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Revisiting relative neighborhood graph-based broadcasting algorithms for multimedia ad hoc wireless networks

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Abstract Multimedia broadcasting is a popular application in an ad hoc wireless network, itself composed of battery-operated nodes. Hence, energy conservation and avoidance of frequent re-construction of broadcast paths are crucial to ensure robust and uninterrupted service of multimedia broadcasting applications. This paper introduces a class of distributed broadcast algorithms based on variations of Relative Neighborhood Graphs (RNG). In contrast to the original RNG-based algorithms, the proposed algorithms consider the remaining battery energy of nodes and the distance between nodes as criteria for determining the relative neighborhood of a node. This

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This work is a significant improvement of the RNG-based broadcasting algorithms proposed in (Proc. CyberC (Intl. Conference on Cyber-Enabled Distributed Computing and Knowledge Discovery), pp. 94–100, 2010; Proc. National Symposium on Telecom. (NST), pp. 1–5, 2010).

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approach is intended to boost the resiliency of the broadcast path by avoiding the choice of nodes with low remaining battery capacity as rebroadcast nodes. Extensive simulations are conducted, demonstrating that the proposed algorithms improve over the original RNG in several aspects, including the reduction of broadcast storms, longer path lifetime, and shorter broadcast latency.

Keywords Multimedia applications · Broadcasting · RNG · Forbidden set · Modified RNG · Simulation

1 Introduction

Wireless ad hoc networks have witnessed growth in popularity and diversity of applications. Typically, such networks have dynamic topologies without the support of an infrastructure. Moreover, connectivity is maintained in a decentralized fashion through a form of multi-hop radio network. Broadcasting is a special routing process used to transmit a packet so that each node in the network receives a copy of it. Blind flooding is the simplest and most widely used approach by which broadcasting can be achieved without the need for global information. However, redundant transmissions due to blind flooding [1] may cause broadcast storm, resulting in contention and collision, thereby lowering the broadcast efficiency and wasting unnecessary energy.

In general, broadcasting can be optimized using two approaches. The first one consists in reducing the quantity of the needed relaying nodes [2–8] and the second one consists in limiting the transmission power generated at each node [9–14]. Recently, we proposed an energy saving broadcast routing protocol for ad hoc networks with asymmetric link costs [15], based on Edmonds' algorithm. A distributed version of this algorithm was presented in [16]. Residual battery energy is a precious resource in handheld devices. Maximization of the minimum residual energy of nodes after transmission of data packets for multicast applications in mobile ad hoc networks was studied in [17].

A Relative Neighborhood Graph over a set of nodes was studied in [18]. The RNG contains the edges of a minimum spanning tree of the set of nodes. In turn, the edges of the RNG belong to a Delaunay triangulation of the nodes [19]. The application of the RNG in the design of broadcast routing algorithms was investigated in [20, 21], where it was assumed that each node can get its own location information by various positioning techniques, and can obtain locations of its neighbors through exchanging the HELLO packets. Such information is used to calculate the distance among nodes and to build the RNG graph. Afterwards, the transmission power can be adjusted accordingly.

The concept of forbidden set routing was introduced in [22] and [23] in the context of policy-based routing. Each node in a network is allowed to define its own set of forbidden nodes in accordance with security concerns or for economical reasons. A routing path defined with a forbidden set K is said to be K-constrained. Further, a distributed labeling scheme was devised with $O(n)$ space requirement at each node where n is the number of nodes. In [24], the forbidden set was explored from a graph-theoretical perspective. In particular, the effects of the forbidden set on the minimal connected dominating set for a graph were examined. Similarly, in [25], a forbidden set was used in the design of routing algorithms for wireless ad hoc networks based on the remaining battery energy at each node. We follow the same idea in this paper.

In this paper, the relative neighborhood graph and forbidden set concepts are used in conjunction in the design of broadcast methods for ad hoc networks [3], yielding a distributed broadcasting algorithm called RNGF. Then the nature of wireless transmissions using omni-directional antennas is exploited to eliminate redundant rebroadcasts, resulting to our so-called RNGF-R algorithm. The second set of algorithms is defined in a similar vein by defining a weighting factor based on two patterns: the remaining battery energy capacity of a node and the distance between nodes. The performance of the proposed algorithms is evaluated by simulations, using few predefined metrics.

The paper is organized as follows. Section 2 examines the requirements of multimedia applications in ad hoc wireless networks and the use of geometric routing protocols based on RNG and similar graph-theoretical approaches. We also discuss and contrast our work against previous works on this area. In Sect. 3, the RNGF and RNGF-R algorithms are briefly reviewed. A novel mechanism to remove redundant rebroadcasts is also presented. In Sect. 4, generalized modified RNG algorithms are presented, which use the above mechanism to further increase the energy conservation. In Sect. 5, the performances of the studied algorithms are compared through intensive simulations, using: (i) the number of rebroadcast nodes, (ii) the average degree of domination, (iii) the total energy consumption, (iv) the lifetime of broadcast path, and (v) the broadcast latency as performance metrics. Finally, in Sect. 6, we conclude our work and point to future research.

2 Motivation of our work

The flexibility and ease of deployment have made ad hoc networks highly popular. In recent years, more and more applications have been implemented in ad hoc networks, among which sharing of multimedia information has experienced tremendous growth. As smart phones and various types of handheld devices are equipped with greater computing and communication capabilities, sharing of movies, pictures, and other formats of multimedia data has become a common form of entertainment. This type of information sharing requires broadcast of multimedia from one source to all other nodes in an ad hoc network.

Multimedia applications have stringent quality of service (QoS) requirements. They are sensitive to delays and jitters and are also intolerant of broadcast path failures. Thus, energy-efficient and reliable schemes need to be designed to support multimedia broadcasting in such a network setting. In this regards, RNG possesses many desirable features, making it a suitable basis upon which algorithms can be devised to meet multimedia broadcast requirements.

