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# Energy Issues and Energy aware Routing in Wireless Ad-hoc Networks

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## 1. Introduction

The problem of energy efficiency in MANETs can be addressed at different layers. In recent years, many researchers have focused on the optimization of energy consumption of mobile nodes, from different points of view. Some of the proposed solutions try to adjust the transmission power of wireless nodes, other proposals tend to efficiently manage a sleep state for the nodes (these solutions range from pure MAC-layer solutions (as the power management of 802.11) to solutions combining MAC and routing functionality). Finally, there are many proposals which try to define an energy efficient routing protocol, capable of routing data over the network and of saving the battery power of mobile nodes. Such proposals are often completely new, while others aim to add energy-aware functionalities to existing protocols (like AODV, DSR and OLSR).

The aim of energy-aware routing protocols is to reduce energy consumption in transmission of packets between a source and a destination, to avoid routing of packets through nodes with low residual energy, to optimize flooding of routing information over the network and to avoid interference and medium collisions. Many energy efficient routing protocol proposals were originally studied for sensor networks, where the limited energy of nodes is a strong constraint; in MANET, however, the requirements are different: a node has generally more hardware resources (capable of better performance, but consuming more energy) and the protocol must preserve the resources of every node in the network (not only a subset of them, because each node can be, at any time, source or destination of data). 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, instead, are oriented towards personal communication and the loss of connectivity to any node is significant.

In the routing protocol design of mobile nodes, many issues need to be considered in order to offer many important properties such as scalability, QoS support, security, low power consumption and so on. In this chapter we focus on the energy issues facing some important aspects going from the energy model definition for the computation of the energy consumption to energy-aware metrics definition and routing protocol design. If a network composed of mobile nodes communicating using a wireless radio and where each node can communicate with each other using the other mobile nodes as relay nodes is applied in a communication system, many challenging design issues need to be addressed. MANET technology became, in the last years, more commercial in comparison with the past where it was used for military purpose and this implies more additional features to offer to the end-

user with particular reference to quality of service, security and to node lifetime duration. In this chapter energy saving techniques at network layer and the routing strategies that allow a better energy expenditure and load distribution in order to prolong the network lifetime are considered. After defining a simple energy consumption model to use as reference for the protocol performance evaluation and after introducing some well-known energy based metric, some routing protocols belonging to different families of routing strategies are briefly presented. In particular we refer to proactive routing protocols with particular reference to OLSR, reactive routing with reference to AODV, DSR and LEAR, hybrid routing with reference to GAF, and scalable routing strategies based on the concept of clustering or topological hierarchy.

## 2. Wireless ad-hoc networks

MANET is a special type of wireless network in which a collection of mobile network interfaces may form a temporary network without aid of any established infrastructure or centralized administration. Ad Hoc wireless network has applications in emergency search-and-rescue operations, decision making in the battlefield, data acquisition operations in hostile terrain, etc. It is featured by dynamic topology (infrastructureless), multi-hop communication, limited resources (bandwidth, CPU, battery, etc.) and limited security. These characteristics put special challenges in routing protocol design. The one of the most important objectives of MANET routing protocol is to maximize energy efficiency, since nodes in MANET depend on limited energy resources.

The primary objectives of MANET routing protocols are to maximize network throughput, to maximize network lifetime, and to minimize delay. The network throughput is usually measured by packet delivery ratio while the most significant contribution to energy consumption is measured by routing overhead which is the number or size of routing control packets. A major challenge that a routing protocol designed for ad hoc wireless networks faces is resource constraints. Devices used in the ad hoc wireless networks in most cases require portability and hence they also have size and weight constraints along with the restrictions on the power source. Increasing the battery power may make the nodes bulky and less portable. The energy efficiency remains an important design consideration for these networks. Therefore ad hoc routing protocol must optimally balance these conflicting aspects.

To achieve the desired behavior, some proposals make use of clustering or maintain multiple paths to destinations (in order to share the routing load among different nodes).

The majority of energy efficient routing protocols for MANET try to reduce energy consumption by means of an energy efficient routing metric, used in routing table computation instead of the minimum-hop metric. This way, a routing protocol can easily introduce energy efficiency in its packet forwarding. These protocols try either to route data through the path with maximum energy bottleneck, or to minimize the end-to-end transmission energy for packets, or a weighted combination of both.

