

Localized energy efficient broadcast for wireless networks with directional antennas

Julien Cartigny, David Simplot, and Ivan Stojmenović

Abstract—Directional antennas reduce the beamwidth angle to diffuse the radio transmission to one direction and thus use less energy than omnidirectional antennas. Combined with the idea of reducing the transmission power, these devices can be used for the minimal energy broadcasting problem. The problem is to minimize the total energy consumption but still enable a message originated from a source node to reach all other nodes in an ad-hoc wireless network. We assume that directional antennas are able to emit with a small angle beamwidth. Existing solutions are globalized, that is based on the assumption that each node knows the global network information (including distances between any two neighboring nodes in the network and the geographic position of itself and each neighbor). In this paper, we describe a localized algorithm where each node needs to know only geographic position of itself and its neighbors. This solution is based on the use of relative neighborhood graphs (RNG) which preserves connectivity. Each node that receives a message for the first time from one of its RNG neighbors will rebroadcast it to each of its remaining RNG neighbors separately. Directional antennas are used for these rebroadcasts, and the transmission power is adjusted for each transmission to the minimal necessary for reaching the particular neighbor. Therefore, the protocol decomposes each retransmission to few one-to-one unidirectional messages. Since the average degree of RNG is about 2.5, approximately 1.5 rebroadcasts are done by each node to its neighbors. We also introduce a new energy consumption model for directional antennas, that generalizes models commonly used. It captures various costs involved in the medium access layer. We compare our localized protocol with the globalized BIP based protocols adapted for directional antennas. The total energy consumption of RNG based protocol with directional antennas is roughly about 50% more than BIP based solutions. This is expected because in the minimal spanning tree type of structure, each node has about 2 neighbors. However, this comparison doesn't take into account the huge communication overhead required for topology maintenance in globalized solutions. The localized solution proposed in this paper is therefore superior for ad-hoc networks with significant node mobility or frequent changes in the node activity status (from “active” to “passive” and vice-versa).

Index Terms—Energy conservation, wireless ad-hoc networks, broadcasting, localized algorithms, directional antennas.

I. INTRODUCTION

In wireless ad-hoc networks, nodes cooperate to handle network facilities. These networks are power constrained because

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Julien Cartigny and David Simplot are at the Fundamental Computer Science Laboratory of Lille (LIFL), France (<http://www.lifl.fr>). E-mail: {cartigny,simplot}@lifl.fr.

Ivan Stojmenović is with SITE at the University of Ottawa, Ontario, K1N 6N5, Canada. E-mail: ivan@site.uottowa.ca.

nodes operate with restricted battery power. A solution to economize energy is to control the emitted transmission power. This idea can be improved by using directional antennas, which reduce the radio beamwidth to a particular angle. We consider nodes that have the capacity to modify the area of coverage with its transmission radius and its directional antennas. Indeed, control of emitted transmission power and beamwidth angle allows to reduce the energy consumption and so to increase lifetime of the network. Nodes have to manage these adjustments while maintaining the connectivity of the network to avoid topology alterations like loss of connectivity.

Several communication models exist: one-to-all mode, variable angular model and one-to-one model. In one-to-all model, mobile nodes use omnidirectional antennas. The communication zone is a disk with the sender node at the center. For variable angular range model, the nodes can target several neighbors with one transmission by choosing direction and width of the beam. The one-to-one model is a particular case of the previous one where mobiles use non-variable narrow beam. These devices aim the emission to a small angle to a single target at a time. Since the communication zone of the node is a narrow beam from this node to the targeted zone, the directional antennas provide more energy savings and interference reduction. A lot of solutions have been developed for omnidirectional model [2], [10], [11], [18] but only few research have been done about directional antennas [14], [19]. We focus in this paper on one-to-one model with directional antennas. We assume that nodes can control the power and the direction of narrow radio beam.