A number of geometric spanners, including RNG, Gabriel graph (GG), and local Delaunay triangulation, have been proposed for multimedia applications in ad hoc networks. In particular, RNG and GG have been incorporated as the underlying network topology in several geometric routing protocols to support guaranteed packet delivery in multimedia communications [26–28]. The performances of these protocols in terms of QoS parameters were compared in [29].

In our previous works [29–31], we have developed a number of RNG-based broadcast algorithms. More precisely, in [30], a combination of the RNG and the forbidden set was introduced for the first time to design a distributed broadcasting algorithm for wireless ad hoc networks and the effect of different threshold values (inherited from the definition of the forbidden set) on the performance of this algorithm was investigated. In [31], this same algorithm was further improved by adopting the energy cost model introduced by Heizelman et al. [35] in order to reduce the redundant rebroadcasts. In [32], a modified version of RNG was introduced, yielding two classes of algorithms (referred to as $\text{MRNG}(1,1)$ and $\text{MRNG}(1,2)$).

In this paper, the RNG-broadcasting algorithms proposed in [31, 32] are revisited and improved as follows. An alternative novel approach to removing redundant rebroadcasts is described and implemented. This approach is different from the previous ones in the sense that (i) the nominal battery voltage is taken into account in the calculation of the path lifetime, (ii) the receiving and transmitting energy at each node is considered as design parameters to more accurately reflect the actual energy consumption in the network, and (iii) the graphs generated are loop-free. A generalization of the MRNG algorithms resulting from this approach is referred to as $\text{MRNG}(\alpha,\beta)$ where the parameters α and β are used to embody the effect of both the distance between nodes and the remaining battery energy at a given node.

3 RNGF and removal of redundant rebroadcasts

3.1 Constructing the relative neighbor graph

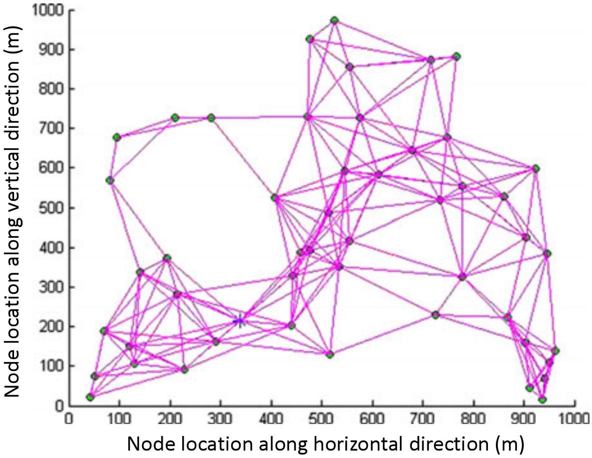
Let $\mathbf{V}$ be the set of nodes in an ad hoc network and $\mathbf{E}$ be the set of links between the nodes in $\mathbf{V}$. The graph $\mathbf{G}(\mathbf{V},\mathbf{E})$ denotes the underlying graph of network. Let us assume that each node can transmit the data to a maximum distance $r_{\max}$ and the distance between two nodes u and v is $d(u,v)$. The neighbor set of u, denoted $\mathbf{N}(u)$, is defined as $\mathbf{N}(u)=\{v|d(u,v)\le r_{\max}\}$ and there exists a link (u,v) between nodes u and v. Let $\mathbf{G_R}(\mathbf{V},\mathbf{E_R})$ be the relative neighborhood graph induced on G. $\mathbf{E_R}$ is a subset of $\mathbf{E}$ and can be defined as follows:

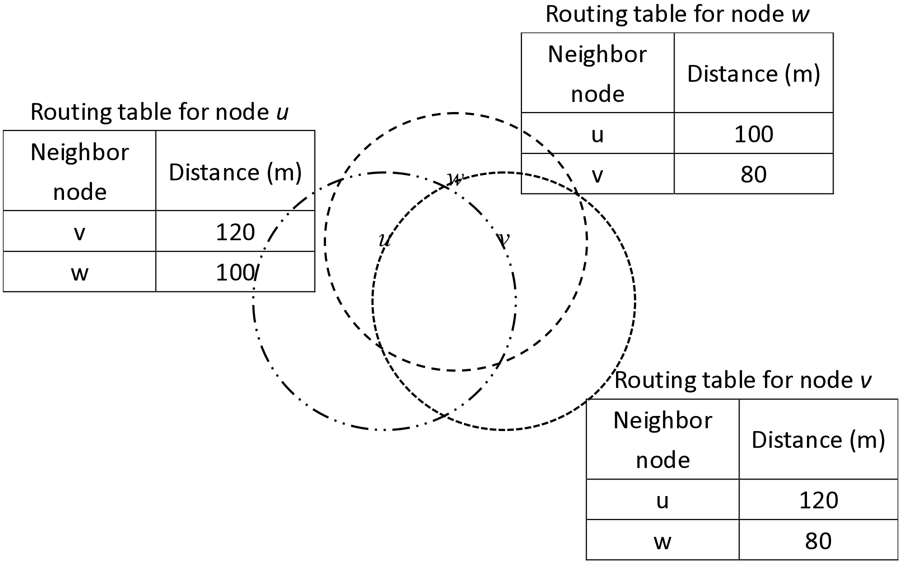
$$\mathbf{E_R}=\Bigg\{(u,v)\in\mathbf{E}\;|!\exists w\in\mathbf{V},(u,w)\in\mathbf{E},(w,v)\in\mathbf{E} \wedge\left[\frac{1}{d(u,w)}>\frac{1}{d(u,v)}\right]\wedge\left[\frac{1}{d(v,w)}>\frac{1}{d(u,v)}\right]\Bigg\} \tag{1}$$

As an example:

Figure 1 depicts a network consisting of 50 nodes randomly distributed in an area of $1000\times 1000\ \text{m}^2$ with $r_{\max}=250$ m. It is assumed that the remaining battery capacity is uniformly distributed between 15% and 100%, with 100% corresponding to a fully charged battery. The node marked with an asterisk serves as source node.

