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Routing and Broadcast Development for Minimizing Transmission Interruption in Multi rate Wireless Mesh Networks using Directional Antennas

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Abstract
Using directional antennas to reduce interference and improve throughput in multi hop wireless networks has attracted much attention from the research community in recent years. In this paper, we consider the issue of minimum delay broadcast in multi rate wireless mesh networks using directional antennas. We are given a set of mesh routers equipped with directional antennas, one of which is the gateway node and the source of the broadcast. Our objective is to minimize the total transmission delay for all the other nodes to receive a broadcast packet from the source, by determining the set of relay nodes and computing the number and orientations of beams formed by each relay node. We propose a heuristic solution with two steps. Firstly, we construct a broadcast routing tree by defining a new routing metric to select the relay nodes and compute the optimal antenna beams for each relay node. Then, we use a greedy method to make scheduling of concurrent transmissions without causing beam interference. Extensive simulations have demonstrated that our proposed method can reduce the broadcast delay significantly compared with the methods using omnidirectional antennas and single-rate transmission. In addition, the results also show that our method performs better than the method with fixed antenna beams.
Keywords: Multihop, Wireless, Mesh, Omnidirectional

1. Introduction

Broadcast is an essential and frequently used operation in wireless mesh networks (WMNs). This is because the gateway node often acts as the source to broadcast packets to all mesh routers that are connected to it [1, 2]. A wide range of applications of broadcast are time-critical, and they impose a stringent requirement on communication delay. Thus, minimizing broadcast delay in such networks is an important task. This paper discusses the issue of minimizing broadcast delay in multirate WMNs that use directional antennas.

Directional antennas have become one of the most effective technologies to improve network throughput in recent years. Directional antennas consist of an array of omnidirectional antenna elements. Signals transmitted from each of these antenna elements can be weighted in both amplitude and phase to focus the signal strength into a narrow direction to reduce the interference area of the transmitters and increase the signal-to-noise ratio (SNR) at the targeted receivers [3-5]. However, the use of directional antennas will incur high transmission cost for broadcast operations compared with the use of omnidirectional antennas. By using omnidirectional antennas, a node can transmit data to all its receivers with a single transmission, but a node with directional antennas may require several transmissions to cover all its receivers.

This minimum delay broadcast issue is further complicated by the multirate capable transmissions. The link with higher SNR value at the receiver can transmit data at a higher data rate. This brings another optimization dimension to reduce the broadcast delay. On one hand, if we include more nodes in a broadcast, the delay of the transmission is long because the data rate is constrained by the slowest node; on the other hand, if we increase the data rate, less nodes will be covered and the transmission can be carried out in a much shorter time. The nodes that are further away from the transmitter (i.e., the nodes with lower SNR value) can be reached later by other concurrent transmissions. Taking Figure 1 for example, the source node v0 intends to broadcast a packet to all the four nodes in the network. The circles with solid line separately denote the transmission range of v0 at 6 and 18 Mbps, whereas the circles with dotted line separately show the transmission range of v1 at 24 Mbps and v3 at 6 Mbps. Suppose the size of a data packet is set to 1 Mb. We consider two different forwarding cases. In the first case, v0 first broadcasts the packet to v1, v2, and v3 at 6 Mbps, which is followed by packet transmission of v3 to v4 at 6 Mbps. The total delay is $t = 1/6 + 1/6 = 0.333$ s. In the second case, v0 first broadcasts the packet to v1 and v3using 18 Mbps; then, the transmission of v1 to v2 and v3 to v4 can be carried out concurrently without causing interference. The total delay is $t = 1/18 + 1/6 = 0.222$ s, resulting a 33% delay reduction compared with the first approach. This example illustrates an important fact that multirate transmission can provide more opportunities for concurrent transmissions, which may improve network performance.

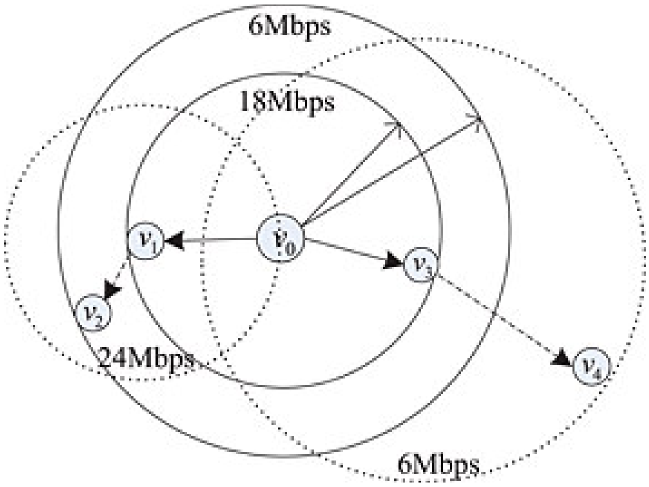

Figure 1.
An example of multirate transmission.

The problem of our concern is defined as follows. We are given a set of mesh routers equipped with directional antennas, and one of them is the source of the broadcast (i.e., the gateway node). We assume that all directional antennas have fixed beamwidth and all the nodes have fixed transmission power. Our task is to design routing and scheduling algorithms such that the total transmission delay for the source node to broadcast a packet to all the other nodes in the network is minimized. We need to determine the following: (1) a routing tree that is rooted from the source node and connects to all the other nodes in the system; (2) for each nonleaf node, the number of transmissions and who are the recipients in each transmission; and (3) the scheduling of concurrent transmissions without causing interference.

The problem is nondeterministic polynomial-time hard (NP-hard), and we propose a heuristic solution with two steps: (1) We construct a routing tree by defining a new routing metric to select the relay nodes and compute the optimal antenna beams for each relay node. (2) We use a greedy method to make scheduling of concurrent transmissions without causing beam interference.

Even though extensive research has been made on the issue of minimum delay broadcast scheduling [6-8], to our best knowledge, this is the first work in the literature that considers the minimum delay broadcast in the context of using directional antennas with multirate transmission.

