Link Scheduling and Power Control in Wireless Mesh Networks with Directional Antennas

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Abstract— **Directional antennas are very attractive in Wireless Mesh Networks (WMN). We study the problem of link scheduling and power control in a Time-Division Multiple Access (TDMA) WMN where the nodes use directional antennas. This is a cross-layer design problem spanning the physical and the link layers. Link scheduling in WMNs requires careful modeling of interference. Interference models used for omni-directional antennas cannot be used for directional antennas. We develop a generalized interference model applicable to directional antennas. Then, we use this model to formulate the link scheduling and power control problem as a Mixed Integer Linear Program. We also propose a heuristic algorithm to solve the problem efficiently.**

***Index Terms*— Wireless Mesh Networks, Directional Antennas, Link Scheduling, Power Control, Cross Layer Design**

I. INTRODUCTION

Directional antennas (DAs) focus the available power into desired directions as opposed to omni-directional transmission where the power is equally dispersed in all directions. DAs can thus provide the benefits of increased range, reduced interference, and increased spatial reuse of bandwidth. DAs have been studied for cellular networks and have been deployed for cell-sectoring. Beamforming and power control are physical-layer issues while link scheduling is a medium access control (MAC) layer functionality. DAs have also been studied for medium access control in ad hoc networks [1] and routing protocols [2]. Link scheduling and power control have been traditionally dealt with independently at their respecive layers. Such an approach leads to unnecessary collisions and also unnecessary restraint from transmission. These problems become more pronounced when DAs are used at the physical layer. The full benefits provided by DAs cannot be tapped if the scheduling does not take into account the nature of the beam formation at each node, the physical network topology, and the propogation environment.

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Recently WMNs have received a lot of attention due to their potential to provide high-speed Internet connecitivity without much wired infrastructure in a city. In a WMN, there are three types of nodes: mesh routers, mesh clients, and gateways. A group of wireless routers are placed at strategic locations in the city to serve as a regional backbone network to wireless clients. Wireless routers are envisioned to use smart antenna radio technology to enhance their connectivity and also improve the network capacity [3]. The wireless backbone consists of a set of self-configuring links which adapt to node failures and traffic pattern variations. These wireless routers are connected through multiple hops to one or more gatways which are connected to the rest of the Internet. In this study, we are concerned primarily with the wireless backbone and not the wireless clients.

Link scheduling with power control has been studied previously for omni-directional antennas [4, 5] with varied objectives. Most of the work has focussed on minimimizing the power [4]. Minimizing power and thereby increasing battery life-time is important for ad hoc and sensor networks. However, power consumption is not a major issue in WMNs (because the mesh routers are at fixed loocations where power supply is readily available). In our study, the major concern regarding power in a WMN is the maximum power constraint. This maximum power is dictated by the FCC regulations rather than battery-life considerations. However, it should be noted that power control can also help in reducing interference and is therefore also important in WMNs. So our aim is to maximize throughput under a maximum power constraint. Some recent work [5, 6] focussed on maxmizing the throughput with omni-directional antennas. Using the same methodologies for DAs leads to serious limitations as we show later in this paper. Therefore, new methods for link scheduling are required for DAs.

In this study, we consider a TDMA (Time-Division Multiple Access) based MAC layer. Link scheduling for TDMA-based wireless networks has been studied in the literature [7, 8]. However, most of the studies use the protocol interference [9] model and also assume omni-directional transmission. Reference [10] uses a more physical-layer oriented model but assumes omni-directional transmission. Our study differs in these respects: first, we use a good DAmodel; and second, we use a more realistic interference model which is suited forDAs. We study link scheduling and power control as a cross-layer design problem to maximize the network throughput under this model. We formulate and solve the problem as an MILP (Mixed Integer Linear Program) and then develop a good heuristic to approximately solve the problem faster.

The rest of the paper is organised as follows. Section II describes our WMN model, including the interference model with directional antennas. In Section III, we formulate the problem of link scheduling and power control as an MILP. In Section IV we propose an efficient heuristic to do the same job. Section V provides some representative illustrative examples and Section VI concludes the paper.

