A comparative study of energy efficient routing strategies based on OLSR

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Abstract: Energy efficiency is a key issue in wireless ad hoc and sensor networks. In order to maximize network lifetime, several directions have been explored, among them energy efficient routing. In this report, we show how to extend the standardized OLSR routing protocol, in order to make it energy efficient. To take into account residual node energy, the native selection of multipoint relays of OLSR is changed. Three selection algorithms based on the minimum residual energy are evaluated and the best one is chosen. The OLSR extension we propose, selects the path minimizing the energy consumed in the end-to-end transmission of a flow packet and avoids nodes with low residual energy. As it has been shown that two-path routing is energy efficient, we compare this extension with a two-path source routing strategy (with different links or different nodes). An extensive performance evaluation allows us to conclude that our proposal maximizes both network lifetime and the amount of data delivered.

Key-words: energy efficiency, energy efficient routing, wireless ad hoc networks, sensor networks, OLSR, routing protocol, network lifetime, multipoint relay.

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Etude comparative de différentes stratégies de routage efficaces en énergie et basées sur OLSR

Résumé : L'efficacicité énergétique est un problème majeur des réseaux sans fil ad hoc et des réseaux de capteurs. Plusieurs axes ont été explorés pour maximiser la durée de vie d'un réseau, parmi eux, le routage économe en énergie. Dans ce rapport, nous montrons comment étendre le protocole de routage OLSR, standardisé à l'IETF, pour améliorer son efficacité énergétique. Pour prendre en compte l'énergie résiduelle des noeuds, l'algorithme natif de sélection des relais multipoint dans OLSR doit être modifié. Nous évaluons trois variantes et choisissons la meilleure. L' extension d'OLSR que nous proposons sélectionne le chemin minimisant l'énergie consommée par la transmission de bout-en-bout d'un paquet du flux et évite les noeuds avec une faible énergie résiduelle. Comme par ailleurs, il a été montré que router un flux sur deux routes préserve l'énergie, nous comparons cette extension avec un routage par la source maintenant deux routes par flux (les routes sont à liens disjoints ou à noeuds disjoints). Une évaluation de performances nous permet de conclure que notre proposition maximise la durée de vie du réseau d'une part et la quantité de données remises d'autre part.

Mots-clés : efficacité énergétique, routage économe en énergie, réseaux mobiles ad hoc, réseaux de capteurs, OLSR, protocole de routage, durée de vie du réseau, relais multipoint.

Contents

1 Motivation

The diversity of the applications supported by wireless sensor networks explain the success of this type of network. These applications concern as various domains as environmental monitoring, wildlife protection, emergency rescue, home monitoring, target tracking, exploration mission in hostile environments... Sensor nodes are characterized by a small size, a low cost, an advanced communication technology, but also a limited amount of energy. This energy can be very expensive, difficult or even impossible to renew. That is why, energy efficient strategies are required in such networks in order to maximize network lifetime.

Network lifetime can be defined as:

- *Definition D1: the time to the first node failure due to battery outage*;
- *Definition D2: the time to the unavailability of an application functionnnality.* For instance, a vital parameter of a patient is no longer controlled, a target is no longer tracked. Definition D2 differs from D1 insofar as redundancy is provided: if for instance any area to be monitored is covered by k sensors, the failure of $k-1$ sensors is perfectly tolerated.
- *Definition D3: the time to the first network partitioning.* As soon as the network is no longer connected, vital information can no longer be transferred to its destination.

In the absence of knowledge of the application supported by the network, definitions D1 and D3 are the most useful ones to compare different energy efficent strategies. In the following, we use definition D3 to evaluate the network lifetime.

Solutions to maximize network lifetime can be classified into four categories. Some adjust the transmission power of wireless nodes like [1, 2]; others reduce the volume of information transferred by means of aggregation like [3, 4, 5]; other too make nodes sleep in order to spare energy like [6, 7, 8]; finally the last ones use energy efficient routing, [9, 10, 11, 12, 13, 14, 15, 16, 17]. In this paper, we focus on solutions belonging to this last category, for multiple reasons:

- a multihop transmission is energy consuming and reducing the energy spent in the transmission of a packet from its source to its destination would increase network lifetime;
- avoiding nodes with a low residual energy would also contribute to prolong network lifetime;
- optimizing network flooding would also reduce the number of transmissions needed to reach all nodes in the network and therefore spare node energy;
- avoiding nodes that already have a high traffic load would reduce medium access contention, collisions if the medium access type is CSMA-CA and then spare energy lost in useless transmissions.

