A Study on the Min-Max Power-Aware Manycast Routing Problem in Static Ad Hoc Networks

Pi-Rong Sheu Yu-Ting Li
Department of Electrical Engineering, National Yunlin University of Science & Technology
Touliu, Yunlin 640, Taiwan, R.O.C.
Email: sheupr@yuntech.edu.tw

Abstract

In manycast transmission, a number of servers provide the same type of services and resources. When a client wants to get services or resources, the manycast routing algorithm will arrange a set of suitable servers to it. In this paper, we will consider the problem of designing a manycast routing algorithm to efficiently arrange manycast transmission requirements such that the power consumption of each node is as even as possible to extend the network's lifetime. In this paper, we will first show such a problem to be NP-complete. Next, based on Dijkstra's algorithm, an efficient heuristic algorithm is developed for the difficult problem. Computer simulations verify that the lifetimes of networks generated by our power-balanced manycast routing algorithm are longer than those generated by our another shortest-path-based manycast routing algorithm.

Keywords: Ad Hoc Network, Manycast, Routing, NP-Completeness, Power-Aware.

1. Introduction

An ad hoc network is formed by a group of hosts (or nodes) not embedded in an infrastructure of fixed base stations [13]. A host in an ad hoc network can act as both a general host and a router, i.e., it can generate as well as forward packets. Two hosts in such a network can communicate directly with each other through a single-hop routing path in the shared wireless media if their positions are close enough. Otherwise, they need a multi-hop routing path to finish their communications. In a multi-hop routing path, the packets sent by a source are relayed by several intermediate hosts before reaching their destinations. Ad hoc networks are found in applications such as short-term events, battlefield communications, disaster relief operations, and so on. Undoubtedly, ad hoc networks play a critical role in an environment where a wired infrastructure is neither available nor easy to establish [13].

Battery power has always remained one of the central issues in ad hoc networks. This is because the operation of a host in an ad hoc network is totally subject to its power capacity and consumption rate [9]. When battery power is drained, the host will disappear from the ad hoc network, risking the overall operation of the network as well as the transmissions of data packets. In designing routing protocols for ad hoc networks, if the factor of node's power consumption is neglected, two undesirable consequences may arise. First, every node may experience an unequal degree of power consumption. As a result, some nodes will consume power faster than other nodes [9][4][12]. Eventually, the lifetime of network will be shortened [12]. Second, the overall power in the network will be consumed on a large scale, endangering its lifetime (One of the common definitions of the network's lifetime is the time period from the beginning of the network's operation to the time when one of the nodes exhausts its battery power [13].) In view of these flaws, the inclusion of a power-aware mechanism into routing protocols (or algorithms) has recently become a focus of study in an ad hoc network. In general, there are two main strategies for designing power-aware routing protocols (or algorithms) in the related literature. The first strategy attempts to reduce each node's power consumption equally such that the lifetime of network is prolonged. The other tries to decrease the network's overall battery power consumption in quest of a longer network's lifetime. Let us use Figure 1 to illustrate the difference between the two strategies. In Figure 1, each node is supposed to possess the same battery power of 100. The number next to each link represents the power to be consumed when one connection is delivered through the link. Now, consider that node v_1 will send k data packets to node v_4. If node v_1 selects path $v_1 \rightarrow v_2 \rightarrow v_3 \rightarrow v_4$ as its routing path, the network's total transmission power consumption will be $(15+3+3)\times k = 21\times k$ and the network's lifetime will be $\min\{\left\lfloor \frac{100}{15} \right\rfloor, \left\lfloor \frac{100}{3} \right\rfloor, \left\lfloor \frac{100}{3} \right\rfloor\} = \min\{6,33,33\} = 6$. If node v_1 selects path $v_1 \rightarrow v_5 \rightarrow v_6 \rightarrow v_4$ as its routing path, the network's total transmission power consumption will be $(8+8+8)\times k = 24\times k$ and the network's lifetime will be $\min\{\left\lfloor \frac{100}{8} \right\rfloor, \left\lfloor \frac{100}{8} \right\rfloor, \left\lfloor \frac{100}{8} \right\rfloor\} = \min\{12,12,12\} = 12$. If node v_1 selects path $v_1 \rightarrow v_7 \rightarrow v_8 \rightarrow v_4$ as its routing path, the network's total transmission power consumption will be $(10+10+7)\times k = 27\times k$ and the network's lifetime will be $\min\{\left\lfloor \frac{100}{10} \right\rfloor, \left\lfloor \frac{100}{10} \right\rfloor, \left\lfloor \frac{100}{7} \right\rfloor\} = \min\{10,10,14\} = 10$. In the three situations, it is easy to observe that a smaller total transmission power does not always imply a longer network lifetime, exemplified by path $v_1 \rightarrow v_2 \rightarrow v_3 \rightarrow v_4$. On the other hand, we discover that when the power consumptions of nodes even out, the associated network's lifetime will be longer, as path $v_1 \rightarrow v_5 \rightarrow v_6 \rightarrow v_4$ shows. In this paper, we will take the approach of leveling each node's power consumptions as a starting point.

