Improving minimal flow for wireless mesh networks by optimizing antenna placement

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***Abstract*—For some time, directional antennas have been considered as a measure of solving connectivity and interference issues in wireless networks. However, previous work mainly concerns either link scheduling or antenna placement but not combination of the two. In this paper we study the problem of maximizing the minimal flow rate from gateways to mesh routers by optimizing the placement of directional antennas. Mixed integer programming models are presented for joint optimization of antenna placement, link scheduling and link rate allocation for preset and non-preset routing.**

I. Introduction

In many deployment scenarios, wireless mesh networks (WMN) operate in highly dense network topologies where interference between the WMN nodes as well as from external nodes may cause degradation of network performance. Directional antennas can improve network performance by focusing transmission energy between communicating pairs of nodes. However, they also bring extra interference to the nodes which are not the dedicated receivers but situated in the beams. Therefore, the locations for placing directional antennas should be optimized [1].

We study the problem of maximizing the minimal flow between gateways and routers when omni and directional antennas are used alternatively. Transmission scheduling is based on Time Division Multiple Access (TDMA) variant where a group of active links satisfying the signal-to-interference-plus-noise-ratio (SINR) constraint is selected for each time slot. SINR depends on the type of antennas installed in the nodes and we therefore derive an antenna-aware SINR constraint for transmission scheduling. The data rate of the active link is controlled by selecting different modulation and coding schemes (MCSs). We incorporate routing into the model in two different ways. One way is to establish routing in advance and the optimization model is built on the determined topology. The other way is to optimize the routing within the optimization model. Besides, the number of available directional antennas is also limited.

II. Optimization models

The considered WMN networks consist of gateways $\mathcal{G}$, mesh routers $\mathcal{R}$ and radio links $\mathcal{E}$. Note that there are no links between gateways as each gateway is connected directly to the Internet. Each mesh router $r \in \mathcal{R}$ downloads traffic from a gateway $g(r) \in \mathcal{G}$. For each link $e \in \mathcal{E}$, the originating node and the terminating node are denoted by $a(e)$ and $b(e)$, respectively. Further, $\delta^+(v)$ represents the outgoing links from node v while $\delta^-(v)$ represents the links incoming to node v.

TABLE I: Notations for optimization models

constants	
$n(e)$	the number of routes passing through link e
$B(e,i)$	data rate of link e in compatible set i
$d(v,i)$	equals to 1 if node v is active in compatible set $\mathcal{C}(i)$ and uses a directional antenna; 0 otherwise
$o(v,i)$	equals to 1 if node v is active in compatible set $\mathcal{C}(i)$ and uses an omni antenna; 0 otherwise
K	the number of available directional antennas
variables	
f	continuous, uniform flow assigned to the routes
t_i	nonnegative continuous, the time assigned to compatible set $i \in \mathcal{I}$
S_v	binary, indicating whether v uses a directional antenna ($S_v = 1$) or an omni antenna ($S_v = 0$)
x_{er}	binary, indicating whether link e is used in route r

The concept of compatible set is introduced to represent a set of links which can be active simultaneously without violating SINR constraint. The link capacity c_e is determined by a selected link transmission schedule. Such a schedule is defined for the sequence of time slots to which the time interval $[0, T]$ is divided, and consists of specifying the slots in which the particular link e is active. Certainly, the set of links active in each time slot must constitute a compatible set. For our purposes, the transmission schedule for the links can be defined in a simpler way. We partition the interval $[0, T]$ into subintervals indexed with $i \in \mathcal{I}$. Each such interval has length t_i and is assigned a compatible set $\mathcal{C}(i)$ that are active for the whole time t_i. Let $B(e, i) = B(m)$ if link e belongs to compatible set $\mathcal{C}(i)$ and utilizes MCS m in that set; otherwise, when e does not belong to $\mathcal{C}(i)$, we put $B(e, i) = 0$. In such a setting, the total amount of data that can be sent over link e during time T is equal to $c_e = \sum_{i \in \mathcal{I}} B(e, i)t_i$.

Below, we present models utilizing the notion of compatible sets for maximizing the minimal flow.

A. The model under fixed routing

In this model, the routing path for each mesh router is fixed. The objective is to maximize the uniform flow f sent on all routes $R(r), r \in \mathcal{R}$. The formulations are given in (1). The input links $\mathcal{E}^F$ only includes the links which are used by routing paths. Constraints (1c) and (1d) make sure that a node use either a directional antenna or an omni antenna over all selected compatible sets. Constraint (1e) limits the number of available directional antennas.

$$
\begin{aligned}
&\textbf{maximize} \quad f \\
&\textbf{subject to:} \\
&\quad \textstyle\sum_{i\in\mathcal{I}} t_i = T && \text{(1a)}\\
&\quad n(e)f \le \textstyle\sum_{i\in\mathcal{I}} B(e,i)t_i,\ e\in\mathcal{E}^F && \text{(1b)}\\
&\quad \textstyle\sum_{i\in\mathcal{I}} d(v,i)t_i \le S_v T,\ v\in\mathcal{V} && \text{(1c)}\\
&\quad \textstyle\sum_{i\in\mathcal{I}} o(v,i)t_i \le (1-S_v)T,\ v\in\mathcal{V} && \text{(1d)}\\
&\quad \textstyle\sum_{v\in\mathcal{V}} S_v \le K && \text{(1e)}
\end{aligned}
$$

B. The model with optimized routing

In this case, the routing paths for each mesh router are not fixed but optimized with antenna placement and link scheduling. The set of links $\mathcal{E}^O$ is defined as all pairs of nodes. Constraints (2b) and (2c) express the flow conservation rule. The optimized routing for each mesh router will be defined by x_{er}.

$$
\begin{aligned}
&\textbf{maximize} \quad f \\
&\textbf{subject to:} \\
&\quad \text{(1a),(1c) – (1e),} \\
&\quad \textstyle\sum_{r\in R(r)} x_{er} \le \sum_{i\in\mathcal{I}} B(e,i)t_i,\ e\in\mathcal{E}^O && \text{(2a)}\\
&\quad \textstyle\sum_{e\in\delta^+(g(r))} x_{er} = f, r\in\mathcal{R} && \text{(2b)}\\
&\quad \textstyle\sum_{e\in\delta^+(v)} x_{er} - \sum_{e\in\delta^-(v)} x_{er} = 0, \\
&\qquad\qquad r\in\mathcal{R}, v\in\mathcal{V}\setminus\mathcal{G}\cup R(r) && \text{(2c)}
\end{aligned}
$$

C. Solution approach

The MIP formulations above are non-compact since the number of potential compatible sets I grows exponentially with the size of problem (network). So, in general, the list of compatible sets necessary to reach the optimum cannot be predefined. However, appropriate compatible sets can be generated during the branch-and-bound (B&B) process while solving the linear relaxations at the visited B&B nodes. Such a combination of B&B and column generation is called branch-and-price (B&P), see [2].

III. CONCLUSION

The models presented in this paper give an optimal way to combine the use of omni and directional antennas with transmission scheduling, link rate allocation and routing. The obtained centralized solution yields theoretical performance bound and therefore represents an useful component for comparing against future solutions aiming at achieving the centrally optimized objectve in a distributed manner.

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