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# Joint routing and scheduling in multi-Tx/Rx wireless mesh networks with random demands

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ABSTRACT

Multiple transmit or receive (MTR) capability is a promising approach that significantly improves the capacity of Wireless Mesh Networks (WMNs). A fundamental problem is deriving a minimal link schedule or superframe that satisfies traffic demands. Existing MTR link schedulers or works that jointly consider routing and scheduling in wireless networks assume traffic demands are known in advance and are fixed. However, in practice, traffic demands are likely to be uncertain. Consequently, any computed solution will lead to either idle slots or congestion. Moreover, uncertain demands may cause a network operator to compute and install a new routing and superframe frequently; this is likely to incur high signaling overheads, especially in large scale multi-hop WMNs. Henceforth, in this paper, we consider random traffic demands characterized by a polyhedral set. We model the problem as a semi-infinite Linear Program (LP). We then propose a novel heuristic algorithm, called Algo-PolyH, that jointly considers both routing and superframe generation to produce a *robust* solution that is valid for all random demands that belong to a given polyhedral set. This fact is confirmed in our evaluation of Algo-PolyH in networks with varying number of degrees, number of flows, number of nodes and number of paths.



## 1. Introduction

The capacity of Wireless Mesh Networks (WMNs) that operate over a *single* frequency can be increased significantly by endowing each router with multiple transmit (Tx) or receive (Rx) (MTR) capability. For example, nodes can be equipped with multiple radios and high-gain parabolic antennas [1], 60 GHz radios [2] or multi-user multiple input multiple output (MIMO) technologies [3]. In these example MTR systems, routers with $N$ antennas/radios are able to simultaneously transmit/receive $N$ packets to/from $N$ distinct neighbors over a *single* frequency. Advantageously, a node will not experience collision when two or more neighbors transmit to it. In fact, interference only occurs if a node transmits *and* receives simultaneously; we call this the no *mix-tx-rx* constraint. For example, referring to Fig. 1, the directional link $AB$ and $CB$ can be activated simultaneously. Notice that this is not possible in conventional wireless systems that adhere to the physical or protocol interference model [4].

The set of links activated in each time slot, and hence, the capacity of a Time Division Multiple Access (TDMA) based MTR WMN, is governed by a link scheduler. Its main responsibility is to derive a superframe that comprises of a number of slots that afford nodes one or more transmission opportunities. Moreover, this superframe is repeated periodically. A short superframe, in terms of total active time of slots, ensures a high capacity as it affords links frequent transmission opportunities. Apart from that, a superframe may need to be generated in a manner that ensures

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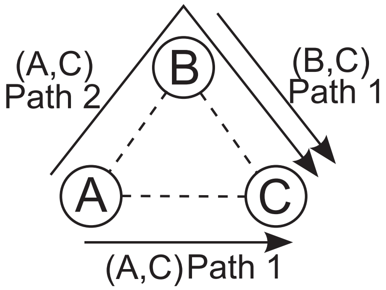



**Fig. 1.** Example MTR WMN with two flows and given paths.

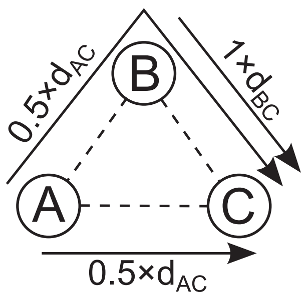
links receive adequate transmission times that commensurate with their load.

To date, there are only a few link schedulers that target MTR WMNs. In [1], the authors propose a scheduler, named 2P, where nodes that transmit in odd numbered time slots become receivers in even numbered slots. However, 2P requires a bipartite graph. Briefly, such a graph has vertices that can be divided into two disjoint sets, and each edge is connecting a vertex in one set to a vertex in the other set. In [5], the authors show that link scheduling in MTR WMNs is equivalent to finding the maximum cut (max cut) in each time slot. That is, each max cut contains the set of non-conflicting links that can be activated at the same time; i.e., they adhere to the no *mix-tx-rx* constraint. To this end, the authors of [5] propose Algo-1, a heuristic scheduler for arbitrary topologies, to solve the NP-complete MAX-CUT problem for every two time slots. In [6], the authors extend their work, named Algo-2, to generate shorter supeframes by maximizing link activation on a slot-by-slot basis. These link schedulers, however, assume the traffic demand over each link is fixed over time and known in advance. However, in practice, traffic is likely to be uncertain and unknown [7]. Moreover as pointed out in [8], estimating Traffic Matrices (TMs) is challenging. Consequently, the computed superframe may have excessive idle slots or cause links to have insufficient capacity at times of peak demands.