In ad hoc networks, common communication models among hosts include unicast (one-to-one) transmission, anycast (one-to-any) transmission [1][6][10][11], multicast (one-to-many) transmission, and broadcast (one-to-all) transmission. Besides, manycast transmission has been comprehensively investigated and become an important communication model recently [3]. In fact, manycast transmission is a group communication model in which a number of servers (or called source nodes) provide the same type of services and resources. When a client (or called a destination node) wants to get services or resources, the manycast routing algorithm will arrange a set of suitable servers to it, i.e., one client will communication with multiple ($k \geq 1$) servers at the same time, where *k* is specified by each client. Notice that when $k = 1$ for each client, manycast transmission becomes anycast transmission. That is, anycast transmission is a special case of manycast transmission. At present, there exist a lot of network applications which adopt manycast transmission. For example, a distributed certificate authority for wired networks has been established by COCA (Cornell On-Line Certification Authority) [17]. Furthermore, such a system has been extended to wireless ad hoc networks by MOCA (Mobile Certificate Authorities) [16]. On three distributed examination key systems, authority is distributed across several servers using threshold cryptography. Therefore a client must contact several servers simultaneously for certification [3].

When designing manycast routing algorithms for ad hoc networks, we must take the main characteristic of ad hoc networks into consideration: the battery power of each host is very limited. If the routing requirements are arranged by those manycast routing algorithms only armed with shortest-path routing paths, individual power consumption may vary although the total transmission power consumption is smaller. As a result, the network may suffer very short lifetime. Instead, if we attempt to evenly distribute packet-relaying loads among nodes to prevent the overuse or abuse of battery power [8][9][12][14], we believe that the network's lifetime will be extended significantly. For example, in the above distributed certificate authority system, when the requirements of most clients are satisfied by the same set of servers, the battery power of some nodes (including source nodes and intermediate nodes) may be consumed abnormally quickly, which implies the lifetime of network may be shortened significantly.

To illustrate the importance of power balance, let us consider the example shown in Figure 2. In Figure 2(a), let nodes v_{s_1}, v_{s_2}, and v_{s_3} be the source nodes and nodes v_{d_1} and v_{d_2} be the destination nodes, respectively. The number next to each link represents the power to be consumed when one connection is delivered through the link. Now, consider that each destination node will require two connections. If the routing paths are allocated as shown in Figure 2(b), obviously, the power of node v_{o_2} will be overused and the network's lifetime may become very short. On the other hand, if the routing paths are allocated carefully, as Figure 2(c) shows, the power consumption of each node will be more balanced. In this case, we are convinced of a longer network's lifetime.

In this paper we will thus define our goal of study: designing an efficient manycast routing algorithm to arrange manycast transmission requirements such that the power consumption of each node is as balanced as possible. We will call it *the min-max power-aware manycast routing (MMPAMR) problem*. To be more specific, given a set of destination nodes each of which requires a different amount of connections, find a set of routing paths between the given source nodes and the given destination nodes such that the power consumption of each node in the network is as even as possible. Undoubtedly, the resulted lifetime of network is extended. While it is easy to find a set of routing paths with the minimal total transmission power consumption to satisfy the connection requirement of each destination hosts, in this paper we will prove that the MMPAMR problem is NP-complete.

To solve the difficult MMPAMR problem, based on Dijkstra's algorithm, an efficient heuristic algorithm with low time complexity is developed. Computer simulations verify that the lifetimes of networks generated by our power-balanced manycast routing algorithm are longer than those generated by our another shortest-path-based manycast routing algorithm.

The rest of the paper is organized as follows. In Section 2, a formal definition of our MMPAMR problem is given. In Section 3, our MMPAMR problem is proved to be NP-complete. In Section 4, efficient heuristic algorithms for the MMPAMR problem are proposed. In Section 5, the performances of our heuristic algorithms are evaluated through computer simulations. Lastly, Section 6 concludes the whole research.

2. The Definition of our MMPAMR Problem

In this section, we will introduce our some assumptions, notations, and definitions. A formal definition of our problem in terms of these notations and definitions will also been stated. In the following, the term "node" is synonymous with the term "host" and the term "link" is synonymous with the term "communication channel".

2.1 Assumptions

The following states some important assumptions used in our research.

(1) We assume that the ad hoc network's topology would not change, i.e. no host gets move. The assumption has been adopted in [2][9][15].

(2) We only consider the transmission power and ignore the reception power. The assumption has been adopted in [5].

(3) We assume that the required transmission power to establish a communication channel between any two hosts x and y is the same. In other words, $c(<v_x, v_y>) = c(<v_y, v_x>)$, where $c(<v_x, v_y>)$ and $c(<v_y, v_x>)$ denote the minimal transmission power required by hosts x and y to establish communication channels $<v_x, v_y>$ and $<v_y, v_x>$, respectively. The assumption has been adopted in [5].

(4) We assume that when one connection passes through a link, the transmission power consumption associated with the link can be an arbitrary value, i.e., can be independent of the Euclidean length of link. The assumption has adopted in [2][5].

2.2 Problem Formulation

We represent an ad hoc network by a weighted graph $G = (V, E)$, where V denotes the set of hosts (including source hosts, destination hosts, and intermediating hosts) and E denotes the set of communication channels connecting the hosts. Let $D = \{v_{d_1}, v_{d_2}, ..., v_{d_n}\}$ be a set of destination hosts. For D, we define *a connection requirement function* $\gamma : D \rightarrow I^+$. The value $\gamma(v_{d_i})$ represents the number of connections required by destination v_{d_i}. For E, we define a *transmission power consumption function* $\beta:\ E \rightarrow\ R^+$ that assigns a nonnegative weight to each link in the network. The value $\beta(v_i, v_j)$ associated with link $(v_i, v_j) \in E$ represents the transmission power that node v_i will consume when one connection is delivered through that link. For E, we define *a connection flow function* $f : E \rightarrow I^+$. The value $f(v_i, v_j)$ denotes the number of connections passing through link (v_i, v_j). For V, we define *a node power consumption function* $\alpha : V \rightarrow R^+$. Thus, $\alpha(v_i) = \sum_{(v_i, v_j) \in E} f(v_i, v_j) \times \beta(v_i, v_j)$ represents the total transmission power that node v_i will consume during the deliveries of all the connections required by all the destination nodes.

