metric. Furthermore, the distribution of the energy of the nodes along the path is not even in any of the protocols. If in the cost function it is taken into account only the specific energy state of the nodes without considering the overall distribution of the energy along the routes, optimal results will not be obtained when the operational lifetime of a network is being examined.

The energy-aware protocols usually implement only energy-wise metrics. An improvement on this general approach is the inclusion of the speed with which the battery is burned. The energy drain rate is helpful in stopping a node from powering down. It does so by deviating traffic when a certain threshold is reached. As discussed in the section that follows, the load at each node and in its neighbouring nodes is an indicator of the energy to be consumed for transmitting packets by a particular node. Moreover, it accounts for the shared nature of the radio as a medium. The network tasks with which each node is entrusted are a main item in the battery budget. When this item is considered along with the current energy state of a node, it can regulate the speed with which energy is consumed.

Additional metrics should be considered, such as the fact that when neighbouring nodes are engaged in transmitting packets, they are competing for the wireless medium. This was pointed out in [18], amongst other MAC-related studies. Retransmissions that may possibly take place

[13] should also be taken into consideration. The resulting collisions and retransmissions are energy-consuming and cannot simply be represented by the residual energy metric.

Although the results in the scientific papers consulted always show an improvement in the energy balance, they are not sufficiently representative as they are either only compared with proposals that do not contemplate energy metrics or because the design of the cost functions implemented is unable to achieve equilibrium of network activities among the constituent nodes.

4. Load balancing

As pointed out earlier, the load balancing solutions in mobile ad hoc networks address the same problems that are encountered in wired networks: (a) load balancing techniques play an important role in achieving good network performance through a better spread of traffic flows; (b) they can alleviate and even prevent the effects of congestion, such as longer packet latency, poor packet delivery (throughput) and high routing overhead.

The bandwidth and power limitations in MANETs mean that the consequences of traffic congestion are further worsened in comparison to wired networks. This is due to an excessive consumption of network resources, which results in a rapid depletion of batteries in the most congested nodes and the consequent partitioning of the network. Load balancing is therefore advantageous for avoiding traffic congestion and for ensuring the even distribution of traffic, which translate into more efficient energy utilization.

Although extending the lifetime of networks is not the prime objective of the works cited in this section, they are discussed here in order to point out useful techniques for evening out the distribution of loads in terms of efficient energy consumption.

4.1. Single path routing

In single path routing, during the route discovery procedure, more than one prominent route may be encountered but only one – the best one found, according to a criterion – is used for traffic forwarding.

A classification of the single path route protocols is provided in Table 1.

Table 1. Single path routing protocols

Protocol	Subclass	Goals	Prime characteristics	Policy
WAL	Static	Better network performance	Metrics: interface occupancy parameter (accounts for the load) and a workload increment metric (accounts for a node's load history to prevent transient situations). A flag mechanism for avoiding partitioning in sparse networks.	Suppression
LBAR	Static	Designed for delay-sensitive applications	A metric that accounts for the shared medium: the best route is the one with min. traffic load and min. interference from neighbouring nodes.	None
MCL	Static	Load balance	A cross-layer approach. It considers other nodes' traffic load (introduces the term <i>contention node</i> – a node that prevents another from obtaining the shared medium when it tries to transmit).	None
DLAR	Adaptive	Efficient utilization of network resources	Monitoring without additional overhead. Destination-supported reconstruction of a route in advance.	Prevention
LSR	Adaptive	Prevention of power depletion of nodes with heavy duties	Statistical information to distribute traffic load evenly. Accounts for the shared nature of the medium.	None
DLBL	Adaptive	Load balance	Path maintenance – distributed. Additional overhead when congestion occurs: congestion status control packets. No mechanism for updating the information for the redundant paths.	Prevention

A common characteristic of most of the single path load balancing protocols, see for example [23, 24 and 31], is the application of a suppression or a prevention policy. Both of these policies treat intermediate nodes in the same manner in that the intermediate nodes do not respond to route requests. The objective of the suppression policy is to avoid using the most loaded nodes, whilst the prevention policy is used to obtain fresh routing information. Although not implemented for energy reasons, the former influences the energy status of the nodes and can be used to save energy.