A key advance in characterizing TMs in a manner that is amenable to computation is the polyhedral model [9]. Specifically, traffic demands are described by a set of linear inequalities. Consider the triangle topology shown in Fig. 1. A possible set of inequalities for the two flows is as follows: $d_{AC} + d_{BC} \leq 0.6$, $d_{AC} \leq 0.4$ and $d_{BC} \leq 0.4$, where $d_{AC}$ and $d_{BC}$ are the demand for the flow emanating from node $A$ and $B$, respectively; here, the values 0.6 and 0.4 are fractions of the unit capacity that represents the amount of traffic. Notice that the demand of both flows can take on a range of values. In this case, each inequality is a constraint. Given the above inequalities, all possible TMs are located in a polytope. Each extreme point or vertex of the polytope represents a TM with one or more maximum demands. The extreme points of the resulting polytope are (0, 0), (0.4, 0.2) and (0.2, 0.4). A key problem is therefore to derive a suitable superframe that supports all possible demand values or TMs as defined by the given polytope.

Another key consideration when generating a superframe is routing. The amount of traffic routed on a given path or links has an impact on the resulting superframe length. In particular, routing determines the load of links and thus their required active time in the derived superframe. Consider Fig. 1 with flow $(A, C)$ and $(B, C)$ that have two and one possible path, respectively. Figs. 2 and 3 show two example routings and the corresponding maximum link load. Recall that nodes support MTR, and thus link $AB$ and $AC$ can be activated together; so can links $BC$ and $AC$. Thus, we have the following transmission sets or max cuts: $\{AB, AC\}$ and $\{BC, AC\}$; these can then be used to construct a superframe. All that is required now is their active time.

Let us first assume that the demand of flow $(A, C)$ is divided equally over Paths 1 and 2, and we route all demand from flow $(B, C)$ over its only path; see Fig. 2. Given the extreme point (0.4, 0.2), the maximum load of link $AB$ is $d_{AC} \times 0.5 = 0.4 \times 0.5 = 0.2$. The maximum load of link $BC$ is $d_{AC} \times 0.5 + d_{BC} = 0.2 + 0.2 = 0.4$. On the other hand, given the extreme point (0.2, 0.4), the maximum load of link $AB$ and $BC$ is $0.2 \times 0.5 = 0.1$ and $0.1 + 0.4 = 0.5$, respectively. From these two instances, to satisfy both extreme points, when deriving a superframe, we must ensure the active time of links $AB$ and $BC$ can support both extreme points. Thus, given this routing, the active time of max cuts $\{AB, AC\}$ and $\{BC, AC\}$ must be set to 0.2 and 0.5 respectively; the total superframe length is thus $0.2 + 0.5 = 0.7$. Now, assume a new routing whereby flow $(A, C)$ routes all of its demand on Path 1; i.e., link $AB$ has no traffic; see Fig. 3. The maximum load of links $BC$ and $AC$ is 0.4 when we consider the two extreme points. Thus, we only need to activate max cut $\{BC, AC\}$ for 0.4 unit time, resulting in a shorter superframe length. From these examples, we see that it is important to jointly




| | Extreme Points | |
|---|---|---|
| | (0.4,0.2) | (0.2,0.4) |
| AB | 0.2 | 0.1 |
| BC | 0.4 | 0.5 |
| AC | 0.2 | 0.1 |

**Fig. 2.** First example routing. Each cell in the table shows the corresponding link load when $(d_{AC}, d_{BC}) = (0.4, 0.2)$ and $(d_{AC}, d_{BC}) = (0.2, 0.4)$.