Based on these notations and definitions, now we can formally describe our min-max power-aware manycast routing (MMPAMR) problem as follows: given a weighted graph G=(V,E), a set of *source hosts* $S = \{v_{s_1}, v_{s_2}, ..., v_{s_m}\}$ and a set of destination hosts $D = \{v_{d_1}, v_{d_2}, ..., v_{d_n}\}$, *a connection requirement function* $\gamma : D \rightarrow I^+$, *a transmission power consumption function* $\beta:\ E \rightarrow\ R^+$, find a set of routing paths such that (1) the connection requirement function of each destination node is satisfied, (2) each source provides at most one connection to each destination, and (3) the maximum of node's transmission power consumption in G is minimized , i.e., $\max_{v_i \in G}\{\alpha(v_i)\}$ is minimized.

As an example, let us consider Figure 2(a) again, where an ad hoc network is shown with three source nodes and two destination nodes. The number next to each node represents the number of connections required by the node. The number next to each link represents the power to be consumed when one connection is delivered through the link. Figure 3 shows a set of routing paths with the best power balance. In this case, the maximum of node's transmission power consumption in the network $\max_{v_i \in G}\{\alpha(v_i)\}$ is equal to $\alpha(v_{s_2})$ = 4 + 4 = 8, which is the best solution.

3. The Complexity of our MMPAMR Problem

In this section, we will show that our MMPAMR problem is NP-complete. To prove our MMPAMR problem to be NP-complete, first let us restate it in its decision version as follows: given a weighted graph G=(V,E), a set of *source hosts* $S = \{v_{s_1}, v_{s_2}, ..., v_{s_m}\}$, a set of destination hosts $D = \{v_{d_1}, v_{d_2}, ..., v_{d_n}\}$, *a connection requirement function* $\gamma : D \rightarrow I^+$, *a transmission power consumption function* $\beta:\ E \rightarrow\ R^+$, *a power-constrained constant* c_p, find a set of routing paths such that (1) the connection requirement function of each destination node is satisfied, (2) each source provides at most one connection to each destination, and (3) the maximum of node's transmission power consumption in G is less than or equal to c_p, i.e., $\max_{v_i \in G}\{\alpha(v_i)\} \leq c_p$. For simplicity, in what follows, we will not distinguish the decision version and the optimal version of the MMPAMR problem when no ambiguity arises.

Next, let us introduce the *3-Dimensional*

Matching (3DM) problem [7].
Instance: A set $M \subseteq W \times X \times Y$, where *W*, *X*, and *Y* are disjoint sets having the same number *q* of elements.
Question: Does *M* contain a *matching*, that is, a subset $M' \subseteq M$ such that $|M'| = q$ and no two elements of M' agree in any coordinate?
This problem was shown to be NP-complete by Karp [7]. Now, we will use it to prove the following theorem.

Theorem 1. The MMPAMR problem is NP-complete.

Proof. First, the MMPAMR problem can be easily seen to be in the class NP. We next transform the 3DM problem to the MMPAMR problem in polynomial time. Let the sets *W*, *X*, *Y*, with $|W| = |X| = |Y| = q$, and $M \subseteq W \times X \times Y$ be an arbitrary instance of 3DM. Let the elements of these sets be denoted by $W=\{w_1,w_2,\cdots,w_q\}$, $X=\{x_1,x_2,\cdots,x_q\}$, $Y=\{y_1,y_2,\cdots,y_q\}$ and $M=\{m_1,m_2,\cdots,m_k\}$, where $k=|M|$. We construct an instance of the MMPAMR problem as follows: For each element w_i (x_i, y_i) of W, the corresponding weighted graph *G* = (*V*, *E*) has a source node v_{w_i} (an intermediate nodes v_{x_i}, a destination node v_{y_i}) (1 ≤ *i* ≤ *q*). Thus, $V = \{v_{w_1}, v_{w_2}, \ldots, v_{w_q}\} \cup \{v_{x_1}, v_{x_2}, \ldots, v_{x_q}\} \cup \{v_{y_1}, v_{y_2}, \ldots, v_{y_q}\}$. If $(w_i, x_j, y_k) \in M$, then there exist one edge $<v_{w_i}, v_{x_j}>$ between nodes v_{w_i} and v_{x_j}, and one edge $<v_{x_j}, v_{y_k}>$ between nodes v_{x_j} and v_{y_k}. Thus, the edge set $E = \{<v_{w_i}, v_{x_j}> : \text{if } (w_i, x_j, y_k) \in M\} \cup \{<v_{x_j}, v_{y_k}> : \text{if } (w_i, x_j, y_k) \in M\}$. The number of connections required by each destination node v_{y_k} is assumed to be $\gamma(v_{y_k}) = 1$. Each edge has a transmission power consumption of 1 when one connection traverses it. Finally, let c_p =1. The constructed *G* is illustrated in Figure 4. It is easy to see that this transformation can be finished in polynomial time.