The energy optimization of a routing protocol, however, can exploit also other network layer mechanisms, like control information forwarding. In OLSR, for example, the MPR selection mechanism can be varied in an energy-aware way: MPRs can be selected by their residual energy, rather than by their 2-hop neighborhood coverage. Some works applied both techniques (MPR selection criteria modification and path determination algorithm modification) to increase the energy efficiency of OLSR protocol.

### 3. Issues in MANETs: Energy, scalability and quality of services

Due to the fact that bandwidth is scarce in MANET nodes and that the population in a MANET is increasing the scalability issue for wireless multi-hop routing protocols is mostly concerned with excessive routing message overhead caused by the increase of network population and mobility. Routing table size is also a concern in MANETs because large routing tables imply large control packet size hence large link overhead. Routing protocols generally use either distance-vector or link-state routing algorithms and only in the last years also geographical routing protocols that make use of node location/position have been investigated (De Rango et al., 2006). However, scalability issues in terms of overhead and, consequently number of nodes operating in the network, are strongly related also to energy consumption because higher number of control packets overhead imply more energy consumption spent in transmission, reception and overhearing. This means that trying to design a more scalable protocols can offer more benefits also to the energy saving of mobile nodes in a MANET.

When we consider the design of an energy efficient routing protocols not always this means that the routing strategies are also scalable because the protocols can reduce the energy consumption under just some specific operative conditions such as lower mobility, light traffic load or low number of nodes. This means that the design of an energy-efficient routing protocols should consider also scalability issue in order to apply it in wider scenarios and to be sure that the protocol performance do not degrade too much when some project parameters are changing. At this purpose, more advanced techniques that try to exploit the clustering formation among nodes, the nodes position, zone location or the hierarchical topology structure have been considered and some of these techniques are referred in this chapter. Moreover, another important issue should be considered in the routing strategies applied to MANETs. It is the QoS in terms of many metrics definition such as minimum bandwidth availability, maximum end-to-end delay, minimum delay jitter, path stability and so on. Often, in literature, these QoS issues are not related to energy consumption but in the protocol design some connection between QoS support and energy consumption exist. In particular, the selection of the lowest energy path among a couple of nodes can led to the selection of a longer route with higher end-to-end delay (De Rango, Guerriero, 2006; De Rango, 2011). Moreover, the possibility to offer higher bandwidth to a connection and consequently higher data rate imply often to deplete the battery charge of a node more quickly. In this view, also QoS aware routing protocols should take into account also the energy issues related to the rationale of the forwarding scheme, route maintenance and path discovery. In the rest of the chapter, some of the most famous approaches related to the energy aware routing protocols are presented with particular reference to proactive, reactive, hybrid, cluster-based, hierarchical and position based routing protocols.

### 4. Energy consumption model

A wireless network interface can be in one of the following four states: Transmit, Receive, Idle or Sleep. Each state represents a different level of energy consumption.

- Transmit: node is transmitting a frame with transmission power  $P_{tx}$ ;
- Receive: node is receiving a frame with reception power  $P_{rx}$ . That energy is consumed even if the frame is discarded by the node (because it was intended for another destination, or it was not correctly decoded);

- Idle (listening): even when no messages are being transmitted over the medium, the nodes stay idle and keep listening the medium with  $P_{idle}$ ;
- Sleep: when the radio is turned off and the node is not capable of detecting signals. No communication is possible. The node uses  $P_{sleep}$  that is largely smaller than any other power.

