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Localized LMST and RNG based minimum-energy broadcast protocols in ad hoc networks ☆

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Abstract

In the minimum energy broadcasting problem, each node adjusts its transmission power to minimize the total energy consumption while still guaranteeing the full coverage of the network. We consider both topology control and broadcast oriented protocols, for which all existing solutions require global network information. In this paper, we describe new localized protocols where nodes require only local informations about their neighborhood (distances or geographic positions). In addition to this, our protocols are shown experimentally to be comparable to the best known globalized BIP solution. Our solutions are based on the use of neighbor elimination scheme applied on the relative neighborhood graph (RNG) and local minimum spanning tree (LMST) which preserve connectivity and are defined in localized manner. Two variants are proposed, one with timeout applied on nodes receiving message from non-RNG (non-LMST) neighbor and retransmitting immediately otherwise (unless list of RNG or LMST neighbors in need of the message is empty), and one with timeout applied on all the nodes. We proved that LMST is a subset of RNG, which explains why LMST always performs better among the two.

Keywords: Energy conservation; Wireless ad hoc networks; Broadcasting; Localized algorithms

1. Introduction

In wireless ad hoc networks, such as sensor networks, all nodes cooperate to handle network facilities. These networks are power constrained as nodes operate with restricted battery power. We consider nodes that have the capacity to modify the area of coverage with its transmission. Indeed, control of the emitted transmission power allows to reduce significantly the energy consumption and so to increase lifetime of the network. However, the adjustment of transmission signal strength generally implies topology alterations like loss of the connectivity. Hence, nodes have to manage their transmission area while maintaining the connectivity of the network.

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In the broadcasting task, a message originated from a source node needs to be forwarded to all the other nodes in the network. In this paper, we focus on the development of protocols for energy-efficient broadcast communications. All existing solutions are globalized, meaning that each node needs global network information. Mobility of nodes, or changes in their activity status (from active to passive and vice versa) may cause global changes in any MST-based structure. Therefore topology changes must be propagated throughout the network for any globalized solution. This may result in extreme and unacceptable communication overhead for ad hoc networks. Hence, because of the limited resources of mobile nodes, it is ideal that each node can decide on its own behavior based only on the information from all nodes within a constant hop distance. Such distributed algorithms and protocols are called localized [1–5]. Of particular interest are protocols where nodes make decisions based solely on the knowledge of its 1-hop or 2-hops neighbors, and distances to them. In non-localized distributed, or globalized algorithms, nodes require knowledge of whole network topology to make decision.

Several different protocols have been proposed to manage energy consumption by adjusting transmitting powers. Among existing protocols, we can distinguish two families of protocols: *topology control oriented protocols* and *broadcast oriented protocols*.

The first family (topology control oriented protocols) assigns the transmission power for each node such that the network is connected independently of broadcast utilization. That means that all nodes can be a source of a broadcast and are able to reach all nodes of the network using pre-assigned transmission radii at each node. The optimization criterion is minimizing the total transmission power assigned according to an energy consumption model. This problem is known as min(-total) assignment problem and was considered by Kiroustis et al. [6] which established that this problem is NP-hard for three-dimensional space. Clementi et al. [7] showed that this complexity result still occurs for two-dimensional space. Approximate solutions [2,8,9] are based on minimum spanning trees or approximation of minimal spanning trees and are globalized.

The second family (broadcast oriented protocols) achieves the same objectives but considers the broadcast process from a given source node. For instance, Wieselthier et al. [9] proposed greedy heuristics which are based on Prim's and Dijkstra's algorithms. The more efficient heuristic, called BIP for broadcasting incremental power, constructs a tree starting from the source node and adds new nodes one at a time according to a cost evaluation. The constraints are not the same as for the first protocol family since in this second case the subgraph induced by the minimum-energy broadcast tree does not need to be strongly connected: the only condition is that the source can reach every node of the network. It has been proved in [10,11] that the minimum-energy broadcast tree problem is NP-complete and [11] proposed an approximate globalized algorithm which gives solutions with bounded ratio against lower bound.

We can also distinguish several communication models: one-to-all model, one-to-one model and variable angular range model. In one-to-all model, mobile nodes use omnidirectional antennas and the communication zone of a node is a disk centered at this node. All above cited works (and all references except [16–18]) use this model. In one-to-one model, nodes are equipped with directional antennas with small angles that can provide more energy savings and interference reduction since the communication zone of a node is a small beam from this node to the targeted node [17]. With variable angular range model, the nodes can choose direction and width of the beam that allows to target several neighbors with one transmission. Hardware solutions using directional antennas (also called *smart antennas*) are more difficult to implement and we focus in this paper on one-to-all model. The broadcast energy problem for directional antenna models are addressed in [16,18].

In this paper, we are mainly interested in *broadcast oriented protocols* in one-to-all communication model in wireless ad hoc networks. The main contribution of this paper is that we propose an algorithm that requires local information while all existing solutions are globalized, that is distributed where nodes require full knowledge of network to make decision. The information needed in our protocols are included in information needed by existing protocols like BIP. In our localized protocols, each node requires only the knowledge of its distance to all neighboring nodes and distances between its neighboring nodes. Distances can be measured by using signal strength, time delay or more sophisticated techniques like microwave distance [19]. If a positioning system (like GPS) is available, each node only needs position information from its neighbor nodes.

The preliminary conference version of this article has been published in [12]. It describes a topology control and broadcast oriented protocol based on the relative neighborhood graph (RNG) (RNG is first described in [15]) and on the neighbor elimination scheme (NES) (NES is proposed in [3,29]), with timeout applied if message is first received by a non-RNG neighbor, while it is immediately forwarded when it is received from a RNG-neighbor (provided NES leaves non-empty list of neighbors in need of the message). We are adding here the version where timeout is applied to all nodes. We also propose here to replace RNG by a localized minimal spanning tree (LMST) (LMST is recently proposed in [13]). Independently, a LMST and neighbor elimination based localized broadcast oriented protocol have been proposed in [14]. Li and Hou [14] also showed that multi-hop retransmission is always more energy efficient than a direct transmission from current node whenever $\alpha \geqslant 2.2$ in the power consumption model where the energy for transmitting a message over a link of length r is proportional to $r^\alpha + c$. However, when constant c is significantly large, the conclusion is questionable, as shown in our subsequent upcoming work [31].

