Exploiting Multiple Beam Antennas for End-to-End Delay Reduction in Ad Hoc Networks

Jean-Daniel Medjo Me Biomo, Thomas Kunz(✉), and Marc St-Hilaire

Department of Systems and Computer Engineering,
Carleton University, Ottawa, ON, Canada
{jemeda,tkunz}@sce.carleton.ca, marc_st_hilaire@carleton.ca

Abstract. Multi-Beam Antennas (MBAs) have two main characteristics: the Multi-Packet Transmission (MPT) capability and the Multi-Packet Reception (MPR) capability whereby a node can transmit/receive multiple packets at the same time. In this paper, we provide an analysis of how this MPT/MPR capability can be used to reduce the end-to-end delay in ad hoc networks. We formulate the delay reduction issue as an optimization problem. Simulations show that in order to exploit the full potential of MBAs for delay reduction, the scheduling of links has to promote the formation of *star nodes* and keep the formation of *bridges* to a minimum; which leads to the selection of routes that very often are not the shortest. We also show that using only the shortest routes has a negative impact on the delay.

Keywords: Multi-beam antenna · Ad hoc network · Optimization
Routing · Delay minimization

1 Introduction

A Multi-Beam Antenna (MBA) is defined by its Multi-Packet Transmission (MPT) and Multi-Packet Reception (MPR) capabilities that allow multiple packets to be transmitted/received at the same time. However, MBA-equipped nodes need to follow a rule called Concurrent Packet Receiving (CPR) and Concurrent Packet Transmission (CPT) due to their half-duplex operation [1]. In other words, an MBA-equipped node cannot transmit signals in some beams and receive signals in other beams at the same time. At a given time, an MBA-equipped node has all its beams operate in either transmission or reception mode (see Fig. 1).

MBAs can be implemented either in the form of Multiple Fixed-Beam directional Antennas (MFBAs) or in the form of Multi-Channel Smart Antennas (MCSAs). To form multiple fixed beams, MFBAs and multiple radios (MRs) with a directional antenna equipped in each radio (transceiver) can be exploited [2,3]. As a result, high network throughput can be achieved. In a stationary environment, the antenna patterns can be optimized to further improve network performance. However, the performance of MFBAs/MRs degrades in a time-varying

Y. Zhou and T. Kunz (Eds.): AdHocNets 2017, LNICST 223, pp. 143–155, 2018.
https://doi.org/10.1007/978-3-319-74439-1_13

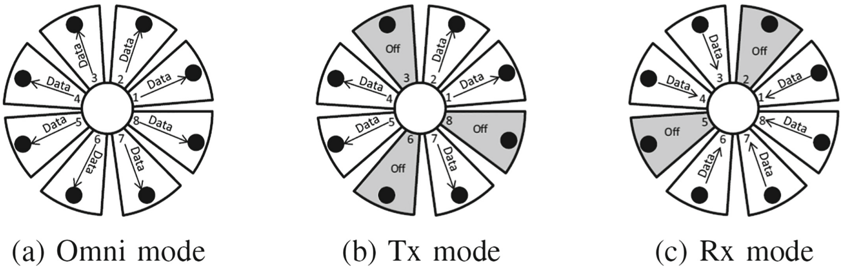

Fig. 1. Multi-beam antenna modes [1]

multipath propagation environment, which is typically experienced in indoor and low-altitude outdoor wireless networks [4]. The alternative approach to implement MBAs is to use MCSAs [5–7]. By using smart antenna techniques, multiple beams can be adaptively and dynamically formed by a node so as to provide robust communication links with multiple users. At the expense of higher complexity, an MCSA-based approach shows the same advantages as the MFBA/MR implementation, but its performance does not degrade in time-varying multipath environments [6,7].

In the literature, the work around MBAs has focused on designing MAC and/or routing protocols that exploit spatial reuse in order to increase network performances such as throughput and packet delivery ratio. Not much has been done to use the full MPT/MPR potential for end-to-end delay reduction. Moreover, a great deal of existing work on MBAs is done for infrastructure-based networks with an applicability to ad hoc networks that is yet to be clarified. Furthermore, some link scheduling proposals for network performance improvement do not consider MBAs at all.