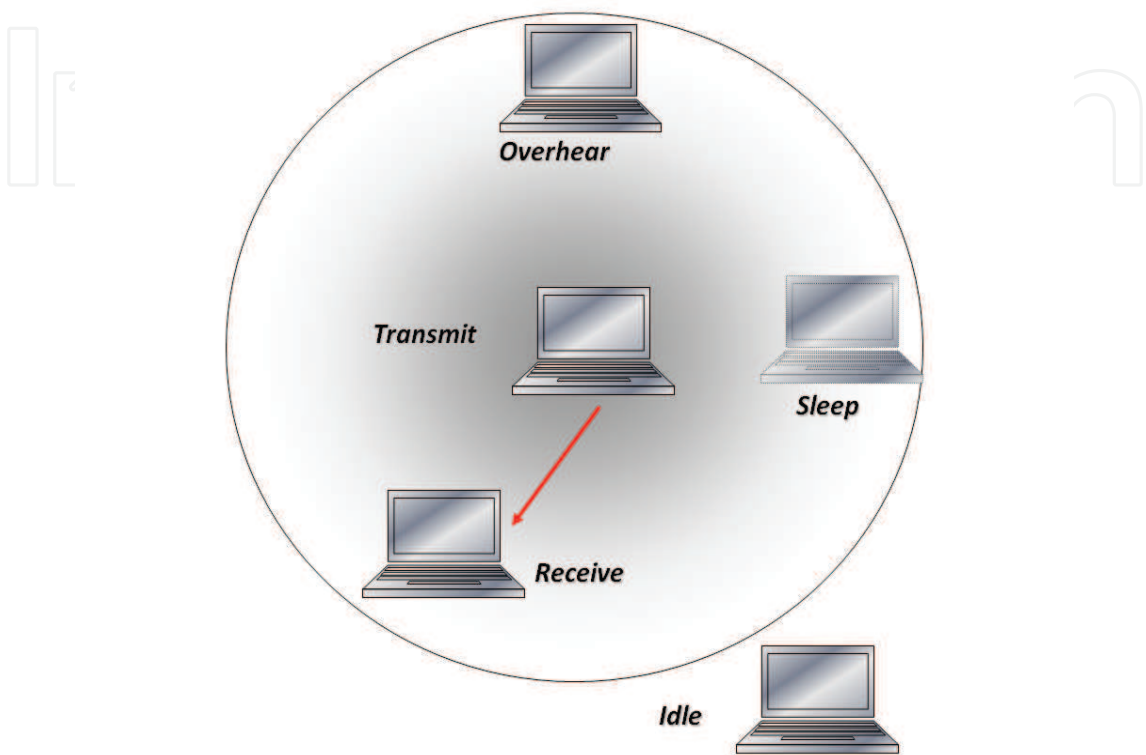


Fig. 1. Energy consumption in a wireless network

In Table 1, typical values of consumption for a wireless interface (measured for a Lucent Silver Wavelan PC Card) are reported.

State	Power value
Transmit	$P_{tx} = 1.3W$
Receive	$P_{rx} = 0.9W$
Idle	$P_{idle} = 0.74W$
Sleep	$P_{sleep} = 0.047W$

Table 1. Power value in each radio state

The energy dissipated in transmitting ( $E_{tx}$ ) or receiving ( $E_{rx}$ ) one packet can be calculated as:

$$\begin{aligned} E_{tx} &= P_{tx} \times Duration \\ E_{rx} &= P_{rx} \times Duration \end{aligned} \tag{1}$$

where *Duration* denote the transmission duration of the packet.  
When a transmitter transmits a packet to the next hop, because of the shared nature of wireless medium, all its neighbors receive this packet even it is intended to only one of them. Moreover, each node situated between transmitter range and interference range

receives this packet but it cannot decode it. These two problems generate loss of energy. So to compute the energy dissipated by one transmission, we must take into account these losses as follows (Allard et al., 2006):

$$\text{cost}_{tx}(i) = E_{tx} + n \times E_{rx} \quad (2)$$

where  $n$  represents the number of non-sleeping nodes belonging to the interference zone of the transmitter  $i$ .

## 5. Energy aware metrics

The majority of energy efficient routing protocols for MANET try to reduce energy consumption by means of an energy efficient routing metric, used in routing table computation instead of the minimum-hop metric. This way, a routing protocol can easily introduce energy efficiency in its packet forwarding. These protocols try either to route data through the path with maximum energy bottleneck, or to minimize the end-to-end transmission energy for packets, or a weighted combination of both.

A first approach for energy-efficient routing is known as MTPR (Minimum Transmission Power Routing; Toh, 2001). That mechanism uses a simple energy metric, represented by the total energy consumed to forward the information along the route. This way, MTPR reduces the overall transmission power consumed per packet, but it does not directly affect the lifetime of each node (because it does not take into account the available energy of network nodes). However, minimizing transmission energy only differs from shortest-hop routing if nodes can adjust transmission power levels, so that multiple short hops are more advantageous, from an energy point of view, than a single long hop (Kunz, 2008). In 802.11 we do not have access to this capability, so that, in a fixed transmission power context, this metric corresponds to a Shortest Path routing.