The paper is organized as follows. In the next section, we present communication and energy models. In Section 3, we give a literature review of minimum energy broadcast protocols. In Section 4, we describe how this problem can be solved with localized algorithms. Section 5 presents the results of our simulations where we demonstrate the efficiency and superiority of our algorithms. Finally, Section 6 presents conclusion and future directions.

2. Preliminaries

2.1. Communication model

We consider multi-hop wireless networks where all nodes cooperate in order to fulfill a given communication task. Such a network can be modeled as follows. A wireless network is represented by a graph $G = (V, E)$ where V is the set of nodes and $E \subseteq V^2$ the edge set which gives the available communications: (u, v) belongs to E means that u can send messages to v. In fact, elements of E depend of node positions and communicating range of nodes. Let us assume that maximum range of communication, denoted by R, is the same for all vertices and that $d(u, v)$ is the distance between nodes u and v.

For instance, the set E can be defined as follows:

$$E = \{(u, v) \in V^2 | u \neq v \wedge d(u, v) \leqslant R\}.$$

So defined graph is known as the *unit graph*, with R as its transmission radius.

In given graph $G = (V, E)$, we denote by $n = |V|$ the number of nodes in ad hoc network. The neighbor set $N(u)$ of vertex u is defined as $N(u) = \{v | (u, v) \in E\}$. The average degree of the network is the average number of neighbors of its nodes.

We will assume that each node can change the power of its transmissions for energy savings reasons (see next section). In this case, the range of a node $u \in V$ represents the maximal distance between u and a node which can receive its transmission. The range of a node $u \in V$ is denoted by $r(u)$ (with $0 \leqslant r(u) \leqslant R$). The graph induced by the range assignment function r is denoted by $G_r = (V, E_r)$ where the edge set E_r is defined by

$$E_r = \{(u, v) \in V^2 | u \neq v \wedge d(u, v) \leqslant r(u)\}.$$

It is straightforward to see that the graph G_r with modified ranges is not always undirectional.

A (directed) graph is strongly connected if for any two vertices u and v, a path connecting u to v exists. In the broadcasting task, a message needs to reach all nodes in the network by transmitting from the source and retransmitting by other network nodes with variable transmission radii. Hence, in case of broadcast, the strong connectivity is not needed, we only need connectivity from source node to all the other nodes in the network.

2.2. Energy model

Commonly, the measurement of the energy consumption of network interfaces when transmitting a unit message depends on the range of the emitter u:

$$E(u) = r(u)^{\alpha},$$

where α is a real constant greater than 2 and $r(u)$ is the range of the transmitting node. This model is used in [2,8–10,20–23]. In reality, however, it has a constant to be added in order to take into account the overhead due to signal processing, minimum energy needed for successful reception and MAC control messages [24]. The general energy consumption formula is

$$E(u) = \begin{cases} r(u)^{\alpha} + c, & \text{if } r(u) \neq 0, \\ 0, & \text{otherwise.} \end{cases}$$

For instance, Rodoplu and Meng [25] consider the model with $E(u) = r(u)^4 + 10^8$. This last model, also used in [26], is more realistic as illustrated is Fig. 1, with parameters $\alpha = 2$ and $c = 0$, it is clear that the transmissions illustrated in (b) cost the same energy as the one in (a) by using Pythagoras theorem. By induction, all illustrated configurations are supposed to have the same energy consumption and can be arbitrary extended. For medium access, signal processing and reception power reason, it is not in accordance with real world.

Another example are nodes placed on a line segment. Assuming $c = 0$ and $\alpha \geqslant 2$, it follows that energy savings are obtained when arbitrary number of nodes are placed between source S and destination D, and these nodes are used to retransmit the message. This will certainly contradict basic signal processing requirement for minimal reception power, and cause significant amount of collisions in medium access layer if used by many simultaneous routing, multicasting and broadcasting tasks.

2.3. Minimum energy broadcasting

A transmission range assignment on the vertices in V is a function r from V into an real interval $[0, R]$ where R is the maximal range of nodes. In some wireless networks, the transmission range at each node has finite number of possible values meaning that r is a function into a finite subset of $\mathbb{R}$. In accordance to reviewed literature, each node can adjust its own power level, i.e. that can adjust its transmission range. Each node has to reduce its transmission range while maintaining the connectivity of the graph. The measurement of total power consumption is given by the following formula:

$$E = \sum_{u \in V} E(u).$$

3. Literature review

3.1. Globalized solutions to the minimum energy broadcasting

We start with *topology control protocols* that aim to adjust transmission power while preserving

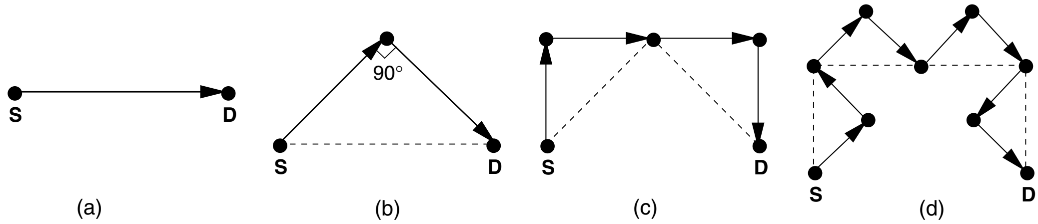

Fig. 1. Configuration with same energy consumption for $\alpha = 2$ and $c = 0$.

strong connectivity of the network. In [6], Kirousis et al. address the tree construction in wireless networks by using globalized protocols. The authors showed that this problem is NP-hard for three dimensional space and gave an approximation algorithm for constructing a spanning tree that minimizes the total power consumption. Clementi et al. showed that the minimum energy range assignment problem is still NP-hard in the two-dimensional case.