Most existing solutions for energy-efficient broadcast communications are globalized, meaning that nodes require knowledge of whole network topology to make decision. Therefore topology changes (mobility of nodes, or change in their activity status) must be propagated throughout the network. This approach gives high overhead for ad-hoc networks. It is better to let each node decide on its own behavior based only on the information from the neighboring (on the knowledge of its 1-hop or 2-hops neighbors). Such protocols are called localized [2], [10], [11].

It is well-known [6] that the problem of finding a broadcast tree (directed tree from a given source) with minimal power, and the problem of broadcasting a message with minimal number of retransmissions (assuming same transmission power at all nodes) are both NP-complete. That is why the heuristic algorithms are used to resolve energy efficient broadcast. For instance, Wieselthier et al. [18] proposed globalized greedy heuristics inspired from Prim's and Dijkstra's algorithms for energy-efficient broadcast. Their algorithm BIP (Broadcast-

ing Incremental Power) is the more efficient heuristic proposed. It constructs a kind of minimum spanning tree (MST) starting from the source node and adds new nodes one at a time according to a cost evaluation. They also proposed some modifications to use directional antennas [19] called Reduced Beam BIP (RB-BIP) and Directional BIP (D-BIP). But, these improvements are also globalized.

In our previous work [4], we proposed a localized protocol called RBOP (RNG Broadcast Oriented Protocol) for one-to-all communication model. Each node requires only the knowledge of its distance to all neighboring nodes and distance between its neighboring nodes (or, alternatively, geographic position of itself and its neighboring nodes). In addition to using only local information, our protocol is shown experimentally to even provide more energy saving than the best know globalized BIP solution. Our solutions are based on the use of relative neighborhood graph which preserves connectivity and is defined in localized manner.

In this paper, we are mainly interested in one-to-one communication model in wireless ad-hoc networks. We propose D-RBOP, a protocol based on RBOP and using directional antennas. This algorithm for energy-efficient broadcast is also localized. Each node requires only the knowledge of the position to all neighboring nodes. This information can be measured from the distance and direction, by using signal strength or time delay combined with direction evaluation done by smart antennas. The position of each node can be also extracted with positioning system (like GPS).

The paper is organized as follows. A presentation of communication and energy models is presented in Section II. In Section III, we give a literature review of minimum energy broadcast protocols. We describe how this problem can be solved with localized algorithms in Section IV. Section V presents the results of our simulations. Finally, Section VI presents conclusion and future directions.

II. PRELIMINARIES

A. Communication Model

A multi-hop wireless networks can be represented by a graph $G = (V, E)$, where V is the set of nodes and $E \subseteq V^2$ the set edge of the available communications. A node u can send message to a node v if an edge (u, v) belongs to E . We define R as the maximum range of communication for all vertices and $d(u, v)$ as the distance between nodes u and v . The set E is defined as follows:

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

Fig. 1 presents an example of such graph. So defined graph is known as the *unit graph*, with R as its transmission radius. We also define the neighbor set $N(u)$ of the vertex u as $N(u) = \{v | (u, v) \in E\}$. The degree of a given node u is the number of nodes in $N(u)$. We also denote by $n = |V|$ the number of nodes in ad-hoc networks.

In one-to-all communication model (omnidirectional antenna), each node in the network can only change the power of its transmissions. The range of a node $u \in V$ represents the maximal distance between u and a node which can receive its

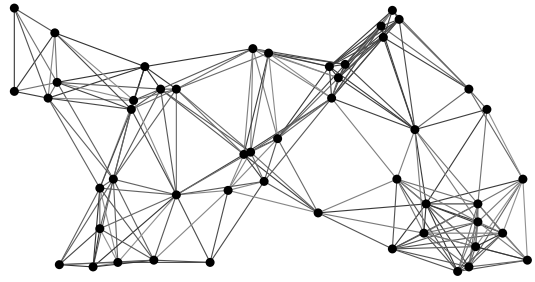


Fig. 1. A graph with average degree 10.

transmission and is denoted by $r(u)$ (with $0 \leq r(u) \leq R$). 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:

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

If, for any two vertices u and v of a graph a path connecting u and v exists, then the (directed) graph is strongly connected. 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 to all the other nodes in the network.

