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Novel joint routing and scheduling algorithms for minimizing end-to-end delays in multi Tx-Rx wireless mesh networks☆

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ABSTRACT

Multiple transmit (Tx) or receive (Rx) capability is a significant advance in wireless communications. This so called MTR capability allows the creation of wireless mesh networks (WMNs) that are ideal for use as a high-speed wireless backbone that spans vast geographical areas. A fundamental problem, however, is deriving a minimal transmission schedule or superframe that yields low end-to-end delays, with the primary constraint that routers are not allowed to Tx *and* Rx simultaneously. In this paper, we consider a joint routing and link scheduling approach that addresses two fundamental issues that influence end-to-end delays: superframe length and transmission slot order. Shortening the superframe length, in terms of slots, is expected to minimize the inter-link activation time while reordering transmission slots increases the likelihood that links on a path are activated consecutively. We propose two algorithms. The first called JRS-Multi-DEC uses a novel metric to minimize the load of each link while the second, called JRS-BIP, uses a Binary Integer Program approach. Both algorithms aim to minimize the overall delay and use slot re-ordering on the resulting schedule to further reduce delay. Numerical results show both algorithms are able to reduce the average end-to-end delay by approximately 50% as compared to a non joint routing algorithm.

1. Introduction

A promising approach to improve the network capacity of wireless mesh networks (WMNs) is to equip routers with multi transmit (Tx) or receive (Rx), aka MTR, capability. Such routers have N antennas/radios and they are able to initiate up to N transmissions/receptions to/from N distinct neighbors concurrently. In particular, they have the ability to null/suppress/ignore interference but cannot transmit and receive at the same time, meaning all links are *half-duplex*. There are three example systems that have MTR capability. The first is the WMN test-bed reported in [25], where Raman et al. created a low cost, long distance WMN using off-the-shelf IEEE 802.11 radios and high-gain parabolic antennas. All radios operate on the same frequency. The MTR capability is achieved using transmission power control, separating incident links by at least 30°, and disabling carrier sense. The second example is to equip nodes with 60 GHz radios. The key feature of the 60 GHz band is its high directivity. Moreover, the use of flat-top antennas means the interference between neighboring links can be ignored. In fact, the authors of [23] conclude that mm-wave (60 GHz) wireless links can be considered as *pseudo-wires*. Critically, the authors show that if the links are highly directional, the interference caused by neighboring transmissions can be ignored in both the physical and protocol interference model. The third example system employs multiple input multiple output (MIMO) technology; e.g., [6] and [9]. For example, in [9], a node is able to transmit/receive independent data streams to/from multiple neighbors over different antenna elements operating in the same frequency. Moreover, the node can use a subset of its antenna elements to null/suppress interference to/from neighbors. Consequently, as pointed out in [29], the widely used physical or protocol interference model is not suitable for MIMO based WMNs.

A key problem in MTR WMNs is link scheduling. The authors of [25] proposed a Spatial reuse Time Division Multiple Access (STDMA) scheduler named 2P. Specifically, at a given time, the 2P protocol requires nodes to operate in one of two phases: synchronous transmitting (SynTx) or synchronous receiving (SynRx). This means when a node is in the SynTx phase, it is transmitting on all links, and vice-versa if it is in the SynRx phase. Note, these two phases are required to avoid interference as all antennas/radios work on the same frequency. A key limitation of 2P is that it requires a WMN to be bipartite. Indeed, generating a schedule amounts to solving the NP-complete, MAX-CUT problem [8]. Consequently, the authors of [8] proposed a novel, fast, greedy link scheduling algorithm, called Algo-1, that operates on

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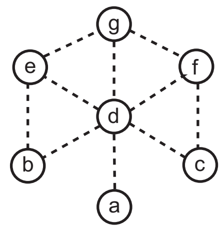

Fig. 1. An example WMN.

Table 1
Link schedule for the topology shown in Fig. 1.

Slot 1	Slot 2	Slot 3	Slot 4
e_{da}	e_{ge}	e_{de}	e_{ed}
e_{db}	e_{gd}	e_{df}	e_{fd}
e_{dc}	e_{gf}		
e_{dg}	e_{be}		
e_{eb}	e_{bd}		
e_{eg}	e_{cd}		
e_{fc}	e_{cf}		
e_{fg}	e_{ad}		

random topologies. One key limitation of 2P and Algo-1 is that nodes transmitting in slot i become receivers in slot $i+1$. This feature leads to longer superframe lengths. Here, superframe length is defined as the total number of time slots needed to transmit all available data from known flows. We adopt the same definition in our work. Note that this length is variable and is a function of the joint routing and scheduling algorithm that we propose. To this end, Loo et al. [22] outline an algorithm called Algo-2 to improve 2P and Algo-1 by maximizing link activations on a slot-by-slot basis. That is, a new activation schedule is computed for each slot as opposed to every other slot.