The OLSR routing protocol has been standardized at IETF [18]. However, this protocol does not take into account the energy. We propose to extend this protocol in order to make it energy efficient. The results that are shown in this paper are valid for any wireless network meeting the following constraints:

Assumption 1: Power conditions: *$P_{idle} < P_{receive}$ and $P_{idle} < P_{transmit}$, where P_{idle} (resp. $P_{transmit}$, $P_{receive}$) is the power used by a wireless node in the idle (resp. transmit, receive) state.*

An IEEE 802.11 network meets those conditions. The performance evaluation reported in Sections 4.2 and 4.3 are based on values taken from Lucent Wavelan silver cards.

For simplicity reasons, we also assume that:

Assumption 2: Radio interferences are limited to two hops.
This assumption is generally admitted in ZigBee and IEEE 802.11 networks.

This paper is organized as follows. In Section 2, we present a brief state of the art dealing with energy efficiency. We then focus more particularly on the OLSR routing protocol and more generally on energy efficient routing. In Section 3, we define our energy consumption model. In Section 4, we show how to extend OLSR to make it energy efficient. This extension, called RE selects the path minimizing the energy consumed in the end-to-end transmission of a flow packet and avoids nodes with low residual energy. To take into account residual node energy, the native selection of multipoint relays of OLSR is changed. Three selection algorithms based on the minimum residual energy are evaluated and the best one, $M1E$ is chosen. As it has been shown that two-path routing is energy efficient, we compare the RE extension with two two-path source routing strategies (DL with different links and DN with different nodes). We show that RE outperforms both DN and DL in terms of network lifetime and delivery rate. Finally, we conclude in Section 5 and give some perspectives for our further work.

2 State of the art

As said in Section 1, energy efficient routing is a way to maximize network lifetime. Before proposing an extension of OLSR routing to make it energy efficient, we will first recall the main principles of OLSR and then briefly present a state of the art related to energy efficient routing.

2.1 The OLSR routing protocol

OLSR (Optimized Link State Routing), [18], is a proactive routing protocol where nodes periodically exchange topology information in order to establish a route to any destination in the network. It is an optimization of a pure link state routing protocol, based on the concept of *multipoint relays* (*MPRs*). First, using *multipoint relays* reduces the size of the control messages: rather than declaring all its links in the network, a node declares only the set of links with its neighbors that have selected it as "*multipoint relay*". The use of *MPRs* also minimizes flooding of control traffic. Indeed only *multipoint relays* forward control messages. This technique significantly reduces the number of retransmissions of broadcast messages.

OLSR consists in two main functionalities:

- *Neighborhood discovery.* Each node acquires the knowledge of its one-hop and two-hop neighborhood by periodic *Hello* messages. It independently selects its own set of *multipoint relays* (MPRs), among its one-hop neighbors in such a way that its MPRs cover (in terms of radio range) all its two-hop neighbors.
- *Topology dissemination.* Each node also maintains topological information about the network obtained by *TC (Topology Control)* messages broadcast by MPR nodes.

Each node computes its routing table by the Dijkstra algorithm. This table provides the shortest route (i.e. the route with the smallest hop number) to any destination in the network. In [19], we reported performance evaluation results showing that a MANET with OLSR routing achieves very satisfying performances.

2.2 Complexity results

Because of radio interferences, while a node N is transmitting a frame to a node D, no other node in the transmission range of N can simultaneously receive another frame. Similarly, while node D is receiving this frame, no other node in its transmission range can simultaneously transmit another frame. To make it simple, no node in the interference area of a transmitter can meanwhile transmit or receive another frame. As already said, we assume that interferences are limited to two-hops from the transmitter. The two following complexity results related to radio interferences have been established:

Result 1: *Because of radio interferences, the selection of a unicast path, between a source and a destination, meeting the requested bandwidth is NP-hard*: see [20].

Result 2: *Because of radio interferences, the selection of a unicast path, between a source and a destination,ensuring that each node has sufficient residual energy is NP-hard*: see [21] where it is also shown that this result is still valid, even if interferences are limited to a single hop.

2.3 Energy efficient routing protocols

Some routing protocols organize wireless nodes into clusters, such as Leach [9]. The author of [10] has established the conditions under which such protocols are energy efficient and determined the optimal radius of a cluster. In the following, we assume that such conditions are not met.

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, such as [11] or [12], have the advantage of sharing load of any flow on several paths, leading to a lesser consumption on the nodes of the selected paths. It has been shown in [13] that two paths with different links are generally sufficient. In Section 4, we will evaluate the performance obtained by multipath routing, when two paths are used with two variants: different links or different nodes.

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 [14] and a more sophisticated protocol [15] 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 [16]. 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 resiudual 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 [17]. In Section 4, we will present different OLSR extensions belonging to this category.

3 Energy consumption model

A wireless node's radio can be in one of the following four states: $Transmit$, *Receive*, *Idle* or *Sleep* and each of which consumes different levels of energy.

- *Transmit*: node is transmitting a frame with transmission power $P_{transmit}$;
- *Receive*: node is receiving a frame with reception power $P_{receive}$. This frame can be decoded by this node or not, it can be intended to this node or not;
- *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.