The rest of the paper is organized as follows. Related work is discussed in Section 2. In Section 3, we present the system model and problem formulation. The details of broadcast tree construction and optimal beam construction in the case of multirate transmission and directional antennas are given in Section 4. InSection 5, we present a greedy heuristic algorithm for beam scheduling. Simulation results are shown in Section 6. Finally, we conclude our paper with a summary in Section 7.

2. RELATED WORK

Because broadcast plays a very important role in multihop wireless networks, there have been a growing class of works carried out to solve the problem of minimum latency broadcast scheduling under omnidirectional antenna model. The minimum latency broadcast scheduling problem in multihop wireless networks has been proven to be NP-hard, and many approximation algorithms are proposed [9-12]. The authors in [13] proposed a simple 12-approximation algorithm for the one-to-all broadcast problem that improves all previously known guarantees for this problem, and they also presented two algorithms with approximation ratios of 20 and 34 for the all-to-all broadcast problem, improving the best result available in the literature. Several works consider both routing and scheduling of the broadcast problem to achieve minimum transmission delay. Rajiv et al. in [6] constructed a breadth-first-search tree and presented a distributed scheduling algorithm without causing interference, producing provably good solutions in terms of latency and number of transmissions. Chouet al. studied the problem of realizing low-latency network-wide broadcast in WMNs where a node can dynamically adjust its link-layer multicast rates to its neighbors. Efficient routing, multicast grouping, and scheduling algorithms are proposed to solve the problem [7]. They also extended the problem to the case of multiradio, multichannel, and multirate WMNs [8].

A large body of works on directional antennas have been investigated for both indoor [4, 14] and outdoor [15, 16] wireless situations to show the advantages of directional antennas on interference reduction and spatial reuse for unicast transmissions. The problem of data broadcast using directional antennas has been firstly discussed on the physical layer. Sidiropoulos et al. [17] presented the idea to maximize the smallest SNR over all the clients around the access point (AP) subject to a bound on the transmission power by employing semidefinite relaxation techniques. Similar works joint with power control can also be found in [18, 19]. These works solved the problem only from the physical layer without considering the beam scheduling for several transmissions.

The study on data broadcast using directional antennas at higher layer is discussed in [20-23]. A method for multicast routing to make lifetime of the wireless network longer using directional antennas is provided in [20]. Aiming to minimize the total transmission delay for an AP to broadcast a packet to all its clients, Sen et al. [21] proposed BeamCast, a two-step solution: the omnidirectional transmission is first employed, and then, one or several sequential single-beam transmissions are followed. In [22], Sundaresan et al. introduced two models for power allocation among multiple active beams of a transmitting node: equal power (EQP) split model and asymmetric power (ASP) split model. Whereas the EQP model splits the power equally among all the beams, the ASP model admits power adjustment among the beams. On the basis of the two models, two greedy algorithms are proposed to get the minimum delay. Zhang et al. [23] revisited the same problem with [22] under EQP and ASP models. They gave an optimal solution under the EQP model and proposed a method with much shorter transmission delay and smaller approximation ratio under the ASP model. With the same objective to minimize the transmission delay for an AP to broadcast a packet to all the clients, our earlier work allows flexible adjustment of beam orientations and the use of multilobe beam pattern [24]. A two-phase method is proposed to solve the problem. First, we use single-lobe beam pattern to cover all clients by adjusting the beam orientations, such that the total delay is minimized. Then, we group these single lobes into a set of multilobes to further minimize the total delay. However, all the aforementioned works only solved the problem under one-hop transmission, which cannot be directly used for multihop wireless networks.

Several papers consider the broadcast routing and scheduling problem in multihop wireless networks using directional antennas. The authors in [25] proposed a novel broadcast protocol called directional self-pruning for ad hoc networks using directional antennas. With lower broadcast redundancy, directional self-pruning is more energy-efficient. Roy in [26] minimized the total energy of broadcast by using directional antennas under four different antenna models: (1) fixed orientation and fixed beamwidth; (2) fixed orientation and variable beamwidth; (3) adjustable orientation and fixed beamwidth; and (4) adjustable orientation and variable beamwidth. They also proposed heuristic algorithms based on the broadcast incremental power algorithm to construct the broadcast tree. The power-constrained broadcast routing problems in wireless ad hoc networks using directional antennas are studied in [27] and [28], where the algorithms for the shortest path tree and minimal Steiner tree are separately used for broadcast tree construction. However, none of these works take multirate transmission into consideration, and the objective is to save the total transmission energy rather than minimize the total transmission delay.

3. SYSTEM MODEL

3.1 Radio and antenna system model

There are two major directional antenna technologies: switched beam antennasand adaptive beam antennas. The switched beam antennas have several available beams that are precomputed before transmission and cannot be changed once the transmission begins. The adaptive beam pattern can adjust beam orientation dynamically on the basis of the channel feedback during the transmission [29]. In this paper, we consider the switched beam antennas for their low cost and simplicity. Suppose all directional antennas have fixed beamwidth θ, which is represented in radians, then a beam can be uniquely described by two parameters: its transmitting node and its orientation. We assume that all the nodes work on the same channel and they cannot transmit and receive data simultaneously. A node with directional antennas can generate multiple beams, but it can only transmit data using one beam at a time. Thus, a node may have to transmit several times to cover all the receivers located in different directions.

3.2 Interference model

We are given a set of mesh routers V = {v0,v1, … ,vN}in a region, where v0 is the gateway node and the source of the broadcast. We assume that the transmission power of all mesh routers are fixed (i.e., no power adjustment) and the reception is omnidirectional. In this paper, we follow the protocol interference model [30]. Suppose the interference range of vi using directional antennas isIr, then the interference area (the area covered by the interference signals) of a radio on vi is modeled as a sector centered at vi, with beamwidth θ and radiusIr. The definitions of link interference and beam interference are given as follows.

Definition 1. (Link interference) A directional link (vi,vj) is said to interfere with (vk,vl) if vl is in the interference area of vi.

Definition 2. (Beam interference) For two beams Bp and Bq, Bp is said to interfere with Bq if link (vi,vj) in Bp interferes with link (vk,vl) in Bq.