In this paper, we make the case that the full potential of the MPT/MPR capability of MBAs can be unlocked to drastically reduce the end-to-end delay in ad hoc networks. We define a formal optimization model for delay reduction, and we observe that the optimal end-to-end delay is attained when links are scheduled in such way that opportunities for MPT/MPR are maximized. This results in a selection of routes that, up to half of the times, are not the shortest. We actually show that using only the shortest routes, a widespread criterion in traditional routing protocols for ad hoc networks, results in higher delays. To the best of our knowledge, no such analysis of the potential of MBAs to reduce/minimize the delay has been conducted thus far for ad hoc networks.

The remainder of this paper is organized as follows. In Sect. 2, a literature review on link scheduling and the utilization of MBAs for the improvement of network performances is presented. Section 3 lays out our optimization model. Simulation results are discussed in Sect. 4, and concluding remarks are provided in Sect. 5.

2 Literature Review on MBAs and Link Scheduling

In [8], Cheng et al. show that the shortest path does not always lead to the minimum delay. End-to-end delay being a result of both the number of hops on the path and the interference level along the path, the shortest path leads to the minimum delay only if the shortest path is the least interfered path. The authors propose a linear programming-based link scheduling scheme that computes timeslot assignments in order to minimize the end-to-end delay without causing conflicting transmissions. The use of MBAs is not considered.

In [9], Wang et al. propose a CSMA/CA-based uplink MAC protocol for wireless LANs with MBA access-points. Spatial reuse is utilized by allowing as many parallel uplink data transmissions as possible in order to improve the throughput. Since all the nodes including the access point run a CSMA/CA-based MAC protocol, the authors claim that the proposed protocol is not limited to the single-hop case, but can be easily extended to multi-hop ad hoc networks. In [10], the same authors go further to present an analytical model to evaluate the performance of multi-beam wireless LANs. The beam-synchronization problem, the beam-overlapping problem, and the mobility issue are also addressed.

Jain et al. [11] present a detailed study of MBAs MAC issues. They propose a cross-layer Hybrid MAC (HMAC) protocol that can leverage the benefits of MBAs in multi-hop networks. Using extensive topological and traffic patterns, the authors demonstrate that employing MBAs and HMAC can result in significant performance improvements in terms of both aggregate throughput and average end-to-end packet delay. In most of the sample topologies, HMAC delivers near-optimal performance. From a study of random topological scenarios, the authors also conclude that both single and multi-beam antennas deliver comparable performance in ad hoc scenarios. But these claims are not based on any formal optimization model of their metrics.

In [12], Tang et al. propose a MAC protocol for WLANs with MBA-equipped access points, omnidirectional-antenna mobile nodes and a single frequency channel. The protocol addresses a series of challenging problems such as the beam-load unbalance problem, the unnecessary defer problem, the receiver blocking problem, the antenna-imperfection problem, and mobility. By addressing these issues, as many parallel transmissions between terminals and the AP as possible are successfully facilitated and the performance (throughput) of the network is improved. There is no indication of how this protocol would fare in ad hoc networks.

Wang and Garcia-Luna-Aceves [13] present an approach that takes advantage of the MPR capability of MBAs to reduce the negative effects of multiple access interference and therefore increase the capacity of an ad hoc network. The MPT capability is not considered, nor is the end-to-end delay performance metric. They formulate an optimization problem under a deterministic model and seek to maximize the aggregate network throughput. They then propose a polynomial-time heuristic algorithm aimed at approximating the optimal solution to the joint routing and channel access problem under MPR. This is a methodology that is similar to our work presented in this paper.

3 Scheduling Problem Formulation and Optimization Model

We assume the following conditions:

- there is a perfect time synchronization for all the nodes in the network,
- the nodes run a perfect TDMA-based MAC protocol for MBA antennas,
- time is divided in timeslots,
- multiple nodes can transmit in the same timeslot if their transmissions do not interfere with one another,
- nodes operate in half-duplex: a given node cannot transmit and receive at the same time.