As we are interested in the additional energy spent during the transmission of a flow packet from its source to its destination with reference to the idle state, the values used for transmission power and reception power are calculated as follows:

$$P_{trans} = P_{transmit} - P_{idle},$$
$$P_{rcv} = P_{receive} - P_{idle}.$$

In Table 1, we report the reference values of $P_{transmit}$, $P_{receive}$, and P_{idle} taken from a Lucent silver wavelan PC card. These values are used in the performance evaluation reported in Section 4.

State	Power value	Power Increment
Transmit	$P_{transmit} = 1.3$W	$P_{trans} = 0.56$W
Receive	$P_{receive} = 0.9$W	$P_{rcv} = 0.16$W
Idle	$P_{idle} = 0.74$W	
Sleep	$P_{sleep} = 0.047$W	

Table 1: Power value in each radio state

Now, we can determine the energy dissipated in transmitting (E_{trans}) or receiving (E_{rcv}) one packet (this energy is the additional energy consumed when transmitting or receiving packet with reference to the idle state). Let *Duration* denote the transmission duration of a packet. We have:

$$E_{trans} = P_{trans} * Duration,$$
$$E_{rcv} = P_{rcv} * Duration.$$

When a transmitter transmits one packet to 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 [22]:

$$cost_{transmission}(i) = E_{trans} + n * E_{rcv},$$

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

We now compute the energy cost of a flow dissipated on its path P.

$$cost(flow) = \sum_{i \in sender(flow)} cost_{transmission}(i),$$

where i is a sender of $flow$ on its path P.

This cost indicates the quantity of energy consumed by one packet of the flow to reach its destination. Our idea to maximize network lifetime, is to minimize the energy consumed by the flow in selecting the best path with minimum energy dissipated. For that, we will use this cost to compute routes for flows. Indeed, instead of using the number of hop between source and destination to select the best route (i.e.; every link has a cost of one), as done in OLSR, we will use $cost(flow)$ as the criterion to choose the best path, where every link $i \rightarrow j$ has a cost equal to $cost_{transmission}(i)$.

4 Routing strategies

4.1 Goal and architecture

In this section, we show how to extend the OLSR routing protocol to make it energy efficient. Hence, our goal is to maximize the network lifetime by:

- Minimizing the energy consumed by a packet transmission from its source to its destination;
- Avoiding the nodes with a low residual energy;
- Avoiding the nodes with a small available bandwidth;
- Reducing the overhead.

Hence, energy must be taken into account in route computation. Indeed, energy must be a criterion of route selection. We can notice that with OLSR, the intermediate nodes in a path are MPRs. As a consequence, the selection of MPRs must also take energy into account. For this purpose, energy information must be included in the topology information exchanged in OLSR. Hence, we get the following architecture, illustrated in Figure 1. Notice that the energy efficient routing we propose can be combined with a solution allowing nodes to sleep: the very short naps of nodes at the MAC level are kept transparent to the routing protocol.

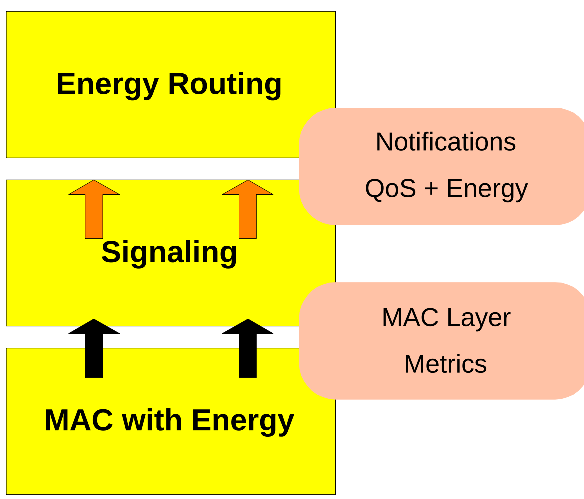

Figure 1: An energy efficient architecture

In order to support the energy efficient extension, no additional message is required. Only additional energy information is included in both *Hello* and *TC* messages, as shown in Section 4.2.2.

4.2 Energy efficient selection of MPRs

4.2.1 Presentation of EMPR selection policies

We now focus on an energy efficient selection of MPRs: the multipoint relays are selected according to the residual energy and are denoted EMPRs. We study three variants depending on the nearby nodes considered for the computation of the minimum residual energy, where $E_R(M)$ denotes the residual energy of node M:

- The E policy considers only $E_R(M)$, the residual energy of the EMPR candidate, M;
- The $M1E$ policy considers the weighted residual energy of the EMPR candidate M and its 1-hop neighbors: $min(\frac{E_R(M)}{P_{trans}+P_{rcv}}, min_{D\in 1hop(M)}(\frac{E_R(D)}{2*P_{rcv}}))$.