Fig. 1 An ad hoc network with 50 nodes randomly distributed





Routing table for node *u*

Neighbor node	Distance (m)
v	120
w	100

Routing table for node *w*

Neighbor node	Distance (m)
u	100
v	80

Routing table for node *v*

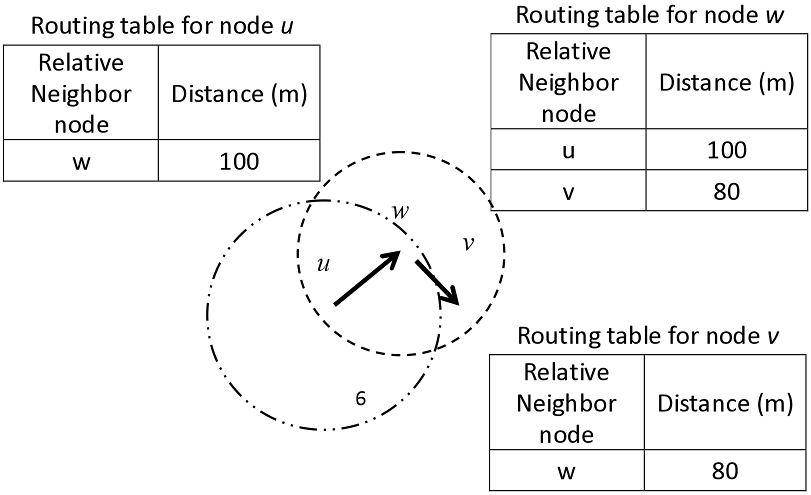
Neighbor node	Distance (m)
u	120
w	80

Fig. 2 Routing tables for determining relative neighbors [31]

Figure 2 shows three nodes that are within the transmission range of each other and the information kept in the routing table of each node. The nodes exchange information in order to determine relative neighbors.

Figure 3 shows how the transmission range is adjusted based on the information exchanged. The updated routing tables during the process of forming the RNG are also shown. Here, nodes u and v do not need to maintain a direct path because the data can be routed via node w, thereby reducing the energy consumption.

Figure 4 shows the RNG for the network of Fig. 1. The threshold value for defining the forbidden nodes is set at 0.36. Therefore, nodes with the remaining battery



Routing table for node *u*

Relative Neighbor node	Distance (m)
w	100

Routing table for node *w*

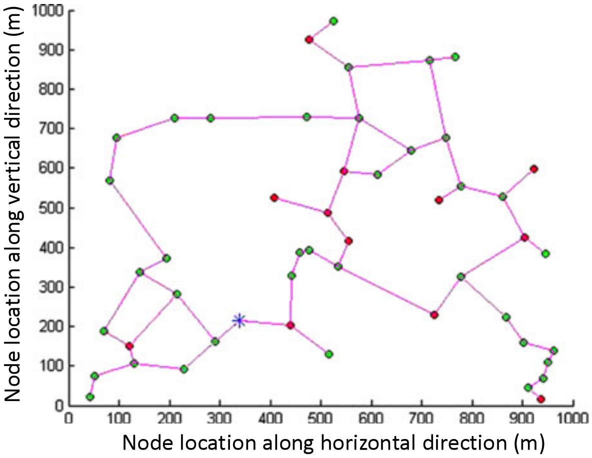
Relative Neighbor node	Distance (m)
u	100
v	80

Routing table for node *v*

Relative Neighbor node	Distance (m)
w	80

Fig. 3 Transmission range adjustment and routing table update [31]

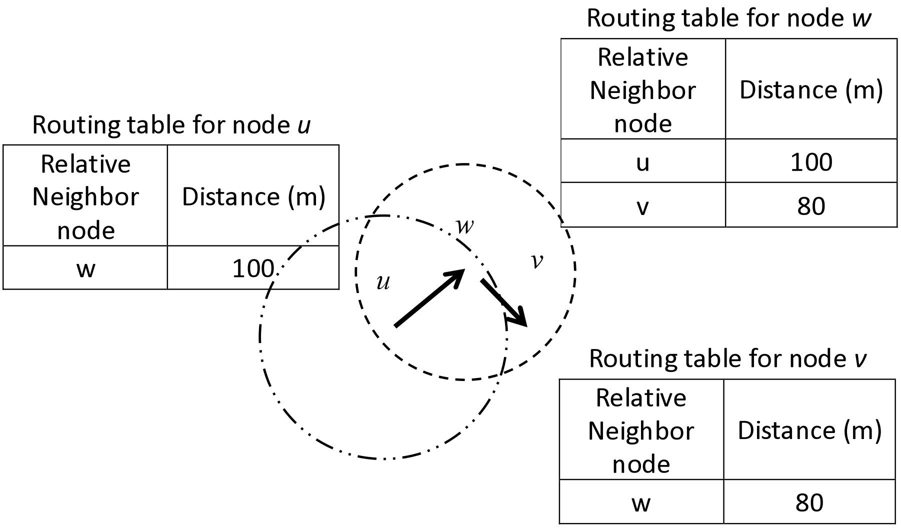
Fig. 4 RNG for the network in Fig. 1



capacity lower than the 0.36 are indicated by the red dots in the figure, whereas those with higher remaining battery capacity are indicated by the green dots.