For a given static network with multiple flows, and provided that the antennas are MPT/MPR capable, we would like to know the route selection (link scheduling) that gives us the lowest end-to-end delay (average) possible. This is an optimization problem. We represent the network with a directed connectivity graph $G(V, E)$, where V represents the set of nodes (or vertices) in the network, and E is the set of directed links (or edges). If node i is within the reception range of node j, then Links (i, j) and (j, i) are members of E. We assume that a node can receive up to M simultaneous packets (MPR capability), or perform up to M simultaneous transmissions (MPT capability) at a time, provided that each reception/transmission occurs at a different antenna beam/sector. Therefore, M is also the number of beams for each antenna.

The inputs of our problem are:

- the connectivity graph $G(V, E)$,
- the MPR/MPT capability, M,
- the number of traffic flows $|F|$ that is the cardinality of the set F containing the numbers that represent the flows.
  $F = \{1, 2, ..., |F|\}$,
- the source and destination of each flow. s_f and d_f are respectively the source and destination of Flow f, with $f \in F$,

The outputs are:

- the selected route for each flow, presented as a sequence of links,
- the delay (in timeslots) of each route. The average delay per route is then the sum of all delays divided by the number of flows.

In order to solve this optimization problem, we define a decision variable α_{ij}^{fk} that tells us whether or not Link (i, j) of Flow f is scheduled at Timeslot k. $\alpha_{ij}^{fk} \in [0, 1]$. T is the set of timeslots. $T = \{1, 2, ..., |E| \times |F|\}$, where $|E|$ is the cardinality of E. The T set is constructed assuming that each flow uses all the available links (edges) and each link from each flow in the network gets its own timeslot and there are no concurrent transmissions (worst case scenario). The problem can be formulated as follows:

minimize

$$\sum_{f \in F} \sum_{k \in T} \sum_{i \in V} \sum_{d_f} \alpha_{id_f}^{fk} \times k \tag{1}$$

subject to the following 6 constraints:

1. Flow Circulation Constraints

$$\sum_{j:(s_f,j) \in E} \quad \sum_{k \in T} \alpha_{s_f j}^{fk} = 1 \qquad \forall f \in F \tag{2}$$

$$\sum_{i:(i,d_f) \in E} \quad \sum_{k \in T} \alpha_{id_f}^{fk} = 1 \qquad \forall f \in F \tag{3}$$

$$\alpha_{ij}^{fk} - \sum_{t=1}^{k-1} \quad \sum_{l:(l,i) \in E} \alpha_{li}^{ft} \leq 0 \forall f \in F, \forall k \in T, \forall i \in V - \{s_f\}, \forall j \in V | (i,j) \in E \tag{4}$$

2. Flow Consistency Constraints

$$\sum_{l:(i,l) \in E} \alpha_{il}^{fk} \leq 1 \qquad \forall f \in F, \forall k \in T, \forall i \in V \tag{5}$$

$$\sum_{l:(l,j) \in E} \alpha_{lj}^{fk} \leq 1 \qquad \forall f \in F, \forall k \in T, \forall j \in V \tag{6}$$

$$\sum_{k \in T} \alpha_{ij}^{fk} \leq 1 \qquad \forall f \in F, \forall (i,j) \in E \tag{7}$$

3. Link Occupancy Constraint

$$\sum_{f \in F} \alpha_{ij}^{fk} \leq 1 \qquad \forall k \in T, \forall (i,j) \in E \tag{8}$$

4. Half-duplex Constraint

$$\sum_{f \in F} (\alpha_{ij}^{fk} + \alpha_{jl}^{fk}) \leq 1 \qquad \forall k \in T, \forall i,j,l \in V \tag{9}$$

5. MPT Capability Constraint

$$\sum_{l:(i,l) \in E} \quad \sum_{f \in F} \alpha_{il}^{fk} \leq M \qquad \forall k \in T, \forall i \in V \tag{10}$$