  The weights of $E_R(M)$ and $E_R(D)$ take into account the role played by the nodes M and D in a transmission from N, the node performing the EMPR selection, to D, one of its two-hop neighbors, via the node M. It represents the maximum transmission duration that can be sustained;
- The $M2E$ policy considers the weighted residual energy of the EMPR candidate M and its 1-hop and 2-hop neighbors:
  $min(\frac{E_R(M)}{P_{trans}+P_{rcv}}, min_{D\in 1hop(M)}(\frac{E_R(D)}{2*P_{rcv}}),$
  $min_{D\in 2hop(M)}(\frac{E_R(D)}{P_{rcv}}))$.

The EMPR selection algorithm, performed by any node N, is the following:

- Node N puts in the set *Uncovered* all its two-hop neighbors.
- Node N sorts its 1-hop neighbors by decreasing order of the selection criterion (e.g.; $E_R(M)$ for E). Let $\mathcal{N}_1$ be this ordered set.
- Node N selects M the first node in $\mathcal{N}_1$ and removes the nodes covered by M from the set *Uncovered*.
- If the successor of M in $\mathcal{N}_1$ covers nodes that are in *Uncovered*, this node is selected as EMPR, and all nodes covered by it are removed from the set *Uncovered*;
- and so on until *Uncovered* becomes empty.

4.2.2 Control messages in the OLSR extension

As previously said, no additional message is required in the OLSR energy extension we propose. In order to select the EMPRs, the *Hello* messages include the following additional information:

- the residual energy of the sending node, in case of E,
- the residual energy of the sending node, and the minimum residual energy of the one-hop nodes, in case of $M1E$,
- the residual energy of the sending node, the minimum residual energy of the one-hop nodes and the minimum residual energy of the two-hop nodes, in case of $M2E$.

In order to compute the energy cost of a flow, we need to know the number of nodes up to two-hop of the node considered (see Section 3). Hence, the TC messages include the number of nodes belonging to the interference area of the TC originator.

4.2.3 Performance evaluation

When a QoS (Quality of Service) criterion, such as energy, local available bandwidth or medium access delay, is used to select QoS MPRs (i.e.; EMPRs when the energy criterion is used), we have the following result:

Result 3: *the average number of neighbors selected as QoS MPRs is in* $O(n^{1/3}log(n))$, *where n is the average number of neighbor per node, whereas the average number of MPRs selected according to the native procedure in OLSR is in* $O(n^{1/3})$: see the proof in [23]. The average number of QoS MPRs selected per node is increased by a $log(n)$ factor.

Simulation parameters: In the following simulations, nodes are uniformly distributed in the network area. The transmission range is equal to 250m. Interferences are limited to 500m. The initial energy of nodes is uniformly distributed in the interval [20J, 60J]. The powers used are those given in Table 1. Results reported in this section are the average of five simulations.

First, we evaluate the average number of EMPRs per node as a function of network density, with the three selection variants. The number of nodes is set to 100. Similarly, the network density (i.e.; the average number of one-hop neighbors per node) being fixed to 10, we study the impact of the node number on the average number of EMPRs per node. In both cases, the native MPR selection is used as a reference. Simulation results are illustrated on Figures 2 and 3.

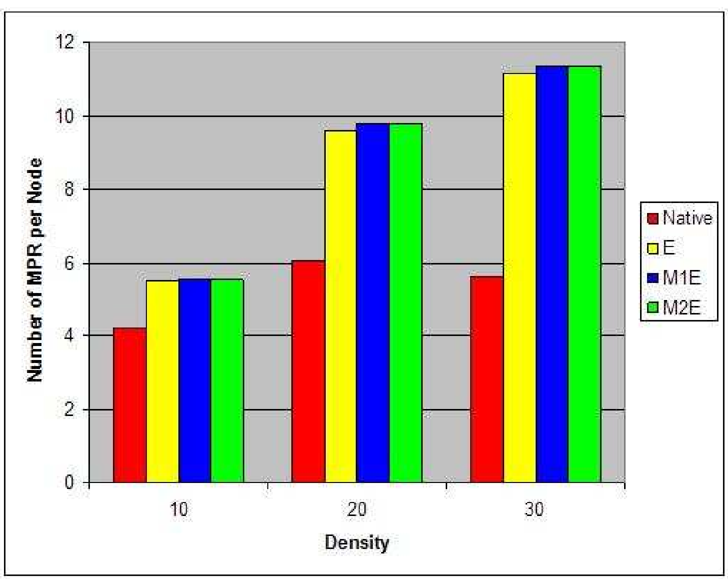

Figure 2: Number of multipoint relays per node, function of network density.

