Improved schemes for power-efficient broadcast in ad hoc networks

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Abstract: Ad hoc wireless networks are a special type of wireless networks in which a collection of mobile hosts (nodes) with wireless network interfaces may form a temporary network without base-stations. How to design an energy efficient broadcast algorithm is very important. In this paper, we propose scalable broadcast algorithms based on reducing the number of forwarding nodes and the transmission range. Simulations show that our schemes use the least energy so far. Furthermore, the two aspects can be combined for less energy consumption and by considering the residue energy in each host, the lifetime of the network can be prolonged.

Keywords: ad hoc wireless networks; broadcast; energy consumption; forwarding nodes; multipoint relay; transmission range.

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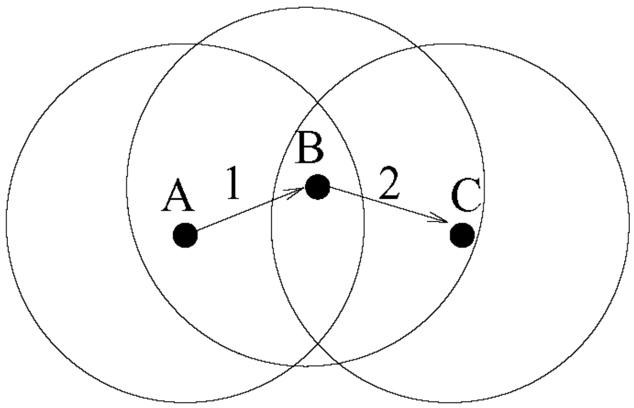
1 Introduction

Recent advances in technology have provided portable computers with wireless interfaces that allow networked communication among mobile users. The resulting computing environment, which is often referred to as *mobile computing*, no longer requires users to maintain a fixed and universally known position in the network and enables almost unrestricted mobility. An *ad hoc wireless network* is a special type of wireless network in which a collection of mobile hosts (nodes) with wireless network interfaces may form a temporary network, without the aid of any established infrastructure or centralised administration.

In ad hoc wireless networks, the sending a packet from one host to another is called *routing*. The sending of a packet from one host to all other hosts is called *broadcasting*. Owing to host mobility, broadcasting is used more frequently to find a route to a particular host, to page a host, or to alarm all the hosts. For example, soldiers equipped with multimode mobile communicators can broadcast a message to other soldiers informing them of a situation. Small vehicular devices equipped with audio sensors and cameras can be deployed at targeted regions to collect important location and environmental information which can be communicated back to processing nodes via ad hoc wireless broadcast communications. Broadcasting among ships at sea is also desirable since it provides alternative communication paths without reliance on ground- or space-based communication infrastructures. Commercial scenarios that use broadcasting include: conferences/meetings/lectures, emergency services, and law enforcement. People today attend meetings and conferences with their laptops, palmtops, and notebooks. A presenter can broadcast slides and audio to recipients and attendees can ask questions and interact on a commonly shared whiteboard.

In ad hoc wireless networks, two mobile hosts can communicate with each other directly only if they are located closely together within each other's *wireless transmission range*. However, if two hosts that want to communicate are outside their wireless transmission ranges, they can communicate only if other hosts between them can forward packets for them. For example, in Figure 1, mobile hosts A and C are outside each other's transmission range. If A and C wish to exchange packets, they may use host B to forward packets for them, if B is within the transmission ranges of both A and C. To facilitate study, an ad hoc wireless network can be represented by a graph $G = \{V, E\}$, where *V* is the set of hosts, and *E* is the edge set of any two hosts *u* and *v* if they are within each other's transmission range. If we assume that all the transmission ranges of all hosts are the same, say *R*, then the graph is called a *unit graph.*

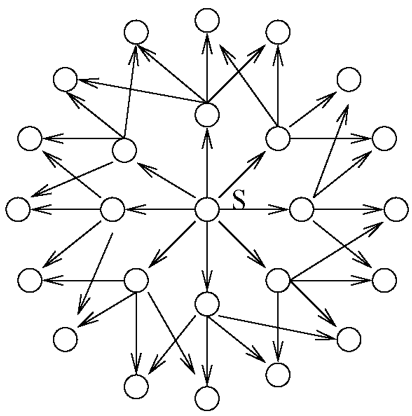
Figure 1 *A* and *C* are communicating through *B*



Because of the nature of a mobile network, communication between hosts poses special challenges. First, the hosts are mobile. Second, wireless networks deliver lower bandwidth than the wired networks. Third, the power of each host is limited. This requires that the algorithms designed be energy efficient, scalable and update information locally. In this paper, we will design broadcast algorithms to meet all these requirements.