Another routing metric, minimizing a function of the remaining battery power of the nodes in a path, is called MBCR (Minimum Battery Cost Routing; Toh, 2001). The proposed battery cost function is

$$f_i(t) = 1 / c_i(t) \quad (3)$$

where  $c_i(t)$  is the battery capacity of node  $n_i$  at time  $t$ . The less capacity a node has, the more reluctant it is to forward packets.

If only the summation of battery costs on a route is considered, a route containing nodes with little remaining battery capacity may still be selected. MMBCR (Minimum Maximum Battery Cost Routing; Toh, 2001), defines the route cost as

$$R(r_j) = \max_{\forall n_i \in r_j} f_i(t) \quad (4)$$

The desired route  $r_O$  is obtained so that

$$R(r_O) = \max_{r_j \in r_*} R(r_j) \quad (5)$$

where  $r_*$  is the set of all possible routes.

Since MMBCR considers the weakest and crucial node over the path, a route with the best condition among paths impacted by each crucial node over each path is selected. CMMBCR



metric (Conditional MMBCR; Toh, 2001) attempts to perform a hybrid approach between MTPR and MMBCR, using the former as long as all nodes in a route have sufficient remaining energy (over a threshold) and the latter when all routes to the destination have at least a node with less energy than the threshold.

Power saving mechanisms based only on the remaining power 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, too much traffic load will be injected through that node. In this sense, the actual drain rate of power consumption of the node will tend to be high, resulting in an unfair sharp reduction of battery power. To address the above problem, the MDR (Minimum Drain Rate; Kim et al., 2003) mechanism can be utilized with a cost function that takes into account the drain rate index (DR) and the residual battery power (RBP) to measure the energy dissipation rate in a given node.

In the MDR mechanism, the ratio

$$f_i(t) = \frac{RBP_i(t)}{DR_i(t)} \quad (6)$$

at node  $n_i$ , calculated at time  $t$ , indicates when the remaining battery of node  $n_i$  will be exhausted, i.e., how long node  $n_i$  can keep up with routing operations with current traffic conditions. Therefore, the maximum lifetime of a given path  $r_j$  is determined by the minimum value of  $f_i(t)$  over the path. Finally, the MDR mechanism is based on selecting the route  $r_O$ , contained in the set of all possible routes between the source and the destination  $r_*$ , having the highest maximum lifetime value.

Since the drain rate is calculated at regular time intervals, its measure is affected by isolated consumption peaks (both positive or negative). To avoid the use of incorrect values of drain rate during these peaks, an  $\alpha$  parameter can be introduced. This parameter makes the drain rate value between adjacent intervals smoother, acting in the following manner: after calculating the drain rate sample at interval  $t$ ,  $DR_{sample}(i)$ , MDR uses a value of drain rate of

$$DR(i) = (1 - \alpha) \cdot DR_{sample}(i) + \alpha \cdot DR(i - 1) \quad (7)$$

MDR suffers from the same problem as MMBCR, ignoring the total transmission power consumed by a single path: this way, it could even lead to a higher overall energy consumption in the network. To prevent this issue, MDR can be introduced in a hybrid way, as a CMDR (Conditional MDR) metric: as far as all nodes in a route have sufficient remaining lifetime (over a threshold), a simple MTPR approach is used.

Other works (like Misra & Banerjee, 2002) use a larger number of variables in the cost function of the algorithms, for example by taking into account not only the residual energy and the transmission power, but also the energy cost of possible packet retransmissions. Similarly to the MDR metric, an important aspect for the design of energy aware routing protocols is highlighted: the estimation of future energy consumption. The energy that is expected to be used in order to successfully send a packet across a given link is estimated by a cost function that comprises both a node-specific parameter (battery power  $B_i$  of node  $i$ ) and a link-specific parameter (packet transmission energy  $E_{i,j}$ ). The cost of the reliable communication across the link (between nodes  $i$  and  $j$ ) is defined as

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

The expected transmission energy is defined by the power needed 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. The maximum lifetime of a given path is determined by the weakest intermediate node.

Another approach (Chiasserini & Rao, 2000) make use of the available battery capacity by means of battery-sensitive routing. That approach studies the lifetime of the battery and proposes an algorithm 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 study led to the design of a cost function that penalizes the discharging loss event and prioritizes routes with "well recovered" nodes. Thus, battery recovery can take place and a node's maximum battery capacity can be attained. The selection function is a minimum function over the cost functions of all routes.