Examples of link interference and beam interference are shown in Figure 2. In Figure 2(a), although B1 and B2 have a small overlapping area, there are no nodes in the interference area of the other transmitting node Thus, there is neither link interference nor beam interference. In Figure 2(b), v4 lies in the interference area of v2. If the broadcast operation of v1 and v2 happens simultaneously, packet collision will occur at v4. Link (v2,v5) interferes with link (v1,v4); hence, B2 interferes with B1.

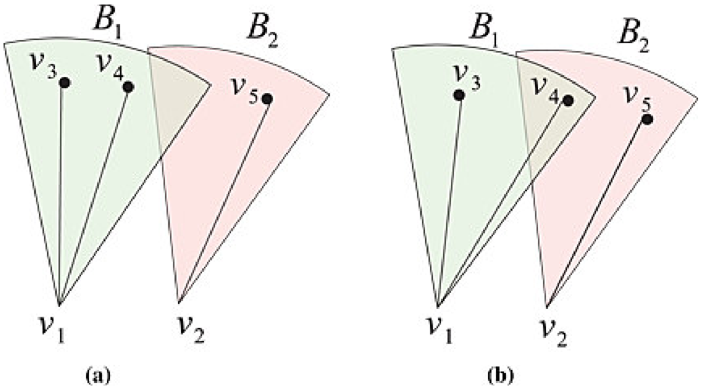

Figure 2.
Link interference and beam interference.

3.3 Problem formulation

Because all traffic in the system is assumed to be destined to or originated from the gateway node, the routing from all nodes to the gateway forms a tree, the root of which is the gateway. Now, we formulate the broadcast delay for the gateway node to broadcast a packet to all mesh routers in the network.

The data rate of a link depends on the received signal strength at the receiver. The received signal strength is determined by the transmission power of the sender, channel gain from the sender to the receiver, and the antenna gain. Letpi denote the transmission power of node vi, gik denote the channel gain fromvi to vk, and aik be the antenna gain. Then, the data rate of link (vi,vk), say rik, can be represented as

$$r_{ik} = f(p_i, g_{ik}, a_{ik}) \quad (1)$$

where f(·) is the function for computing the transmission data rate using the three parameters.

In data broadcasting, the broadcast data rate is bottlenecked by the lowest data rate of the intended recipients of this broadcast. Let B_i^j denote the jth beam ofvi. Note that B_i^j is also regarded as the set of nodes it covers. Then, the broadcast data rate of B_i^j, say R_i^j, is

$$R_i^j = \min_{v_k \in B_i^j} \{r_{ik}\} \quad (2)$$

With Equation (2), suppose the size of a data packet is L, then the transmission time t_i^j for B_i^j is

$$t_i^j = \frac{L}{R_i^j} \quad (3)$$

Because we consider scheduling in our problem, we need to determine the timing of each beam transmission. Let s_i^j denote the start time of B_i^j's transmission. Obviously, a node can start to transmit data only after it has received the packet, that is,

$$s_i^j + t_i^j \leq s_k^l, \forall v_k \in B_i^j \quad (4)$$

The beam transmission must follow two basic rules: (1) A node can only transmit data along one direction using one beam at a time. (2) There should be no interference among the beams that transmit packet simultaneously.

The start time of the broadcast operation is set to 0. Without loss of generality, we assume that the beam transmission time of each leaf node is 0 because the leaf nodes will not transmit packet any more. Let h denote the number of beams (i.e., the number of transmissions) of a node, and h could be different for different transmitting nodes. Then, the total transmission delay for v0 to broadcast a packet to all the other nodes in V can be described as

$$\max_{i \in \{0,\ldots,N\}, j \in \{1,\ldots,h\}} \{s_i^j + t_i^j\} \quad (5)$$

The problem can be formally stated as follows: Given a source node and a set of destinations, the problem of minimum delay broadcast scheduling using directional antennas aims to construct a broadcast tree, compute the number and orientations of beams formed by each nonleaf node, and schedule concurrent beam transmissions, such that the total transmission delay defined by Equation (5) is minimized.

It is not surprising that the general problem of our concern is computationally intractable. We consider a special case: (1) All the nodes transmit data using one single data rate. (2) The beamwidth of directional antennas is 2π, which performs the same as omnidirectional antenna model. Then, this simplified case of the problem is the minimum delay broadcast scheduling problem that has been proved to be NP-hard [6].

4. CONSTRUCTING THE ROUTING TREE AND COMPUTING ANTENNA BEAMS

1) 4.1 Algorithm overview

The data broadcast problem we study aims at minimizing the total transmission delay for the gateway node to broadcast a packet to all the other mesh routers by considering directional antennas and multirate transmission. We take two steps to tackle this problem.

1. *Tree construction*: This step aims to construct a routing tree rooted from the gateway node. We need not only to determine the relay nodes (i.e., the nonleaf nodes in the tree) and their receivers but also to find out the optimal number of beams and the covered nodes of each beam for the relay nodes.
2. *Transmission scheduling*: This step schedules the transmission of all beams obtained from the first step. The objective of this step is to minimize the total transmission delay for the source node to broadcast a packet to all the other nodes.

We present the details of broadcast tree construction and optimal beam construction in Sections 4.2 and 4.3, which is followed by the algorithmic description for beam scheduling in Section 5. Note that the scheduling algorithm can in fact work with any topology construction.

4.2 Broadcast tree construction

A broadcast routing tree is a tree that is rooted from the source node and spans all nodes in the network. The goal of tree construction is to select a set of relay nodes and determine their receivers. In order to minimize the total transmission delay for the source to broadcast a packet to all the other nodes, we shall reduce the number of transmissions and increase the data rate of each transmission as far as possible. We hope that one relay node can broadcast packets to more nodes with higher data rate at a time; that is, it is better to select the nodes that can cover more nodes with less transmission delay as the relay nodes. To identify these nodes, we give the definition of average broadcast time (ABT) of a transmitting node in the case of directional antennas.

Definition 3.

(Average broadcast time) Given *v ' s* receiver set *V i* and beam set *B*that covers nodes in *V i*, $v_i \in V, V_i \subset V, B = \{B_i^1, B_i^2, \ldots, B_i^h\}$, the ABT of *vi* is

$$\mathrm{ABT}(v_i, B) = \frac{\sum_{1 \le j \le h} \frac{L}{R_i^j}}{|V_i|} \quad (6)$$

where | *V i* | is the number of nodes in *V i*.