These aforementioned works, however, do not consider minimizing delays. This is an important consideration as it impacts real-time multimedia applications [7]. Hence, any efforts to minimize end-to-end delays serve only to enhance the QoS received by end users. However, guaranteeing end-to-end delay in WMNs is a challenging problem. As described in Section 4.1, we observe that the delay in MTR is affected by the superframe length, slot order of the derived superframe, and the routing protocol because the number of slots allocated to each link is proportional to its load. Using Fig. 1 as an example where links are bidirectional, let us assume there is a route from node a to g through d. Loo et al.'s algorithm [22] produces the schedule shown in Table 1, where link e_{ad} is activated in slot 2 and link e_{dg} is activated in slot 1. Thus, the end-to-end delay of the route from a to g is $2+3=5$ slots since it must wait for three slots at node d before the out-going link to node g is activated; we call this delay *inter-link activation time* (IAT). On the other hand, if the slots are reordered, i.e., swapping slot 1 with slot 2, the delay would be reduced to two slots since link e_{dg} can be activated right after link e_{ad}. In particular, as described in Section 4.2, we observe that IAT is affected by the superframe length and slot order of the derived superframe [11]. Note, the superframe length of a given WMN is intricately linked to the routing protocol because the number of slots allocated to each link is proportional to its load; i.e., more slots are required for a higher load. Moreover, at each intermediate node, a packet has to wait for its out-going link's time slot to occur [7]. Hence, a short superframe is preferred because it minimizes this waiting time. Apart from that, routing a demand over its shortest path may further reduce the minimum end-to-end delay, assuming slots containing the path's links are placed consecutively. However, as described in Section 4.2, if there are multiple demands, routing over the shortest path may create bottleneck links.

To date, as we have outlined in Section 2, past works have either focused on maximizing network throughput in MTR WMNs [13,18,30], or have only considered minimizing end-to-end delays in WMNs with omni-directional antenna [1,5,7,16,28]. However, no one has proposed MTR based solutions that minimize end-to-end delay through joint routing and scheduling. To this end, we propose two joint routing and scheduling algorithms: JRS-Multi-DEC and JRS-BIP. Their key features include minimizing maximum link load and superframe length, as well as reordering slots to minimize the average IAT. We show that these algorithms are able to reduce the average end-to-end delay as compared to two algorithms, NJR and JRS-Shortest. NJR does not jointly optimize both routing and scheduling. It uses the approach by Loo et al. [22] to first generate a superframe. Demands are then routed on their shortest path. In contrast, JRS-Shortest first decides the shortest path for each demand, and then uses Loo et al.'s approach to generate a superframe that only schedules links in the paths. In summary, this paper makes the following contributions:

- We formulate the joint routing and scheduling problem in MTR WMNs as a nonlinear Integer Programming problem. This formulation is novel as it is targeted at MTR WMNs, and is different from existing approaches such as [7] and [5] that focus on routers with omni-directional antennas. In addition, the MTR WMNs under consideration is also different from those that use multiple channels and multiple radios as our routers operate over a single channel.
- Both JRS-Multi-DEC and JRS-BIP are the first joint routing and scheduling solutions to minimize delays for MTR WMNs. JRS-Multi-DEC uses a heuristic algorithm, and JRS-BIP applies a Binary Integer Program (BIP) solver to select suitable routing paths. Both employ the link scheduling algorithm of [22] to generate a schedule, followed by a novel slot re-ordering algorithm to further reduce end-to-end delays. They can reduce the superframe length by more than 45% as compared to JRS-Shortest and more than 70% as compared to NJR. Numerical results show that our algorithms can reduce end-to-end delays by more than 50% as compared to NJR, and approximately 30% when compared against JRS-Shortest. We also prove that re-ordering slots reduces end-to-end delays by at most $H(|S|-2)+1$ slots for a demand with H hops and superframe length of $|S|$.
- We show that the theorem proposed by Dutta et al. [13] to compute the superframe length is not optimal. We also analyze the relationship between superframe length, routing paths, link weights and end-to-end delay. We show that JRS-Multi-DEC has a computation complexity of $O(\frac{|E|\times|\mathcal{D}|}{|V|^2}\times(|E|+|V|))$, where $|E|$ is the number of links, $|V|$ is the number of nodes, $|\mathcal{D}|$ is the number of demands. In addition, in terms of slot re-ordering, our proposed First-Hop rule, described in Section 5, produces lower end-to-end delays as compared to the Bucket Draining Algorithm (BDA) [22].
- We show that routing each demand via its shortest path is the best case when the number of nodes is significantly higher than the number of traffic demands, or when the number of links is significantly higher than the number of nodes. Further, if a demand can be routed via alternative paths with the same length, our algorithms will select the best one that leads to a lower link weight (defined in Section 5), which helps to reduce end-to-end delays.

This paper has the following structure. Section 2 discusses previous works. Our network model is described in Section 3 followed by the motivation of our research in Section 4.1. The description of the problem at hand is in Section 4.2. Our solutions are outlined in Section 5. Section 6 lists several propositions and lemmas concerning the proposed solutions. In Section 7, we present our experimental results. Lastly, our conclusions are presented in Section 8.

2. Related work

This section focuses on works that address the joint routing and scheduling (JRS) problem in WMNs. Kodialam and Nandagopal [18]