3.2 RNGF algorithm

The RNGF-based broadcast algorithm [30] combines the RNG and a forbidden set in its design. It has a built-in mechanism to exclude certain nodes for acting as relay or rebroadcast nodes. Thus, when creating the RNG, nodes with low remaining battery capacity will be avoided. When the remaining battery capacity of a node is below a certain predefined threshold value, the node will be designated as a forbidden node. Forbidden nodes can only transmit control packets and are not allowed to transmit data packets.



Routing table for node *u*

Relative Neighbor node	Distance (m)
w	100

Routing table for node *w*

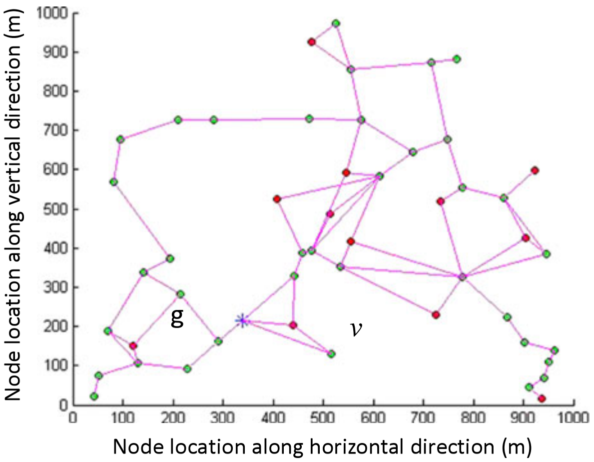
Relative Neighbor node	Distance (m)
u	100
v	80

Routing table for node *v*

Relative Neighbor node	Distance (m)
w	80

Fig. 5 Selection of links for inclusion in RNGF [31]

Fig. 6 RNGF for the network of Fig. 1



The pseudo-code of the RNGF algorithm can be found in [30]. An example illustrating the idea of the algorithm is provided in Fig. 5. For brevity, we will also refer to the sub-graph induced by the RNGF algorithm as RNGF. In Fig. 5, if all the nodes in the intersection of nodes *u* and *v*'s transmission range are forbidden nodes, node *u* will choose *v* as one of its relative neighbors. The forbidden flag in the routing table is used to indicate whether a node is forbidden (flag value equals to 1) or not (flag value equals to 0). If there is no node in the overlap area, node *u* will also set *v* as its relative neighbor. The RNGF for the network in Fig. 1 is depicted in Fig. 6. As expected, all the forbidden nodes are terminal nodes.

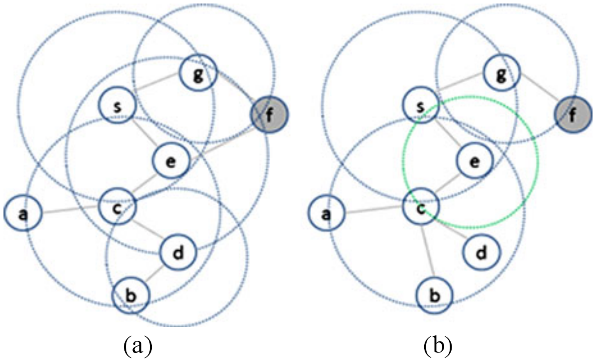


Fig. 7 Removing redundant rebroadcast nodes [31]

3.3 Removal of redundant rebroadcasts

The idea of removing unnecessary rebroadcasts has been used previously in [33, 34] by exploiting the nature of wireless transmissions. After an RNG or RNGF is generated, a similar technique can be used to get rid of redundant rebroadcast. Figure 7 shows two cases where this method can be applied [34].

(i) Consider the forbidden node f in Fig. 7(a). It is covered by both nodes g and e, but since g is closer to f, g will be kept as the upstream node of node f. In addition, node e does not have to cover node f, thus, its transmission range can be shrunk as indicated in Fig. 7(b).

(ii) Node b in Fig. 7(a) is a regular node (i.e., non-forbidden node). It has two upstream nodes c and d, but node d is a relative neighbor of b and node c is not. Node b can send a control message to node d asking it to drop b from its list of relative neighbors. Node b will also send a message to node c asking it to add b as its new relative neighbor. This situation is also illustrated in Fig. 7(b). After the procedure is completed, d can lower its transmission power or will not transmit at all if b was its only downstream node. This method used for the removal of redundant rebroadcast has the advantage of reducing the path length from the source to node d.

Our proposed alternative approach consist in retaining only the upstream node which is a relative neighbor of the target node and has the smallest hop count from the source node in case multiple routes to the target node exist. When there are two or more such nodes, the one which has the shortest distance to the target node is kept and the rest are removed. The graph depicted in Fig. 6 illustrates this idea. Here, node h is a forbidden node and has g, j, k as its upstream nodes. Since node g has the smallest hop count from the source node, it is retained as the relative neighbor of h and the other two are removed. Node j has i and k as upstream nodes. Both of them are 3 hops away from the source node but node k is closer to node j. Therefore, the link from k to j is kept and that from i to k is removed. This approach is adopted in our study. Note that the upstream–downstream relationship is dependent on the source node.