In one-to-one model, we will assume that all the nodes have directional antennas. They can hear messages from every neighbor. They can also send messages to every neighbor in an unicast communications, by aim the beam to the addressee.

B. Energy Model

In [4], we consider a model from [5] to describe energy consumption for omnidirectional antennas. We denote C constant added in order to take into account the overhead due to signal processing, minimum energy needed for successful reception and MAC control messages. We also denote α a real constant greater than 2 (representing the attenuation factor of the environment) and $d(u, v)$ is the range of the transmitting node u to join v . The measurement of the energy consumption to send a message from node u to node v for omnidirectional antennas is given by:

$$e(u, v) = d(u, v)^\alpha + C.$$

We adapt this model for directional antennas. Thus devices can concentrate transmission energy when is needed. We assume that all of the transmitted energy is concentrated uniformly in a beam of width θ (in degree). Hence, we propose this new model for energy consumption:

$$e(u, v) = \theta \frac{d(u, v)^\alpha + C_1}{360} + C_2.$$

The constant C_1 represents overload due to MAC control messages. The constant C_2 denotes the signal processing, minimum energy needed for successful reception and energy needed to tune the direction of the beam. In variable angle mode the beamwidth θ can be chosen from $\theta_{min} \leq \theta \leq \theta_{max}$. In one-to-one model, θ is fixed and assumed to be small. This energy

consumption model generalizes the model used by Wieselthier et al. [19]. We get their model by substituting C_1 and C_2 by zero.

In broadcasting task, we try to minimize the total energy consumption that is defined by:

$$E = \sum_{u \in V, w \in N(u)} E(u, w),$$

with:

$$E(u, w) = \begin{cases} e(u, w) & \text{if } u \text{ forwards a message to } w, \\ 0 & \text{otherwise.} \end{cases}$$

III. LITERATURE REVIEW

A. Globalized solutions

Only a few papers considered directional antennas for energy economy in ad hoc networks. Spyropoulos et al. [14] proposed a centralized algorithm for organizing the network to route the traffic from each node to every node using the minimum amount of energy. The algorithm consists of four major steps. Firstly, the shortest cost routing for each couple of nodes is computed, with the hypothesis that the nodes have omnidirectional antennas. Two different metrics (minimize energy consumed per packet and the maximize network lifetime) are used in order to relate the cost of the link and the node with energy consumption. Secondly, a link flow matrix is calculated from the previous step. It defines the average rate of traffic generated per time unit from a source node to a destination node. Third, an update of the topology is done with the fact that only one link by node can be established, in respect to the directional antennas model. Finally, a scheduling is established for each individual link in a way to minimize the total time it takes to “serve” all links. This last operation is done by using edge-coloring algorithms.

For the minimum-energy broadcast with omnidirectional antennas, Wieselthier et al. have presented in [18] two other globalized greedy heuristics. The BLU (Broadcast Least-Unicast-cost) heuristic merges low-energy unicasts from the source node to all other nodes. The BIP (Broadcast Incremental Power) is based on the Prim’s algorithm. It evaluates additional cost when covering new nodes with the goal of minimizing the additional power. Improvements and analysis of BIP algorithm in one-to-all model can be found in [3], [7], [8], [9], [17].

Wieselthier et al. [19] have proposed two extensions of BIP protocol for the case of directional antennas in variable angle communication model. Reduced Beam BIP (RB-BIP) protocol reduces the antenna beamwidth to the smallest possible value that provides coverage of the node’s downstream neighbors. In the Directional BIP (D-BIP) protocol, at each step of the tree-construction, a single node is selected from the cost computed with the expected transmitted power and beamwidth. The heuristic takes decision to increase range and/or increase bandwidth to join this node from the energy model. They offer the incorporation of resource limitations for affecting the minimal number of frequency when constructing the tree. They also propose the incorporation of energy limitations (avoiding of use nodes with lower battery) by increasing the cost associated with their use.