Wieselthier et al. define in [9] a topology control algorithm based on minimum-power spanning tree (MST in short). Let V be a set of nodes and $G = (V, E)$ the induced graph with maximal range R. We assume that the graph G is strongly connected. The weights of edges are given by the selected energy model (but in fact, the MST does not depend on particular choice of the metric because of monotonicity). The construction of the MST is possible if we can determine distances between nodes. For instance, Fig. 2 shows a graph of 100 vertices and its MST.

It is well-known that the graph $MST(G) = (V, E_{mst})$ of the MST is symmetric (undirected). It is easy to see that every node of V can be a root of a spanning tree by using $MST(G)$. It also well-known that $MST(G)$ is always strongly connected for a strongly connected graph G. Hence, in [9] the authors define the range adjustment as follows:

$$\forall u \in V \quad r(u) = \max\{d(u,v) | v \in V \wedge (u,v) \in E_{mst}\}.$$

That means that each node chooses to reduce its range by just covering its neighbors in MST. We denote by $MST^*(G) = G_r$ the graph with modified ranges by using MST edges. It is clear that $MST(G)$ is included in $MST^*(G)$ ($E_{mst} \subseteq E_r$) and that $MST^*(G)$ is strongly connected. This protocol is called MTCP (MST Topology Control Protocol) in the remaining of this paper. It applies Prim's algorithm to construct a minimum spanning tree.

Wieselthier et al. have proposed in [9] two other globalized greedy heuristics for the minimum-energy broadcast problem. They are called BLU and BIP, and belong to the family of *broadcast oriented protocols*.

The BLU heuristic (Broadcast Least-Unicast-cost) applies the Dijkstra's algorithm. It merges low-energy unicasts from the source node to all other nodes in a single tree that is used instead of MST. In this case, power efficient routing protocols [25,26] can be used to generate the basic structure. The Broadcast Incremental Power (BIP) is a modified version of the Prim's algorithm's where we consider additional cost in order to cover new nodes. The next node v in BIP is selected to minimize the additional power (either by increasing transmission power at one already transmitting node or by changing $r(u) = 0$ to $r(u) = d(u,v)$ at one of MST neighbors). Although the authors [9] use an energy model with constant $c = 0$, BIP fits well with the general model with arbitrary constant.

The authors [9] also proposed the "sweep" operation for removing some unnecessary transmissions, which is illustrated Fig. 3. A node u whose communication area is covered by one of its neighbors (i.e. $\exists v \in N(u)$ such that $d(u,v) + r(u) \leqslant r(v)$) may choose a null range.

There are some improvements of BIP algorithm but always in globalized manner and with an energy model using constant $c = 0$ [2,22,23]. Wan

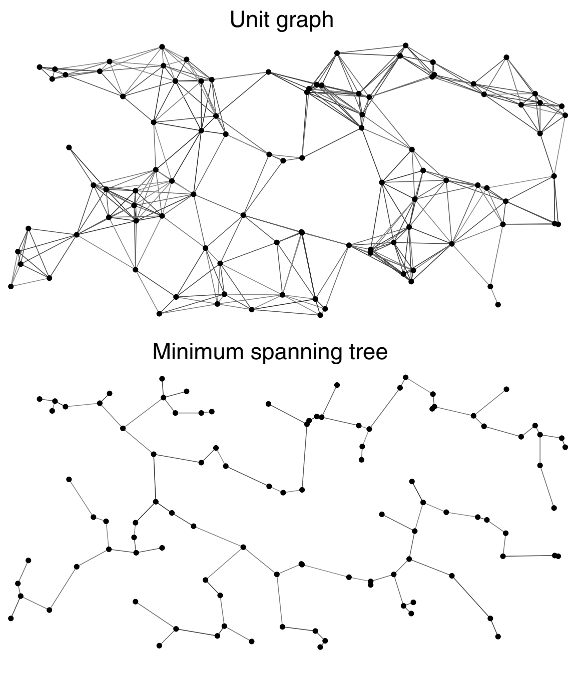

Fig. 2. A graph and its minimum spanning tree.

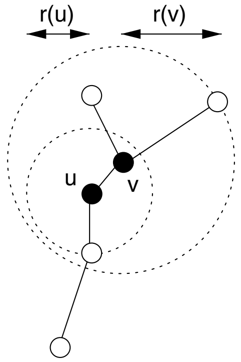

Fig. 3. Communication area of node u is covered by node v.

et al. [23] gave analytical performance of BIP and showed that the approximation ratio of MST is bounded by 12. Liang [11] showed that BIP algorithm can have $\Omega(n)$ performance ratio with respect to the optimum algorithm in the worst case. They propose a sophisticated globalized solution with better performance ratio, but did not evaluate its average case performance. Mark et al. [22] proposed a generic search based globalized protocol for constructing the minimum power tree and claimed about 10% improvement over BIP.

Other works lead to approximation algorithm for the problem of minimizing the total power with a constant performance guarantee. For instance Lloyd et al. [8] propose a globalized algorithm which builds a 2-node-connected graph and assume an arbitrary energy model.

Lindsey and Raghavendra [21] proposed an algorithm which is not based on tree construction but still achieves the broadcast with less than 25% more energy consumption than the optimal solution. Their broadcasting protocol is the following. The source node simply sends a message to a central node (that is closest to all other nodes) by using power efficient routing protocol and the central node transmits the message to all other nodes with a single message. It is obvious that this protocol is not localized for designation of the central node. Moreover, this scheme has good results only for an energy consumption using $\alpha = 2$ (the authors use an energy model with $c = 0$) and is not efficient for higher exponents.

3.2. Relative neighborhood graph (RNG)

In our localized approach, we use the relative neighborhood graph (RNG) [15] (and LMST to be described in the next subsection). RNG was already applied for solving problems in wireless networks. For instance, [27] applied it to minimize the number of messages needed for broadcasting in one-to-one unit graph model. Borbash and Jennings [28] described the localized construction of RNG in details and proposed to use it as connected topology to minimize node degrees, hop-diameter, maximum transmission radius and the number of biconnected components. However, [28] do not describe the use of RNG in solving any specific problem.