The distinguishing feature of the LBAR algorithm [7], which was subsequently used in [14], is the introduction of the traffic load at neighbouring nodes. This was denoted as “traffic interference” in [7] and as a “contention node” in [14]. Traffic interference accounts for possible radio interference due to traffic load and reflects the shared nature of the wireless medium, which as clarified in the previous section is important for achieving energy efficiency. Wu and Harms in [25] present a mathematical approach that utilizes statistical information, such as the standard deviation of the path load, in order to evenly distribute the load.

Insofar as energy conservation is concerned, the main drawback of the protocols examined is that the total and average values of the observed parameters are not enough to achieve an even allocation of the traffic load. If only the average values of the load metrics are relayed, it will not be clear whether or not any of the nodes along the path are heavily loaded, namely, there will be no clear reference for the distribution of the load along the path. The work of Hassanein and Zhou [7] does consider the traffic load at neighbouring nodes besides the load at the node, but for the best route to be selected the algorithm compares the minimum traffic in transmission and minimum interference. It can thus be guaranteed that heavily loaded nodes are excluded but the requirement for the even distribution of the traffic load is not fulfilled. Only Wu and Harms in [26] take standard deviation into consideration in addition to the average load in their comparison function.

4.2. Multipath routing

Multipath routing as a load balancing technique can be advantageous for extending a network’s lifetime, but as aforementioned it is usually used for different end. Here, we have only summarized the intended end purposes and pointed out any open issues that remain unresolved in this area.

Multipath routing has been regarded as an attractive alternative for ad hoc networking because it is able to provide fault tolerance. The use of back-up routes leads to less packet loss, makes communication sessions last longer and provides robustness to mobility and fading. All of these factors result in less energy consumption and there is the potential benefit that the lifetime of the network will be increased. Moreover, by dispatching the data packets of each flow through many network nodes along different paths, a better distribution of the traffic load may be achieved, as demonstrated in the study by Parissidis et al. [16]. As a consequence, the residual energy will be more evenly distributed.

Initially, multipath routing was proposed for the purpose of providing fault tolerance [14, 12, and 53]. In [1] it is applied to guarantee preferential treatment to priority traffic and in [2] as a means of minimizing overhead, which results from route disruptions and the consequent flooding of route requests. Wang et al. [27], Zhang et al. [31], and Yin and Lin [29] contemplate multipath routing from a load balancing perspective.

Although multipath routing can positively influence energy consumption in networks, a number of issues remain open that must be successfully addressed before this protocol can be implemented in ad hoc networks. One of these issues is the possible increase of the total

overhead and packet disorder, which negatively influences some services, such as those that work over TCP [2, 25]. The nature of the shared radio medium also impacts the proper running of multipath techniques since the paths should be node and link-disjoint [15], which makes the mechanisms employed much more complex in comparison to single path routing. A further question is whether route maintenance should be centralized or distributed [2, 14 and 17].

4.3. Common characteristics

Some of the main limitations of load balancing protocols in terms of energy efficiency are discussed below.

Although the main objective of load balancing routing is the efficient utilization of network resources, none of the studies reviewed above takes energy-wise metrics into account. There is no doubt that a better distribution of load leads to the more efficient use of bandwidth, which means that there is less contention and consequently less energy is consumed, but it is not self-contained for achieving complete energy efficiency. Ad hoc networks are not necessarily energy-homogeneous, and there is thus insufficient information about the nodes' load tasks to enable the energy-wise selection of the paths. The current load of a node can be used to estimate the future dissipation of energy but it does not contain a record of past activities and the residual energy level of the node remains hidden.

Since none of the studies applies load balancing for achieving energy efficient consumption, the relevant literature does not contain an energy performance evaluation of load balancing routing protocols.

5. Energy-aware routing with load balancing

There are few recent studies that investigate the idea of using energy and load balancing metrics in routing protocols in order to maximize the life of the network. In [19], the authors point out that when the queue length is taken as a parameter of the routing protocol it has a direct impact on the distribution of the traffic flows, and in particular on energy consumption. However, the idea discussed in [19] is not elaborated further.