II. MODELING A WMN WITH DIRECTIONAL ANTENNAS

A. Antenna and Propagation Models

We use the "exact cone-plus-ball" antenna model [11, 12] which captures the essentials of a directional antenna without going into the complexities of replicating an exact antenna radiation pattern. The radiation pattern is approximated by a main lobe of constant gain g_m and beam-width θ_m and a side lobe of constant gain g_s. Although this is an approximate model which does not take into account the tapering of the antenna gain as we move radially away from the center of the lobe, it is a practical model that can give us useful insights into the effect of beamforming on the network as a whole. In this model, the beam-width θ_m, main-lobe gain g_m, and side-lobe gain g_s are related as (see [12]):

$$g_m(\theta_m, g_s) = \eta\Delta - g_s(\Delta - 1)$$

where $\Delta = 2/(1-\cos(\theta_m/2))$ is the directivity of the antenna and η is the antenna efficiency.

For the propagation environment, we use the standard log-distance path-loss model [13] with a path-loss exponent of n = 4 which is most practical in an urban setting with many buildings and obstructions.

B. Beam-Selection Algorithm (BSA)

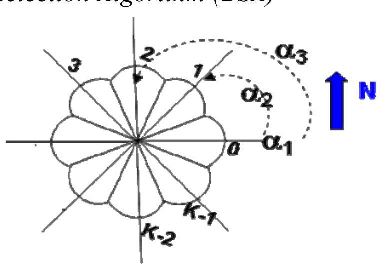

Fig. 1. Switched-beam system.

We assume a switched-beam system as opposed to a beam-steering system because it is attractive for wireless mesh networks due to its lower costs. A switched-beam system with K sectors consists of K selectable beams. We number the beams from 0 though K-1 as shown in Fig. 1, where α_k, k = 0, 2, … , K-1, represents the absolute angular locations of the centers of the K beams. We assume that there is a global reference direction which is known at each node by means of a compass needle. Each node can, in general, have different sectoring. Each node knows the relative location of its neighbors. Since this is a mesh backbone, this assumption is quite appropriate. When a node v_i wants to transmit to its neighboring node v_j, it determines the relative angle of node v_j, Φ_{ij}, with respect to itself. Then, the beam that is used by v_i for transmission to v_j is determined as:

$$\psi_{ij} = \arg\min_{\theta_k} \left|\Phi_{ij} - \alpha_k\right| \quad k = 1...K$$

where ψ_{ij} represents the beam that node v_i would use if it were to transmit to node v_j. We calculate ψ_{ij} for all pairs of nodes in the network even though they may not be neighbors because it will be useful in interference calculations.

C. Network and Traffic Model

The WMN can be modeled as a graph G(V,E) with nodes representing wireless routers. A link exists between two nodes if and only if they are connected. For two mesh nodes to be connected, we require that the signal-to-noise ratio (SNR) at the receiver should exceed a threshold β, i.e.,

$$SNR_r(d) = \frac{k.P_t g_m(\theta_m)}{d^n N_0} \geq \beta$$

where k is a constant, P_t is the transmit power, and N_0 is the ambient noise variance. Our mesh network consists of N_{AP} mesh access points (or routers) and N_G gateways. The total number of nodes in the network is $N = N_{AP} + N_G$. Each node uses beam-switching antennas and uses the BSA for its transmissions. Since we assume a TDMA MAC protocol, time is divided into slots. Each TDMA frame consists of T time slots. Each mesh router has a single radio which has a capacity of C bps. Each mesh router has an aggregate demand γ_s bps that is to be routed to the Internet through one of the gateways. The routes to the gateways from each mesh router can be decided by any routing algorithm. We use the shortest-path routing algorithm to the nearest gateway. Each node (access point) not only has to transmit its own traffic but also forward traffic routed through it by other nodes. Based on the routing algorithm and node demands, the link load $\lambda(e)$ on every link e can be determined. If the link capacity is C, then the number of time slots for which link e needs to be scheduled is given by:

$$d(e) = \left\lceil T.\frac{\lambda(e)}{C} \right\rceil$$

For example, if the demand on a link e is 1.1 Mbps, the link capacity is 11 Mbps, and T = 100 time slots, then link e has to be scheduled for 10 timeslots in every frame. We generalize this to define a unit of traffic so that the study can be valid for any link capacity and traffic demands. We define one unit of traffic as the amount of traffic that can be transmitted over a link under ideal conditions in one time slot. Each node s has traffic of D_s units that it needs to route to the gateways in one time frame. D_s is related to γ_s as $D_s = \lceil T.\gamma_s/C \rceil$. We define the network throughput as the total units of traffic transmitted across the network in one TDMA frame. If the link speed is C bps, then the throughput in bps can be obtained by multiplying the throughput in units by a factor of C/T, i.e.,

$$\text{Throughput (bps)} = \frac{C}{T}\,\text{Throughput (units)}$$

D. Interference Model

Two links in a WMN can be scheduled in the same time slot provided they do not interfere with each other. We classify the various wireless interferences into two main categories:

1) Primary Interference:

The primary interference can be further classified into three sub-categories. To avoid *self interference*, a wireless node cannot transmit and receive at the same time. This is one of the reasons why CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) is used for 802.11 wireless local area networks (WLAN) as opposed to CSMA/CD (CSMA with Collision Detection) that is used in traditional Ethernet. To avoid packet *collision*, two wireless nodes cannot transmit to the same destination. Also a node can transmit data to only one node in a time slot. This means that multicast is not allowed. These three scenarios are illustrated in Fig. 2.

Fig. 2. Primary interference.

2) Secondary Interference

The secondary interference concerns with the interference caused due to simultaneous transmissions between different pairs of nodes. The following common interference models have been used in the literature:

Protocol Interference Model (PrIM): In this model [9], a transmission on link (v_i, v_j) is successful if the distance between the receiver v_j and the source of another simultaneous transmission on link (v_p, v_q) is greater than its distance from the intended source v_i by a factor η, i.e.,

$$\left\|v_p - v_j\right\| \geq (1+\eta)\left\|v_i - v_j\right\|$$

This model does not allow power control. Also, it does not take into account the aggregate interference due to all simultaneous transmissions. These shortcomings have been illustrated in [14, 15].

Fixed Power Protocol Interference model (FPPrIM): In this widely-used model [16], the nodes are assumed to use a fixed power for transmission. Each node has a transmission range R_T and the interference range R_I. Suppose node v_i is transmitting to node v_j which is within its transmission range R_T. Then, another simultaneous transmission from node v_p to node v_q will cause interference to node v_j and destroy the communication from node v_i to node v_j, if node v_j is within the interference range of node v_p. In general, the interference range is larger than the transmission range, i.e., $R_I > R_T$. Efficient scheduling algorithms using this model have been investigated in [16].This model allows for power control but it does not take into account aggregated interference.

Omni-directional Physical Interference Model (OPIM): In this model [5], a transmission from node v_i to node v_j is successful only if the signal-to-interference-and-noise ratio (SINR) at the receiver node v_j is greater than a threshold. In this model, the degradation of power between any signal source and destination is assumed to be just a function of distance, i.e.,

$$\mathrm{SINR}_{(i,j)} = \frac{G_{(i,j)} P_{(i,j)}}{N_o + \sum_{(p,q)\in E} G_{(pj)} P_{pq}} \geq \beta$$

where β represents the SINR threshold and N_0 is the ambient noise variance. Node v_i is transmitting to node v_j at a power level $P_{(i,j)}$. Interference is caused by other simultaneous transmissions that are taking place. As a representative, a transmission from node v_p to node v_q is occurring at power level $P_{(p,\ q)}$. The factor G(i, j) represents the degradation of power with distance. Typically, G(i, j) is proportional to $d_{(i,j)}^{-n}$. The amount of interference caused at node v_j is just dependent on $P_{(p,\ q)}$ and $d_{(p,\ q)}$. This model is very effective for omni-directional transmission. The OPIM model takes into account the aggregate interference due to all transmissions and is therefore much more accurate than the PrIM and FPPrIM models. An MILP-based scheduling algorithm for this model has been studied in [5].

All these models are quite good for networks in which the nodes use isotropic antennas. But they are not good for nodes using DAs which have different gain in different directions. Even the OPIM model fails when DAs are used because DAs have different gain in different directions. An example where FPPrIM and OPIM fail is shown in Fig. 3. Node v_i is transmitting to node v_j and node v_p is transmitting to node v_q. When directional transmission is used, both transmissions can simultaneously take place whereas FPPrIM and OPIM will not allow such transmission because the nodes are too close.

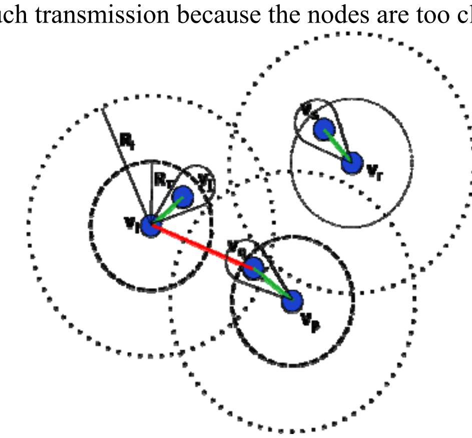

Fig. 3. Failure of FPPrIM [and OPIM] models when beamforming is used.