Let V be a set of vertices and $G = (V, E)$ the induced graph with maximal range. The relative neighborhood graph of G [15] is denoted by $RNG(G) = (V, E_{rng})$ and if defined by

$$E_{rng} = \{(u,v) \in G \mid \nexists w \in V \quad (u,w),(w,v) \in V \\ \wedge\, d(u,w) < d(u,v) \wedge d(v,w) < d(u,v)\}.$$

This condition is illustrated in Fig. 4, an edge (u, v) belongs to the RNG if there does not exist a node w is the gray area. The gray area is the intersection of two circles centered at u and v and with radii $d(u, v)$. We can see in Fig. 5 the RNG of graph given in Fig. 2. In this example, and typically in general, the average degree of RNG is around 2.5 (against 2 for MST).

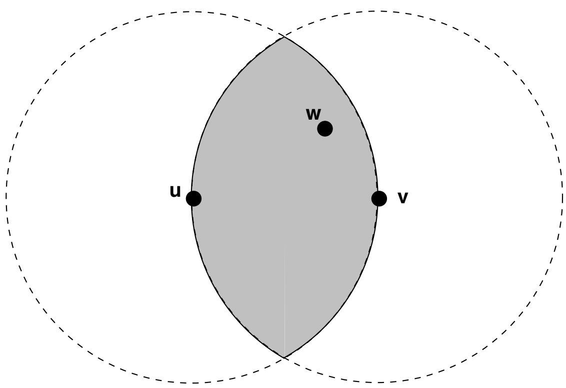

Fig. 4. The edge (u, v) is not in RNG because of w.

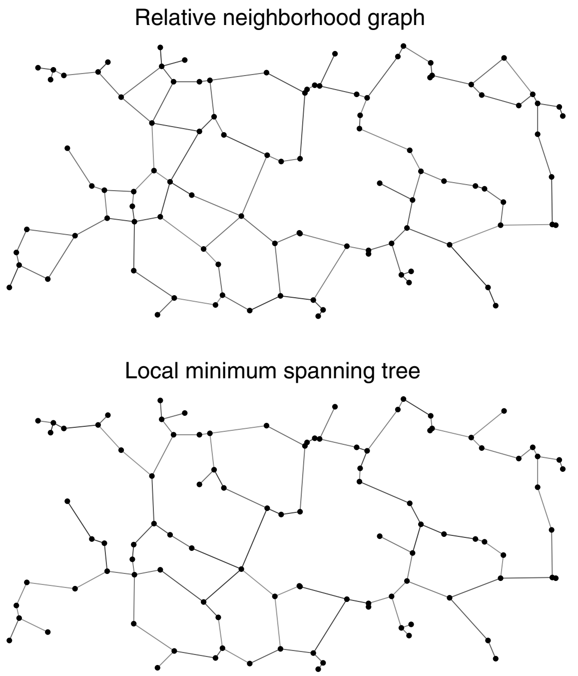

Fig. 5. RNG and LMST for graph in Fig. 2.

The RNG can be deduced locally by each node by using only the distance with its neighbors. With positing system (like GPS), nodes need to send periodically an *HELLO* message with their coordinates. In this way, each node maintains a neighborhood list with neighbor locations that allows to determine whether or not an edge is in RNG. In this case, we need only 1-hop information.

We can observe that if nodes do not have positioning system, they can decide RNG edges if they are able to determine mutual distances (for instance by using signal strength or time delay information). Every node sends in its *HELLO* message the list of its neighbors with distances. Hence, RNG construction does not require more information or different *HELLO* message than the one required to construct MST. More information about RNG construction can be found in [27,28]. The information required to make decision is 2-hop distance information. In both cases, with GPS or with distance measurements, the algorithm for RNG edges determination is localized.

3.3. Local minimal spanning tree (LMST)

Local minimal spanning tree (LMST) has been recently proposed by Li, Hou and Sha [13]. In order to compute LMST, each node computes the MST of its own neighborhood, i.e. $MST(N(u))$. An edge between two nodes u, $v \in V$ belongs to the LMST if and only if u is a neighbor of v in $MST(N(v))$ graph and v is a neighbor of u in $MST(N(u))$. We denote by $LMST(G) = (V, E_{lmst})$ the LMST subgraph of a given graph $G = (V, E)$. It is shown that the LMST transformation preserves the connectivity if the minimum spanning tree derived is unique—the minimum spanning tree may not be unique if there exist multiple edges with the same length. To ensure the uniqueness of MST, Li et al. proposed to consider edge length as the primary key in comparison, and IDs of its two enpoints (in sorted order) as the secondary and ternary keys if needed, as tie breaker [13]. Fig. 5 illustrates LMST for the graph given in Fig. 2.

4. Localized protocols

4.1. RNG and LMST topology control protocols (RTCP and LTCP)

The main disadvantage of existing protocols is that algorithms are not localized. Our proposal is to substitute MST by graphs that can be computed locally: the relative neighborhood graph (RNG) [15] or the local minimum spanning tree (LMST) [13]. More precisely, any connected subgraph of G can be applied, and sparse and locally defined once are preferred.

In the topology control oriented protocols, the range adjustment can be defined in order that each node can reach all its neighbors in the selected connected subgraph. We propose to use $RNG(G)$ and $LMST(G)$, and will refer to these protocols as RTCP (RNG based Topology Control Protocol) and LTCP (LMST based Topology Control Protocol). For instance, in case of $RNG(G)$, the range adjustment is defined as follows:

$$\forall u \in V \quad r(u) = \max\{d(u, v) | v \in V \wedge (u, v) \in E_{rng}\}.$$

The induced graph G_r is denoted by $RNG^*(G)$. It is well-known that $MST(G)$ is included in $RNG(G)$ [1] and it is easy to see that $RNG(G)$ is a subset of $RNG^*(G)$. For a strongly connected graph G, the connectivity of $RNG^*(G)$ is then guaranteed.