When the removal of redundant rebroadcasts is combined with the RNG (resp., RNGF), the resulting algorithm is referred to as RNGR (resp., RNGFR). Figure 8

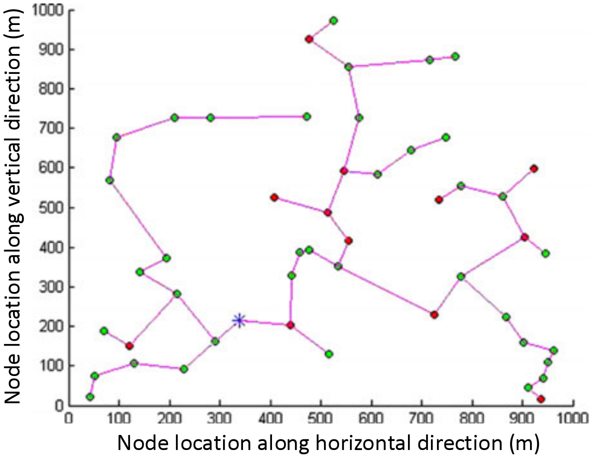


Fig. 8 RNGR corresponding to Fig. 4

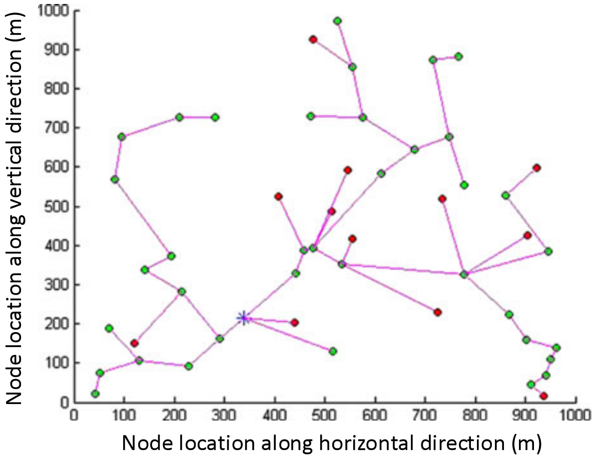


Fig. 9 RNGFR corresponding to Fig. 6

depicts the RNGR corresponding to the graph in Fig. 4. Similarly, Fig. 9 depicts the RNGFR corresponding to the graph in Fig. 6. Note that since only one upstream node is retained, the broadcast graph is loop-free after the removal procedure is performed.

4 Modified RNG algorithms

In RNG, the distances between nodes are considered as the only criterion when determining the relative neighbors of a node. Hence, it might occur that nodes with low remaining battery capacity be selected as rebroadcast nodes, rending the broadcast path vulnerable to failure when those nodes have used up their energy.

To circumvent this problem, the original RNG is modified by considering the remaining battery energy as one of the design criteria of the broadcast algorithms [31]. This has led to a generalization of RNG (denoted MRNG(α, β)), where the parameters α and β are used to embody the effect of both the distance between nodes $d(u, v)$

Algorithm 1 MRNG(α, β)

```
For $u \in \mathbf{V}$
    Obtain the position and the remaining battery information;
    Exchange the information with the neighbors and calculate distance to neighbors;
    For $v \in \mathbf{N}(u)$
        $\mathbf{S}(v) = \mathbf{N}(u) \cap \mathbf{N}(v)$;
        If $\mathbf{S}(v) = \phi$
            Set $v$ as relative neighbor of $u$; break;
        For $z \in \mathbf{S}(v)$
            If $W_{zv} > W_{uv} \wedge W_{zu} > W_{vu}$ break;
        Set $v$ as relative neighbor of $u$;
```

and the remaining battery energy of a node $b(u)$, combined into a weighting factor W. The weighting factor associated with two nodes u and v is defined as:

$$\mathrm{MRNG}(\alpha, \beta) = \frac{b^{\alpha}(u)}{d^{\beta}(u, v)} \tag{2}$$

When $\alpha = 0$ and $\beta = 1$, the original RNG is obtained.

Using the above settings, one can define the edge set $\mathbf{E_{RM}}$ of MRNG(α, β) as:

$$\mathbf{E_{RM}} = \{(u, v) \in \mathbf{E} | !\exists w \in \mathbf{V} \wedge [W_{wv} > W_{uv}] \wedge [W_{wu} > W_{vu}]\}. \tag{3}$$

The operation of the MRNG(α, β) is given in Algorithm 1.

Compared to RNGF which employs a fixed threshold of remaining battery energy in determining the forbidden nodes, MRNG(α, β) considers the distance and remaining energy capacity simultaneously, making it more flexible. When MRNG$(1, 1)$ and MRNG$(1.5, 2)$ are applied to the network in Fig. 1, the broadcast graphs are as shown in Figs. 10 and 11. As before, the graphs generated by the algorithms will also be mentioned by the respective name of the methods when no ambiguity arises. The broadcast paths depend on the distribution of the remaining battery energy capacity. Since no nodes are explicitly designated as forbidden nodes, the nodes are not marked differently.

As for RNG and RNGF, redundant rebroadcasts can be removed after the broadcast paths are established [13]. This step is performed in a way similar to that described previously. When removal of redundant rebroadcast nodes is used in conjunction with MRNG(α, β), the resulting method is denoted as MRNG$(\alpha, \beta)R$. Figures 12 and 13 show the broadcast paths constructed by MRNG$(1, 1)R$ and MRNG$(1.5, 2)R$ for the network in Fig. 1. The graphs contain no loops and can effectively eliminate the collision or interference caused by two or more nodes transmitting to the same node.

5 Performance evaluation

In this section, the performance of the proposed algorithms is compared against the original RNG method.