From the definition, we can see that the shorter *ABT* a node has, the more efficient it contributes to minimizing the delay of the broadcast. It is a good indicator about which nodes can be chosen as the relay nodes. With the definition of *ABT*, we propose a method for tree construction and show it in Algorithm 1.

Algorithm 1 Broadcast tree construction.

Require: $V = \{v_0, v_1, \ldots v_N\}$, $R = \{r_1', r_2', \ldots, r_M'\}$

Ensure: Broadcast tree T; Optimal antenna beams for the relay nodes

```
T ← {v0}, U ← V − {v0}
while U ≠ ∅ do
  for v_i ∈ T do
    for r'_k ∈ R do
      V_i ← The set of nodes in U that can be reached by v_i using r'_k
      B ← ComputeBeams(v_i, V_i)
      Compute ABT(v_i, B) by Equation (6)
    end for
  end for
  Select the node v*_i that has the minimum value of ABT as the relay node
  Let V*_i be the set of targeted receivers of v*_i and B* be beam set for v*_i to cover V*_i
  T ← T ∪ V*_i
  U ← U − V*_i
end while
```

The algorithm follows a greedy strategy for broadcast tree construction in the case of multirate transmission and directional antennas. Let *T* denote the set of nodes that are already added in the tree and *U* denote the set of remaining nodes. Initially, *T* contains only the source node *v*0. For each node *vi* in *T*, we compute the optimal antenna beams to cover its receivers and get its *ABT* value by Equation (6). Then, we select the node that can produce the minimum *ABT* value as the relay node, add its receivers in *T*, and delete them from *U*. Repeat the aforementioned operation until *U* is empty, where all nodes in *U* are added in *T*. The algorithm finally produces a broadcast routing tree *T* and the optimal antenna beams for each relay node.

In our algorithm, we consider multirate transmission and directional antennas. The key point is how to compute the *ABT* of a node. From Equation (6), we can see that the *ABT* value of node *vi* depends on two factors: (1) The set of the intended receivers *V i*. *V i* is determined by the transmission data rate of *vi* because lower data rate has larger transmission range to cover more nodes, whereas higher data rate has smaller transmission range to cover less nodes. Because there is a limited set of modulation-coding rates $R = \{r'1, r'2, \ldots, r'M\}$ available in wireless networks, we can get *M* different *V i* in accordance with *M* different transmission range of data rate, compute *M ABTs*, and select the optimal one. (2) The optimal beam set *B* for *vi* to cover the nodes in *V i*. These antenna beams are produced by ComputeBeams(*vi*,*V i*). The details of which will be described in Section 4.3.

4.3 Solution for optimal antenna beams

In this section, we discuss how to compute the optimal antenna beams formed by the relay nodes in the tree. The problem of beam construction can be described as follows: Given any node $vi \in T$ and its targeted receiver set *V i*, our task is to partition the targeted receivers into beams such that the total delay for *vi* to cover all nodes in *V i* is minimized.

Computing optimal antenna beams is not a trivial issue because the orientation of beams can be of arbitrary direction, then there may exist overlapping areas among different beams. As the data rate of beam transmission is constrained by the lowest node covered by this beam, this overlapping possibility can produce many candidate partitions. Let us take Figure 3 for example: *v*1 is the transmitting node, and the receivers are *v*2,*v*3,*v*4, and *v*5. Suppose the unicast data rate for *v*1 to transmit packet to the four nodes is different. There are totally four kinds of partition strategies: (1) $B1 = \{v2\}$ and $B2 = \{v3, v4, v5\}$; (2) $B1 = \{v2, v3\}$ and $B2 = \{v4, v5\}$; (3) $B1 = \{v2, v4\}$ and $B2 = \{v3, v5\}$; and (4) $B1 = \{v2, v3, v4\}$ and $B2 = \{v5\}$. The one with the minimum delay will be chosen for transmission.

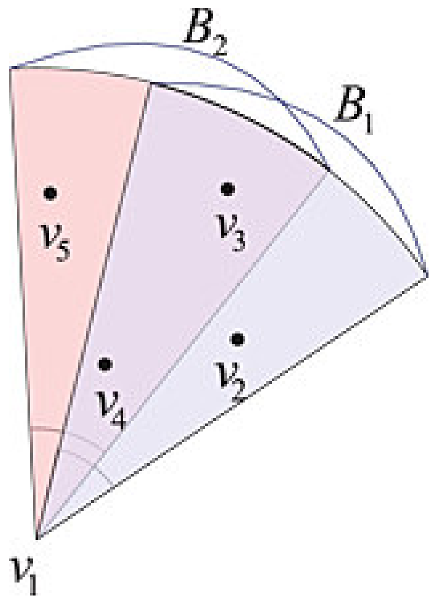

Figure 3.

Two beams with overlapping cover range.

The existence of beam overlapping makes this problem more difficult to handle because it may produce a large number of candidate beams. However, there is an important observation: it is better that receivers in the same transmission beam are contiguous in location. To verify this observation, we first introduce the definition of disjoint partition. Given a node *vi* and its receiver set *V i*, $\Gamma = \{B_i^1, B_i^2, \ldots, B_i^h\}$ is called a *disjoint partition* of *V i*, if $\cup_k B_i^k = V_i$ and , where $1 \le k, l \le h$, $k \ne l$.

For each beam in Γ, if all nodes in this beam are contiguous in location, we say that it is *contiguous*; otherwise, it is *noncontiguous*. Take Figure 3 for example again; if $B1 = \{v2, v3, v4\}$, then it is contiguous. If $B1 = \{v2, v4\}$, then it is noncontiguous. Let *D*(Γ) denote the total transmission delay for beams in Γ to cover all the nodes. On the basis of the definition of disjoint partition, we have the following theorem.

Theorem 1. Let Γ denote a disjoint partition of V_i that some elements in Γ are noncontiguous, then for any Γ, there exists at least one Γ' that satisfies $D(\Gamma') \leq D(\Gamma)$, where Γ' is a disjoint partition of V_i that every element in Γ' is contiguous.