Generalized Physical Interference Model (GPIM): We propose the Generalized Physical Interference Model (GPIM) which extends OPIM to take into account the directional transmissions. As in OPIM, for a transmission from node v_i to node v_j to be successful, the SINR at node v_j must be greater than a certain threshold β. The SINR is a dynamic quantity that not only depends on the desired signal power but also the power from all other simultaneous transmissions.

Consider two simultaneous transmissions – from node v_i to node v_j and from node v_p to node v_q. The transmission from v_i to v_j is the one for which we are seeking the SINR for and the transmission from v_p to v_q is a representative of an interfering transmission. Both nodes v_i and v_p use DAs. We also allow for power control where the transmission powers of different links may be different but with the constraint that they must be less than a maximum power allowed P_{max}. The transmission on link (v_i, v_j) is taking place at power $P_{(i,\ j)}$ while the transmission on link (v_p, v_q) is taking place at power $P_{(p,\ q)}$. We denote by $g_i(\theta,\phi)$ the three-dimensional antenna gain pattern used for transmission over link (v_i, v_j). Then, the SINR at receiver j is given by:

$$SINR_{(i,j)} = \frac{g_i\left(\theta_{ij},\Phi_{ij}\right)d_{(i,j)}^{-n}P_{(i,j)}}{N_o + \sum_{(p,q)\in E} g_p\left(\theta_{pj},\Phi_{pj}\right)d_{(p,j)}^{-n}P_{pq}} \geq \beta$$

This model is very general but also complex. To simplify, we model the antenna pattern using the "Exact Cone-plus-ball" model [12]. We also use beam switching at the mesh nodes. In general, when using beam switching, the beam-width used by a node v_i may be different from that used by another node v_p. Both the transmitting nodes v_i and v_p use the beam-selection algorithm to select the appropriate beam for transmission. The SINR at receiver j is given by:

$$\frac{G_{(i,j)}P_{(i,j)}}{N_o + \sum_{(p,q)\in E-(i,j)} I_{(p,q,i,j)}P_{pq}} \geq \beta$$

where $G_{(i,j)} = d_{(i,j)}^{-n}g_i\left(\Phi_{ij}\right)g_j\left(\Phi_{ji}\right)$ is the total gain from node v_i to node v_j taking into account the distance and also the antenna gains, and $g_i\left(\phi\right) = g_i\left(\pi/2,\phi\right)$ is the 2-D projection of the 3-D antenna pattern on the principal plane. Also, since we are using the cone-plus-ball model, we have:

$$g_i\left(\phi\right) = \begin{cases} g_m & \text{if } \phi \text{ is within main lobe} \\ g_s & \text{if } \phi \text{ is within side lobe} \end{cases}$$

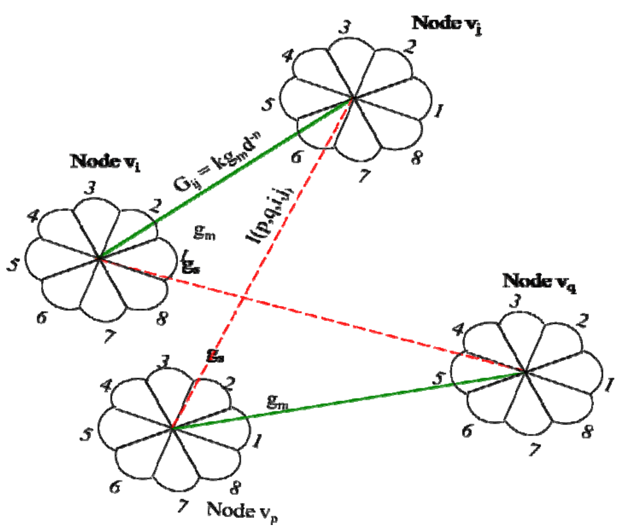

Fig. 4. Interference model with beam switching.