Simulation results confirm Result 3: the number of EMPR per node is higher than the number of MPR per node. We can also notice that the difference increases with network density and does not depend on node number. Furthermore, with the power values taken, the $M1E$ and $M2E$ selections give the same results. The reason is that the criterion used to sort the nodes leads to the same value with both $M1E$ and $M2E$. Indeed the third term in formula 2 (see Section 3) is negligible compared to the first two terms. So the use of $M1E$ is more interesting than $M2E$ because it is less complicated to compute and needs less information from the network.

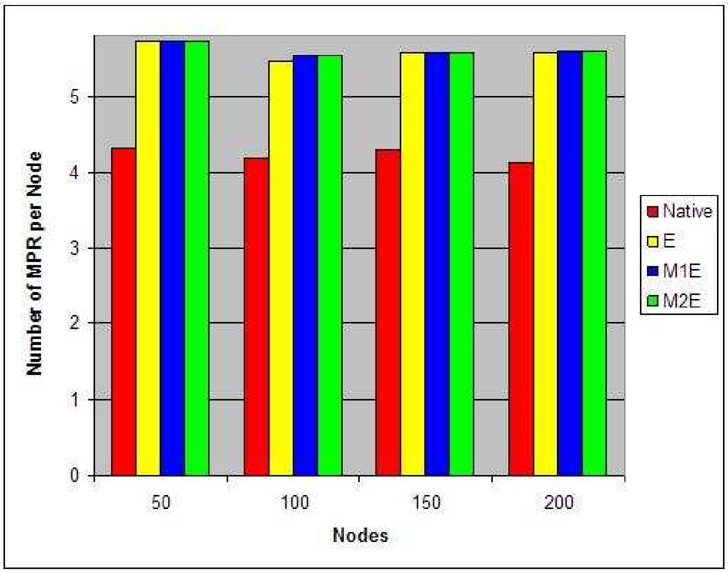

Figure 3: Number of multipoint relays per node, function of node number.

Multipoint relays are used in OLSR to optimize network flooding by means of the following forwarding rule:

OLSR forwarding rule: a node forwards once a broadcast message with a non-null time-to-live only if it has received this message for the first time from a node that has selected it as MPR.

Figure 4 depicts the number of retransmissions per TC, as a function of network density. Similarly, Figure 5 depicts the number of TCs received per node in a TC period, as a function of network density. These numbers are a good indication of the overhead induced by the extension of the OLSR routing protocol.

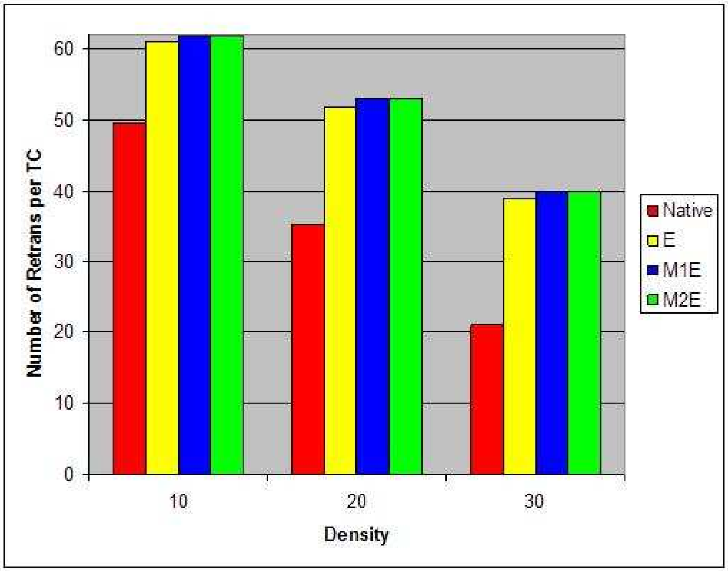

Figure 4: Number of retransmissions per TC, function of network density.

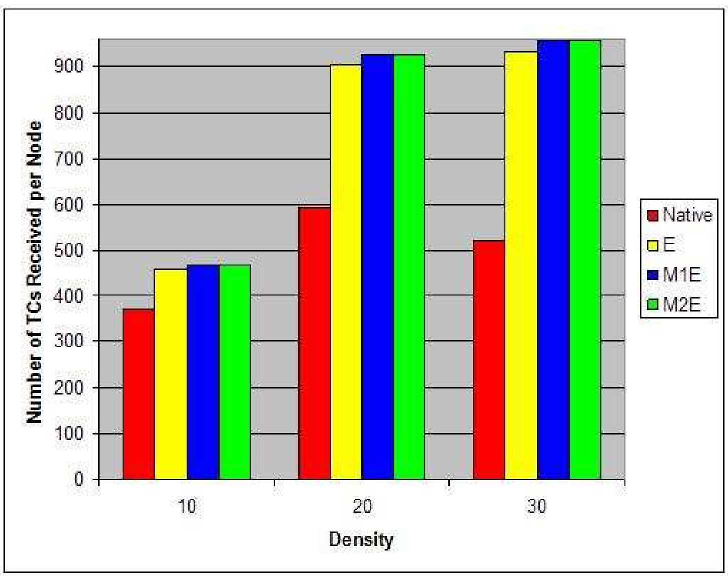

Figure 5: Number of TCs received per node, function of network density.