## 6. Energy saving techniques at routing layer

The problem of energy efficiency in MANETs can be addressed at different layers. In recent years, many researchers have focused on the optimization of energy consumption of mobile nodes, from different points of view. Some of the proposed solutions try to adjust the transmission power of wireless nodes (Cardei et al., 2004; Ingelrest et al., 2006). Other proposals tend to efficiently manage a sleep state for the nodes: these solutions range from pure MAC-layer solutions (as the power management of 802.11) to solutions combining MAC and routing functionality (Xu et al., 2001). Finally, there are many proposals which try to define an energy efficient routing protocol, capable of routing data over the network and of saving the battery power of mobile nodes (Toh, 2001; Jones et al., 2001; Lindsey et al., 2001; Wan et al., 2001; Kim et al., 2003; Jinet al., 2005; Taddia et al., 2005). Such proposals are often completely new, while others aim to add energy-aware functionalities to existing protocols, like AODV (Senouci & Naimi, 2005; Jung et al., 2005), DSR (Garcia et al., 2003; Luo et al., 2003) and OLSR (Ghanem et al., 2005; Benslimane et al., 2006; Guo & Malakooti, 2007).

The aim of energy-aware routing protocols is to reduce energy consumption in transmission of packets between a source and a destination, to avoid routing of packets through nodes with low residual energy, to optimize flooding of routing information over the network and to avoid interference and medium collisions.

Some routing protocols organize wireless nodes into clusters, such as Leach (Heinzelman et al., 2000). In (Xia & Vlajic, 2007) the conditions under which such protocols are energy efficient are established and the optimal radius of a cluster is determined.

Existing energy efficient routing protocols can be first distinguished by the number of paths maintained to a destination: a single path or multiple paths.

Multipath routing protocols (Shah & Rabaey, 2002; Ganesan et al., 2001) have the advantage of sharing load of any flow on several paths, leading to a lower consumption on the nodes



of the selected paths. It has been shown in (Srinivas & Modiano, 2003) that two paths with different links are generally sufficient.

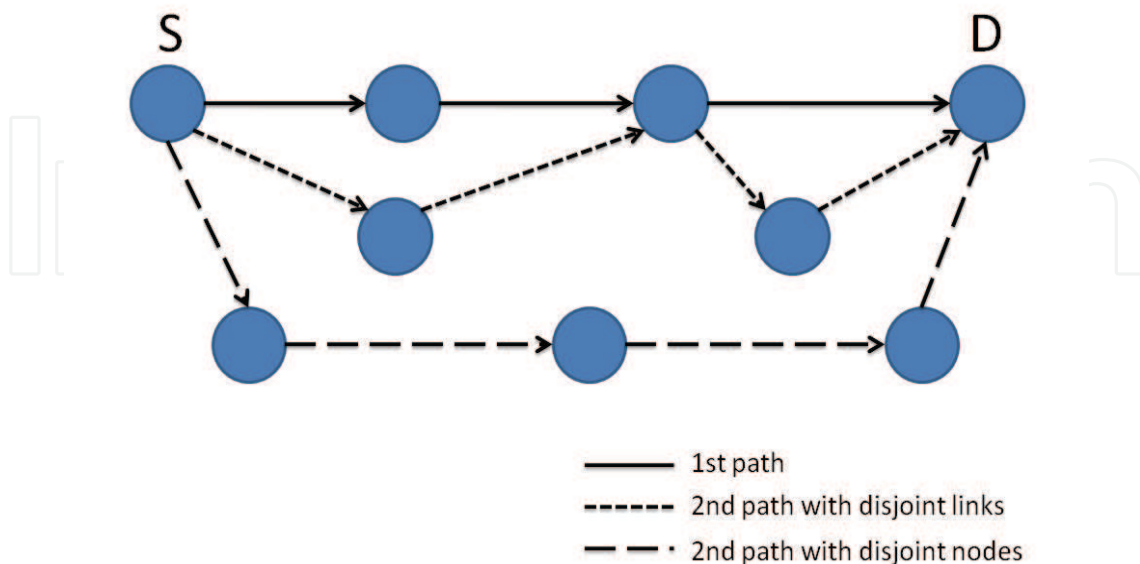


Fig. 2. Multipath Routing

We can distinguish three families of energy efficient routing protocols:

- the protocols selecting the path consuming the minimum energy. The advantage is that each transmission of a packet from its source to its destination minimizes the energy consumed. We can cite for example (Senouci & Naimi, 2005) and a more sophisticated protocol (Kwon & Shroff, 2006) where the selected path minimizes the additional energy dissipated by the routing of the new flow, taking into account the SINR and the energy lost in interferences. However, such protocols use always the same nodes (those minimizing the energy consumed) without any consideration on their residual energy. Consequently, these nodes will exhaust their battery more quickly than the others and the network lifetime is not maximized.
- the protocols selecting the path visiting the nodes with the highest residual energy, such as (Hassanein, 2006). Each flow is ensured to have enough energy on the selected path: depleted nodes are avoided. However, the path selected does not minimize the energy needed to transmit a flow packet from its source to its destination. Hence, the network lifetime may not be maximized.
- the hybrid protocols selecting the path with the minimum cost, where the cost takes into account the residual energy of each visited node (and possibly its neighbors) and the energy consumption of a packet on this path. These protocols avoid the problems encountered by the protocols of the two previous categories by weighing the factors used in the cost computation. We can cite for instance (Shrestha, 2006).

Routing protocols for mobile ad hoc networks have different features. Regarding the way to exchange routing information, the main difference is between reactive and proactive routing protocols. A reactive (or on-demand) routing protocol determines routes only when there is any data to send. If a route is unknown the source node initiates a search to find one and it is primarily interested in finding any route to a destination, not necessarily the optimal route. A proactive routing protocol, instead, attempts to maintain routes to all destinations

at all time, regardless of whether they are needed. To support this, the routing protocol propagates information updates about the network's topology or connectivity through the network. From the node organization point of view, there can be a hierarchical routing system (some routers form a sort of backbone) or a flat address space (where the routers are peers of all others).

### 6.1 Proactive energy-aware routing

With table-driven routing protocols, each node attempts to maintain consistent, up-to-date routing information to every other node in the network. This is done in response to changes in the network by having each node update its routing table and propagate the updates to its neighboring nodes. Thus, it is *proactive* in the sense that when a packet needs to be forwarded the route is already known and can be immediately used. As is the case for wired networks, the routing table is constructed using either *link-state* or *distance vector* algorithms containing a list of all the destinations, the next hop, and the number of hops to each destination. Many routing protocols including *Destination-Sequenced Distance Vector (DSDV)* and *Fisheye State Routing (FSR)* protocol belong to this category, and they differ in the number of routing tables manipulated and the methods used to exchange and maintain routing tables.

The energy optimization of a proactive routing protocol can exploit various network layer mechanisms, like control information forwarding. In OLSR, for example, the MPR selection mechanism can be varied in an energy-aware way. As suggested in RFC 3626, MPRs can be selected by their residual energy, rather than by their 2-hop neighborhood coverage (Ghanem et al., 2005). Some works applied both techniques (MPR selection criteria modification and path determination algorithm modification) to increase the energy efficiency of OLSR protocol (Benslimane et al, 2006; De Rango et al., 2008; Kunz, 2008).

Another mechanism that allows energy saving in OLSR protocol (without changing its behavior) is the Overhearing Exclusion (De Rango et al., 2008). Turning off the device when a unicast message exchange happens in the node's neighborhood, can save a large amount of energy. This can be achieved using the signaling mechanisms of the lower layers (i.e. the RTS/CTS exchange performed by IEEE 802.11 to avoid collisions), and does not affect protocol performance. In fact, OLSR does not take any advantage from unicast network information directed to other nodes (while other protocols, such as DSR, have mechanisms to do so).

### 6.2 Reactive energy-aware routing

With on-demand driven routing, routes are discovered only when a source node desires them. *Route discovery* and *route maintenance* are two main procedures: The route discovery process involves sending route-request packets from a source to its neighbor nodes, which then forward the request to their neighbors, and so on. Once the route-request reaches the destination node, it responds by unicasting a route-reply packet back to the source node via the neighbor from which it first received the route-request. When the route-request reaches an intermediate node that has a sufficiently up-to-date route, it stops forwarding and sends a route-reply message back to the source. Once the route is established, some form of route maintenance process maintains it in each node's internal data structure called a route-cache until the destination becomes inaccessible along the route. Note that each node learns the routing paths as time passes not only as a source or an intermediate node but also as an

overhearing neighbor node. In contrast to table-driven routing protocols, not all up-to-date routes are maintained at every node. *Dynamic Source Routing* (DSR) and *Ad-Hoc On-Demand Distance Vector* (AODV) are examples of on-demand driven protocols.