6. MPR Capability Constraint

$$\sum_{l:(l,j) \in E} \quad \sum_{f \in F} \alpha_{lj}^{fk} \leq M \qquad \forall k \in T, \forall j \in V \tag{11}$$

Concerning the objective function at Eq. 1, the goal is to minimize the average number of timeslots per flow required to complete all the flows. This is equivalent to finding routes where the last link (link to the destination node) occurs the earliest possible, such that the average end-to-end delay is minimal. To that effect, k in the function represents the cost for each timeslot. The constraints are explained as follows:

1. Flow Circulation Constraints
   - Constraint 2: a flow always starts, meaning the source node should be scheduled exactly once.
   - Constraint 3: the destination of a flow must always be reached, by exactly one link.
   - Constraint 4: Link (i, j) can be scheduled for Flow f only if i has previously received a packet before; meaning there exist a completed (l, i) link from the same flow. Except if i is the source of the flow.
2. Flow Consistency Constraints
   - Constraint 5: the same flow cannot have multiple next hops at any given intermediate node belonging to the route.
   - Constraint 6: the same flow cannot be received from multiple previous hops at any given intermediate node belonging to the route.
   - Constraint 7: a link can be scheduled only once at most, for any given flow.
3. Link Occupancy Constraint
   - Constraint 8: only one flow is permitted on a link at a time.
4. Half-duplex Constraint
   - Constraint 9: transmission and reception cannot occur at same time at any given node.
5. MPT Capability Constraint
   - Constraint 10: up to M outgoing links can be scheduled at a node at any timeslot.
6. MPR Capability Constraint
   - Constraint 11: up to M incoming links can be scheduled at a node at any timeslot.

4 Simulation and Analysis

We solved the foregoing optimization model using the Optimization Programming Language (OPL) with IBM-ILOG-CPLEX Optimization Studio 12.7.1 [14], with all the parameters set to their default values. We considered two topologies, Topology 1 and Topology 2.

4.1 Topology 1

Topology 1 (Fig. 2) is a static grid topology of 16 nodes. The grid is of size $3D \times 3D$, and the transmission range of the nodes is R, with $R = D\sqrt{2}$. We set M such that any node can simultaneously communicate with all its neighbors. Given our topology, the maximum number of neighbors that a node can have is 8; Let us consider eight traffic flows, Flow 1 through Flow 8, as follows: $1 \longrightarrow 15$, $3 \longrightarrow 13$, $5 \longrightarrow 12$, $9 \longrightarrow 8$, $15 \longrightarrow 2$, $13 \longrightarrow 4$, $12 \longrightarrow 1$, and $8 \longrightarrow 5$.

Table 1 presents the optimal link scheduling of the network as found by the solver. We can obtain from the table that the optimal average end-to-end delay is 3.25 slots per flow. 6 flows are completed in 3 slots and 2 flows are completed in 4 slots, thus the average of 3.25 slots. All the 8 routes chosen are also the

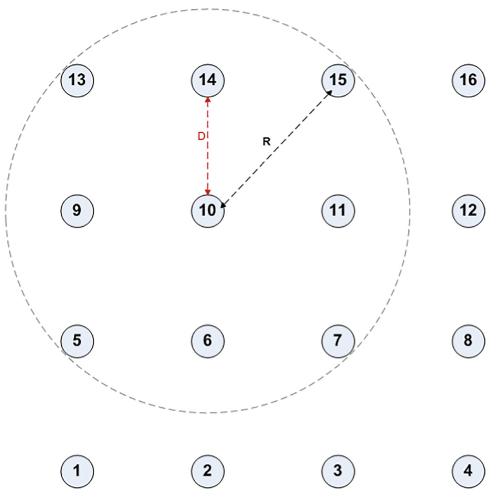

Fig. 2. Topology 1

Table 1. Topology 1, optimal link scheduling with 8 flows

Traffic flow	Slot 1	Slot 2	Slot 3	Slot 4
$1\longrightarrow 15$	(1,6)	(6,11)	(11,15)	
$3\longrightarrow 13$	(3,6)	(6,9)	(9,13)	
$5\longrightarrow 12$	(5,6)	(6,7)	(7,12)	
$9\longrightarrow 8$	(9,6)	(6,3)	(3,8)	
$15\longrightarrow 2$	(15,12)	(12,7)	(7,2)	
$13\longrightarrow 4$	(13,10)	(10,7)	(7,4)	
$12\longrightarrow 1$		(12,11)	(11,6)	(6,1)
$8\longrightarrow 5$		(8,3)	(3,6)	(6,5)