We next show that there exists a set of feasible routing paths for the MMPAMR problem in *G* if and only if the set *M* contains a matching M'. First, suppose *M* contains a *matching*, that is, a subset $M' \subseteq M$ such that $|M'| = q$ and no two elements of M' agree in any coordinate. If $(w'_i, x'_j, y'_k) \in M'$, then we let $(v_{w'_i}, v_{x'_j}, v_{y'_k})$ be a routing path in G between source node $v_{w'_i}$ and destination node $v_{y'_k}$. Since $|M'| = q$, there are *q* routing paths each of which is for a different pair of source and destination nodes. Since no two elements of M' agree in any coordinate, these routing paths are pairwise node-disjoint. Because they are pairwise node-disjoint, any link (v_i, v_j) belongs to at most one of these *q* paths. Therefore, for each link $(v_i, v_j) \in E$, $f(v_i, v_j) \le 1$. Similarly, any node v_i belongs to at most one of these *q* paths. So, for any $v_i \in V$, $\sum_{(v_i,v_j)\in E} f(v_i, v_j) \le 1$. Thus, for any $v_i \in V$, we have $\alpha(v_i) = \sum_{(v_i,v_j)\in E} \beta(v_i,v_j) \times f(v_i,v_j) = \sum_{(v_i,v_j)\in E} 1 \times f(v_i,v_j) \le 1$. As a result, $\max_{v_i \in G}\{\alpha(v_i)\} \le 1 = c_p$. Thus, these *q* routing paths form a set of feasible routing paths for the corresponding MMPAMR problem in G. Next, suppose we have a solution for the MMPAMR problem in the weighted graph *G*. Let $\overline{P}_1, \overline{P}_2, \cdots, \overline{P}_q$ be one of the possible solutions in G. Because $\max_{v_i \in G}\{\alpha(v_i)\} \le 1 = c_p$, $\alpha(v_i) \le 1$ for each node v_i. Furthermore, each link has a transmission power consumption of 1, each node v_i belongs to at most one path $\overline{P}_l$ (otherwise, $\alpha(v_i) > c_p = 1$). Thus paths $\overline{P}_1, \overline{P}_2, \cdots, \overline{P}_q$ are pairwise node-disjoint. If $\overline{P}_t \in (\overline{P}_1, \overline{P}_2, \cdots, \overline{P}_q)$, where $\overline{P}_t = (v_{\overline{w}_{t_i}}, v_{\overline{x}_{t_j}}, v_{\overline{y}_{t_k}})$, then let $(\overline{w}_{t_i}, \overline{x}_{t_j}, \overline{y}_{t_k}) \in M'$. Clearly $|M'| = q$, $M' \subseteq M$, and no two elements of M' agree in any coordinate. Thus, M' is a matching. This completes our proof of NP-completeness. ▓

From the proof of Theorem 1, we can obtain the following results easily.

Corollary 1. The MMPAMR problem is strongly NP-complete. That is, the problem remains NP-complete even if the transmission power consumption of each line is constrained to be below a given constant.

Corollary 2. The MMPAMR problem is still NP-complete even when the transmission power consumptions of all the lines are the same.

When a problem is proved to be NP-complete, the follow-up quest will be to search for various heuristic algorithms for the problem and evaluate them by computer simulations. In the next section, we will design efficient heuristic algorithms for the

MMPAMR problems.

4. Efficient Heuristic Algorithms for the MMPAMR Problem

In this section, we will propose two heuristic algorithms for the MMPAMR problem. One is simpler and faster while the other is more efficient. The first one is based on a shortest path algorithm, and we call it the shortest path manycast routing algorithm (the SPMR algorithm, for short). The other is a routing algorithm with power-balanced, and we call it the power-balanced manycast routing algorithm (the PBMR algorithm, for short).

The spirit of the SPMR algorithm is to use the Dijkstra's algorithm to satisfy each connection requirement. Figure 5 is the description of the SPMR algorithm. The P in line 2 is to save the set of the routing path for all the connection requirements, $\hat{P}$ is to save the set of the shortest paths in each round, and $list_{xy}$ records the connection status ($list_{xy}$=1 represents that node v_{d_y} will be not able to establish any connection to node v_{s_x} in the following rounds). Line 4 to line 9 are to find the shortest path for each pair of source and destination. Line 10 to line 12 search the routing path with the minimal power consumption among the routing paths existing in set $\hat{P}$ to establish the connection, and set $list_{xy}$=1 where v_{s_x} is the source node and v_{d_y} is the destination node. The process will not stop until we generate the routing paths for all the connection requirements. Line 14 to line 16 compute the transmission power consumption of each node. Line 18 outputs the set of routing paths P and the transmission power consumption of each node.

Our second heuristic algorithm, the PBMR algorithm, is to improve the SPMR algorithm. We discover that the power of some nodes will be overused when most routing paths bypass the same set of nodes. This will result in decreasing the lifetime of network. The basic idea of our PBMR algorithm is as follows: after one connection is established, we remove the node with maximal transmission power consumption in the network temporarily to prevent the overuse of this node. Figure 6 is the description of our PBMR algorithm.

The P in line 2 is used to save the set of the routing path for all the connection requirements, $\hat{P}$ is used to save the set of the shortest paths in each round, Q_j is used to indicate whether there are paths connect the node v_{d_j} to any source node, V' is the set of residual nodes after each round, and $list_{xy}$ is to record the connection status ($list_{xy}$=1 represents that node v_{d_y} will be able not to establish any connection to node v_{s_x} in the following rounds). Line 4 to line 9 are used to find the shortest path for each pair of source and destination. Line 11 makes V' to be recovered from V when there doesn't exist any path to connect the destination v_{d_j} with non-zero remaining connection requirements to any source. And then we will search the shortest paths for v_{d_j} to all the source nodes. Line 12 to line 14 search the routing path with the minimal power consumption among the routing paths existing in set $\hat{P}$ to establish the connection, and set $list_{xy}$=1 where v_{s_x} is the source node and v_{d_y} is the destination node. Line 15 removes the node with maximal transmission power consumption in the network and produces a new graph $G=(V',E)$. The process will not stop until we obtain the routing paths for all the connection requirements. Line 18 to line 20 compute the transmission power consumption of each node. Line 21 outputs the set of routing paths P and the transmission power consumption of each node.