B. Localized solutions

We proposed in [4] to substitute minimum spanning tree (MST), used in most globalized algorithms, by the relative neighborhood graph (RNG) to construct the graph for energy-saving broadcasting. The main advantage is to have a localized algorithm. We define V a set of vertices and $G = (V, E)$ the induced graph with maximal range. The relative neighborhood graph of G is denoted by $RNG(G) = (V, E_{rng})$ and is defined by:

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

The condition is illustrated Fig. 2. The gray area is the intersection of two circles centered at u and v with radius $d(u, v)$. An edge (u, v) belongs to the RNG if there does not exist a node w in gray area. We can see in Fig. 3 the RNG of graph given Fig. 1. In this example, and typically in general, the average degree of RNG is around 2.5 (against 2 for MST).

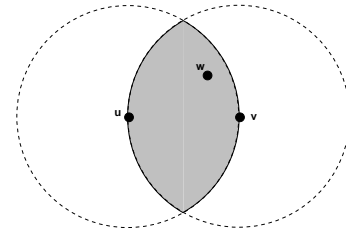


Fig. 2. The edge (u, v) is not in RNG because of w .

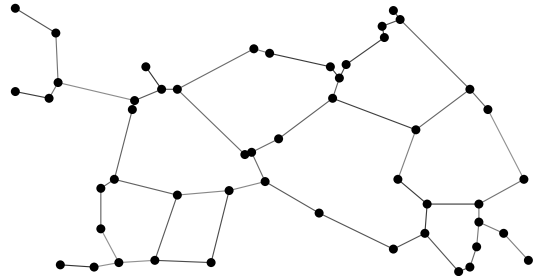


Fig. 3. Relative neighborhood graph for graph in Fig. 1.

The range adjustment can be defined in order that each node can reach all its neighbors in RNG. It is well-known [13], [16] that the RNG graph preserves connectivity.

The most interesting point is that RNG can be deduced locally by each node just by using the distance with its neighbors [1]. Each node maintains a neighborhood list that allows to determine whether or not an edge is in RNG. With a positioning system (like GPS) nodes need neighbor locations, so nodes need to send periodically an “HELLO” message with coordinates. Without positioning system, nodes can achieve RNG edges determination if they are able to determine mutual distances (by using signal strength or time delay informations). In both cases, with GPS or with distance ability, the algorithm for RNG edges determination is localized. Furthermore, the connectivity of RNG assures that all nodes receive the message for any choice of the source node.

A first improvement is to omit source node in the list of RNG edges. An second improvement use a similar approach to *neighbor elimination scheme* [10], [15]. Most nodes shall receive the message from a RNG-neighbor. Hence, if a node receives the broadcasted message from a non-RNG edge, it does not forward it immediately but simply activates a neighbor elimination scheme. This protocol, called RBOP (RNG Broadcast Oriented Protocol), is fully described and performance evaluations are given in [4]. It is shown that RBOP (that is localized) is better than the best known globalized solution BIP.

RNG was already applied for solving problems in wireless networks in [13] where the authors applied it to minimize the number of messages needed for broadcasting in one-to-one unit graph model. Borbash and Jennings [1] also 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.

IV. DIRECTIONAL RBOP (D-RBOP)

The directional antennas are now used to decompose the omnidirectional message in several unicast messages.

A node receiving a message from one of its RNG-neighbors forwards it individually to its other RNG-neighbors with a narrow beam. This is interesting because the average degree in RNG is about 2.5. It means that the node will send one or two forward messages because the node does not forward the message to its incoming node.

Let us consider the RNG graph given Fig. 4. The node S wants to broadcast a message to the whole network. It sends two separate messages to its RNG-neighbors: A and B . For this two messages, S uses two different transmission range: $d(S, A)$ and $d(S, B)$ respectively. When the node A receives the message from S , it retransmit the message to its RNG-neighbors except S since the message comes from S . Hence A sends three different messages with appropriate transmission ranges to D , C and G . At the same time, B sends the message to D and F .