A simple solution to broadcast is to let each node retransmit the packet after it receives the first copy of the packet. In Figure 2, the packet is retransmitted by all the intermediate nodes in order to diffuse it in the network. This technique is known as *pure flooding*.

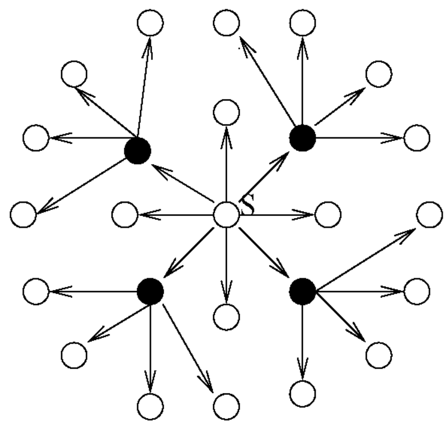
Figure 2 Pure flooding



Pure flooding forwarding rule: A node retransmits the packet only once after having received the packet.

Pure flooding is simple, easy to implement, and gives a high probability that each node, which is not isolated from the network, will receive the broadcast packet. However, flooding contains too many redundant broadcasts in that every node is a forwarding node. In Figure 2, it uses nine broadcasts to send a message to all hosts, one broadcast from the source, another eight broadcasts from the 1-hop neighbours of the source. The total energy consumed which is the summation of the energy consumed by each broadcast is large. The energy consumption model is defined in Section 3.1. To reduce the total energy consumption, in literature, there are basically two methods. One method is to reduce the number of forwarding nodes (Adjih et al., 2002; Qayyum et al., 2002; Wu, 2003). For example, in Figure 3, actually four nodes (four black ones) are enough to retransmit the message. Another method is to let a forwarding node use the reduced transmission range (Cartigny et al., 2003) to broadcast a message. Generally speaking, the transmission range *R* is used as the range for a source to broadcast a message. But if the longest distance between a source and its 1-hop neighbours is less than the transmission range *R*, then the longest distance can be used as the transmission range to broadcast the message. In this paper, we design energy efficient broadcast algorithms based on these two methods.

Figure 3 Four nodes are forwarding nodes



The rest of the paper is organised as follows: Section 2 presents algorithms using the first method: reducing the number of forwarding nodes. Section 3 shows algorithms applying the second method: using the reduced transmission range to broadcast a message. The conclusion and future work are in Section 4.

2 Method 1: reduce forwarding nodes

Several algorithms have been proposed to reduce the number of forwarding nodes using the concept of *dominating set*. A dominating set is a set of nodes such that any node in the network is either in this set or is a neighbour of some node in the set. A dominating set is connected if the subgraph formed by this set is connected. From graph theory, we know that the set of nodes that will retransmit a given broadcast packet (including the source) must form a *Connected Dominating Set* (CDS). The connectedness of the dominating set insures that all nodes of the CDS will receive the packet and will thus be able to retransmit it. If a CDS has been formed, then the forwarding rule becomes:

CDS forwarding rule: A node retransmits the packet only once after having received the packet if it belongs to the CDS.

Thus, the forwarding nodes are only those nodes in the CDS. Obviously, the smaller the CDS size, the fewer the retransmissions. However, computing a minimum size CDS is NP hard. Several good heuristic algorithms such as (Adjih et al., 2002; Wu, 2003) have been proposed recently to compute a small size CDS in the network based on multipoint relay technique.

2.1 Related work

In the algorithms of Adjih et al. (2002) and Wu (2003), a 2-*hop neighbourhood information model* is used, that is, a node knows the information of its neighbours and the neighbours of its neighbours. This information can be obtained by regularly exchanging Hello messages containing lists of neighbours between nodes. The algorithms are very attractive for ad hoc wireless networks since they need only local updates at each detected topology change and no global knowledge of the network topology is needed.

In Adjih et al. (2002) and Wu (2003), the computing of a small CDS is based on the multipoint relay technique. The idea behind this technique is to compute some kind of local dominating set for each node v. Each node v selects its forwarding nodes out of its 1-hop neighbours based on the information of its 2-hop neighbours. These selected forwarding nodes are called *multipoint relays* and they form a multipoint relay set of v denoted by $M(v)$. The node v is called the *selector* of them. If v has a packet to broadcast, only multipoint relays it selected will be allowed to rebroadcast it. These multipoint relays plus node v form a local dominating set of the two hop neighbourhood of node v. The smaller the multipoint relay set, the fewer the retransmissions. It is NP hard to compute a minimum size multipoint relay set. But some heuristics can be used to reduce the size of the set such as preferring neighbours with large node degree. Qayyum et al. (2002) proposes a Greedy Algorithm for node v to select its multipoint relays from its 1-hop neighbours to cover all its 2-hop neighbours. A node *v covers u* if u is a neighbour of v.