In generic on-demand (also known as reactive) 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 Local Energy-Aware Routing (LEAR; Woo et al., 2001) algorithm grants each node in the network permission to decide whether to participate in route searching; this way, the decision process is spread among all nodes in the network. That algorithm uses the energy profile of the nodes as a main criterion for the routing decision. The residual energy of each node defines the reluctance or willingness of that node to reply to route requests and forward data traffic. When energy  $E_i$  in a node  $i$  is lower than a given threshold  $Th$

$$E_i < Th \quad (10)$$

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

The technique of spreading the responsibility from the source/destination nodes to the intermediate nodes avoids the needing for a periodic exchange of control information, thus leading to reduced bandwidth and energy consumption. This technique has been commonly used to improve the performance of the routing protocols in many recent approaches.

### 6.3 Hybrid energy-aware routing

The work in (Xu et al., 2001) introduces a new way of optimizing the energy consumption in a wireless network, independently from the routing protocol adopted by the nodes. Assuming that all the devices in the network are equipped with a GPS (Global Positioning System) receiver, that work introduces the Geographical Adaptive Fidelity (GAF) for ad-hoc wireless networks. GAF conserves energy by identifying nodes that are equivalent from a routing perspective and then turning off unnecessary nodes, keeping a constant level of routing fidelity. GAF moderates this policy using application- and system-level information; nodes that source or sink data remain on and intermediate nodes monitor and balance energy use. Simulations of GAF suggest that network lifetime increases proportionally to node density. Power consumption in current wireless networks is idle-time dominated, so GAF focus on turning the radio off as much as possible.

### 6.4 Comparative performance evaluation from an energetic point of view

Many energy efficient routing protocol proposals were originally studied for sensor networks, where the limited energy of nodes is a strong constraint; in MANET, however, the requirements are different: a node has generally more hardware resources (capable of better performance, but consuming more energy) and the protocol must preserve the resources of every node in the network (not only a subset of them, because each node can be, at any time, source or destination of data). 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, instead, are oriented towards personal communication and the loss of connectivity to any node is significant.

The lifetime of a network is usually defined according to the following criteria (Vassileva & Barcelo-Arroyo, 2008):

- the time until the first node burns out its entire battery budget;

- the time until a certain proportion of the nodes fails;
- the time until network partitioning occurs.

A single node failure represents a serious problem in ad-hoc networks, because its occurrence can lead to the network partitioning. In contrast, 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. Consider, for example, a disaster recovery scenario. In such case, it is important that the rescuers do not lose connectivity with any other member of their team, and the connectivity among rescuers should be maintained as long as possible, or at least 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. While the former cannot be controlled by the routing protocol, the latter can be avoided through appropriate routing decisions.

Operational lifetime can be defined as the time until network partitioning occurs due to battery outage. In order to achieve the objective of maintaining connectivity as long as possible, the distribution of network 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. The network must be designed to achieve the simultaneous failure of the nodes (due to a lack of energy), so that communication requirements are met. This leads to consider as the operational lifetime of such networks their relative lifetime, rather than the absolute lifetime of their devices. The useful lifetime of ad-hoc networks can be significantly lower than the network's devices lifetime, but 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.

Many works have been presented in literature to give a measure of the energy consumption of various routing solutions in a wide range of scenarios, exploring the behavior of different protocols (especially OLSR and DSR) and trying to highlight the strength and weakness points of each of them (De Rango et al., 2008; Fotino et al., 2007; McCabe et al., 2005; Zhao & Tong, 2005). These researches are a good starting point for every energy-aware routing proposal for MANETs.

To achieve the desired behavior, some proposals make use of clustering (Heinzelman et al., 2000) or maintain multiple paths to destinations (in order to share the routing load among different nodes; Srinivas & Modiano, 2003).

## 7. Scalable energy-aware routing

In a hierarchical network, the network elements are partitioned into several groups, called clusters. In each cluster, there is a master node that manages all the other nodes (slave nodes) within the cluster. The depth of the network can vary from a single tier to multiple tiers. However, most hierarchical networks are two-tier networks.