According to non-determinism of the MAC layer, D can first receive the message from A or B . Let us consider that the message comes first from A , D retransmits to its RNG-neighbors except A : B . In the same time, B which has received the message from S can simultaneously attempt to send the message to D . Hence, B and D try to send each other the broadcasted message. If the MAC layer does not allow to send two messages simultaneously, the first node which gets the message will cancel its transmission. With this rule, E and F which have received the message from B do not forward the message. The node G retransmits the message to C and C sends the message to G .

The communications resulting of D-RBOP are illustrated Fig. 5.

V. PERFORMANCE EVALUATION

In our simulations, we compare three protocols: MST (Minimum Spanning Tree), D-RBOP and D-BIP. The MST protocol is globalized and consists in sending messages using edges of the MST. The protocols MST and D-RBOP use the one-to-one

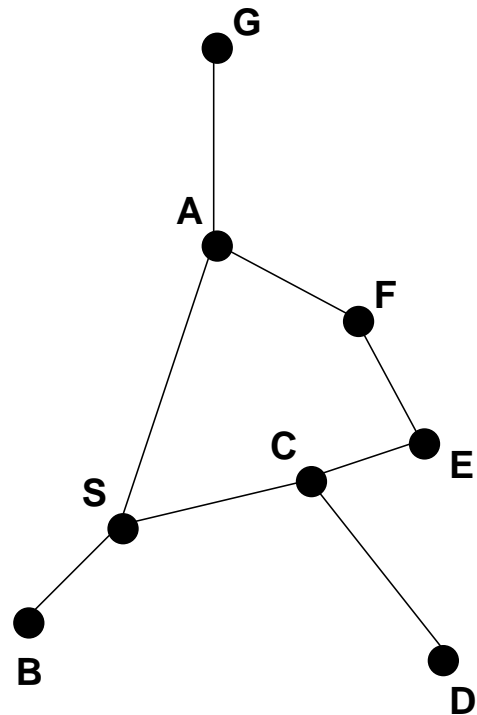


Fig. 4. RNG graph example.

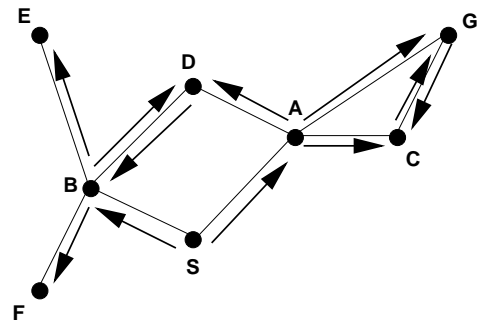


Fig. 5. Transmissions in R-BOP protocol for a broadcast from S .

communication model (one node targeted by one small beam). The globalized D-BIP algorithm [19] uses a variable angle communication model. This protocol is included in our study in order to evaluate for which beamwidth it is interesting to use one-to-one model or variable angle model. In D-BIP, we use an angle greater than the parameter θ which is the fixed beam width for D-RBOP. We use two values for θ : 5° for very narrow beam and 20° for wider beam.

In order to permit comparison with works in literature, we use two different energy models: $\alpha = 2$, $C_1 = C_2 = 0$ and $\alpha = 4$, $C_1 = 8 \cdot 10^7$ and $C_2 = 2 \cdot 10^7$. This last energy model has been chosen to be comparable with Rodoplu et al. omnidirectional energy model [12] where the energy consumption of a node u is given by $r(u)^4 + 10^8$ where $r(u)$ is the transmission range of u . Hence, we choose C_1 and C_2 constants such that $C_1 + C_2 = 10^8$. We have chosen arbitrarily to share the 10^8 constant cost with a greater constant C_1 because we believe that MAC and interference signal costs are more significant than minimal power cost included in C_2 . These values have to be investigated in order to reflect more the reality.