Fig. 10 MRNG(1, 1) for the network of Fig. 1

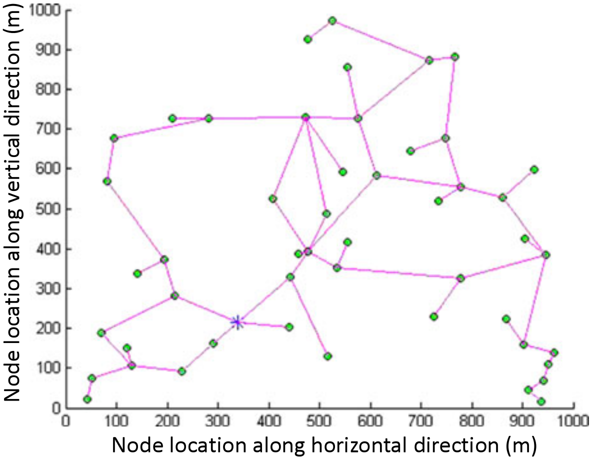
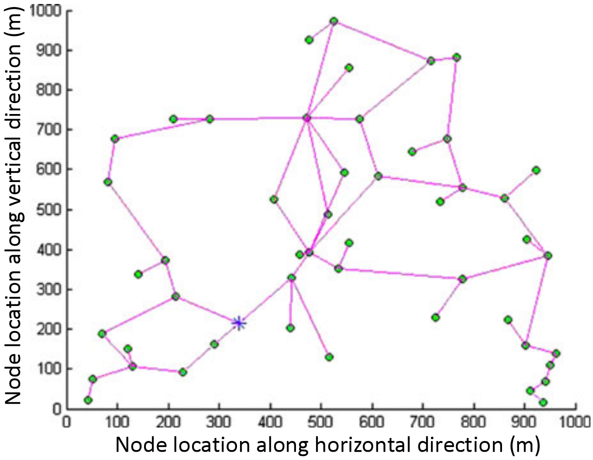


Fig. 11 MRNG(1.5, 2) for the network of Fig. 1



5.1 Performance metrics

Visual C++ was used to implement RNG, RNGF, and RNGFR under the Windows operating system. The energy cost model introduced in [35] is adopted, in which the energy E_{Tx} taken for transmitting l bits for a distance of d is calculated as:

$$\begin{aligned} E_{Tx}(l,d) &= E_{Tx\text{-elec}}(l) + E_{Tx\text{-amp}}(l,d) \\ &= \begin{cases} lE_{\text{elec}} + l\varepsilon_{\text{fs}}d^2, & \text{if } d < d_0, \\ lE_{\text{elec}} + l\varepsilon_{\text{mp}}d^4, & \text{if } d \geq d_0, \end{cases} \end{aligned} \tag{4}$$

where E_{elec} is the energy expenditure of the electronic circuit for transmitting one bit of data and it is independent of the distance d, ε_{fs} is the proportionality constant in free space where path loss is quadratic with distance, ε_{mp} is the proportionality constant when multipath fading affects the channel quality, d_0 is the distance at which the transition between free space and multipath fading channel models occurs. According

Fig. 12 MRNG$(1, 1)R$ corresponding to Fig. 10

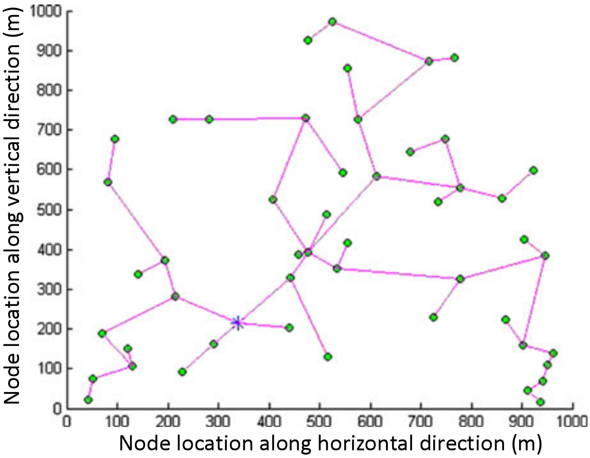
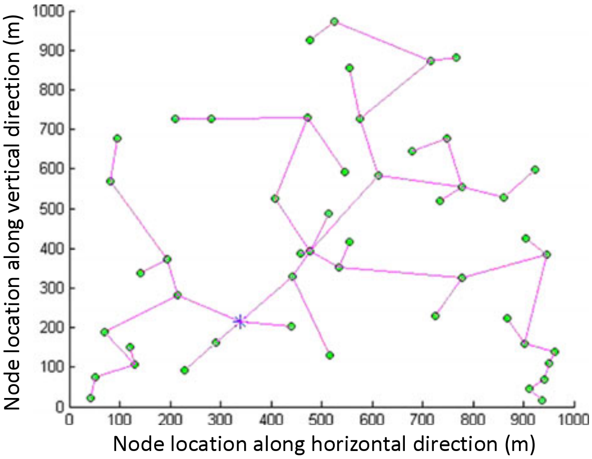


Fig. 13 MRNG$(1.5, 2)R$ corresponding to Fig. 11



to [35], the values of the above-mentioned parameters are chosen as $E_{\mathrm{elec}} = 50$ nJ/bit, $\varepsilon_{\mathrm{fs}} = 10$ pJ/bit-m^2, and $\varepsilon_{\mathrm{mp}} = 0.0013$ pJ/bit-m^4. The values of $\varepsilon_{\mathrm{fs}}$ and $\varepsilon_{\mathrm{mp}}$ allow us to derive the approximate value of d_0 to be 87 m. The radio energy expenditure for receiving each bit of data is equal to E_{elec}, assuming that each node is equipped with a Li-ion battery with a nominal voltage of 3.6 V.

The simulation parameters are captured in Table 1.

Different node distributions are generated with different seed values for random numbers and 300 topologies for which all the algorithms can successfully generate broadcast paths are examined to eliminate possible bias. For each topology, a regular node is randomly selected as the source node. For comparison purpose, the following performance metrics are used:

- Number of rebroadcast nodes: number of intermediate nodes involved in relaying the data packets.

Table 1 Simulation parameters

Parameter	Value
Size of topology (m^2)	1000×1000
Maximum transmission radius (m)	250
Number of nodes	$40 \sim 100$
E_{full} (Full battery capacity)	1000 mAh
Distribution of remaining battery capacity (%)	$15 \sim 100$
Threshold of forbidden nodes (%)	32
Data rate	2 Mbps

- Average degree of domination: the mean number of downstream nodes for each rebroadcast node.
- Total energy consumption: sum of the energy expenditure of rebroadcast nodes.
- Lifetime of broadcast path: the time when the first node on the broadcast path runs out of energy, provided that data are continuously sent out from the source node at a fixed bit rate.
- Broadcast latency: the maximum number of hops from the source node to any other node in the ad hoc network.