shortest (3 hops). Note that, given the regularity of our grid topology, each flow has many possibilities for its shortest route.

The optimal (delay-wise optimality) routes selected form a lot of *star nodes* in the network. We define *star nodes* as nodes that use their MPR capability at one timeslot before using their MPT capability at the following timeslot. With a star node, packets from distinct traffic flows travel two hops in two consecutive timeslots, which is obviously a desirable effect for the minimization of the delay. From Table 1, we can see that one star node, namely Node 6, is formed between Slot 1 and Slot 2. In effect, Flows 1 through 4 all send a packet to Node 6 at Slot 1 from different previous nodes (Nodes 1, 3, 5, and 9 respectively) and all 4 packets leave Node 6 for different next hops (Nodes 11, 9, 7 and 3 respectively). Similarly, three star nodes (Nodes 11, 7, and 3) are formed between Slot 2 and Slot 3. Finally, between Slot 3 and Slot 4, one star node (Node 6) is formed.

We note that we do not have any *bridges* formed in the network with the optimal scheduling. We define a *bridge* as a beam (equivalent to a link in our configuration) that routes two or more different flows that have arrived at a given node at the same timeslot. For example, as already mentioned, Node 6 receives four different flows from four different links (beams, as we assume that each neighbor lies in its own beam, no two neighbors share a beam) during Slot 1. It then forwards the four different packets using four different links (beams). For a bridge to be formed, we would have had less than four outgoing links at Node 6 at Slot 2, with the missing link being already scheduled for a different flow. It would have therefore waited for a subsequent slot. For example, at Slot 2 we have the following outgoing links from Node 6: $(6, 11)$, $(6, 9)$, $(6, 7)$, and $(6, 3)$. Had we had a bridge on the beam that covers Link $(6, 7)$ for instance, the four outgoing links from Node 6 would had been: $(6, 11)$, $(6, 9)$, $(6, 7)$, and $(6, 7)$, with Link $(6, 7)$ appearing twice for the forwarding of two different flows (Flow 3 and Flow 4) at the same timeslot. In this case, only three outgoing links would had been scheduled at Slot 2: $(6, 11)$, $(6, 9)$, and $(6, 7)$. The packet from Flow 4 that is supposed to go through Link $(6, 7)$ would have had to be scheduled at a later slot, since two packets cannot be transmitted at the same time on the same beam (corresponding to the same link in our configuration). Note that we do not have to have a duplicate link in order to have a bridge. Two links can be different (obviously still sharing the same origin, such as $(6, 7)$ and an hypothetic $(6, X)$), but as long as they are serviced by the same beam and compete for scheduling at the same time, a bridge is formed. As we can see from the table, no bridge is formed on any of the nodes that receive multiple flows at once at given timeslots (Node 6 at Slot 1, Nodes 11, 7, 3 at Slot 2, and Node 6 again at Slot 3).

When MBAs are not used ($M = 1$), the performance (Table 2) degrades as follows. Only two flows (Flow 4 and Flow 7) are completed in 3 slots, five flows are completed in 4 slots, and one flow needs 6 slots to complete. This gives an average of 4 slots per flow, hence a degradation of 0.75 slot compared to when MBAs are used. We also notice that three of the eight flows do not use their shortest path (3 hops), and use a longer (4 hops) path instead. This tells us that in some cases, using longer paths can improve the overall delay. Note that