A topology control algorithm can be also derived from LMST. The range adjustment can be defined in order that each node can reach all its neighbors in $LMST(G)$ as follows:

$$\forall u \in V \quad r(u) = \max\{d(u,v) | v \in V \wedge (u,v) \in E_{lmst}\}.$$

The induced graph G_r is denoted by $LMST^*(G)$ and contains $LMST(G)$ which is connected if G is connected. We will refer to this protocol as LTCP (LMST Topology Control Protocol).

The connectivity of RNG and LMST assures that all nodes receive the message for any choice of the source node. Experimentally, the average degree of a LMST node is approximately 2.04, which is closer to the MST degree (1.99) than RNG (2.6). We will prove now that the difference is not only statistical, but that indeed LMST is always sparser than RNG.

Theorem 4.1. *$LMST(G)$ is a subgraph of $RNG(G)$.*

Proof. It suffices to show that if an edge (u,v) belongs to E_{lmst}, then this edge belongs to E_{rng}. By contradiction, let us suppose that there exists an edge (u,v) such that $(u,v) \in E_{lmst}$ and $(u,v) \notin E_{rng}$. The edge (u,v) belongs to $MST(N(u))$ and to $MST(N(v))$, and since (u,v) does not belong to RNG, it means that there exist a node $w \in N(u) \cap N(v)$ such that (u,v) is the 'longest' edge in the triangle uvw. One of edges (u,w) or (v,w) is not in E_{lmst}, since E_{lmst} is a tree. Suppose that (u,w) is not in E_{lmst}. Then (u,v) can be replaced by (u,w) in $MST(N(u))$, giving a spanning tree with lower overall weight (total sum of all edge lengths) than the minimal one ($MST(N(u))$), which is a contradiction. Note that in the proof it is assumed that no two edges can have the same length. This is achieved by a tie breaker which adds node IDs as the secondary and ternary keys to the edge lengths in comparisons. Therefore LMST is subgraph of RNG. □

Hence, the LMST subgraph offers a better graph reduction than RNG, with a degree of approximately 2.04. The LMST algorithm is localized and offers a lower subgraph degree (in fact, LMST is a subgraph of RNG). Experimentally, the degree is approximately 2.04, which is closer to the BIP degree (1.99) than RNG (2.6).

4.2. RNG and LMST broadcast oriented protocols (RBOP and LBOP)

A topology control protocol aims to reduce transmission range while maintaining connectivity. For broadcasting, this kind of protocol provides efficient energy savings even by using blind flooding, but we can enhance the energy savings further. The idea is that when receiving a message from given neighbor it is not needed to reach this node, or nodes already covered by this node, by our retransmission. We propose here three broadcast algorithms: RBOP (originally proposed in the conference version of this article [12]), RBOP-T where timeout is applied on all nodes, and LBOP-T which is RBOP-T scheme with RNG being replaced by LMST.

4.2.1. RBOP protocol

Let us consider the graph illustrated in Fig. 6 where non-RNG edges have been omitted. If the node S wants to send a broadcast message, it transmits it with the minimal range which allows to join its RNG-neighbors (namely A, B and C). Then S emits its message with the range $d(S,A)$ and A, B and C receive the message. Hence S forwards the message with the range $d(A,S)$ (since A is its furthest RNG-neighbor). It is quite obvious that A could adjust its range to $d(A,G)$ since S already has the message. In similar way, B does not have to retransmit the message since all its RNG-neighbors (S) have already received the message. This scheme is similar to *neighbor elimination scheme* (NES) [3,29] but only applied to neighbors in RNG graph.

Let us continue the broadcast. Node C also receives the message from S. According to the preceeding remark, C resends the message with range $d(C,D)$. It is received by nodes D, E but also F even if it is not a RNG-neighbor. Hence F re-

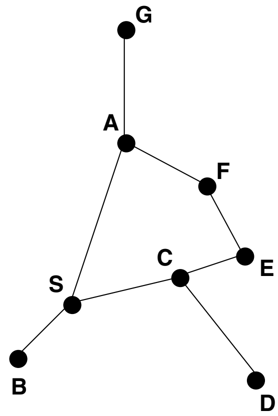

Fig. 6. Example of RNG graph for broadcast.

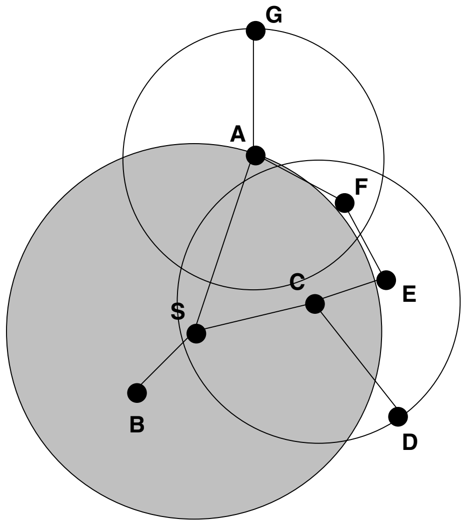

Fig. 7. Broadcast from S with neighbor elimination.

ceives the broadcast from a non-RNG edge. In this case, it is better that F applies neighbor elimination but does not retransmit the message immediately. The reason is that normally another message from one of its RNG neighbors can be expected, and the neighbor elimination scheme eliminates more nodes in the process. On the other hand, nodes (like F) receiving message from non-RNG neighbors cannot wait for the same message from an RNG neighbor indefinitely, since such a message may not arrive at all. All RNG neighbors of F may have their neighbor list eliminated in full, but the neighbor list of F may still be nonempty. In our example, F eliminates E for this broadcast message. The set of remaining neighbors for F contains only A. At the same time E decides not to send the message since all its RNG-neighbors are eliminated with message from C. It is the same case for D. When A forwards the message, F and G eliminate A from their respective neighborhood list and terminate the protocol for this broadcast since their lists became empty. The broadcast is accomplished by three transmissions: from S with radius $d(S,A)$, from C with radius $d(C,D)$ and A with radius $d(A,G)$ (see Fig. 7).