Proof. Consider the situation $\Gamma = \{B_i^1, B_i^2\}$ at least one element of which is noncontiguous. It is obvious that the two beams have overlapping cover range just like Figure 3. If $R_i^1 \leq R_i^2$, which means that the node with the lowest data rate is in B_i^1, then we can group all the nodes that lie in the overlapping area into B_i^1. This grouping operation will not change the value of R_i^1. Once we remove some nodes from B_i^2, the transmission data rate is no less than the situation without removing them. Thus, a new disjoint partition is generated as $\Gamma' = \{B_i^{1'}, B_i^{2'}\}$. Then, the total transmission delay to broadcast a packet is $D(\Gamma') = \frac{L}{R_i^{1'}} + \frac{L}{R_i^{2'}} \doteq \frac{L}{R_i^1} + \frac{L}{R_i^{2'}} \leq \frac{L}{R_i^1} + \frac{L}{R_i^2} = D(\Gamma)$

Similar grouping is also applicable when $R_i^1 > R_i^2$. Thus, we can always get a disjoint partition that only contains contiguous elements with less transmission delay. This argument can be easily extended to the disjoint partition with higher number of elements. Therefore, it is always better to group nodes with its neighboring nodes.□

Because of Theorem 1, the number of candidate beams for transmission decreases and the problem is reduced to a contiguous partition problem. We can solve the problem optimally by using dynamic programming based on Theorem 2.

Theorem 2. If $\Gamma = \{B_i^1, B_i^2, \ldots, B_i^h\}$ is an optimal disjoint partition of V_i (i.e., with minimum transmission delay), then $\Gamma - \{B_i^h\}$ should be an optimal disjoint partition of $V_i - B_i^h$.

Proof. We prove it by contradiction. If $\Gamma - \{B_i^h\}$ is not an optimal disjoint partition of $V_i - B_i^h$, we can construct an optimal disjoint partition Γ_{-h}, then the new disjoint partition of V_i is $\Gamma_{-h} \cup \{B_i^h\}$ and we have $D(\Gamma_{-h} \cup \{B_i^h\}) = D(\Gamma_{-h}) + t_i^h < D(\Gamma - \{B_i^h\}) + t_i^h = D(\Gamma)$, which contradicts the assumption that Γ is an optimal disjoint partition.□

On the basis of Theorem 2, we consider the beam construction at node v_i to cover nodes in V_i. Suppose all the nodes are ordered into a circular list according to their locations in counterclockwise direction, denoted by $\langle v_{i_1}, v_{i_2}, \ldots, v_{i_{|V_i|}} \rangle$. Our task is to divide this circular list into several segments (i.e., beams) such that the delay for v_i to cover nodes in V_i is minimized. We first construct the dynamic programming formulation. Let $\Gamma_{k,l}$ denote a disjoint partition that covers the set of nodes from v_{i_k} to v_{i_l} in the circular list and $d_{\overline{ul}}$ denote the transmission time of one single beam that can cover nodes from v_{i_u} to v_{i_l} in the circular list. Then, we have

$$D(\Gamma_{k,l}) = \min_u \{ D(\Gamma_{k,u-1}) + d_{\overline{ul}} \} \quad (7)$$

where

$$d_{\overline{ul}} = \frac{L}{\min_w \{r_{iw}\}} \quad (8)$$

Let c denote the subscript of i of the foremost node that can be grouped together with v_{i_l} in the circular list; then, the value range of u in Equation (7)depends on the value of c, that is,

$$\begin{cases} c \leq u \leq l & \text{if } c \leq l \\ 1 \leq u \leq l \quad \text{or} \quad c \leq u \leq |V_i| & \text{otherwise} \end{cases}$$

And the value range of w in Equation (8) is

$$\begin{cases} u \leq w \leq l & \text{if } u \leq l \\ 1 \leq w \leq l \quad \text{or} \quad u \leq w \leq |V_i| & \text{otherwise} \end{cases}$$

Because the optimal partition can start from any node in the circular list, the optimal solution for computing optimal transmission beams is the one that produces the minimum value of $D(\Gamma_{1,|V_i|})$, $D(\Gamma_{2,1})$, … , $D(\Gamma_{|V_i|,|V_i|-1})$. Let D^* be the minimum value among them, which is

$$D^* = \min \{ D(\Gamma_{1,|V_i|}), D(\Gamma_{2,1}), \ldots, D(\Gamma_{|V_i|,|V_i|-1}) \} \quad (9)$$

The details of beam construction are presented in Algorithm 2. The time complexity of Algorithm 2 is $O(|V_i|^3)$.

Algorithm 2 ComputeBeams

Require: transmitting node v_i, receiver set V_i

Ensure: $B = \{B_i^1, B_i^2, \dots, B_i^h\}$

Label v_i's receivers by a circular list $\langle v_{i_1}, v_{i_2}, \dots, v_{i_{|V_i|}} \rangle$ according to their locations in counterclockwise direction

Compute $D(\Gamma_{1,|V_i|})$ by Equation (7)

for $k = 2$ to $|V_i|$ **do**

  $l \leftarrow k - 1$

  Compute $D(\Gamma_{k,l})$ by Equation (7)

end for

Get the optimal value D^* by Equation (9) and the beam set that produces D^*

5. SCHEDULING OF BEAM TRANSMISSIONS

Because our objective is to minimize the total transmission delay of a broadcast, when this delay is bottlenecked by a long path from the source to a leaf node in the tree, we shall let the nodes on this path transmit packet first. To identify these 'bottleneck' nodes, we estimate the remaining broadcast time (RBT) of each node without considering interference.

Definition 4. (Remaining broadcast time) Given a broadcast tree and the antenna beams for each relay node, the RBT of a nonleaf node is the longest delay among all leaf nodes in its subtree to receive the broadcast packet from this node under the circumstance that no interference is considered

From the definition, we can see that *RBT* is the lower bound of the broadcast delay. It is a good indicator about which paths or which nodes are bottlenecks of minimizing the overall broadcast delay. In order to reduce the longest broadcast delay, we shall give high priority for transmission to the nodes with large *RBTs*. Figure 4 shows an example. Because a node may use several beams to cover its receivers, the edge (vi,vk) in the figure denotes the beam that covers vk with its transmitting node vi and the edge value denote the transmission time of this beam. Then, the *RBTs* for $v0$,$v1$,$v2$, and $v5$ are 9, 2, 6, and 2, respectively.