Two-tier mobile ad hoc networks require sophisticated algorithms to perform clustering based on limited resources, such as the energy of each node, to communicate with each other. The cluster area of a node is related to the transmission power. Therefore, a larger



cluster area requires more energy. The energy required by a two-tier mobile ad hoc network varies with the clustering configuration (the master node selection of slave nodes) because the transmission power of each node must be set to satisfy the minimum power level at the receiving node.

Therefore, there exists an optimum clustering configuration that minimizes the call drop rate and the energy required for the still snapshot of the network. However, the optimum clustering configuration cannot be calculated quickly. A heuristic clustering scheme resulting in energy conservation for the network that can be implemented and executed in a limited time is needed for real-time clustering.

In (Ryu et al., 2001) the authors propose two distributed heuristic clustering schemes for energy conservation in two-tiered mobile ad hoc networks. The proposed schemes can be implemented and executed in real time. The mean transmission power and the call drop rate for the proposed schemes approximate optimum results. Hence, the proposed schemes are suitable for periodic or event-driven cluster reconfiguration. The proposed double-phase scheme is useful when energy conservation and call completion are more important than computing power and the speed of the scheme. In the opposite case, the proposed single-phase scheme can be adopted.

## 8. Implementation issues in energy management functionalities

Aiming to extend the time until network partitioning, routing protocol designers often try to optimize the use of battery power, in order to maximize the life of a node. However, extending nodes' lifetime could not be the better way to increase the connectivity between all of the nodes in the network.

The min-max algorithms are implemented 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, when nodes with low residual energy are excluded. However, if these protocols are analyzed in terms of a network's operational lifetime, the problem of extending the network's lifespan for as long as possible persists. Simulation results (like in Cao et al., 2007) 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. The load at each node and in its neighbors 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 in which each node is involved 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 of energy consumption.

Additional metrics should be considered, such as the fact that when neighboring nodes are engaged in transmitting packets, they are competing for the wireless medium.



Retransmissions that may possibly take place (Misra & Banerjee, 2002) should also be taken into consideration. The resulting collisions and retransmissions are energy-consuming and cannot simply be represented by the residual energy metric.

## 9. Conclusions

Since the majority of the devices for personal mobile communication are powered by batteries, the study of energy efficiency in wireless networks raised as a primary constraint for MANETs. In the last few years, a number of researchers have focused their attention on this issue. While the energy consumption problem has been widely considered in wireless sensor networks, mobile ad-hoc networks present a completely different set of constraints to take into account. This work tries to briefly survey the state of the art about energy efficient routing approaches for ad-hoc networks.

The main proposals in literature are presented and the main approaches adopted for ad-hoc energy consumption reduction are explained. The works presented are categorized by the nature of their behavior: proactive, reactive and hybrid ones. In many cases, it is difficult to compare them directly since each method has a different goal with different assumptions and employs different means to achieve the goal. Moreover, the energy-aware protocols' performance are often compared with classical (non energy-aware) protocols, making difficult to compare the different proposed solutions among them.

The primary goal of this work is to highlight all the energy-aware approaches to date, putting in evidence their strength and weakness points. The needing for an efficient, energy-aware routing scheme for the devices of a mobile ad-hoc network is rising very fast, with the growing diffusion of devices for personal communications.

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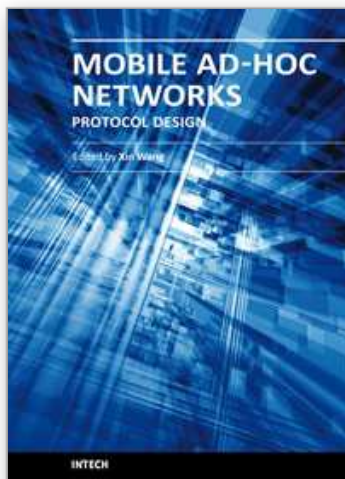
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### **Mobile Ad-Hoc Networks: Protocol Design**

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Being infrastructure-less and without central administration control, wireless ad-hoc networking is playing a more and more important role in extending the coverage of traditional wireless infrastructure (cellular networks, wireless LAN, etc). This book includes state-of-the-art techniques and solutions for wireless ad-hoc networks. It focuses on the following topics in ad-hoc networks: quality-of-service and video communication, routing protocol and cross-layer design. A few interesting problems about security and delay-tolerant networks are also discussed. This book is targeted to provide network engineers and researchers with design guidelines for large scale wireless ad hoc networks.

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