Example

We will explain the operation of our PBMR algorithm by using Figure 7. In Figure 7(a), let nodes v_{s_1}, v_{s_2}, and v_{s_3} be the source nodes and nodes v_{d_1} and v_{d_2} be the destination nodes, respectively. The number next to each link represents the power to be consumed when one connection bypasses this link. Now, consider that each destination node will require two connections. First of all, we will find the shortest paths for each pair of source and destination, shown as Figure 7(b). In Figure 7(c), we select the routing path with minimal power consumption from the set of routing paths and set it as the first routing path for all the connection requirements. Next, we will remove the node with the maximal transmission power consumption in the network, which is node is v_2. We repeat this process until all the connection requirements are satisfied. In Figure 7(f), there is one connection requirement for v_{d_1} yet and we can not find any routing path for v_{d_1}. At this time, we will use the original graph G to find the shortest paths from all the source nodes to v_{d_1}, and then repeat the process we mention before, shown in Figure 7(g). Figure 7(h) shows the result produced by our PBMR algorithm while Figure 7(i) shows the result produced by our SPMR algorithm. We can see that the node with maximal transmission power consumption obtained by our PBMR algorithm is v_{s_2}, whose

$\alpha(v_{s_1})$ is 8. On the other hand, the node with maximal transmission power consumption obtained by the SPMR algorithm is v_{s_1}, whose $\alpha(v_{s_1})$ is 13. Therefore, we can see that our PBMR algorithm is more efficient than the SPMR algorithm. We will further justify the fact by the computer simulation in Section 5.

5. Computer Simulations

In this section, by means of computer simulations, we will examine the efficiency of the SPMR algorithm and the PBMR algorithm. We will observe the maximal node's power consumption in the network and the network's lifetime. The lifetime of network is measured in terms of $\frac{\text{residual power}}{\max_{v_i \in V}\{\alpha(v_i)\}}$ (where we set the residual power of each node to be 10000), i.e., the connections have been successfully established from their sources to their destinations during the time period from the beginning of network's operation to the time when the first node exhausts its residual power.

5.1 Simulation Results

In this subsection, we will present and discuss the simulation results of the SPMR algorithm and the PBMR algorithm in four different simulation environments.

The environments in our first simulation are set as follows: the network consists of 100 nodes which are located in a 100×100 m^2 area randomly. The number of links is set to $N\times(N-1)/4$, where N is 100. The transmission power consumption of each link is assigned to a value between 10 and 40 randomly. The number of destination nodes is set to 10. The number of connections required by each destination node is assigned to a value between 1 and 10 randomly. In our first simulation environment, we will observe how the number of source nodes impacts on the performances of our PBMR algorithm and the SPMR algorithm. Figure 8 shows the simulation results, where we vary the number of source nodes from 10 to 50. From Figure 8(a), it can be found that the maximal node's power transmission consumption in the network produced by our PBMR is much lower than those produced by the SPMR algorithms. We can also observe that the maximal node's transmission power consumption decreases with the raising of the number of source nodes. This is because the more source nodes exist, there are more chances for manycast routing algorithms to select the proper source nodes to establish connections to each destination node. From Figure 8(b), we can see that our PBMR algorithm has longer lifetime than the SPMR algorithm before the first node shuts down (i.e. the first node exhausts its residual power).

The environments in our second simulation are set as follows: the network consists of 50 nodes which are located in a 100×100 m^2 area randomly. The transmission power consumption of each link is assigned to a value between 10 and 40 randomly. The number of source nodes is set to 20 and the number of destination nodes is set to 10. The number of connections required by each destination node is assigned to a value between 1 and 10 randomly. In our second simulation environment, we will observe how the total number of links impacts on the performances of the two heuristic algorithms. From Figure 9(a) (where N denotes the total number of nodes in the network, and in this case N is 50), it can be easily found that the maximal node's transmission power consumption of the two heuristic algorithms decrease with the raising of the total number of links. This is because the more the total number of links is, there are more chances for the manycast routing algorithms to select the proper routing paths each destination node. The maximal node's transmission power consumption obtained by PBRM algorithm is also lower than the values obtained by the SPMR algorithm. Figure 9(b) shows our PBMR algorithm has longer lifetime than the SPMR algorithm.

The environments in our third simulation are set as follows: the network consists of variant numbers of nodes which are located in a 100×100 m^2 area randomly. The number of links is set to $N\times(N-1)/4$ (where N denotes the total number of nodes). The transmission power consumption of each link is assigned to a value between 10 and 40 randomly. The number of source nodes is set to 20 and the number of destination nodes is set to 10. The number of connections required by each destination node is assigned to a value between 1 and 10 randomly. In our third simulation environment, we will observe how the size of network impacts on the performances of our PBRM algorithm and the SPMR algorithm. Figure 10 gives the simulation results when the total number of nodes varies from 60 to 100. Figure 10(a) and Figure 10(b) tell us that the size of network doesn't affect the performances of these two algorithms too much.

The environments in our fourth simulation are set as follows: the network consists of variant numbers of nodes which are located in a 100×100 m^2 area randomly. The total number of nodes varies from 20 to 100. The number of links is set to $N\times(N-1)/4$ (where N denotes the total number of nodes in network). The transmission power consumption of a links is assigned to a value between 10 and 40 randomly. The number of source nodes is set to $1/2\times N$, and the number of destination nodes is set to $1/4\times N$. The number of connections required by each destination node is assigned to a value between 1 and 10 randomly. In our forth simulation environment, we will observe how the structure of network impacts on the performances of the two heuristic algorithms. Figure 11(a) and Figure 11(b) show that the maximal node's transmission power consumption of the two heuristic algorithms decreases with the raising of the total number of nodes. Because the number of connections required by each destination node is fixed, the power of each node in the network with small structure will may be overused. That is, the larger the structure is, the lower the maximal node's transmission power consumption is.