The localized RBOP protocol can be described more formally as follows:

1. The source node u of a broadcast emits its message with determined range $r(u)$ from RTCP.
2. When receiving a new broadcast message:
   a. if the emitter is a RNG-neighbor. The node calculates the furthest of its RNG-neighbors that did not receive this message. The node resends the message according to this range or ignores the message if all its RNG-neighbors have received the message.
   b. Otherwise, the node generates, for this broadcast, the list of RNG-neighbors that have not received this message. After a given timeout, if the neighbor list is not empty (neighbors can be removed by action 3b), the node retransmits the message with a range allowing to reach the furthest neighbor left in the associated list.
3. When receiving an already received message:
   a. the node ignores the message if it has already forwarded it;
   b. the node removes nodes that received this message from the associated neighborhood list;
   c. the message is ignored (no retransmission occurs) if the associated list becomes empty;
   d. otherwise, if the message arrives on a RNG-edge, send the message with range allowing to reach furthest neighbor in the list of non-eliminated RNG neighbors.

4.2.2. RBOP-T and LBOP-T with full neighbor elimination scheme

For an energy consumption model $r^\alpha + c$ where c is not null, it is not always better for a node which receives the message from a RNG neighbor to retransmit immediately. That is why we propose to consider two new protocols based on RNG or LMST graph:

1. the source node u of a broadcast emits its message with determined range $r(u)$ from RTCP (or LTCP);
2. when receiving a new broadcast message, the node generates, for this broadcast, the list of RNG-neighbors (or LMST-neighbors) that have not received this message. After a given timeout, if the neighbor list is not empty, the node retransmits the message with a range allowing to reach furthest neighbor in the associated list;
3. when receiving an already received message:
   a. the node ignores the message if it has already forwarded it or if the associated neighborhood list is empty,
   b. the node removes nodes that are reached by the message from the associated neighborhood list.

This protocol based on RNG is designated by RBOP-T (RNG Broadcast Oriented Protocol with full Timeout) and the one based on LMST in called LBOP-T. The difference between RBOP and RBOP-T is that all nodes in RBOP-T apply timeout before possible retransmission, while in RBOP only nodes receiving message from non-RNG edge do so.

In next section, we give simulation results for presented protocols, RBOP, RBOP-T and LBOP-T, and other protocols described in this and previous sections.

5. Performance evaluation

In our simulations, we compare seven protocols. Two of these protocols are globalized: MST Topology Control Protocol (MTCP) and the Broadcast Incremental Power (BIP) from [9] (enhanced with the sweep operation). The other protocols are the localized algorithms we propose: RNG and LMST Topology Control Protocol (RTCP and LTCP), RNG Broadcast Oriented Protocol (RBOP) and the two variants with full neighbor elimination and LMST based RBOP-T and LBOP-T. In order to permit comparison with works in the literature, we use two different energy models: $\alpha = 2$, $c = 0$ and $\alpha = 4$, $c = 10^8$.

The parameters of our simulations are the following. The number of nodes n is always 100 and nodes are static. The maximum communication radius R is fixed to 250 m. The MAC layer is assumed to be ideal. Nodes are randomly placed in a square area whose size is computed to obtain a given density (from 6 neighbors per node to 30). The timeout used in neighbor elimination scheme in RBOP is fixed to three times the duration of a message sending. Only connected sets are retained. For each measure, 5000 broadcasts have been run.

Because of ideal MAC layer and nature of protocols, all nodes receive broadcasted messages. Hence, the *reachability*, that measure the coverage of network, is always 100%. The observed parameter is the energy consumption (according to both energy models). For each broadcast, we calculate the total energy consumption:

$$E_{total} = \sum_{u \in V} E(u),$$

where $E(u)$ depends of the transmission radius as explained in Section 2. This total energy consumption E is compared with total energy consumption needed for blind flooding protocol with maximal range:

$$E_{flooding} = n \times (R^\alpha + c).$$

For the four considered protocols, we computed the average *expended energy ratio* (EER) that is defined by

$$EER = \frac{E_{total}}{E_{flooding}} \times 100.$$

In Fig. 8 and Table 1, we show the comparison of saved energy for $\alpha = 2$ and $c = 0$. The average degree of the network varies with density but is not exactly the same because of border effect. Indeed, nodes that are placed on border of the

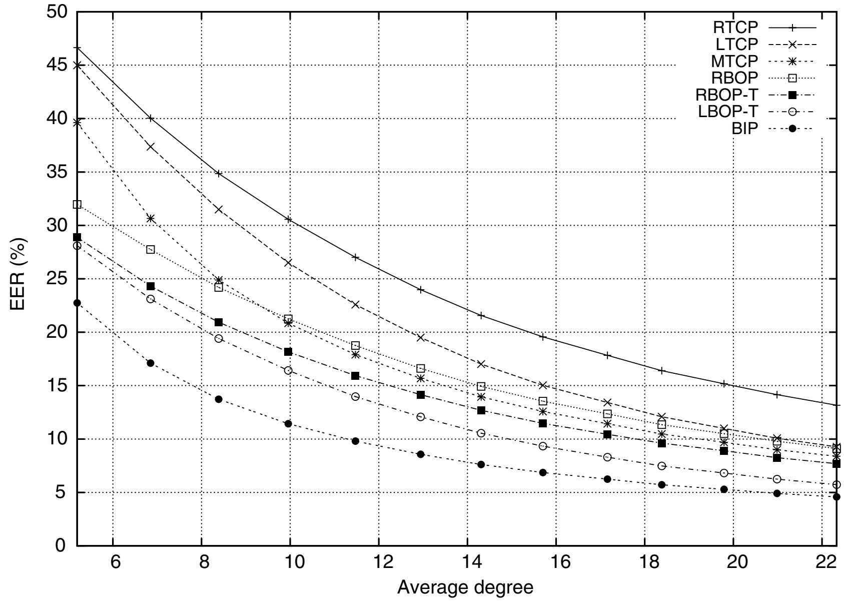

Fig. 8. Expended energy ratio comparison with $\alpha = 2$ and $c = 0$.