For the first time, a recent study [10] explored energy and load metrics as part of the path searching phase of the routing algorithm. Kim et al. [10] consider the traffic load of nodes and lifetime deviation of nodes along with their energy status to prolong a network's lifetime and achieve load balancing – although we argue that the latter is a mechanism rather than an objective. The nodes use the criterion first introduced by Kim et al. in [8] that reflects a node's lifetime. The energy dissipation rate gives the estimated energy consumption per unit of time. A route's lifetime is used as a route selection criterion; thus, the route with the longest estimated lifetime is selected for forwarding traffic flows. The algorithm forms part of max-min algorithms, which use the minimum lifetime of the intermediate nodes for determining path lifetime. The proposal is the first to observe the interaction between the routing metrics discussed above. One of its shortcomings is that it does not overcome the weakness of the MMBCR approach. The protocols lack a route monitoring function, which is essential for achieving energy efficiency.

The work of Xie et al. [51] supports the conclusions drawn in Section 3.7. The proposed algorithm takes into account the traffic to be forwarded by the node and its residual battery capacity. Compared to the LEAR protocol (see [27]), which only considers the residual energy level at each node, the protocol in [51] achieves a more even distribution of the consumed energy. It improves the standard deviation by more than 25% compared to LEAR under different traffic loads.

The solution of Xiang et al. [52] is in line with the comments in Section 3.7 and 4.3. The protocol routes the traffic depending on the state of the nodes – it takes into account the energy and the load at each node. It selects the route with the maximum estimated lifetime to forward any pending traffic. The simulation results in [52] demonstrate that the average energy consumption for varying send rates is always lowest for this protocol when compared with reactive (DSR), load-aware (DLAR [23]) or energy-aware (MMBCR [21]) protocols.

The aforementioned studies are the first to explore the synergy between energy-aware and load-aware routing protocols for maximizing network lifetime. As pointed out by their authors, they need to be further enhanced by relaxing some of the assumptions and determining some of the heuristically proposed parameters [52]. Other possible paths for improving them are to consider metrics such as traffic interference [7], which accounts for the nature of the medium and the traffic activity in the neighbouring nodes. Nevertheless, [51 and 52] provide evidence to prove that better results can be obtained when the metrics of the algorithms are not simply restricted to the energy status of the nodes, but take into account also load-related metrics.

6. Conclusions

In this survey the main focus is on routing protocols for extending operational life span of mobile ad hoc networks. The consulted proposals are summarised, based on shared principals. Some common drawbacks are detected. Furthermore, the work reveals factors that influence the depletion of energy in ad hoc networks. This should aid the design of energy-efficient solutions.

Although the studies consulted address energy conservation (Section 3) and the improved utilization of a network's resources (Section 4), not all aspects of the problem of extending the operational lifetime of MANETs have been considered. Since the solutions proposed do not observe the whole range of metrics that influence the final performance of a network, they only tackle a restricted number of factors.

Energy-constrained routing and load-balance routing are mutually related and by employing one, the other is improved. However, when both of these metrics are taken into account, more significant results in terms of network lifetime can be achieved as demonstrated by the studies reviewed in Section 5.

The notion of energy-aware routing should be further enriched with load balancing techniques and the synergy of these techniques needs to be fully investigated in order to achieve the maximum useful lifetime of the network.

7. Acknowledgements

This research was funded by the Spanish Government and FEDER through the Plan Nacional de I+D (TEC2006-09466/TCM).

8. References

- [1] G. Alandjani, E.E. Johnson, "Fuzzy routing in ad hoc networks", in Proc. 22nd IPCCC, IEEE, 2003, pp. 525-530.
- [2] N. Akhtar, R. Tafazolli, "Traffic-based multipath routing for mobile ad hoc networks", in Proc. Int. Workshop on Wireless Ad-Hoc Networks, IEEE, 2004, pp. 201-206.
- [3] S. Basagni, M. Conti, S. Giordano, Iv. Stojmenovic, "Chapter 11: Energy-efficient communication in ad hoc wireless networks", Mobile ad hoc networking, Wiley-IEEE Press, 2004.
- [4] L. Cao, T. Dahlberg, Y. Wang, "Performance evaluation of energy efficient ad hoc routing protocols", in Proc. IPCCC, IEEE, 2007, pp. 306-313.
- [5] C.-F. Chiasserini and R.R. Rao, "Routing protocols to maximize battery efficiency", in Proc. MILCOM, IEEE, 2000, pp. 496-500.