As expected, the number of retransmissions of a flooded message is higher when EMPRs are used, instead of MPRs. Similarly, the number of TCs received per node in a TC period is higher with EMPRs. As we want to reduce the overhead, we recommend to use two types of multipoint relays:

- MPRs to optimize flooding,

- EMPRs to build energy efficient routes: all intermediate nodes on a path to a destination are EMPRs. Moreover, as in our case, both $M1E$ and $M2E$ provide the same results and the criterion used in $M1E$ is simpler to compute than in $M2E$ and requires less additional information in the *Hello* messages, we recommend the use of $M1E$. This will be confirmed in the next section.

4.3 Energy efficient routing

In this section, we present three energy efficient routing strategies based on the OLSR protocol and evaluate their performance in terms of network lifetime, delivery rate and residual energy distribution. For the three strategies, the cost of a route is equal to the energy consumed by the transmission of a packet from its source to its destination as computed in Section 3. Each node computes its route of minimum energy towards any other node in the network, using the Dijkstra algorithm, with the energy cost.

4.3.1 Presentation of different routing policies

The first policy we will study is **one hop-by-hop energy efficient routing**, denoted RE, where each node forwards the received packet toward the next hop on the minimum cost route. In order to avoid frequent route changes, the selection of EMPRs is changed only when the topology changes or the ratio

$$\frac{E(new\_EMPR)-E(old\_EMPR)}{E(old\_EMPR)} > 10\%.$$

Another policy that can be used to spare energy is to share the load among the nodes. Multipath routing has been introduced for that purpose. In this paper, we will also study this policy, assuming multipath source routing. The source is in charge of computing the two paths used by its flow. For each flow packet, the source selects one of the paths inversely proportionally to its cost. The selected path will be encapsulated in the packet. Hence, each visited node forwards the packet to the next hop on the path selected by the source. We distinguish two variants:

- **two paths with disjoint links**, denoted DL. The source of the flow computes a first path minimizing the cost, with Dijkstra algorithm. It then removes all the links used to compute the second path minimizing the cost with this new topology. Notice however that a same node (see node 2 in Figure 6) can belong to both paths and then deplete early.

- **two path with disjoint intermediate nodes**, denoted DN. As previously, the source of the flow computes a first path minimizing the cost, with Dijkstra algorithm. It then removes all the intermediate nodes used and then computes the second path minimizing the cost with this new topology.

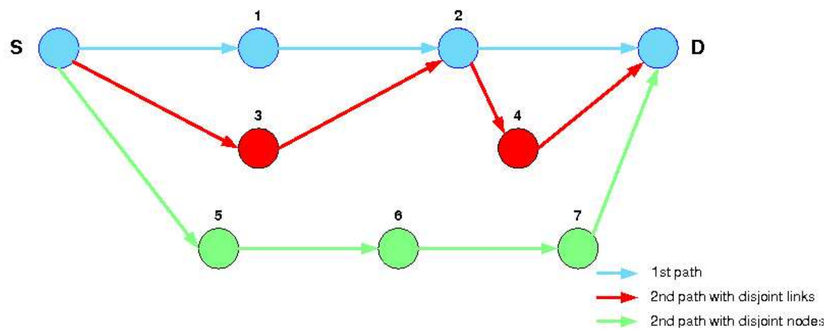

Figure 6: Multipath routing

4.3.2 Performance evaluation

In the following simulations, nodes are uniformly distributed in the network area. The network density is set to 10 which represents the average number of neighbors per node. Each node implements the IEEE 802.11b PHY-MAC layers, the IP network layer with the energy efficient extension of OLSR. Network bandwidth is set to 2Mbps. The initial energy of the nodes is uniformly distributed in [20J, 60J]. The transmission range is equal to 250m, interferences are limited to 2-hop. We consider 30 point-to-point CBR flows, whose sources and destinations are randomly chosen. The packet size is set to 512 bytes and the interarrival time is 250 ms. Energy consumption computation is done according to the model presented in Section 3. Results reported in this section are the average of five simulations.

Evaluation of RE with different EMPR selections

We first compare the network lifetime obtained with RE, using E, $M1E$ and $M2E$ EMPR selection policies. Results are shown on Figure 7. First, we observe that $M2E$ and $M1E$ EMPR selection policies provide the same result. We notice that RE obtains the best performance when used with $M1E$ or $M2E$. That is because, unlike E, $M1E$ takes into acount the energy dissipated in packet transmission and reception on the 1-hop neighbors of the transmitter. As $M1E$ is simpler than $M2E$, the EMPR selection is done according to $M1E$, for all the energy efficient routing strategies evaluated.