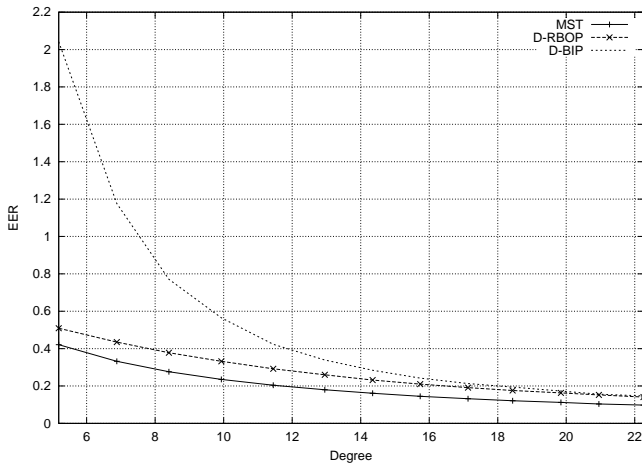
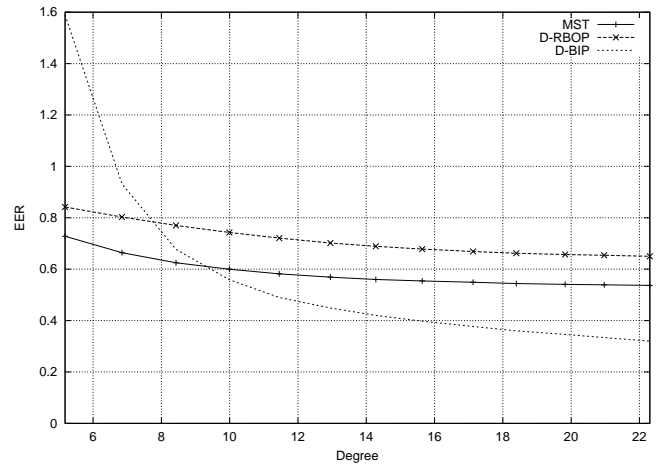
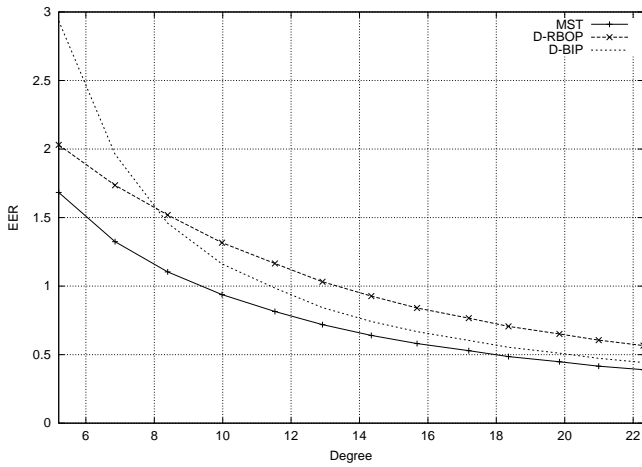
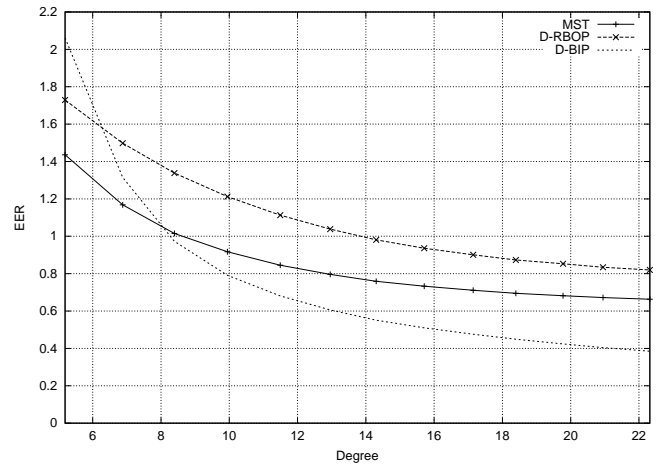

 (a) $\alpha = 2, C_1 = C_2 = 0, \theta = 5^\circ$

 (b) $\alpha = 4, C_1 = 8.10^7, C_2 = 2.10^7, \theta = 5^\circ$

 (c) $\alpha = 2, C_1 = C_2 = 0, \theta = 20^\circ$

 (d) $\alpha = 4, C_1 = 8.10^7, C_2 = 2.10^7, \theta = 20^\circ$

Fig. 6. Expanded energy ratio comparison.