- [6] M. C. Domingo, D. Remondo, O. Leon, "A simpler routing scheme for improving ad hoc network survivability", in Proc. GLOBECOM, IEEE, 2003, pp.718-723.
- [7] H. Hassanein, A. Zhou, "Routing with load balancing in wireless ad hoc networks", in Proc. 4th MSWiM, ACM, 2001, pp. 89-96.
- [8] D. Kim, G.-L. Aceves, K. Obraczka, J.-C. Cano, P. Manzoni, "Power-aware routing based on the energy drain rate for mobile ad hoc networks", in Proc. 14th ICCCN, IEEE, 2002, pp. 565-569.
- [9] D. Kim, G.L. Aceves, K. Obraczka, J.-C. Cano, P. Manzoni, "Routing mechanisms for mobile ad hoc networks based on the energy drain rate", in Trans. Mobile Computing, IEEE, April-June 2003, vol. 2, no. 2, pp. 161-173.
- [10] D.-H. Kim, R. Ha, H. Cha, "Traffic load and lifetime deviation based power-aware routing protocol for wireless ad hoc networks", in Proc. 4th WWIC, Springer, 2006, pp. 325-336.
- [11] B.C. Kim, J.Y. Lee, H.S. Lee, J.S. Ma, "An ad-hoc routing with minimum contention time and load balancing", in Proc. GLOBECOM, IEEE, 2003, pp. 81-85.
- [12] S. J. Lee, M. Gerla, "AODV-BR: backup routing in ad hoc networks", Proc. WCNC, IEEE, 2000, pp. 1311-1316.
- [13] A. Misra and S. Banerjee, "MRPC: Maximizing network lifetime for reliable routing in wireless environments", in Proc. IEEE WCNC, 2002, pp. 800 – 806.
- [14] A. Nasipuri, S. R. Das, "On-demand multipath routing for mobile ad hoc networks", in Proc. IEEE 8th ICCCN, 1999, pp. 64 – 70.
- [15] M. R. Pearlman, Z. J. Haas, P. Sholander, S. S. Tabrizi, "On the impact of alternate path routing for load balancing in mobile ad hoc networks", in Proc. 1st ACM MobiHoc, 2000, pp. 3-10.
- [16] G. Parissidis, V. Lenders, M. May, B. Plattner, "Multi-path routing protocols in wireless mobile ad hoc networks: a quantitative comparison", in Proc. 6th NEW2AN, 2006, pp. 313-326.
- [17] P.P. Pham and S. Perreau, "Performance analysis of reactive shortest path and multi-path routing mechanism with load balance", in Proc. 22nd INFOCOM, 2003, pp. 251-259.
- [18] A. Safwat, H. Hassanein, H. Mouftah, "Energy-aware routing in MANETs: analysis and enhancements", in Proc. 5th ACM/IEEE Int. MSWiM, 2002, 46-53.
- [19] L.M. Sánchez, N.V. Vassileva, F. Barceló, P.F. Carbajo, "Energy and delay-constrained routing in mobile ad hoc networks: an initial approach", Proc. Int. Workshop PE-WASUN, ACM, 2005, pp. 262-263.
- [20] S. Singh, M. Woo, C. S. Raghavendra, "Power-aware routing in mobile ad hoc networks", Proc. 4th MobiCom, ACM/IEEE, 1998, pp. 181-190.
- [21] C.-K. Toh, "Maximum battery life routing to support ubiquitous mobile computing in wireless ad hoc networks", Comm. Mag., IEEE, June 2001, vol.39, issue 6, pp. 138-147.
- [22] C.-K. Toh, H. Cobb, D.A. Scott, "Performance evaluation of battery-life-aware routing schemes for wireless ad hoc networks", Proc. ICC, IEEE, 2001, pp. 2824-2829.
- [23] S.-J. Lee, M. Gerla, "Dynamic load-aware routing in ad hoc networks", Proc. ICC, IEEE, 2001, pp. 3206-3210.
- [24] A. Valera, W. K. G. Seah, S. V. Rao, "Cooperative packet caching and shortest multipath routing in mobile ad hoc networks", Proc. 22nd Annual Joint Conf. INFOCOM, IEEE, 2003, pp. 260-269.
- [25] K. Wu, J. Harms, "Load-sensitive routing for mobile ad hoc networks", Proc. 10th ICCCN, IEEE, 2001, pp. 540-546.
- [26] L. Wang, L. Zhang, Y. Shu, M. Dong, "Multipath source routing in wireless ad hoc networks", Proc. Canadian Conf. Electrical and Computer Engineering, IEEE, 2000, pp. 471-483.
- [27] K. Woo, C. Yu, D. Lee, H. Youn, B. Lee, "Non-blocking, localized routing algorithm for balanced energy consumption in mobile ad hoc networks", Proc. MSCOTS, ACM/IEEE, 2001, pp.117-124.
- [28] S. Yin, X. Lin, "Multipath minimum energy routing in ad hoc network", Proc. Int. Conf. Communications (ICC), IEEE, 2005, pp. 3182-3186.
- [29] C. Ma and Y. Yang, "Battery-aware routing in wireless ad hoc networks – part I: energy model", Proc. 19th ITC-19, 2005, pp. 293-302.
- [30] X. Zheng, W. Guo, R. Liu, Y. Tian, "A new dynamic load-aware based load-balanced routing for ad hoc networks", Proc. ICCAS, IEEE, 2004, pp. 407-411.
- [31] J. Broch, D.A. Maltz, D.B. Johnson, Y.-C. Hu, J. Jetcheva, "A performance comparison of multi-hop wireless ad hoc network routing protocols", Proc. 4th Annual Int. Conf. Mobile Computing and Networking (MobiCom), ACM/IEEE, 1998, pp. 85-97.