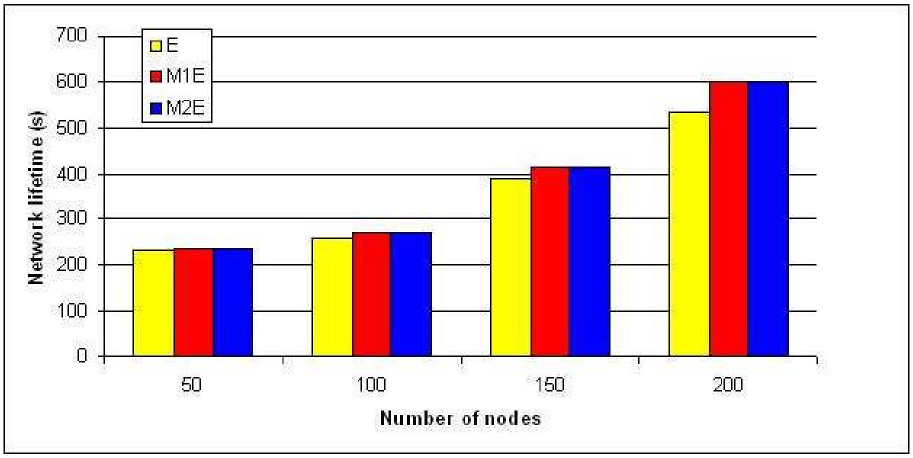

Figure 7: Impact of the EMPR selection policy on the network lifetime

Evaluation of network lifetime with RE, DN and DL versus OLSR

In this second series of experiments, we compare the three energy efficient routing strategies RE, DN and DL with regard to the network lifetime, when the number of nodes ranges from 50 to 200, the network density is set to 10. The OLSR routing protocol that does never take energy into account and always selects the shortest path (i.e.; the path with the minimum hop number), is used as a reference. Simulation results are illustrated in Figure 8.

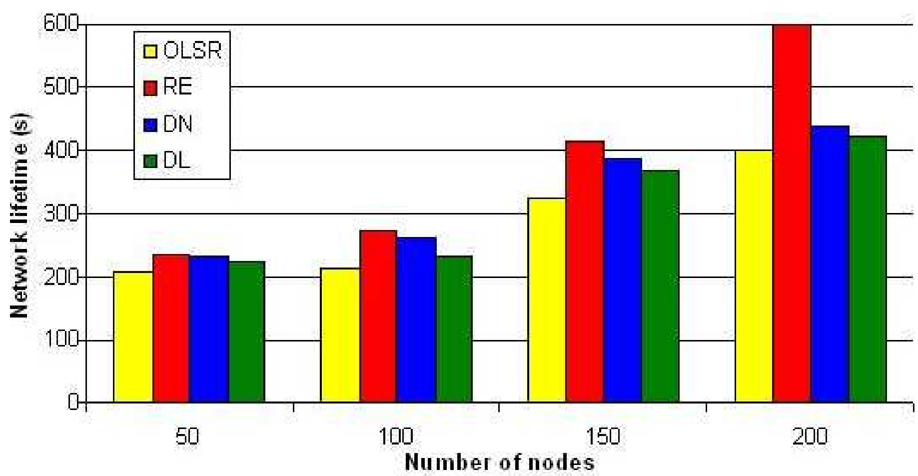

Figure 8: Comparison of network lifetime with RE, DN and DL versus OLSR

As expected, OLSR provides the smallest network lifetime. This shows that the selection of the shortest path is not sufficient to save energy. Concerning the two 2-path source routing strategies, DN provides better results than DL. This is not surprising insofar as energy is dissipated per nodes and not per wireless link. Hence, DL that allows common nodes in the two paths can exhaust the energy of these common nodes more quickly. The main conclusion of these experiments is that RE significantly outperforms DN and DL whatever the number of nodes. Moreover, the gain is increasing with the network size. RE prolonges the network lifetime of 50% compared with OLSR for a network of 200 nodes. Notice that in the same conditions, DN prolonges the network lifetime of only 10%. Indeed, the two paths chosen by the source of the flow are used for all flow packets independently of the residual energy of these nodes. So the intermediates nodes exhaust their energy more quickly.

Evaluation of the amount of data delivered with RE, DN and DL versus OLSR

Notice that the selection of an energy efficient routing protocol maximizing network lifetime, would provide no advantage to the application, if this increase in network lifetime was not followed by an increase in the amount of user data delivered. That is why, in this third series of experiments, we evaluate the delivery rate with the three routing strategies RE, DN and DL, when the number of nodes ranges from 50 to 200, the network density being set to 10. This delivery rate is compared with this provided by OLSR. Results are given in Figure 9. As previously, RE provides the best delivery rate, followed by DN, DL and finally $OLSR$. In conclusion, RE allows a real benefit to the application by delivering a higher amount of data with the same initial energy.