We use the following parameters in our simulations. We compute 1000 broadcast for each measure. The number of nodes n is equal to 100. The nodes are static and their maximum communication radius R is fixed to 250 meters. They are randomly placed in an area whose size is computed to obtain a given density (from 6 to 30 nodes by communication nodes). We retained only connected sets. The MAC layer is assumed to be ideal. Hence, with the nature of protocols, we are sure that all nodes receive broadcasted messages because the “reachability” is always 100%.

The overhead due to mobility is exactly the overhead needed to maintain neighborhood information, which is the minimum necessary for any solution (global or decentralized). Thus we do not have additional overhead due to mobility with respect to other solutions. Therefore we did not measure it.

The observed parameter is the energy consumption (according to the two energy models). The total energy consumption is calculated for each broadcast with the following formula:

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

where $E(u, w)$ depends of the transmission radius and the

beamwidth of the directional antennas (as explained in Section II). This result is compared with total energy consumption needed for simple flooding protocol with omnidirectional antennas ($\theta = 360$):

$$E_{flooding} = n(R^\alpha + C_1 + C_2).$$

We computed the average *expanded energy ratio* (EER) for the three protocols:

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

We present the comparison of expended energy in Fig. 6 and Tables I-IV. The average degree varies with density (in nodes per communication nodes) but is not exactly the same because of border effect.

The performance of MST is better than D-RBOP because it provides the optimal solution for one-to-one model. So, it is very difficult to have better results. But MST is a globalized scheme while our solution D-RBOP is localized and does not need further communications to establish the broadcast.

As expected, it can be observed that the energy consumption of D-RBOP localized algorithm with $C_1 = C_2 = 0$ is 50%

more than the energy consumption of MST globalized algorithm (sub-figures 6.a and 6.b). This is due to the fact that, in the minimal spanning tree type of structure, each node has about 2 neighbors while in the relative neighborhood graph, the average degree is 2.5. The energy model with $\alpha = 4$, $C_1 = 8 \cdot 10^7$ and $C_2 = 2 \cdot 10^7$ (sub-figures 6.b and 6.d) gives similar results but with smaller difference between MST and D-RBOP. This results show that localized approach can give performance close to globalized protocol results.

In comparison with variable angle communication model, the one-to-one model is competitive for small beamwidth (see sub-figures 6.a and 6.c when $C_1 = C_2 = 0$). This is due to the fact that expended energy in MST and D-RBOP are both linear with the angle θ while energy in D-BIP is less penalized because the minimal angle is less used.

In MST and D-RBOP, we reach a node per message while in D-BIP we reach several nodes with the same message. That is why with an energy model with non-null constants (see sub-figures 6.b and 6.d) the one-to-one model is worse than variable angle model for dense network.

density	degree	EER		
		one-to-one		var. angle
		MST	D-RBOP	D-BIP
6	5.186	0.421	0.509	2.042
8	6.881	0.332	0.435	1.176
10	8.402	0.276	0.378	0.771
12	9.934	0.235	0.332	0.565
14	11.449	0.204	0.292	0.423
16	12.951	0.180	0.260	0.339
18	14.349	0.161	0.232	0.284
20	15.738	0.145	0.210	0.242
22	17.133	0.132	0.191	0.213
24	18.434	0.121	0.176	0.194
26	19.845	0.112	0.163	0.173
28	20.952	0.104	0.152	0.156
30	22.255	0.098	0.141	0.147

TABLE I

EXPENDED ENERGY RATIO FOR $\alpha = 2$, $C_1 = C_2 = 0$, $\theta = 5^\circ$.