- [32] P. Johansson, T. Larsson, N. Hedman, B. Mielczaker, M. Degermark, "Scenario-based performance analysis of routing protocols for mobile ad-hoc networks", Proc. 5th Annual Int. Conf. Mobile Computing and Networking (MobiCom), ACM/IEEE, 1998, pp. 195-206.
- [33] S.-J. Lee, M. Gerla, C.-K. Toh, "A simulation study of table-driven and on-demand routing protocols for mobile ad hoc networks", Network Mag., IEEE, July/Aug. 1999, vol. 13, issue 14, pp. 48-54.
- [34] E.M. Royer, C.-K. Toh, "A review of current routing protocols for ad hoc mobile wireless networks", Personal Comm. Mag., IEEE, 1999, vol. 6, issue 2, pp. 46-55.
- [35] C.E. Perkins, E.M. Royer, S.R. Das, M.K. Marina, "Performance comparison of two on-demand routing protocols for ad hoc networks", Personal Comm. Mag., IEEE, Feb. 1999, vol. 8, issue 2, pp. 16-28.
- [36] D.A. Maltz, J. Broch, J. Jetcheva, D.B. Johnson, "The effects of on-demand behaviour in routing protocols for multihop wireless ad hoc networks", J. Select. Areas Comm., IEEE, Aug. 1999, vol. 17, no. 8, pp. 1439-1453.
- [37] L. Layuan, L. Chunlin, Y. Peiyan, "Performance evaluation and simulation of routing protocols in ad hoc networks", Computer Communications 30, Elsevier, 2007, pp. 1890-1898.
- [38] H. Pucha, S.M. Das, Y.C. Hu, "The performance impact of traffic patterns on routing protocols in mobile ad hoc networks", Computer Networks 51, Elsevier, 2007, pp. 3595-3616.
- [39] V. Naumov, T. Gross, "Scalability of routing methods in ad hoc networks", Int. J. Performance Evaluation 62, Elsevier, 2005, pp. 193-209.
- [40] S.-J. Lee, J. Hsu, R. Hayashida, M. Gerla, R. Bagrodia, "Selecting a routing strategy for your ad hoc networks", Computer Communications 26, Elsevier, 2003, pp. 723-733.
- [41] L. Feeney, "An energy consumption model for performance analysis of routing protocols for mobile ad hoc networks", J. Mobile Networks and Applications (MONET) 6, Kluwer Academic Publishers, 2001, pp. 239-250.
- [42] S. Bansal, R. Shorey, A. Misra, "Comparing the routing energy overheads of ad-hoc routing protocols", in Proc. Wireless Communications and Networking Conf. (WCNC), IEEE, March 2003, vol. 2, pp. 1155-1161.
- [43] H.D. Trung, W. Benjapolakul, P.M. Due, "Performance evaluation and comparison of different ad hoc routing protocols", Computer Communications 30, Elsevier, 2007, pp. 2478-2496.
- [44] C.-K. Toh, H. Cobb, D. A. Scott, "Performance evaluation of battery-life-aware routing schemes for wireless ad hoc networks", Proc. Int. Conf. Communications (ICC), IEEE, June 2001, vol. 9, pp. 2824-2829.
- [45] Y. J. Lee, G. F. Riley, "A workload-based adaptive load-balancing technique for mobile ad hoc networks", Proc. WCNC, IEEE, 2005, pp. 2002-2007.
- [46] A. Safwat, H. Hassanein, and H. Mouftah, "Energy-aware routing in MANETs: analysis and enhancements", Proc. of 5th Int. Workshop MSWiM, IEEE, 2002, pp. 46-53.
- [47] J.-E. Garcia, A. Kallel, K. Kyamakya, K. Jobmann, J.-C. Cano, P. Manzoni, "A novel DSR-based energy-efficient routing algorithm for mobile ad hoc networks", Proc. of 58th Vehicular Technology Conf. (VTC), IEEE, 2003, vol. 5, pp. 2849-2854.
- [48] B.C. Kim, J.Y. Lee, H.D. Lee, and J.S. Ma, "An ad-hoc routing with minimum contention time and load balancing", Proc. GLOBECOM, IEEE, 2003, vol. 1, pp. 81-85.
- [49] M. Maleki, K. Dantu, and M. Pedram, "Lifetime prediction routing in mobile ad hoc networks", Proc. of Wireless Communications and Networking Conf. (WCNC), IEEE, 2003, vol.2, pp. 1185-1190.
- [50] L. Romdhani, and C. Bohnet, "Energy consumption speed-based routing for mobile ad hoc networks", Proc. of 24th Int. ICDCSW IEEE, 2004, pp. 729-734.
- [51] F. Xie, L. Du, Y. Bai, and L. Chen, "Energy aware reliable routing protocol for mobile ad hoc networks", Proc. Wireless Communications and Networking Conf. (WCNC), IEEE, 2007, pp. 4316-4320.
- [52] J. Xiang, S. Sesay, Y. Wang, and J. He, "Ad hoc network state aware routing protocol", Proc. Wireless Communications and Networking Conf. (WCNC), IEEE, 2007, pp. 3749-3753.
- [53] W.K. Lai, S.-Y. Hsiao, Y.-C. Lin, "Adaptive backup routing for ad hoc networks", Computer Communications 30, Elsevier, 2007, pp. 453-464.