Table 2. Topology 1, optimal link scheduling with 8 flows, no MBA

Traffic flow	Slot 1	Slot 2	Slot 3	Slot 4	Slot 5	Slot 6
1⟶ 15		(1,5)	(5,10)	(10,15)		
3⟶ 13	(3,6)	(6,9)		(9,13)		
5⟶ 12	(5,10)	(10,15)	(15,16)	(16,12)		
9⟶ 8	(9,14)	(14,11)	(11,8)			
15⟶ 2	(15,16)	(16,12)	(12,7)	(7,2)		
13⟶ 4			(13,14)	(14,11)	(11,7)	(7,4)
12⟶ 1	(12,7)	(7,2)	(2,1)			
8⟶ 5		(8,3)	(3,6)	(6,5)		

in any scenario, the scheduling of a given link is prohibited at a given timeslot for two reasons: the non-availability of the MPT/MPR capability and/or the half-duplex constraint.

4.2 Topology 2

Topology 2 (Fig. 3) is obtained by constraining/altering Topology 1 significantly. Nodes 5, 8, 9, and 12 are suppressed, resulting in a 12-node topology. In this

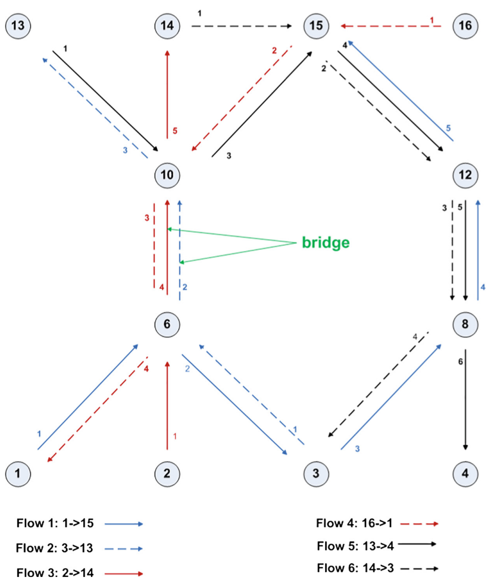

Fig. 3. Topology 2

network we have 6 traffic flows, Flow 1 through Flow 6, as follows: 1 ⟶ 15, 3 ⟶ 13, 2 ⟶ 14, 16 ⟶ 1, 13 ⟶ 4, and 14 ⟶ 3.

The optimal link scheduling for Topology 2 is presented in Table 3 and Fig. 3. It can be observed that the optimal average end-to-end delay is 4.5 slots per flow.

From Table 3, we can see that five star nodes are formed as well as one bridge. Node 6 is a star node for Flows 1 and 2 between Slots 1 and 2. However, Node 6 also forms a bridge for Flows 2 and 3 at Slot 2. In effect, packets from Flows 2 and 3 both arrive at Node 6 at Slot 1, and both packets (from two different flows) are scheduled to leave Node 6 using the same link $(6, 10)$, thus the same antenna beam: this is a bridge. Consequently, one of the flows has to wait until a subsequent slot. As we can see, Link $(6, 10)$ of Flow 3 is rescheduled for Slot 4. It cannot be rescheduled for Slot 2 because it is already scheduled for Flow 2 at that slot, and it cannot be rescheduled at Slot 3 either because of the half-duplex constraint (Node 6 that is supposed to be the transmitter is already at the receiving end of Link $(10, 6)$ of Flow 4). Table 3 gives us the optimal solution, which means that this bridge could not be avoided. Had this bridge been avoided at all cost, it would have resulted in a higher delay.