VI. CONCLUSION

In this paper, we have presented a localized RNG based minimum energy broadcast protocol for directional antennas in one-to-one communication model. Based on the RBOP protocol [4], this protocol is roughly about 50% more expensive than MST (that corresponds to lower bound of BIP in one-to-one model). The reason is that in the minimal spanning tree type of structure, each node has about 2 neighbors. So a node sends one message by broadcast. The RNG tree type of structure has in average 2.5 neighbors, so each node sends one or two nodes messages by broadcast. Nevertheless, D-RBOP is the only one protocol which offers a localized approach, well adapted for ad-hoc networks with significant node mobility or with frequent changes in the node activity status (from "active" to "passive" and vice-versa).

density	degree	EER		
		one-to-one		var. angle
		MST	D-RBOP	D-BIP
6	5.180	0.728	0.842	1.589
8	6.845	0.664	0.803	0.932
10	8.428	0.625	0.770	0.677
12	9.990	0.600	0.743	0.559
14	11.452	0.582	0.721	0.490
16	12.949	0.569	0.702	0.449
18	14.282	0.560	0.689	0.420
20	15.639	0.554	0.678	0.398
22	17.128	0.549	0.669	0.377
24	18.395	0.544	0.662	0.360
26	19.824	0.541	0.657	0.346
28	20.968	0.539	0.654	0.334
30	22.305	0.537	0.650	0.320

TABLE II

EXPENDED ENERGY RATIO FOR $\alpha = 4$, $C_1 = 8 \cdot 10^7$, $C_2 = 2 \cdot 10^7$, $\theta = 5^\circ$.

density	degree	EER		
		one-to-one		var. angle
		MST	D-RBOP	D-BIP
6	5.205	1.683	2.030	2.935
8	6.851	1.324	1.736	1.962
10	8.391	1.104	1.519	1.459
12	9.978	0.938	1.317	1.162
14	11.525	0.815	1.165	0.986
16	12.918	0.719	1.032	0.843
18	14.346	0.640	0.927	0.742
20	15.681	0.581	0.840	0.668
22	17.195	0.529	0.766	0.604
24	18.355	0.486	0.706	0.554
26	19.846	0.448	0.651	0.511
28	20.993	0.416	0.606	0.473
30	22.303	0.390	0.566	0.443

TABLE III

EXPENDED ENERGY RATIO FOR $\alpha = 2$, $C_1 = C_2 = 0$, $\theta = 20^\circ$.

Moreover, it seems that this localized protocol can be extended to variable angle communication model. We will combine ideas presented in [4], presented in this paper, and some new ideas to produce improved localized protocols protocols with respect to using only narrow beam antennas. One transmission with wider antennas directed toward two or more neighbors can be more energy efficient than individual transmissions with narrow beam antennas toward each of neighbors. This model is especially attractive if the constant energy cost (C_2 which includes signal processing energy and beam orientation energy) in the energy model is significant. The extension of *RBOP* for variable angle model is now investigated by our group.

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density	degree	EER		
		one-to-one		var. angle
		MST	D-RBOP	D-BIP
6	5.191	1.436	1.729	2.061
8	6.879	1.168	1.498	1.315
10	8.393	1.015	1.338	0.973
12	9.945	0.917	1.212	0.791
14	11.493	0.845	1.113	0.681
16	12.957	0.796	1.038	0.606
18	14.303	0.759	0.981	0.551
20	15.710	0.733	0.936	0.510
22	17.143	0.711	0.901	0.476
24	18.393	0.695	0.873	0.449
26	19.776	0.682	0.853	0.424
28	20.946	0.672	0.834	0.404
30	22.318	0.663	0.820	0.385

TABLE IV

EXPENDED ENERGY RATIO FOR $\alpha = 4$, $C_1 = 8.10^7$, $C_2 = 2.10^7$,
 $\theta = 20^\circ$.

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