Table 1
Expended energy ratio for $\alpha = 2$ and $c = 0$

Density	Average degree	EER						
		RTCP	LTCP	MTCP	RBOP	RBOP-T	LBOP-T	BIP
6	5.19	46.64	44.99	39.62	31.96	28.87	28.10	22.74
8	6.84	40.04	37.37	30.64	27.74	24.31	23.11	17.10
10	8.38	34.85	31.49	24.88	24.18	20.93	19.41	13.72
12	9.95	30.57	26.50	20.84	21.25	18.16	16.42	11.43
14	11.47	27.01	22.58	17.89	18.76	15.94	13.97	9.80
16	12.94	23.98	19.50	15.67	16.61	14.15	12.07	8.56
18	14.30	21.55	17.01	13.94	14.92	12.69	10.55	7.61
20	15.70	19.56	15.03	12.57	13.54	11.47	9.33	6.85
22	17.15	17.83	13.42	11.43	12.35	10.45	8.30	6.24
24	18.38	16.39	12.09	10.46	11.34	9.61	7.48	5.71
26	19.78	15.17	11.00	9.69	10.50	8.91	6.82	5.28
28	20.98	14.15	10.07	9.00	9.79	8.26	6.24	4.91
30	22.32	13.16	9.27	8.39	9.10	7.69	5.73	4.57

area have less neighbors than others. This results in a real degree that is different from the theoretical one. In Fig. 9, we used normalized energy consumption: the results are normalized as function of the lowest energy consumption, made equal to 100. Since the best algorithm is always the globalized protocol BIP, this figure represents the energy overhead of the six other protocols compared with BIP.

Figs. 10 and 11 and Table 2 give same experimentations results for the energy model $\alpha = 4$ and $c = 10^8$.

Our experimental data illustrate that localized algorithms can be very competitive with globalized ones. But it is not surprising to see that the best algorithm is globalized: it can make better choice with full knowledge of the network than with a local view of the network. For instance, in both

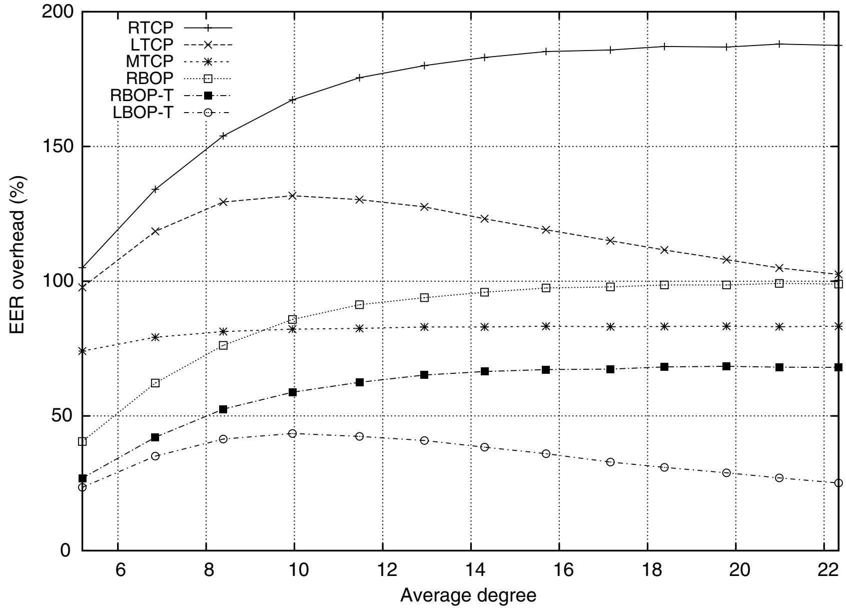

Fig. 9. EER overhead compared to BIP with $\alpha = 2$ and $c = 0$.

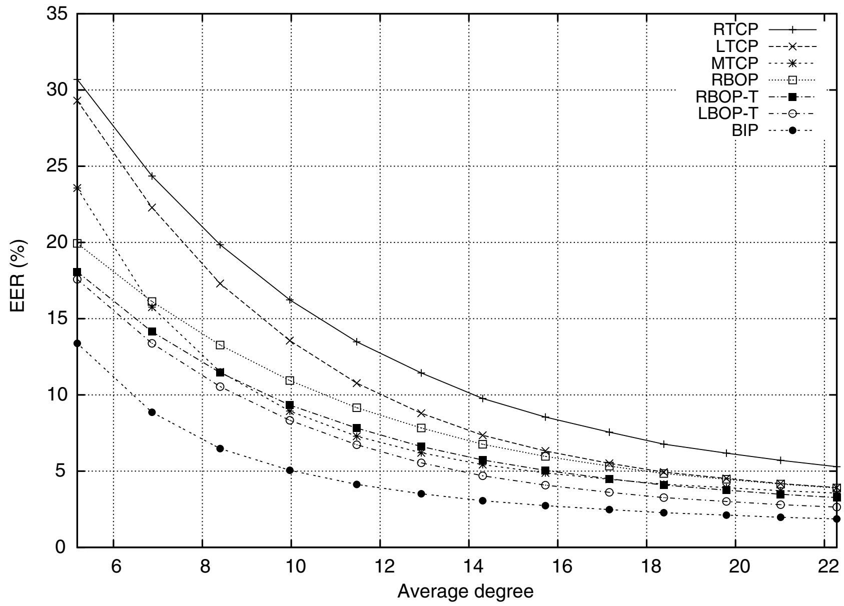

Fig. 10. Expended energy ratio comparison with $\alpha = 4$ and $c = 10^8$.

energy models, BIP spends 50% less energy than RBOP in average case. This overhead during broadcasting task for our localized RBOP protocol compensates the network load which is needed to achieve full knowledge of network in globalized solutions. It can be also observed that expended