Let $N(v)$ denote the set of node v and its 1-hop neighbours, $N_1(v) = N(v) - v$ denote v's 1-hop neighbours, and $N_2(v) = N(N(v)) - N(v)$ denote v's 2-hop neighbours.

Greedy Algorithm:

1. Add $u \in N_1(v)$ to $M(v)$, if there is a node in $N_2(v)$ covered only by u.
2. Add $u \in N_1(v)$ to $M(v)$, if u covers the largest number of nodes in $N_2(v)$ that have not been covered.

The Greedy Algorithm can be applied by each node locally in a distributed way. If a node S wants to broadcast a packet, it sends the packet to its multipoint relays, and these multipoint relays send it to their multipoint relays. Eventually, all nodes will get the packet.

Naturally, the first dominating set for the whole network is the set of these multipoint relays. A node belongs to the dominating set if it is a multipoint relay of at least one node in the network. But it is shown in Adjih et al. (2002) that this dominating set is not optimal because it has too many nodes. In order to reduce the size of the dominating set, Adjih et al. (2002) introduces the following rules to eliminate some nodes. Furthermore, the algorithm they introduced, unlike the above, is no longer dependent on the source node.

2.1.1 Source-independent MPR

In this algorithm (Adjih et al., 2002), it requires the knowledge of a total order of the nodes. One can possibly use IP address of a node as an ID. So, a node is smaller than another node if it has a smaller ID.

A node will be selected into the dominating set of the network using the following rules.

Rule 1: The node has a smaller ID than all its neighbours'.

Rule 2: Or it is a multipoint relay of its neighbour with the smallest ID.

When Rule 2 is applied, the Greedy Algorithm is used to compute the multipoint relay sets. It has been proved that the set of nodes selected by Rules 1 and 2 forms a CDS (Adjih et al., 2002). And applying Rules 1 and 2 to the Greedy Algorithm generates a smaller CDS (Adjih et al., 2002).

2.1.2 Wu's enhanced approach

Wu (2003) observes two drawbacks in the Source-Independent MPR:

- the nodes selected by Rule 1 is not essential for a CDS
- the Greedy Algorithm does not take advantage of Rule 2.

Therefore, he replaces Rule 1 with the following Enhanced Rule 1 and the Greedy Algorithm with the Extended Greedy Algorithm.

Enhanced Rule 1: The node has a smaller ID than all its neighbours' and it has two unconnected neighbours.

Extended Greedy Algorithm:

Node u is a *free neighbour* of v if v is not the smallest ID neighbour of u.

- Add all free neighbours to $M(v)$.
- Add $u \in N_1(v)$ to $M(v)$, if there is an uncovered node in $N_2(v)$ covered only by u.
- Add $u \in N_1(v)$ to $M(v)$, if u covers the largest number of uncovered nodes in $N_2(v)$ that have not been covered by the current $M(v)$. Use node ID to break a tie when two nodes cover the same number of uncovered nodes.

He proved that the Enhanced Rule 1 together with the original Rule 2 generate a CDS under all cases except complete graphs.

2.2 Our approach

To further reduce the size of CDS, we observe that what is more related to the size of CDS is the node degree, not the node ID. So, node degree should have higher priority than node ID. Node ID can be used whenever there is a tie. Therefore, we propose the following three improvements to the rules to construct a CDS. The differences among the improvements are highlighted in bold letters.

New Improvement 1

A node will be selected into the dominating set of the network using the following rules. In New Rule 2, each node *v* selects its multipoint relays using the *Greedy Algorithm*.

New Rule 1: The node has the *largest degree* than all its neighbours'.

New Rule 2: Or the node is a multipoint relay selected by its neighbour with the *largest degree*.

New Improvement 2

A node will be selected into the dominating set of the network using the following rules. In New Rule 2, each node *v* selects its multipoint relays using the *Greedy Algorithm*.

New Rule 1': The node has the *largest degree* than all its neighbours' *and it has two unconnected neighbours*.

New Rule 2: Or the node is a multipoint relay selected by its neighbour with the *largest degree*.

New Improvement 3

A node will be selected into the dominating set of the network using the following rules. In New Rule 2, each node *v* selects its multipoint relays using the *Extended Greedy Algorithm*.

New Rule 1': The node has the *largest degree* than all its neighbours' *and it has two unconnected neighbours*.

New Rule 2: Or the node is a multipoint relay selected by its neighbour with the *largest degree*.