6. Conclusions

In this paper, we have shown the MMPAMR problem to be NP-complete. Based on the Dijkstra's algorithm, two heuristic algorithms with low time complexities have been developed. The SPMR algorithm is simpler and faster while the PBMR algorithm is more efficient. Computer simulations verify that of the PBMR algorithm is more efficient than the SPMR algorithm.

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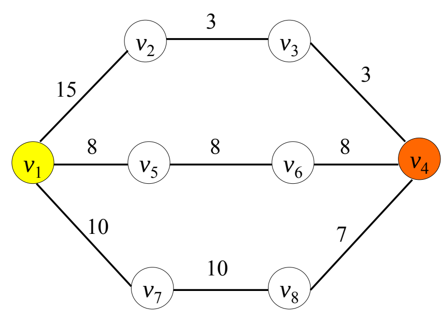
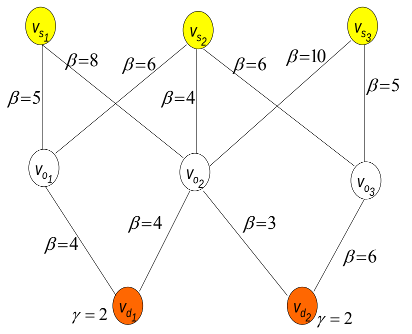
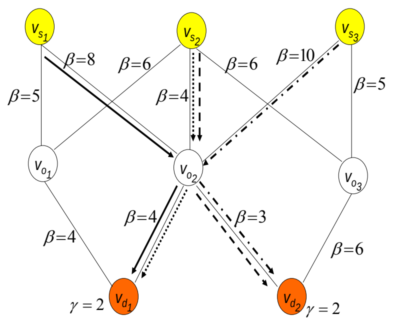


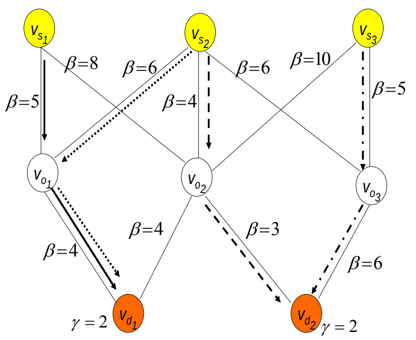
Figure 1: A smaller total transmission power does not always imply a longer network's lifetime.



(a)



(b)



(c)

Figure 2: The importance of power balance.

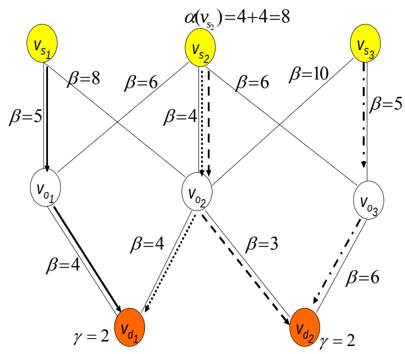


Figure 3: An illustration of our MMPAMR problem.

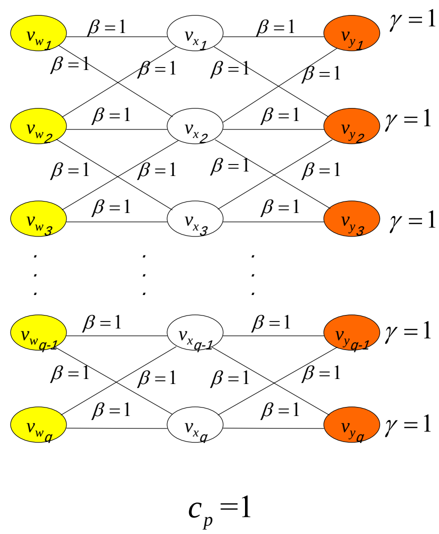


Figure 4: An illustration of Theorem 1.

The SPMR algorithm

Input: Given a weighted graph G=(V,E), a set of *source hosts* $S=\{v_{s_1},v_{s_2},...,v_{s_m}\}$ and a set of destination hosts $D=\{v_{d_1},v_{d_2},...,v_{d_n}\}$, *a connection requirement function* $\gamma: D \rightarrow I^+$, *a transmission power consumption function* $\beta: E \rightarrow R^+$

Output: (1) a routing path for each connection requirement

(2) the power consumption of each node $\alpha(v_i)$

1. begin
2. $P=\Phi$; $\hat{P}=\Phi$; $V'=V$; $f(v_i,v_j)=0$ for each $(v_i,v_j)\in E$; $\alpha(v_i)=0$ for each $v_i\in V$; $list_{xy}=0$ for each $v_{s_x},v_{d_y}\in V$;
3. while $\gamma(v_{d_i})\neq 0$, for any $v_d \in D$ do
4. for $i=1$ to m
5. for $j=1$ to n
6. if there exists paths between v_{s_i} and v_{d_j} in G then {find P_{ij} with the smallest total transmission consumption power between v_{s_i} and v_{d_j} in G by the Dijkstra's algorithm ; }
7. $P=P\cup\{P_{ij}\}$;
8. end of for j loop
9. end of for i loop
10. **label 1:** select P'_{xy} with the smallest total transmission consumption power from P ;
11. if $\gamma(v_{d_y})=0$ or $list_{xy}=1$ then $\{P=P-\{P'_{xy}\}$; go to **label 1** ; }
12. else $\{\gamma(v_{d_y})=\gamma(v_{d_y})-1$; $f(v_i,v_j)=f(v_i,v_j)+1$ for each $(v_i,v_j)\in P'_{xy}$; $\hat{P}=\hat{P}\cup\{P'_{xy}\}$; $list_{xy}=1\}$
13. end of while
14. for each $v_i\in V$ do
15. $\alpha(v_i)=\sum_{(v_i,v_j)\in E}(\beta(v_i,v_j)\times f(v_i,v_j))$;
16. end of for loop
17. return P , α ;
18. end of the algorithm ;

Figure 5: The SPMR algorithm.