If we consider directional transmission and omni-directional reception, then we have $G_{(i,j)} = d_{(i,j)}^{-n}g_i\left(\phi\right)$. $I_{(p,q,i,j)}$ represents the fraction of power transmitted over link (v_p, v_q) that causes interference at node v_j. It depends on the distance between nodes v_p and v_j, $d_{(p,j)}$, the gain pattern that node v_p is using at that time, and on the angle between the main-lobe direction of node v_p's gain pattern relative to the angle Φ_{pj} between node p and node j. In the special case of omni-directional transmission and reception, $I_{(p,q,i,j)} = G_{(p,j)}$. For a switched beamforming system, the interference model is illustrated in Fig. 4. The intended transmissions are always using the main lobe. To determine the interference cause by transmission on link (v_p, v_q) to (v_i, v_j), we first determine the beam that node v_p would use if it were to transmit to node v_j. If it is same as the beam it is using for its present transmission to node v_q, then the interference would involve the main-lobe gain g_m, otherwise it would involve the side-lobe gain g_s, i.e.,

$$\begin{aligned} &\text{If}\left(\psi_{pj} == \psi_{pq}\right) \\ &\qquad I_{(p,q,i,j)} = g_m \\ &\text{else} \\ &\qquad I_{(p,q,i,j)} = g_s \end{aligned}$$

III. MILP FOR LINK SCHEDULING AND POWER CONTROL (LSPC)

The general problem of joint routing, link scheduling, and power control with DAs is very complex, so we separate the routing problem from link scheduling and power control. We formulate the problem of link scheduling with power control (LSPC) as a Mixed Integer Linear Program (MILP) which takes as its input the routes found by the routing algorithm. In LSPC, we consider those wireless links which are on at least one of the paths and discard other links. This approach leads to a considerable reduction in the problem size and is also a practical approach when operating with standard routing algorithms. The specifications of LSPC are as follows:

Input: Location of mesh access points (mesh nodes), gateways, aggregated traffic demand at each mesh node, path(s) to be followed for each node.

Output: An interference-free transmission schedule for each link along with the corresponding power for transmission.

Objective: Maximize the network throughput, i.e., the total traffic carried in a TDMA frame consisting of T time slots.

Variables:

i) $X_{(t,\ i,\ j)}$ is a binary variable which is equal to one if link (i, j) is scheduled in time slot t.

ii) $P_{(t,\ i,\ j)}$ is the power used over link (i,j) in time slot t. It is zero if link (i, j) is not scheduled in time slot t..

iii) P_k represents the k^{th} path. $P_k[m]$ represents the m^{th} node in path P_i.

iv) r_k is the achieved flow on path k.

v) $f_{(k,\ i,\ j)}$ is a variable representing the quantity of flow for path k that is passing through link (i,j)

Primary interference is taken care of by the inequality:

$$\sum_{(i,\ j)\in E} X_{(t,i,\ j)} + \sum_{(j,\ l)\in E} X_{(t,\ j,l)} \leq 1 \qquad \forall\, j \in V$$

This constraint restricts transmission on any two links which may lead to collision, self-interference, and multicast as shown in Fig. 2.

The secondary interference model discussed in the previous section can be used to derive the secondary interference constraint as follows:

If $X_{(i,j,t)} = 1$,

$$\frac{G_{(i,j)} P_{(i,j,t)}}{N_o + \sum_{(p,q)\in E-(i,j)} I_{(p,q,i,j)} P_{(p,q,t)}} \geq \beta$$

i.e., $G_{(i,j)} P_{(i,j,t)} - \beta N_0 - \beta \sum_{(p,q)\in E-(i,j)} I_{(p,q,i,j)} P_{(p,q,t)} \geq 0 \quad \text{if } X_{ij}^{t} = 1$

Also $P_{(i,j,t)} = 0$ when $X_{(i,j,t)} = 0$, since no transmission is taking place. Combining the above conditions, we get the secondary interference constraint as:

$$G_{(i,j)} P_{(t,i,j)} - \beta \sum_{(p,q)\in L_t/(i,j)} I_{(p,q,i,j)} P_{(t,p,q)} - \beta N_0 \geq \mathrm{Big}\left(X_{(t,i,j)} - 1\right) \quad \forall (i,j) \in E,\ 1 \leq t \leq T$$

where L_t represents the set of all transmissions taking place in time slot t.