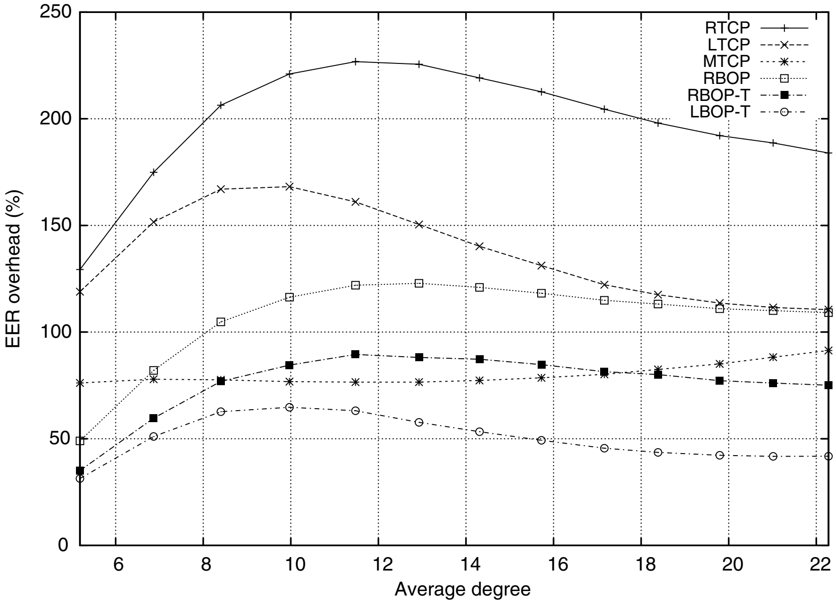

Fig. 11. EER overhead compared to BIP with $\alpha = 4$ and $c = 10^8$.

Table 2
Expended energy ratio for $\alpha = 4$ and $c = 10^8$

Density	Average degree	EER						
		RTCP	LTCP	MTCP	RBOP	RBOP-T	LBOP-T	BIP
6	5.19	30.69	29.30	23.57	19.94	18.07	17.58	13.38
8	6.87	24.35	22.29	15.76	16.13	14.14	13.38	8.86
10	8.40	19.85	17.30	11.51	13.27	11.46	10.54	6.48
12	9.97	16.23	13.56	8.94	10.94	9.33	8.33	5.06
14	11.48	13.49	10.77	7.28	9.16	7.82	6.73	4.13
16	12.93	11.44	8.80	6.20	7.83	6.61	5.54	3.51
18	14.31	9.77	7.35	5.43	6.76	5.73	4.69	3.06
20	15.72	8.55	6.32	4.88	5.97	5.05	4.08	2.73
22	17.16	7.55	5.51	4.47	5.33	4.50	3.61	2.48
24	18.39	6.77	4.94	4.15	4.84	4.09	3.26	2.27
26	19.80	6.18	4.52	3.92	4.46	3.75	3.01	2.12
28	21.02	5.70	4.18	3.72	4.15	3.48	2.80	1.98
30	22.28	5.29	3.92	3.56	3.89	3.26	2.64	1.86

energy ratios (EER) for both protocols decrease with increased density, or increased values for α and c. It can be observed that BIP protocol has roughly the same performance in both energy models. On the other hand, EER of RBOP decreased with increased α and c.

The use of full neighbor elimination scheme in RBOP-T allows spending up to 15% less energy compared to RBOP. The substitution of RNG by LMST in LMST-T leads to an improvement of 20% that corresponds to the average degree reduction (from 2.6 for RNG to 2.04 for LMST). The best localized algorithm is LBOP-T. Its overhead compared to globalized BIP is less than 45% with $\alpha = 2$, $c = 0$ and less than 65% with $\alpha = 4$, $c = 10^8$.

6. Conclusion

In this paper, we presented a localized RNG based minimum energy broadcast RBOP protocol and two of its improvements, one that applied full neighbor elimination scheme (RBOP-T), and other that replaces RNG in RBOP-T by sparser local graph LMST (LBOP-T). These protocols are competitive with globalized BIP protocol [9] or minimum spanning tree based protocol. Our best protocol, LBOP-T, has energy consumption about 50% higher that BIP protocol in all our experimental measurements. This is a great compensation for communication overhead that is ignored in BIP, which is the energy needed for maintaining global network information at each node when nodes move or when nodes change their activity status between active and sleep periods.

LBOP-T approached the performance of BIP by increasing latency, which is the price when applying timeout in neighbor elimination scheme (the timeout applied here is three times the message length). It is an open problem to optimize latency while keeping close performance of localized protocol.

One can observe that our protocols do not depend on constants α and c (only the measured energy consumption does). This is because RNG and LMST are not affected by these constants, because of monotonicity of the metric. The structures are equal under both x and $x^\alpha + c$ metrics since $x^\alpha + c < y^\alpha + c$ if and only if $x < y$. Similar observation is valid for MST based globalized protocol. Hence BIP protocol will adapt according to parameter modifications while our localized protocols ignore them and will spend more energy than really necessary for higher values of α and c. We have addressed this problem in our upcoming article [31]. The improvement in [31] is obtained by observing that the nature of broadcasting task differs from the nature of routing task. While MST structure closely resembles energy requirements of a routing task, it does not necessarily capture the structural properties in case of broadcasting. Increased transmission radius beyond the value of furthest uncovered neighbor in any MST like or RNG structure does not necessarily increase the overall energy consumption. The value $r(u)$ in RBOP, RBOP-T or LBOP-T is actually the minimum possible transmission radius which is required to maintain connectivity of the broadcast process. It is quite possible that a small increase beyond longest RNG or LMST edge will reach several new neighboring nodes, and therefore the energy needed per one reached node may actually decrease (in one-to-all communication model).

We have also addressed the problem of the one-to-one communication model with directional antennas in a recent work [32]. We propose [32] an adaptive protocol that combines two different algorithms which are efficient for sparse or dense networks, respectively. The two protocols that are combined use narrow and wide beam antennas, respectively, and adjust their transmission radii to either furthest uncovered LMST neighbor or a target radius, whose ideal value is theoretically derived.

Networks where nodes can only choose between active (range set to maximum) or inactive state (range set to zero) are special cases which have been addressed by several works. Dominating sets protocols [5,29] can be seen as a solution for the minimum assignment problem for this case. MPR (Multipoint relaying) broadcast [4] and stochastic flooding [30] can be seen as energy-efficient broadcast protocols for active-inactive power assignment networks. Some ideas of these protocols, or some combinations between RBOP and these protocols may allow to improve our present results further.

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