2.3 Correctness of the three improvements

The correctness of the three improvements can be straightforwardly derived from the theorems regarding Rules 1 and 2 and Enhanced Rule 1 proved in Adjih et al. (2002) and Wu (2003). To make the paper self-complete, we include these theorems as Lemmas 1 and 2 as follows:

Lemma 1 *(Adjih et al., 2002)***:** *The set of nodes selected by Rules 1 and 2 forms a CDS.*

Proof: Let us call D the set of all nodes that have decided to be in the CDS. The smallest node of the network is clearly in D by Rule 1. Let C be the connected component of the smallest node in the subgraph induced by D. We are going to show that C is a dominating set for the network (assuming the network is connected of course). This will prove in particular that any node in D has a neighbour in C, implying that C indeed equals D. This will thus prove that D is connected on the one hand and that D is a dominating set on the other hand.

Assume by contradiction that C is not a dominating set. Let $\mathcal{N}(C)$ denote the set of all nodes that are in a given set C or have a neighbour in C. There must exist some nodes that are not in $\mathcal{N}(C)$. Consider the set V of nodes connecting some node in C to some node in $\overline{\mathcal{N}(C)}$, the complementary of $\mathcal{N}(C)$. V is the set of nodes which have at least one neighbour in C and at least one neighbour in $\overline{\mathcal{N}(C)}$. As the network is connected, our assumption implies that V is not empty. Notice that $V \cap C = \emptyset$ by construction. We now consider the smallest node m in $\mathcal{N}(V)$.

- Either m is in $\overline{\mathcal{N}(C)}$. As $m \in \mathcal{N}(V)$, there exists a neighbour v of m in V. Let c be a neighbour of v in C. Consider the multipoint replay set of m: as c is a two hop neighbour of m, there must exist some multipoint relay r of m which is a neighbour of c. Notice that r must be in V. As the smallest neighbour of r is m, r should have elected itself in D by Rule 2, contradicting $V \cap C = \emptyset$.
- Either m is in $\mathcal{N}(C)$ which can be partitioned in V and $\mathcal{N}(C) - V$:
  - If m is in V, m should have elected itself as being in D since all its neighbours are greater. This is again a contradiction with $V \cap C = \emptyset$.
  - On the other hand if m is not in V, it cannot have any neighbour in $\overline{\mathcal{N}(C)}$. Let v be a neighbour of m in V, and let x be a neighbour of v in $\overline{\mathcal{N}(C)}$. As m has no neighbour in $\overline{\mathcal{N}(C)}$, x is not a neighbour of m and some multipoint relay r of m must be connected to x. As m cannot have any neighbour in $\overline{\mathcal{N}(C)}$, r must be in $\mathcal{N}(C)$. As r has a neighbour in $\overline{\mathcal{N}(C)}$, it is in V. The smallest neighbour of r is thus m implying that r should be in D by Rule 2, contradicting again $V \cap C = \emptyset$.

In all cases we get a contradiction. C thus have to be a dominating set. As mentioned before, this implies that $D = C$ is a CDS. □

Lemma 2 *(Wu, 2003)*: *If the given graph is not a complete graph, the set of forwarding nodes selected by the Enhanced Rules 1 and 2 forms a CDS.*

Proof: By Lemma 1, forwarding nodes selected by Rules 1 and 2 form a CDS. We only need to show that whenever a smallest ID node *v* within its 1-hop neighbourhood is removed based on the Enhanced Rule 1, the resultant forwarding nodes still form a CDS.

Because the graph is not a complete graph and all of *v*′s neighbours are pair-wise connected, there must exist anode that is not a neighbour of *v*. Let *w* be such a node with the smallest ID. Since *v* has the smallest ID in its1-hop neighbourhood, either *v* or *w* has the smallest ID in the 1-hop neighbourhood of any neighbour of *v*. When one neighbour of *v*, say *u*, is selected by its smallest ID neighbour *v*(*w*) to reach *w*(*v*) in Source-Independent MPR, based on Rule 2, *u* is a forwarding node and it covers *v* and all neighbours of *v*. Therefore, *v* can be removed. □

Now we can prove the correctness of our three new improvements:

Theorem 1: *The dominating set chosen by the New Rules forms a CDS of the network.*

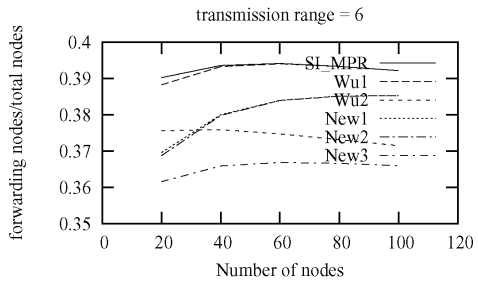
Proof: We can assign the largest degree node with the smallest ID and order the nodes by their degrees in a non-increasing order. If New Rules 1 and 2 are used, the proof will follow Lemma 1. And if New Rules 1’ and 2 are used, the proof will follow Lemma 2. Therefore, the dominating set chosen by the New Rules forms a CDS of the network. □