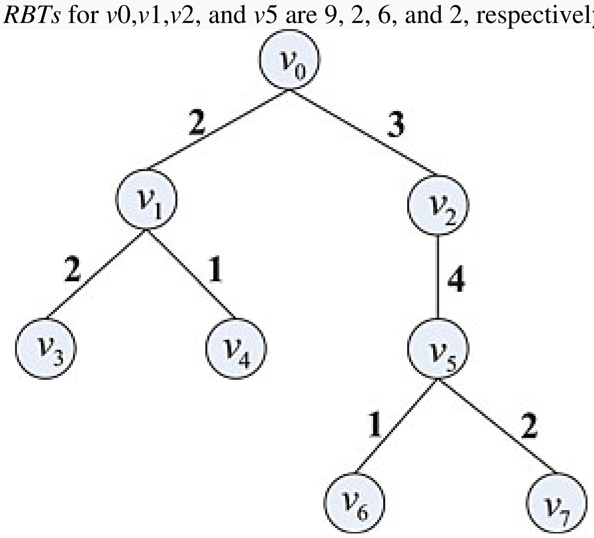

Figure 4.
A broadcast routing tree.

The scheduling problem has been proved to be NP-hard, and many approximation algorithms were proposed. Here, we use a heuristic method based on [6] by taking the *RBT* value defined earlier as a metric for choosing beams for transmission. The algorithm uses a greedy strategy, and the main idea is as follows. Let *F* denote a set of beams that are ready to transmit. Initially, *F*contains the beams whose transmitting node is $v0$. The beams in *F* are sorted in the descending order of their *RBTs*. Then, for each beam in *F*, if it does not cause interference with beams that are transmitting, assign them to transmit data; otherwise, leave it in *F* for the next schedule. The assigned beams are removed from *F*, and their child beams are added in. Repeat the aforementioned operation until *F* is empty, where all beams have been assigned for transmission.

6. SIMULATION

In this section, we evaluate the performance of our proposed method through an extensive simulation study. For the purpose of comparison, we will study altogether four heuristics of broadcast tree construction followed by the same scheduling algorithm shown in Section 5. The routing algorithms to be considered are as follows.

1. Algorithm MD: Routing in the case of multirate transmission and directional antennas shown in Section 4.
2. Algorithm MO: Routing in the case of multirate transmission and omnidirectional antennas, which is used in [7]. Here, we regard the omnidirectional antennas as a special case of directional antenna with$\theta = 2\pi$, and we can use the algorithm in Section 5 for scheduling.
3. Algorithm SD: Routing in the case of single-rate transmission and directional antennas. In this routing method, for each relay node, there is no need to try every data rate to determine the receivers, and only one single data rate is used.
4. Algorithm MS: Routing in the case of multirate transmission and sector antennas. In the sector antenna model, used in [22], a wireless node is associated with K fixed disjoint beams for 2π coverage, and every beam has the same beamwidth $2\pi/K$. Only one beam can be active for transmission at a time. Under such an antenna model, for a transmitting node and its receivers, there is no need to compute optimal beams because the beams are given.

6.1 Simulation setting

Our simulation is built using C++, which generates a wireless network with mesh routers randomly distributed in a $300\ \text{m} \times 300\ \text{m}$ square region. The gateway node is randomly picked from the mesh routers. We assume that 802.11g protocol is used in the network and the size of transmission packet is set to 1 Mb. Table 1 shows the mapping relationship between transmission power and transmission data rate with corresponding transmission range and interference range. It is obtained by Huawei Technologies Co. The antenna gain is set to $2\pi/\theta$, and we assume that the transmission power of a node with beamwidth θ is $2\pi/\theta$ times that of a node with omnidirectional antennas. Like most of the simulations about directional antennas, our simulation only sets the beamwidthθ as $\pi/6$, $\pi/4$, $\pi/3$, and $\pi/2$. When we set the beamwidth as $\pi/2$ and $\pi/4$, the increase of transmission power is 6 and 9 dBm, and we can easily find the correspondence in the table to get the data we need. When the beamwidth is $\pi/3$, the increase of the transmission power is 7.7 dBm, nearly the mean value of 6 and 9 dBm. Under such a situation, we simply set the transmission range as the mean value of the corresponding transmission range of the power with the increase of 6 and 9 dBm. And so does the interference range. For the case of $\pi/6$, we follow the same method. Because there is a limited set of data rate available in wireless network, nodes that are within a certain range of distance have the same data rate; thus, some small errors will not cause much effect on the performance.

All the data points were averaged over 100 simulation runs on the connected graph. The performance metric that we consider to evaluate the effectiveness of our method is the total transmission delay. We will study how this metric is affected by varying three parameters over a wide range: the beamwidth of directional antennas, the transmission power of each wireless node, and the number of mesh routers deployed in the network.

6.2 Compare MD with MO

In the first group of simulations, we evaluate the performance of our method MD through the comparison with MO. Figure 5 shows the transmission delay versus the transmission power and the number of mesh routers. From Figure 5, we can make the following observations:

1. MD performs much better than MO under a different value of beamwidth. The reason is that directional antennas can produce higher SNR at the receiver and offer more opportunities for concurrent transmissions. In Figure 5(a), with the increase of the transmission power, almost every node can use higher data rate for transmission, then the total transmission delay decreases. In this case, the gap between different lines is mainly determined by the different groupings of receivers using different beamwidths. In Figure 5(b), as the number of mesh routers increases, the network becomes dense, which will cause much more interference by using omnidirectional antenna model. For such a situation, directional antennas can reduce the interference to provide more parallel transmissions with higher data rate.
2. The smaller the beamwidth is, the better the performance is. Especially when the beamwidth is 2π, it is the same with omnidirectional antennas, which produces the worst results. The reason is that although the directional antennas with smaller beamwidth cover less nodes in one transmission, it can produce higher data rate and more opportunities for concurrent transmissions, which can significantly reduce the

broadcast delay in WMNs. The delay reduction by MD increases as the number of mesh routers increases.