The first two metrics characterize the sub-graph generated by each algorithm. The third metric reflects the energy efficiency of an algorithm. The last two metrics are similar to those suggested by IETF MANET Working Group [36].

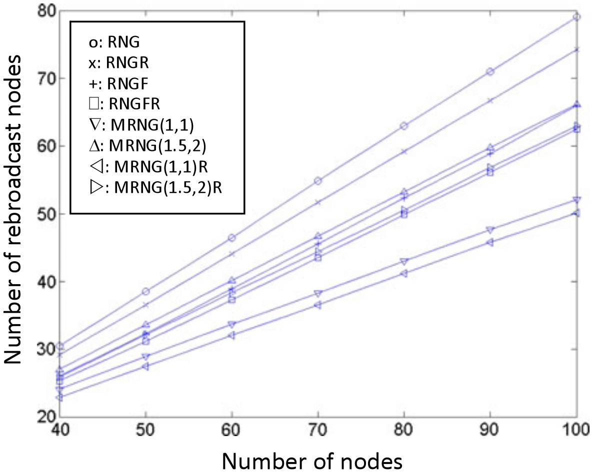
5.2 Results

Figure 14 shows the number of rebroadcast nodes as a function of the total nodes. In this figure, it can be observed that for all the methods the number of rebroadcast nodes increases when the number of nodes increases. In all cases, RNG has the largest number of rebroadcast nodes because it favors the use of many shorter links over a small number of long links. MRNG$(1, 2.5)$ has the second largest number of rebroadcast nodes because it assigns a relatively high weighting to distance, and therefore also prefers short links to long links. On the other hand, MRNG(1,1) gives an equal weight to the remaining battery capacity and distance and has the lowest number of rebroadcast nodes. The number of rebroadcast nodes for RNGF depends on the threshold value for the forbidden nodes since these nodes are banned from serving as rebroadcast nodes.

With the parameter values given in Table 1, approximately 20% of nodes are forbidden nodes; this limits the number of rebroadcast nodes. Removal of redundant rebroadcast effectively cuts down the number of rebroadcast nodes.

Figure 15 compares the degree of domination for each rebroadcast node. A higher degree of domination means that each transmission can reach more downstream nodes. Except for MRNG$(1, 1)$, all the methods have an average degree of domination below 2. It is also observed that the degree of domination is almost a constant, regardless of the number of nodes in the network. In general, the degree of domination shows a trend contrary to the number of rebroadcast nodes. Thus, MRNG$(1, 1)$ has

Fig. 14 Number of rebroadcast nodes versus total nodes



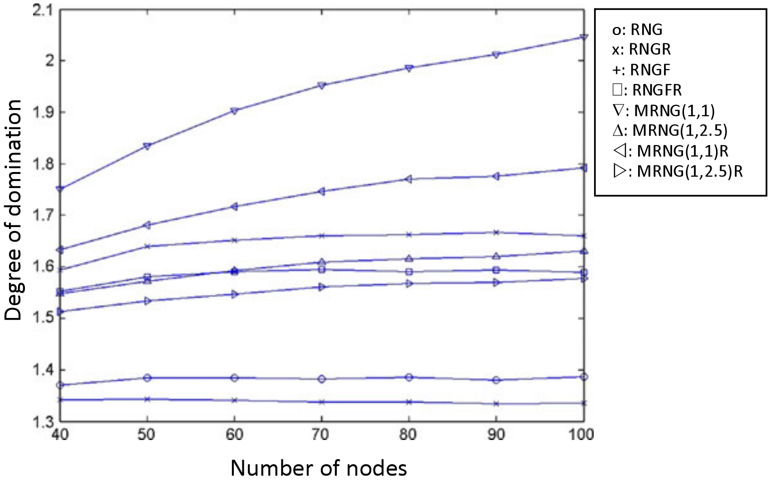


Fig. 15 Average degree of domination

the least number of rebroadcast nodes and the largest degree of domination. Interestingly, removal of redundant rebroadcast nodes also reduces the degree of domination for all of the methods. This can be justified by the fact that most rebroadcast nodes will have only one downstream node after the removal.

Figure 16 shows the total energy consumption of the broadcast path produced by all methods. This is the sum of the energy expended by all the nodes along the broadcast path, both transmitting and receiving data. The transmitting energy of a node in this study grows at least with the square of distance and with the fourth power beyond 87 m. Moreover, this energy is determined by the longest link between a rebroadcast node and its downstream nodes. Given that the maximum transmission is 250 m, the energy cost increases rapidly when the link is long. Since the number

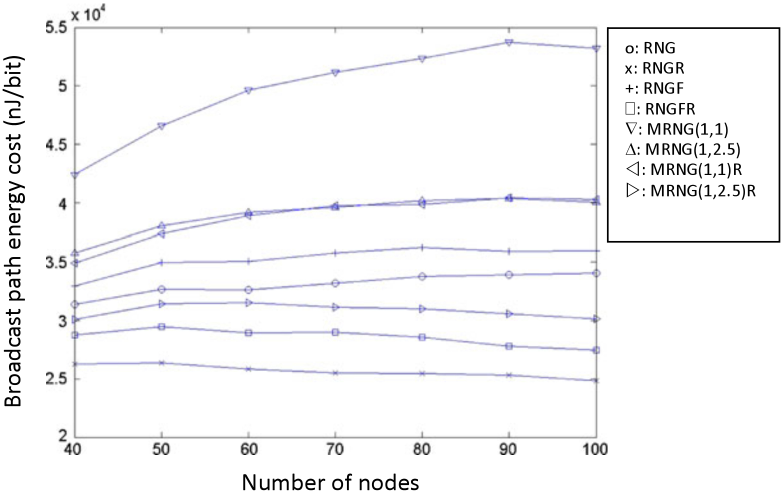


Fig. 16 Energy consumption of broadcast path

of rebroadcast nodes is smaller for MRNG(1, 1), it is likely to have few long links. This accounts for the relatively high energy expenditure for the method.