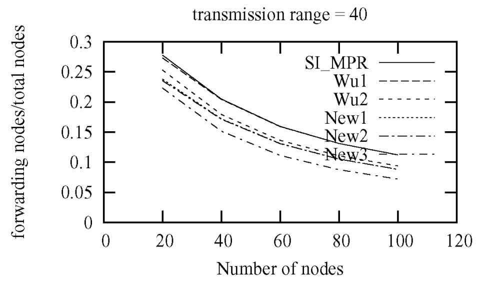
2.4 Simulations

Simulations are conducted to show which of the following algorithms generates a smaller CDS.

- Source-Independent MPR (denoted by SI_MPR)
- Wu’s algorithm using Enhanced Rule 1 only (denoted by Wu1)
- Wu’s algorithm using both Enhanced Rule 1 and the Extended Greedy Algorithm (denoted by Wu2)
- New Improvement 1 (denoted by New1)
- New Improvement 2 (denoted by New2)
- New Improvement 3 (denoted by New3).

Random nodes are distributed in a 100×100 space. Transmission ranges of 6 (dense graph) and 40 (sparse graph) are considered (see the following figures). The number of nodes ranges from 20 to 100. The ratio of the nodes in CDS (forwarding nodes) and the total nodes is calculated using the six algorithms.





From the simulation results, SI_MPR generates the largest CDS while New3 generates the smallest CDS. Wu1 is close to SI_MPR but is a little better. New1 and New2 are very close, when the number of nodes is small, they are better than Wu2 but when the number of nodes gets larger, Wu2 is better than New1 and New2.

3 Method 2: reduce transmission range

In the second method, we assume that a host can change its transmission range for power saving purposes. In order to calculate the energy consumption, an energy model needs to be defined.

3.1 Energy model

The general formula to calculate the energy consumption when transmitting a unit message is as follows:

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

where α is a constant larger than 2 and $r(u)$ is the range that the sender uses to broadcast the message. This energy model is used in Chu and Nikolaidis (2002), Das et al. (2002), Egecioglu and Gonzales (2001), Lindsey and Raghavendra (2001), Lloyd et al. (2002) and Wieselthier et al. (2000). In reality, it has a constant added to consider the overhead due to signal processing, minimum energy needed for successful reception and MAC control messages (Feeney, 2001). Now the formula becomes:

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

Different values can be assigned to α and c. Rodoplu and Meng (1999) uses $\alpha = 4$ and $c = 10^8$. The more realistic pair of values is $\alpha = 2$ and $c = 0$, which is used in Li and Wan (2001), and also used in our simulations.

The total energy consumed in a broadcast from a source host to all the hosts is the summation of the energy consumed by each broadcast. That is,

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

3.2 Related work

In Cartigny et al. (2003), it provides two algorithms *RNG Topology Control Protocol* (RTCP) and *RNG Broadcast Oriented Protocol* (RBOP) using reduced transmission range. These two algorithms are based on the construction of RNG. RNG is the *Relative Neighbourhood Graph* of *G*, the edges of which are defined by:

$$E_{\text{rng}} = \{(u,v) \in G \mid \text{not exists } w \in V \text{ such that } (u,w), (w,v) \in \text{G} \wedge d(u,w) \le d(u,v) \wedge d(v,w) \le d(u,v)\}.$$

In the above, $d(x, y)$ means the Euclidean distance between host *x* and host *y*. The definition means an edge (u, v) belongs to the RNG if there does not exist a host *w* in the intersection area of two circles centered at *u* and *v* and with radius $d(u, v)$ (See Figure 4). Since *u*, *v*, and *w* are within each other's transmission range, there are edges between *u* and *v*, *u* and *w*, *w* and *v* in *G*. Thus hosts *u*, *v*, *w*, and *w* form a triangle, see Figure 5. Obviously, edge *u*, *v* is the longest of the three. So the RNG of the original graph *G* can be formed by removing the longest edge in any triangle in *G*. It is easy to prove that RNG is connected if *G* is connected. The RNG can be constructed locally by each host. If GPS system is available, the hosts can exchange their coordinates by sending periodically Hello messages. If GPS is not available, the hosts can measure the distance to their neighbours by the strength of signals or time delay information. Once the distance information to their neighbours is known to the hosts, it is not difficult to find out if a triangle exists and if so remove the longest edge.