3. The gap between the results of $\pi/6$ and $\pi/4$, as well as $\pi/3$ and $\pi/2$, is not so big. This is because there is a limited set of data rate available in wireless networks. Once the received signal strength is within a certain range, the transmission data rate is fixed. Figure 5 shows that the effects of beamwidth $\pi/6$ and $\pi/4$, as well as $\pi/3$ and $\pi/2$, on the overall performance are more or less the same.

In Figure 6, the total transmission delay is divided into two types. One is ‘sequential transmission’, which means that beams are transmitted one by one on the basis of the routing tree obtained in Section 4. The other is ‘concurrent transmission’, which means that the total delay are obtained by using scheduling method in Section 5. Figure 6 shows the comparison between these two types of delay under different beamwidths.

We can see that, if we transmit packets through beams one by one, there is no obvious performance improvement of directional antennas compared with omnidirectional antennas. Because every relay node may need several transmissions to cover its receivers, the number of sequential beam transmissions will be large, resulting a longer transmission delay. If we use both routing and scheduling, more beams can transmit packets together to save time because directional antennas can produce smaller interference area than omnidirectional antennas.

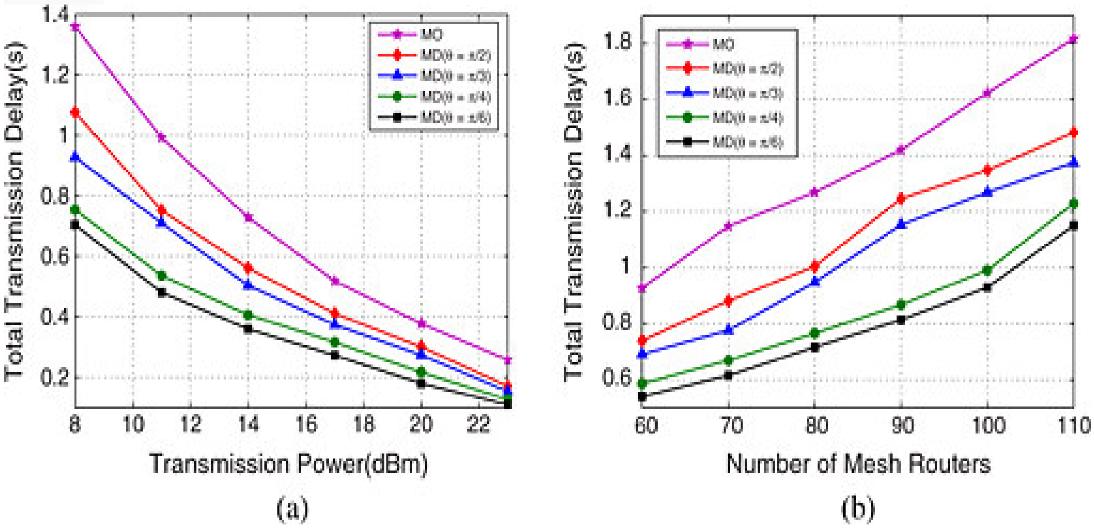

Figure 5.
Comparison of MD and MO.

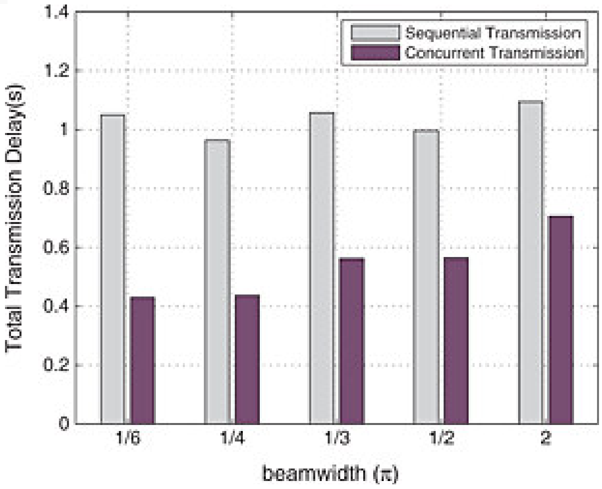

Figure 6.
Total transmission delay for variable beamwidth.

6.3 Compare MD with SD

In the second group of simulations, we compare MD with SD. Under single-rate transmission, for each relay node, it only uses one single data rate to determine its receivers. Among all available data rate, we select the lowest data rate (i.e., 6 Mbps), the highest data rate (i.e., 54 Mbps), and a middle data rate (i.e., 24 Mbps) for comparison. The simulation results are shown in Figure 7, and we can make the following observations:

1. MD outperforms all SDs with different data rates because MD can choose the appropriate data rate to determine the receivers. Figure 7(a) shows transmission delay versus beamwidth of directional antennas. Same with the results in Figure 7, the delay increases with the increase of beamwidth. Figure 7(b) shows transmission delay versus the number of mesh routers in the network. As the number of mesh routers increases, there may be a need for more relay nodes for forwarding packets; because there is only one beam active at a time, the total transmission delay will be longer.
2. For the SDs with different data rate, we can see that the lower the data rate is, the better the performance is. There are two main reasons for such a conclusion. First, higher data rate means smaller transmission range and less covered nodes; under such circumstance, the number of relay nodes becomes large and so does the number of transmissions. Second, once we use the lower data rate to determine the receivers, we need to compute the optimal antenna beams to cover these receivers. The transmission data rate for some beams may be higher because it may only cover the nodes that are close to the transmitting node. In practice, because of various factors such as fading and shadowing, only a small minority of the receivers can receive the packet at a very high data rate; thus, lower data rate will be used more often.