With a proportion of nodes prohibited from serving as rebroadcast nodes, RNGF is forced to choose longer links. Hence, its energy cost is higher than that of RNG. MRNG(1, 2.5) may also choose long links, but for a different reason, thus, it also tends to have high energy cost. As the number of nodes increases, the node density also increases. This means that the distance between nodes will decrease and lower the energy cost, as reflected in the curves. The reduction is particularly pronounced for MRNG(1, 1). Removal of redundant rebroadcasts is effective in curbing the energy waste. As can be seen in Fig. 16, most methods see a significant energy reduction by using the approach. This reduction is especially pronounced for MRNG(1, 1).

The lifetime of the broadcast path is compared next. This performance metric is different from the total path energy consumption. Instead, it is closely related to the ratio of the remaining battery energy at a node and the energy cost expended by it. In particular, the node which has the lowest ratio will decide the path lifetime and is critical to multimedia sharing applications. Figure 17 shows the results for the various methods.

The path lifetime improves with the number of nodes for all the methods. This is a result of shorter links as nodes get denser. RNG has a modest performance compared to other methods, better than MRNG(1, 1) but inferior to the others. RNGF outperforms the other methods when the number of nodes is small. This attests to the effectiveness of choosing nodes with high remaining battery capacity for rebroadcasting in extending the path lifetime. When the number of nodes is large, MRNG(1, 2.5) prevails. This can be attributed to the facts that MRNG(1, 2.5) takes the remaining energy into account and the way weighting is defined more closely matches with the energy cost model. Removal of redundant rebroadcasts again plays an important role in elongating the broadcast path lifetime. It should be noted that the lifetime of nodes on the broadcast path varies widely. Indeed certain nodes on the path can last for sev-

Fig. 17 Broadcast path lifetime

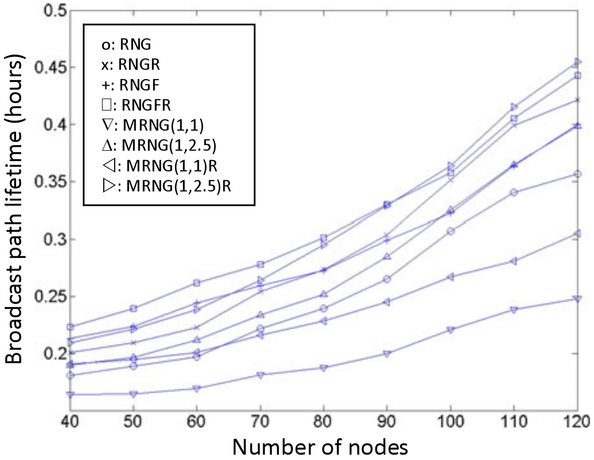
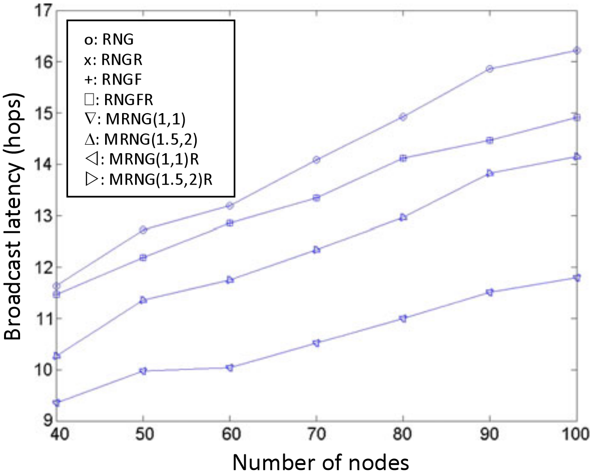


Fig. 18 Broadcast latency versus total nodes



eral hours before running out of battery energy. For the path lifetime, the shortest of node lifetimes is used.

The amount of time taken for a piece of data to arrive at all the nodes is also important in multimedia broadcasting applications. Figure 18 demonstrates the broadcast latency in terms of hop count. Note that because of the way the removal of redundant rebroadcasts is performed, the operation does not affect the broadcast latency. This is reflected in Fig. 18. Not surprisingly, since RNG opts for short links, it also has the longest latency. RNGF has to skip certain nodes and therefore has a shorter latency than RNG. The two MRNG algorithms exhibit the best performance in this aspect. A comparison of Fig. 14 with Fig. 18 shows that, in general, the more the rebroadcast nodes, the longer the latency.

6 Conclusions

This paper has investigated a number of approaches for incorporating the remaining battery energy as design parameters to boost the performance of RNG-based algorithms. These have led to a generalization of RNG-based algorithms (so-called MRNG(α, β) algorithms). The superiority of these algorithms in terms of performance over the original RNG-based algorithms has been established by simulations. The versatility of the design features of the MRNG(α, β) algorithms makes these algorithms suitable for use in ad hoc networks for multimedia applications. Another desirable feature of the algorithms is that they involve only localized information exchange, thereby making them appealing for a mobile environment consisting of moving nodes. This will be further investigated in our future research. In such an environment, it is important to cut down the overhead of control message interchanges. Some of the ideas discussed in [17] can be incorporated in the adaptation of the proposed algorithms.

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