Figure 4 The edge (u, v) is not in RNG because of *w*

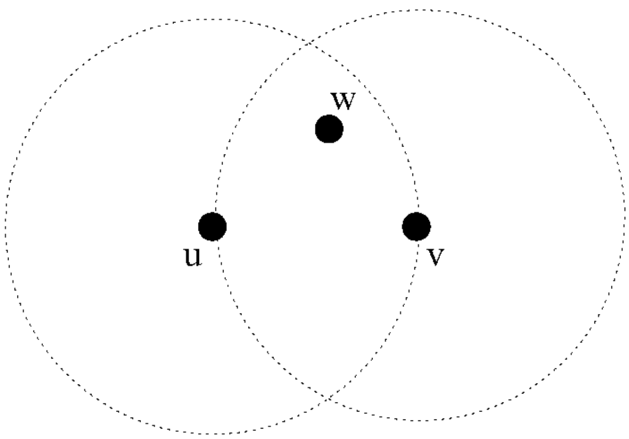
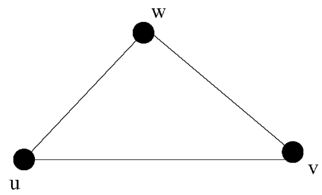


Figure 5 A triangle



The idea behind using RNG instead of the original *G* is that in a triangle such as that in Figure 5, suppose *u* is the source, if edge *uv* is removed, it is possible that the total energy consumed by broadcasting from *u* to *w* using $d(u, w)$ as the transmission range and then from *w* to *v* using $d(w, v)$ as the transmission range is less than the energy consumed from *u* broadcasting to *v* directly using $d(u, v)$ as the transmission range.

After an RNG is constructed from *G*, Cartigny et al. (2003) applied two algorithms RTCP and RBOP.

RTCP Algorithm:

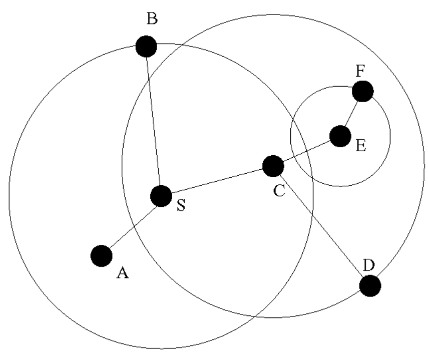
In RTCP, each host *u* adjusts its broadcast range $r(u)$ to the distance between itself and its farthest 1-hop neighbour so that it can reach all its 1-hop neighbours in RNG. That is,

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

To implement the algorithm, each host has an associated neighbourhood list which contains all its one-hop neighbours that have not received the message. See Figure 6 for an example of using RTCP, the source host *S* uses range $r_{SB} = d(S, B)$ to broadcast the message since *B* is its farthest neighbour. This broadcast will cover all of its one-hop neighbours *A*, *B* and *C*. Then hosts *A* and B's jobs are done because all of their one-hop neighbours have got the message, so their associated neighbourhood lists are empty. Host *C* will only consider neighbours *D* and *E* since *S* is the source and it will use range $r_{CD} = d(C, D)$ to broadcast the message. Then *D*'s job is done because its associated neighbourhood list is empty. *E* will use range $r_{EF} = d(E, F)$ to broadcast the message to *F*. Therefore, there are three broadcasts in this process. The total energy consumed is

$$r_{SB}^{\alpha} + c + r_{CD}^{\alpha} + c + r_{EF}^{\alpha} + c.$$

Figure 6 Broadcast using RTCP

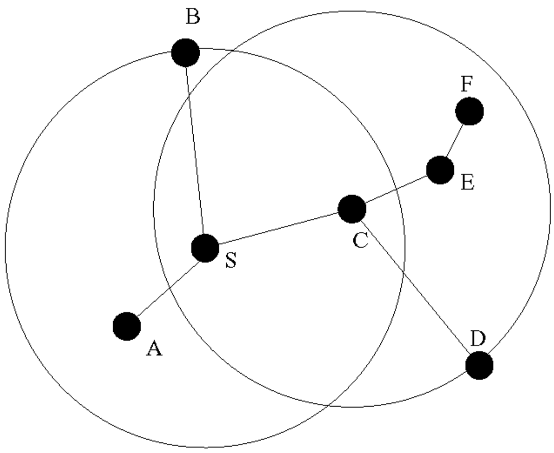


RBOP Algorithm:

RBOP improves RTCP by eliminating neighbouring hosts that have already been covered by a previous broadcast. As in Figure 7, since *F* has already been covered by the broadcast from *C*, unlike RTCP, a broadcast from *E* to *F* is not necessary. Thus, the total energy consumed is: $r_{SB}^{\alpha} + c + r_{CD}^{\alpha} + c.$ The following is the RBOP algorithm:

- the source node *u* of a broadcast emits its message with determined range *r*(*u*) from RTCP
- when receiving a new broadcast message:
  - if the emitter is an RNG-neighbour: the node calculates the farthest of its RNG-neighbours that did not receive this message. The node resends the message according to this range or ignores the message if all of its RNG-neighbours have received the message
  - otherwise, the node generates, for this broadcast, the list of RNG-neighbours that have not received this message. After a given timeout, if the neighbour list is not empty (neighbours can be removed by action 3b), the node retransmits the message with a range allowing to reach the farthest neighbour in the associate list
- when receiving an already received message:
  - the node ignores the message if it has already forwarded it
  - the node removes nodes that received this message from the associated neighbourhood list
  - the message is ignored if the associated list is empty
  - otherwise, if the message arrives on an RNG-edge, send the message with range allowing to reach the farthest neighbour in the list of non-eliminated RNG neighbours.

Figure 7 Broadcast using RBOP



3.3 Our approach

We observe that the removal of the longest edge in a triangle in the RNG method is not directly related to the energy consumption. The total energy can be reduced by constructing a different graph called the *Energy Neighbourhood Graph* (ENG) from *G* by considering the energy model using the following Edge_Removal_Rule:

Edge_Removal_Rule: assume hosts *u*, *v*, and *w* form a triangle. Suppose edge *uv* is the longest edge. If $c + r_{wv}^{\alpha} + c < r_{uv}^{\alpha} + c,$ then remove edge *uv*; otherwise, do nothing.

This rule can be applied by each host locally just as in the RNG method. Next we show that in many cases this ENG method is better than the RNG method in energy saving. Suppose in a triangle *uvw*, *uv* is the longest edge (See Figure 5).

Case 1: *u* is the source host to broadcast a message.

By the RNG method, edge *uv* is removed since it is the longest of the three. So *u* will first use $r_{uw} = d(u, w)$ to broadcast the message to *w* and *w* will use $r_{wv} = d(w, v)$ to broadcast the message to *v*. The total energy consumed based on RNG is: $r_{uv}^{\alpha} + c + r_{wv}^{\alpha} + c.$ Using our edge_removal_rule, if $r_{uw}^{\alpha} + c + r_{wv}^{\alpha} + c < r_{uv}^{\alpha} + c,$ edge *uv* is removed, the resulting energy consumed by the broadcast is the same as that in the RNG method. If the condition is not true, that is, $r_{uw}^{\alpha} + c + r_{wv}^{\alpha} + c > r_{uv}^{\alpha} + c,$ edge *uv* will be kept. The source host *u* will use r_{uv} to broadcast the message. The broadcast will cover both hosts *w* and *v*. The total energy consumed is: $r_{uw}^{\alpha} + c$ which is less than the energy used in the RNG method.

Case 2: *w* is the source host to broadcast a message.

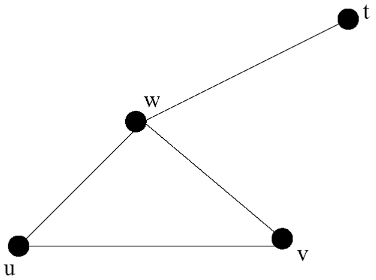
By the RNG method, *w* will use max(r_{uw} r_{wv}) to broadcast the message. The total energy consumption is: max$(r_{um}, r_{wv})^{\alpha} + c$. Using our edge_removal_rule, whether edge *uv* is removed or not, the total energy consumed will be the same as in the RNG method.

Case 3: *v* is the source host to broadcast a message.

Due to symmetry, the discussion of this case is the same as in Case 1.

However, not in all cases the energy consumption using our method is less than that using the RNG method. For example, in Figure 8, edge *uv* is the longest in triangle *uvw*. Suppose *u* is the source, host *t* is connected to host *w* with *d*(*w*, *t*) larger than *d*(*w*, *v*). According to the RNG method, edge *uv* is removed. Thus source *u* will use $r_{uw} = d(u, w)$ to broadcast the message and then host *w* will use $r_{wt} = d(w, t)$ to broadcast the message since *d*(*w*, *t*) is larger than *d*(*w*, *v*). The total energy consumption is: $r_{uv}^{\alpha} + c + r_{wt}^{\alpha} + c.$ Suppose by our rule, edge *uv* is not removed. So source host *u* will use $r_{uv} = d(u, v)$ to broadcast followed by host *w* using $r_{wt} = d(w, t)$ to broadcast. The total energy consumed is: $r_{uv}^{\alpha} + c + r_{wt}^{\alpha} + c,$ which is more than the energy consumed by the RNG method.