Only half the routes chosen are also the shortest (Flows 2, 3, and 4). For Flow 1, a 5-hop route is chosen, marking a 2-hop increase from the shortest route. Similarly, for Flow 5, the 5-hop route chosen is 1 hop longer than the shortest route between Node 13 and Node 4 (which is 4 hops with this new topology, unlike Topology 1). For Flow 6, the chosen route is 1 hop longer than

Table 3. Topology 2, optimal link scheduling with 6 flows

Traffic flow	Slot 1	Slot 2	Slot 3	Slot 4	Slot 5	Slot 6
1⟶ 15	(1,6)	(6,3)	(3,8)	(8,12)	(12,15)	
3⟶ 13	(3,6)	(6,10)	(10,13)			
2⟶ 14	(2,6)			(6,10)	(10,14)	
16⟶ 1	(16,15)	(15,10)	(10,6)	(6,1)		
13⟶ 4	(13,10)		(10,15)	(15,12)	(12,8)	(8,4)
14⟶ 3	(14,15)	(15,12)	(12,8)	(8,3)		

Table 4. Topology 2, optimal link scheduling with 6 flows, no MBA

Traffic flow	Slot 1	Slot 2	Slot 3	Slot 4	Slot 5	Slot 6	Slot 7
1⟶ 15			(1,6)	(6,10)	(10,15)		
3⟶ 13	(3,6)	(6,10)	(10,13)				
2⟶ 14					(2,6)	(6,10)	(10,14)
16⟶ 1	(16,12)	(12,8)	(8,3)	(3,2)		(2,1)	
13⟶ 4		(13,14)	(14,15)	(15,16)	(16,12)	(12,8)	(8,4)
14⟶ 3	(14,15)	(15,16)	(16,12)	(12,8)	(8,3)		

Table 5. Topology 2, link scheduling with 6 flows, shortest path

Flow	Slot 1	Slot 2	Slot 3	Slot 4	Slot 5	Slot 6	Slot 7	Slot 8	Slot 9	Slot 10
1→15	(1,6)	(6,10)			(10,15)					
3→13	(3,6)		(6,10)		(10,13)					
2→14	(2,6)			(6,10)	(10,14)					
16→1	(16,15)	(15,10)					(10,6)	(6,1)		
13→4	(13,10)				(10,6)			(6,3)		(3,4)
14→3	(14,10)					(10,6)			(6,3)	

the shortest route. We therefore observe that, even with MPT/MPR enabled, longer routes than the shortest are often preferred in order to attain the minimal end-to-end delay.

The number of transmissions performed is equal to the number of links scheduled. With the optimal link scheduling, we have a total of 24 transmissions.

When MBAs are not used ($M = 1$), the performance (Table 4) degrades as follows. Two flows are completed in 7 slots, one flow is completed in 6 slots, two flows are completed in 5 slots, and one flow needs 3 slots to complete. This gives an average of 5.5 slots per flow. This is a degradation of 1 slot per route compared to when MBA are used. Here too, only half the routes chosen are also the shortest (Flows 1, 2, and 3). We see that with this topology also, using longer paths does improve the overall delay. With no MPT/MPR capability, the number of transmissions for the optimal scheduling is 25, a mere 4% increase from the case with MPT/MPR.

With Topology 2, unlike with Topology 1, there is only one possible shortest path for each flow; therefore we can also quantify the cost (in terms of delay) of using the shortest path here. The scheduling in Table 5 shows that if flows are restricted to their shortest route we have a considerable degradation in delay, even if MBAs are used. In effect, we can deduct from the table an average delay of 7 slots per flow, which is a degradation of 2.5 slots from the optimal solution described above (4.5 slots). Therefore, the latter is a 36% decrease in delay compared to the former. Moreover, using only shortest routes with MBAs also shows a 1.5 slot degradation from the optimal solution without MBAs. We therefore observe that limiting routes to the shortest paths, even while using MBAs, is detrimental to the delay to the point that having a "smarter" choice of paths (some paths being longer than the shortest) without MBAs is better. The number of transmissions here is equal to 20, a 16% decrease from the optimal scheduling presented earlier.