The PBMR algorithm

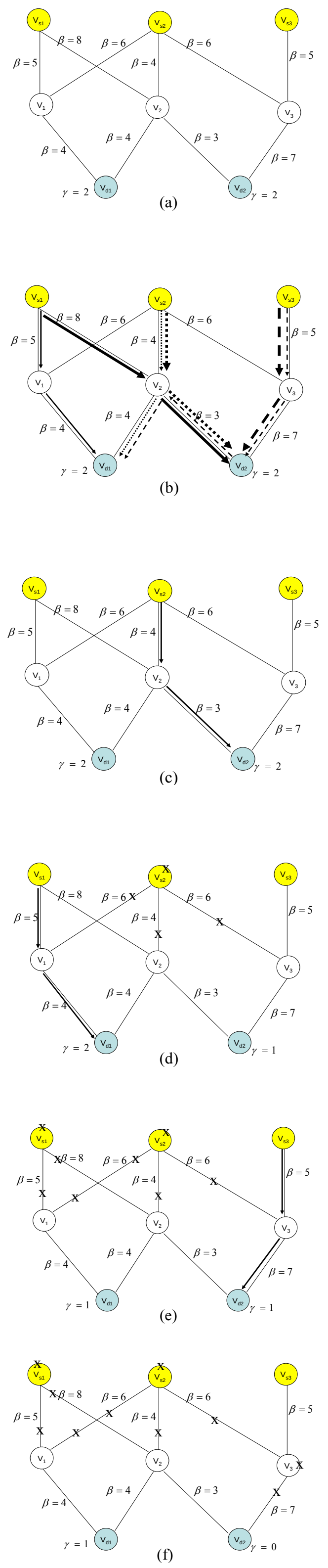
Input: Given a weighted graph G=(V,E), a set of *source hosts* $S=\{v_{s_1},v_{s_2},...,v_{s_m}\}$ and a set of destination hosts $D=\{v_{d_1},v_{d_2},...,v_{d_n}\}$, *a connection requirement function* $\gamma: D \rightarrow I^+$, *a transmission power consumption function* $\beta: E \rightarrow R^+$

Output: (1) a routing path for each connection requirement

(2) the power consumption of each node $\alpha(v_i)$

1. begin
2. $P=\Phi$; $\hat{P}=\Phi$; $V'=V$; $f(v_i,v_j)=0$ for each $(v_i,v_j)\in E$; $\alpha(v_i)=0$ for each $v_i\in V$; $Q_j=0$ for each $v_{d_j}\in V$; $list_{xy}=0$ for each $v_{s_x},v_{d_y}\in V$;
3. while $\gamma(v_{d_i})\neq 0$, for any $v_{d_i} \in D$ do
4. for $i=1$ to m
5. for $j=1$ to n
6. if there exists paths between v_{s_i} and v_{d_j} in G then {find P_{ij} with the smallest total transmission consumption power between v_{s_i} and v_{d_j} in G by the Dijkstra's algorithm ; }
7. $P=P\cup\{P_{ij}\}$;
8. end of for j loop
9. end of for i loop
10. if there is no path exists between v_{d_j} and any source node then $Q_j=1$;
11. if $Q_j=1$ and $\gamma(v_{dj})\neq 0$ then $\{V'=V$; $G=(V',E)$;
for $i=1$ to m
if there exists paths between v_{s_i} and v_{d_j} in G then {find P_{ij} with the smallest total transmission consumption power between v_{si} and v_{dj} in G by the Dijkstra's algorithm ; $P=P\cup\{P_{ij}\}$; $Q_j=0$;
end of for i loop }
12. **label 1:** select P'_{xy} with the smallest total transmission consumption power from P ;
13. if $\gamma(v_{d_y})=0$ or $list_{xy}=1$ then $\{P=P-\{P'_{xy}\}$; go to **label 1** ; }
14. else $\{\gamma(v_{d_y})=\gamma(v_{d_y})-1$; $f(v_i,v_j)=f(v_i,v_j)+1$ for each $(v_i,v_j)\in P'_{xy}$; $\hat{P}=\hat{P}\cup\{P'_{xy}\}$; $list_{xy}=1\}$
15. find the node $V_{\max}$ with the maximum $\alpha(v_i)=\sum_{(v_i,v_j)\in E}(\beta(v_i,v_j)\times f(v_i,v_j))$ for each $v_i\in V$;
16. $V'=V'-\{V_{\max}\}$; $G=(V',E)$;
17. end of while
18. for each $v_i\in V$ do
19. $\alpha(v_i)=\sum_{(v_i,v_j)\in E}(\beta(v_i,v_j)\times f(v_i,v_j))$;
20. end of for loop
21. return P , α ;
22. end of the algorithm ;

Figure 6: The PBMR algorithm.