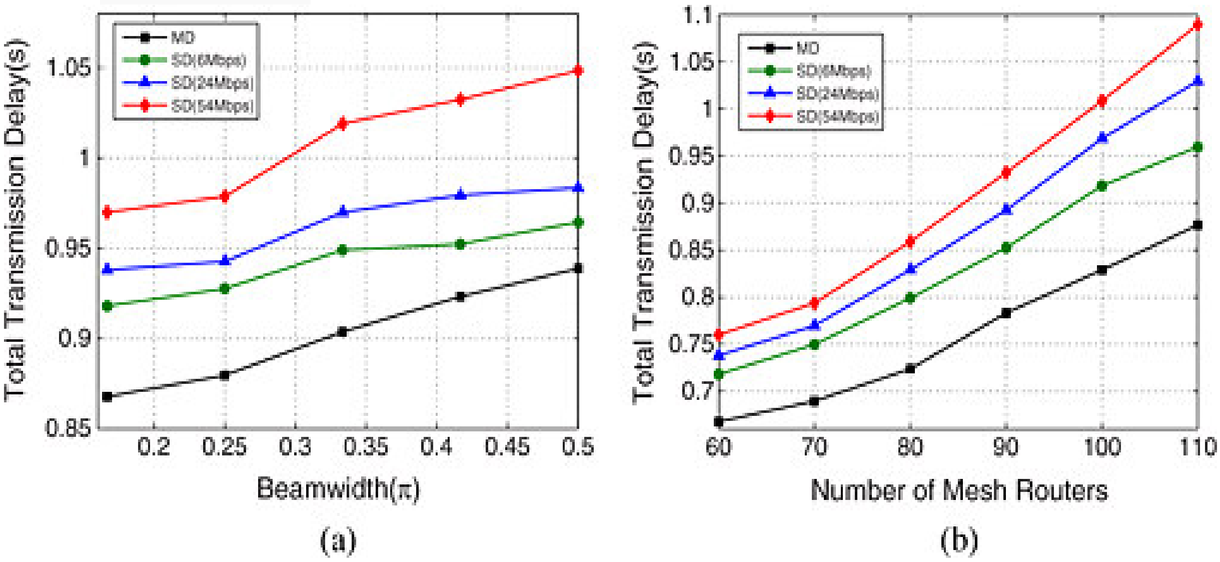

Figure 7.
Comparison of MD and SD.

6.4 Compare MD with MS

In the third group of simulations, we compare MD with MS. Figure 8 shows the total transmission delay versus the number of mesh routers, beamwidth, and transmission power. We can see that MD always performs better than MS with a 10%–20% improvement. The reason lies in that the beams of sector antennas to cover the receivers are given, which may not be the optimal grouping of those receivers. For instance, once we fix the beam orientation, two nodes that ought to transmit together for delay saving are included in two separated beams under the sector antenna model, resulting a longer transmission delay.

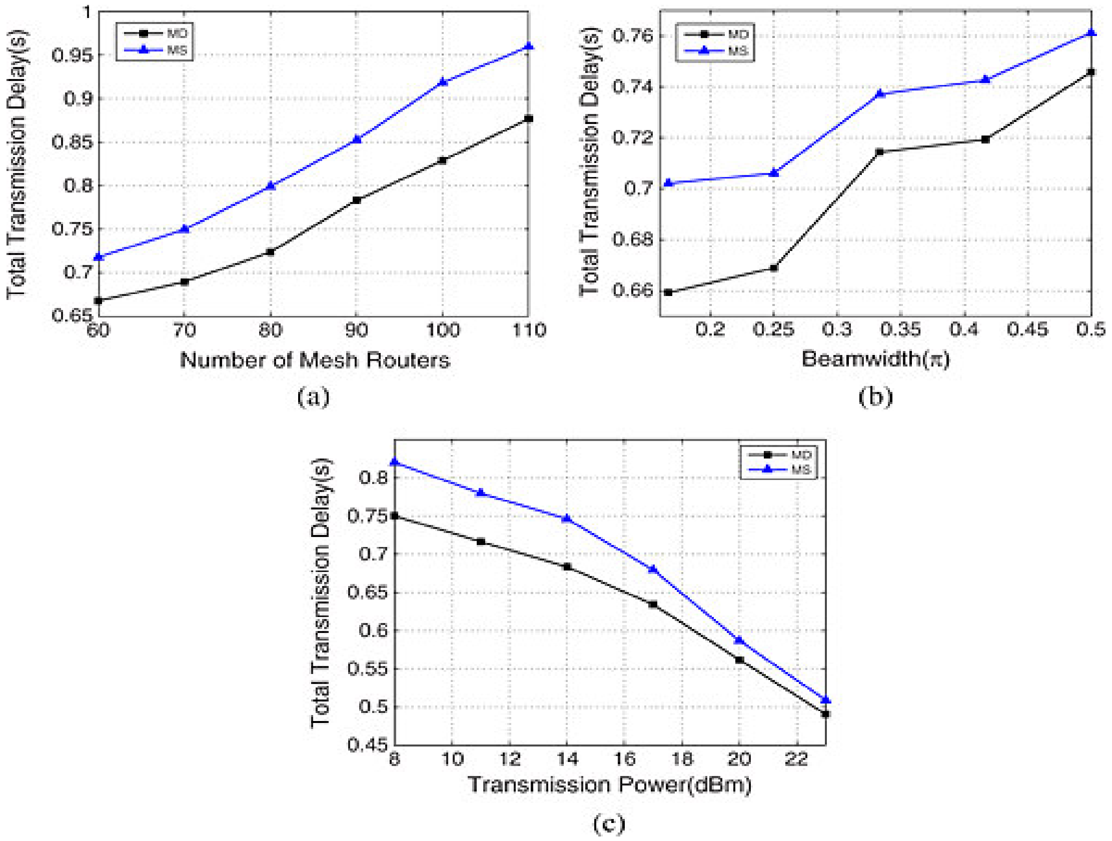

Figure 8.
Comparison of MD and MS.

7. CONCLUSION

In this paper, we have studied the issue of broadcast scheduling using directional antennas with multirate transmission in WMNs. The objective is to minimize the total transmission delay for the source to broadcast a packet to all the other nodes. We proposed a heuristic solution with two steps to tackle this problem. Firstly, we construct a routing tree by selecting the node that can produce the minimum value of *ABT* as the relay node and compute optimal antenna beams for each relay node. Secondly, we use a greedy method to make scheduling of concurrent transmissions without causing beam interference. Extensive simulations have demonstrated that our proposed method can reduce the total broadcast delay significantly compared with the other routing methods. In addition, the results also show that our method performs better than the method with fixed antenna beams.

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