5 Conclusions

In this paper, we have shown that MBAs need to be used for delay reduction in ad hoc networks. Moreover, with static deterministic topologies with multi-flow scenarios, we have shown that in order to exploit the full potential of MBAs for that end-to-end delay reduction, the selection of routes needs to include other criteria such as the promotion of star nodes and the minimization of the number of bridges. We have shown that the mere use of shortest routes, as it is the case in most existing routing protocols for ad hoc networks, results in relatively high delays because such paths usually result in the formation of bridges in multi-flow scenarios; and bridges incur waiting and rescheduling delays that add to the end-to-end delay. We formulated determining the best route selection (best link scheduling) as an optimization problem that we solved using linear programming. Our scenarios showed that the optimal link scheduling forms a lot of star nodes and eliminates bridges as much as possible for a considerable 36% reduction in end-to-end delay. Our optimization model finds the lower bound of the end-to-end delay. However, this huge reduction in delay comes at the expense of a 16% increase in overhead measured by the total number of transmissions.

As future work, we will include beamforming into the model. Furthermore, we will design a protocol that establishes routes in light of what we have learnt here, and is able to deliver near-optimal results for end-to-end delay.

References

1. Bao, K., Hu, F., Bentley, E., Kumar, S.: Diamond-shaped mesh network routing with cross-layer design to explore the benefits of multi-beam smart antennas. In: 2016 25th International Conference on Computer Communication and Networks (ICCCN), pp. 1–5 (2016)
2. Bahl, P., Adya, A., Padhye, J., Walman, A.: Reconsidering wireless systems with multiple radios. SIGCOMM Comput. Commun. Rev. **34**(5), 39–46 (2004). https://doi.org/10.1145/1039111.1039122
3. Draves, R., Padhye, J., Zill, B.: Routing in multi-radio, multi-hop wireless mesh networks. In: Proceedings of the 10th Annual International Conference on Mobile Computing and Networking, MobiCom 2004, pp. 114–128. ACM, New York (2004). https://doi.org/10.1145/1023720.1023732
4. Winters, J.H.: Smart antenna techniques and their application to wireless ad hoc networks. IEEE Wirel. Commun. **13**(4), 77–83 (2006)
5. Singh, A., Ramanathan, P., Veen, B.V.: Spatial reuse through adaptive interference cancellation in multi-antenna wireless networks. In: 2005 IEEE Global Telecommunications Conference, GLOBECOM 2005, vol. 5, pp. 3092-3096, 5 pp. (2005)
6. Zhang, Y., Li, X., Amin, M.G.: Multi-channel smart antennas in wireless networks. In: 2006 Fortieth Asilomar Conference on Signals, Systems and Computers, pp. 305–309 (2006)
7. Li, X., Zhang, Y., Amin, M.G.: Performance evaluation of wireless networks exploiting multi-beam antennas in multipath environments. In: 2007 International Waveform Diversity and Design Conference, pp. 188–192 (2007)
8. Cheng, M.X., Gong, X., Xu, Y., Cai, L.: Link activity scheduling for minimum end-to-end latency in multihop wireless sensor networks. In: 2011 IEEE Global Telecommunications Conference - GLOBECOM 2011, pp. 1–5 (2011)
9. Wang, J., Fang, Y., Wu, D.: Uplink medium access control for WLANs with multi-beam access point. In: 2005 IEEE Global Telecommunications Conference, GLOBECOM 2005, vol. 5, pp. 3012–3016, 5 pp. (2005)

10. Wang, J., Fang, Y., Wu, D.: Enhancing the performance of medium access control for wlans with multi-beam access point. IEEE Trans. Wirel. Commun. **6**(2), 556–565 (2007)
11. Jain, V., Gupta, A., Agrawal, D.P.: On-demand medium access in multihop wireless networks with multiple beam smart antennas. IEEE Trans. Parallel Distrib. Syst. **19**(4), 489–502 (2008)
12. Tang, Z., Xing, X., Jiang, F.: Providing balanced and enhanced transmission for WLANs with multi-beam access point. In: 6th Annual Communication Networks and Services Research Conference (CNSR 2008), pp. 242–248 (2008)
13. Wang, X., Garcia-Luna-Aceves, J.J.: Embracing interference in ad hoc networks using joint routing and scheduling with multiple packet reception. In: IEEE INFOCOM 2008 - The 27th Conference on Computer Communications (2008)
14. IBM ILOG CPLEX optimization studio. https://www.ibm.com/jm-en/marketplace/ibm-ilog-cplex