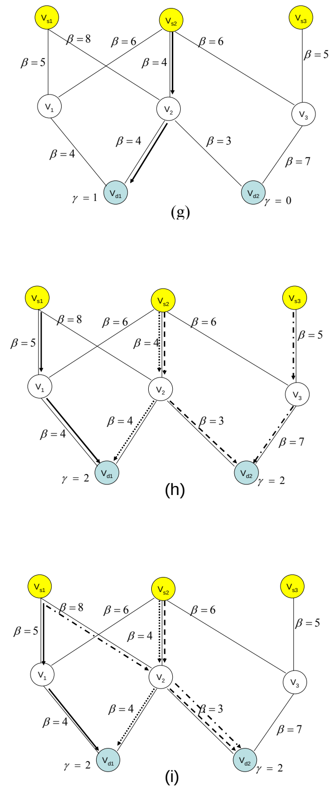
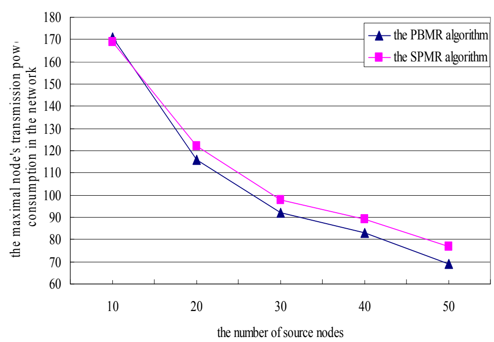
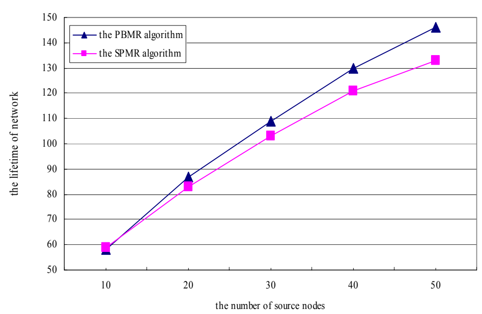


Figure 7: An example to illustrate the operation of the PBMR algorithm.

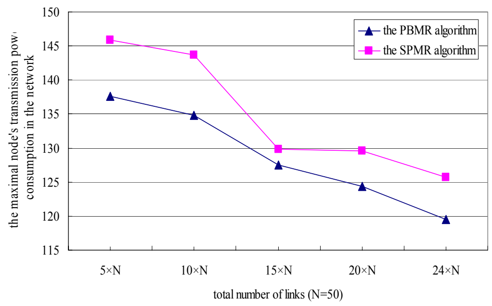


(a)The effect of the number of source nodes on the maximal node's transmission power consumption in the network

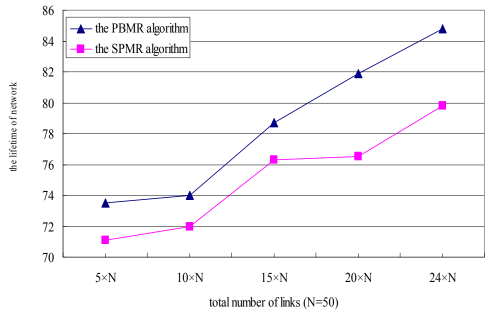


(b)The effect of the number of source nodes on the lifetime of network

Figure 8: The influence of the number of source nodes.

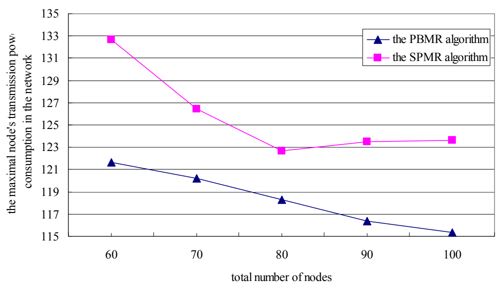


(a)The effect of the total number of links on the maximal node's transmission power consumption in the network

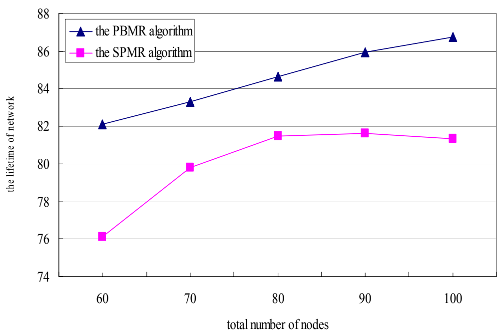


(b)The effect of the total number of links on the lifetime of network

Figure 9: The influence of the total number of links.

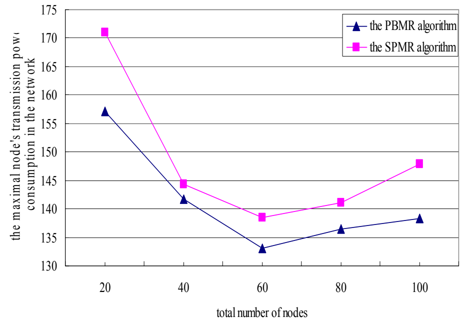


(a)The effect of the size of network on the maximal node's transmission power consumption in the network

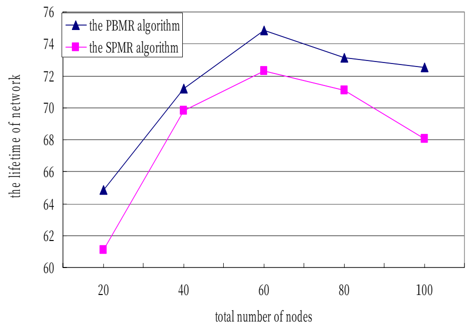


(b)The effect of the size of network on the lifetime of network

Figure 10: The influence of the size of network.



(a)The effect of the structure of network on the maximal node's transmission power consumption in the network



(b)The effect of the structure of network on the lifetime of network

Figure 11: The influence of the structure of network.