Authors



Natalia Vassileva earned a degree in telecommunications engineering from the Technical University of Sofia, Bulgaria, in 2001. After graduation she worked for M-Tel, a telecommunications operator in Bulgaria. In 2002, she joined the Department of Telecommunications at the Technical University of Sofia, Bulgaria, where she did research in the field of broadband networks. In 2004, she joined the Department of Telematics Engineering at the Universitat Politècnica de Catalunya (UPC), Barcelona, Spain, where she is currently working on her PhD degree. Her main research interests include wireless ad hoc networks, teletraffic modelling and the evaluation of personal and mobile communication networks.



Francisco Barcelo-Arroyo earned a degree in telecommunications engineering and a PhD from the Universitat Politècnica de Catalunya (UPC), in 1986 and 1997, respectively. In 1987, he joined the School of Telecommunications Engineering of Barcelona at UPC, where he has been teaching design and planning of communication networks, teletraffic and wireless networks. After graduation, he did research in the areas of digital network synchronization and switching. Since 1997, he has been an associate professor at the Department of Telematics Engineering at UPC. He has also served as a consultant to the telecommunications industry and operators in Spain. He is currently involved in several research projects that are supported by the Spanish Government and the European Commission, which include IST Emily, IST Liaison and COST 290. His current research interests lie in assessing the capacity and teletraffic performance of wired and wireless networks, and in studying location-based services in wireless networks with or without infrastructure.