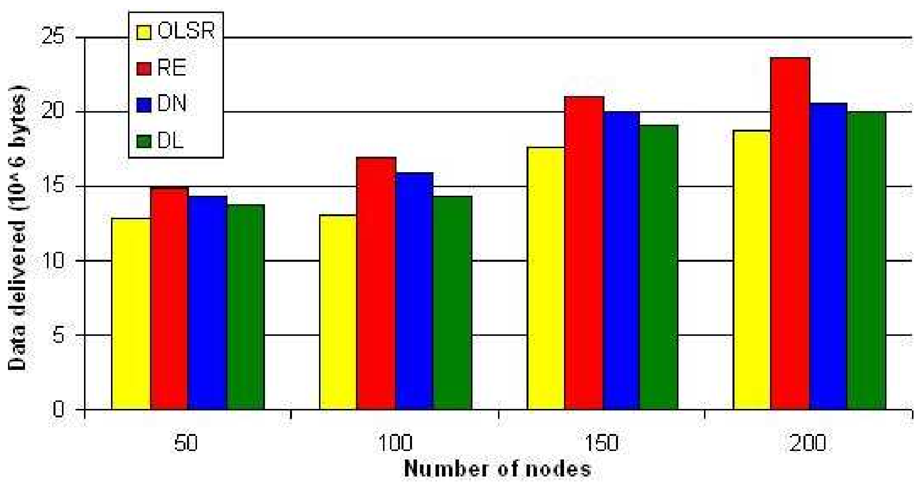

Figure 9: Comparison of delivery rate with RE, DN and DL versus OLSR

Distribution of residual energy

In this fourth series of experiments, we measure the residual energy at each node at a given time, (time = 400s corresponding to the network lifetime obtained with OLSR), for a network of 200 nodes with a network density of 10. We recall that the initial energy of a node is randomly selected in the interval [20, 60] Joules and is represented in violet on Figure 10. We compare the values obtained by OLSR and RE. We observe that at time 400s, 86 nodes have a residual energy less than 20 Joules. With RE, half of the nodes have an energy in [20, 40] Joules. This can be explained by:

- the EMPR selection that takes into account the residual energy of nodes.
- the selection of the route with the minimum energy cost.

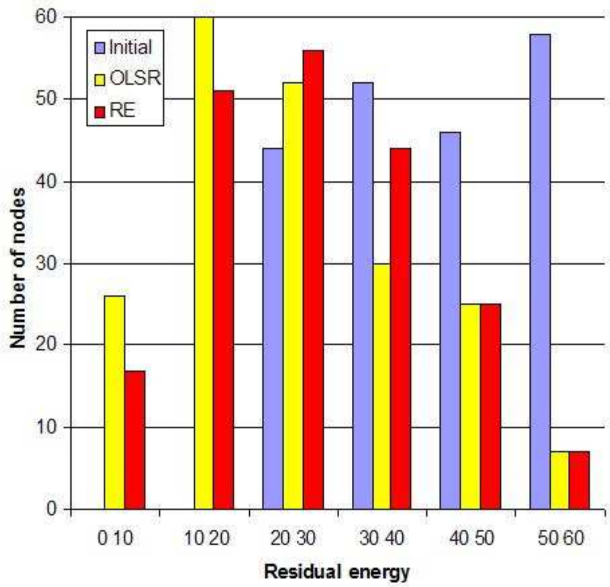

Figure 10: Distribution of residual energy at time 200s

As RE outperforms the other routing policies with regard to both network lifetime and delivery rate, we decide to select it, with $M1E$, the best variant of EMPR selection. That is the solution we recommend for an energy efficient routing based on OLSR.

5 Conclusion

Wireless ad hoc and sensor networks are faced with the problem of energy efficiency in order to maximize network lifetime. The aim of this paper was to extend the OLSR routing protocol to make it energy efficient. We have defined an energy model and express its validity conditions. We have studied different variants of multipoint relay selection based on residual energy. The variant $M1E$ takes into account the energy dissipated in transmission and reception up to one-hop from the transmitter. $M1E$ presents the best tradeoff between the energy consumed and the overhead induced. Moreover, we recommend to keep the native MPR selection to optimize network flooding and to use the $M1E$ selection to build energy efficient routes.

We have also compared different routing strategies:

- RE, a hop-by-hop adaptive strategy selecting the route with minimum energy cost while avoiding nodes with a low residual energy,

- *DL*, a two-path routing strategy with different links,
- *DN*, a two-path routing strategy with different nodes.

Simulation results show that *RE* outperforms the other two strategies with regard to both network lifetime and delivery rate. Moreover, *RE* tends to maintain a higher residual energy level at each node. For these reasons, we recommend to use this strategy. In a further work, we will see how to use this strategy in a network where nodes are allowed to switch to the sleeping state for short periods.

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