Figure 8 A case that the RNG method saves more energy



In the next section, we are going to use simulations to compare the energy consumed by RTCP and RBOP algorithms based on our ENG method and the RNG method.

3.4 Simulations

In the simulations, we compare the following four algorithms.

- *RNG Topology Control Protocol (RTCP)*: remove edges using the RNG method from the original *G* and then apply RTCP algorithm
- *New Topology Control Protocol (NTCP)*: remove edges using our Edge_Removal_Rule from the original *G* and then apply RTCP algorithm
- *RNG Broadcast Oriented Protocol (RBOP)*: remove edges using the RNG method from the original *G* and then apply RBOP algorithm
- *New Broadcast Oriented Protocol (NBOP)*: remove edges using our Edge-Removal-Rule from the original *G* and then apply RBOP algorithm with the changes to replace all the RNG edges in the algorithm by the ENG edges.

Our simulations are conducted as follows: n static hosts are randomly generated in a space of 100×100. We consider a network with 30 hosts and a network with 60 hosts. The average node degree ranges from 8 to 30 in the network with 30 hosts and the average node degree ranges from 10 to 60 in the network with 60 hosts. The *average node degree* of the network is the average number of neighbours of all hosts. We set $\alpha = 2$, $c = 0$ in the energy model. The MAC layer is assumed to be ideal. The timeout used in neighbour elimination scheme in RBOP and NBOP is fixed to three times the duration of a message sending. Only connected network is considered. For each measure, 5000 broadcasts have been run.

Because of ideal MAC layer and nature of protocols, we are sure that all nodes receive the broadcast messages. Hence, the reachability is always 100%. For each broadcast, we calculate the total energy consumption:

$$E_{\text{total}} = \sum E(u),$$

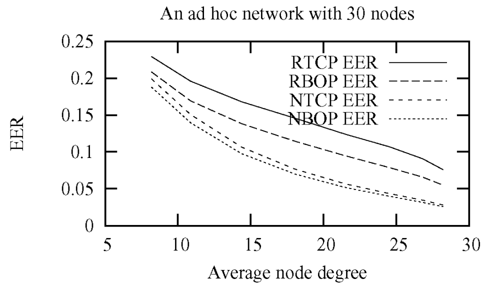
where $E(u)$ depends on the transmission radius as explained in the algorithms. The total energy consumption E_{total} is compared with total energy consumption needed for flooding algorithm with maximal range R:

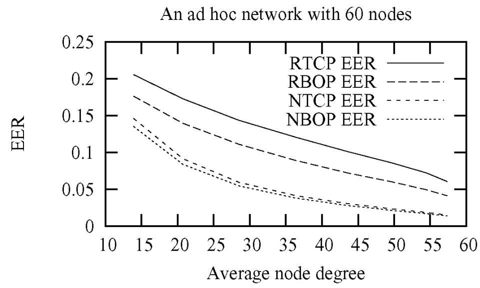
$$E_{\text{flooding}} = n \times (R^{\alpha} + c).$$

For the four algorithms considered, we compute the average *Expended Energy Ratio* (EER) that is defined by:

$$EER = \frac{E_{\text{total}}}{E_{\text{flooding}}}.$$

The simulation results are shown in figures with 30 nodes and 60 nodes respectively as follows. In both figures, with the increase of the average node degree, all four algorithms save more and more energy comparing with flooding. Especially, NTCP and NBOP can save more energy than RTCP and RBOP. Though the Edge_Removal_Rule is not always the best for all the cases, it is better statistically than the method based on RNG. Obviously, RBOP is better than RTCP regardless of the edge removal rules.





4 Conclusion and future work

In this paper, improved algorithms are proposed to reduce the broadcast energy consumption based on the reduction of the number of forwarding nodes and the reduction of the transmission range. Simulations have shown that these improved algorithms are better than the existing ones. So far methods 1 and 2 are developed independently and no connection between them has ever been investigated. Our next step will combine the ideas of these two methods. That is, first use the algorithm based on method 1 to find a small size forwarding node set and then each forwarding node uses the longest distance to its farthest neighbour as the reduced transmission range to broadcast the message. The total energy saving of the combination comparing with the existing ones will be our future work.

Another point that needs to be noted is that in our algorithm to find a minimal size forwarding node set, node degree is used as a criteria to select a multipoint relay.

To be more energy efficient, when a node selects its multipoint relays from its 1-hop neighbours, the residue energy in each neighbour should be considered before the node degree so as to avoid the power of a particular node from being depleted quickly if it is frequently selected as a multipoint relay. Thus, the network can be more reliable and stay connected longer. The hosts can exchange the residue power information by sending each other Hello messages. The increase in the network lifetime considering the residue energy comparing to that without considering it will be studied in our future work.

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