Formally, LSPC can be stated as follows:

LSPC

Maximize $\sum_{k=1}^{K} r_k$

subject to

Demand Constraint :

$$\sum_{\substack{\text{All paths } P_k \text{ that} \\ \text{start from node } i}} r_k \leq D_i \qquad 1 \leq i \leq N$$

Flow Conservation constraints:

$$f_{(k, P_k[0], P_k[1])} - r_k = 0 \qquad 1 \leq k \leq K$$

$$f_{(k, P_k[i-1], P_k[i])} - f_{(k, P_k[i], P_k[i-1])} = 0 \quad 1 \leq k \leq K$$

$$f_{(k, P_k[last-1], P_k[last])} - r_k = 0 \qquad 1 \leq k \leq K$$

Relation between f and X:

$$\sum_{k=1}^{N} f_{(k,i,j)} \leq \sum_{t=1}^{T} X_{(t,i,j)} \qquad \forall (i,j) \in E$$

Primary Interference Constraints:

$$\sum_{(i,j)\in E} X_{(t,i,j)} + \sum_{(j,l)\in E} X_{(t,j,l)} \leq 1 \quad \forall j \in V$$

Secondary Interference Constraints:

$$G_{(i,j)} P_{(t,i,j)} - \beta \sum_{(p,q)\in L_t/(i,j)} I_{(p,q,i,j)} P_{(t,p,q)} - \beta N_0 \geq \mathrm{Big}\left(X_{(t,i,j)} - 1\right) \quad \forall (i,j) \in E,\ 1 \leq t \leq T$$

Maximum Power Constraints:

$$0 \leq P_{(t,i,j)} \leq P_{max} X_{(t,i,j)} \qquad \forall (i,j) \in E,\ 1 \leq t \leq T$$

The objective is to maximize the total traffic scheduled in the network. The total throughput is equal to the sum of the flows achieved on all the paths. The demand constraint dictates that the total flow achieved for node v_i is at most equal to the demand. The flow-conservation constraint dictates that conservation of flow must be valid for each node along each path. The constraint relating flows f and schedule X dictates that the sum of time slots scheduled on a given link (v_i, v_j) must be greater than the aggregated flows passing through that link. The maximum power constraint dictates that whenever any node, say node v_i, transmits to node v_j, i.e., when $X_{(t,i,j)} = 1$, power used for transmission $P_{(t,i,j)}$ should be less than P_{max}.

IV. Heuristic for Link Scheduling and Power Control with Directional Antennas

For a large number of nodes, the MILP proposed in the previous section becomes very large and may not be solvable in a reasonable amount of time. So, we propose a heuristic to approximately solve the link scheduling and power control problem quickly. Our heuristic consists of two steps:

1) Sort links based on interference

First, we sort all the links based on primary interference. To do this, we use a conflict-graph based approach [17]. A conflict graph is a directed graph with its nodes being the links in the wireless network. There is an edge between two nodes in the conflict graph, if there is a primary interference between the two corresponding links. Two nodes in a conflict graph which are not connected do not have primary interference. Still such links may not be scheduled together due to SINR constraint which takes into account the aggregate interference in a time slot (this is unique in our work).

2) Schedule the sorted links in order as soon as feasible

The first link in the sorted list is put into as many time slots as it requires. Then, we try to schedule other links in order as soon as possible without violating any wireless constraints. For scheduling a link (v_i, v_j) in a time slot t, the following "*Admissibility Criteria*" must be satisfied

a) Link (v_i, v_j) should not have primary interference with any link that is already scheduled in the same time slot, and

b) After scheduling link (v_i, v_j), the SINR constraint must not be violated for any link already scheduled in time slot t.

Since we are allowing power control, criteria b) implies that we need to ensure that the power levels of all the transmissions scheduled in the present time slot can be adjusted within limits to allow all transmissions. Given a set of links L_t to be scheduled in time slot t, we can find a set of feasible power levels without violating any SINR constraint if the following linear program FP (feasible power) has a feasible solution.

FP (Link Set L_t)

Minimize $\sum_{(v_i,v_j)\in L_t} P_{(i,j)}$

subject to

Interference Constraint:

$$G_{(i,j)} P_{(i,j)} - \beta \sum_{(p,q)\in L_t \setminus (v_i,v_j)} I_{(p,q,i,j)} P_{(p,q)} - \beta N_0 \geq 0 \quad \forall (v_i, v_j) \in L_t$$

Maximum Power Constraint:

$$0 \leq P_{(i,j)} \leq P_{max} \qquad \forall (v_i, v_j) \in L_t$$

We examine links in the sorted list in order. We try to schedule a link e in as many time slots as it requires without violating any interference constraint. To determine if link e can be scheduled in time slot t, we add e to L_t and then see if FP(L_t) has a feasible solution. If it has a feasible solution, we set the power levels of all transmissions in L_t equal to that returned by FP and reduce the demand of link e by one. Otherwise, link e cannot be scheduled in the present time slot. So, we remove link e from L_t and use the same procedure to find out if it can be scheduled in the next time slot.

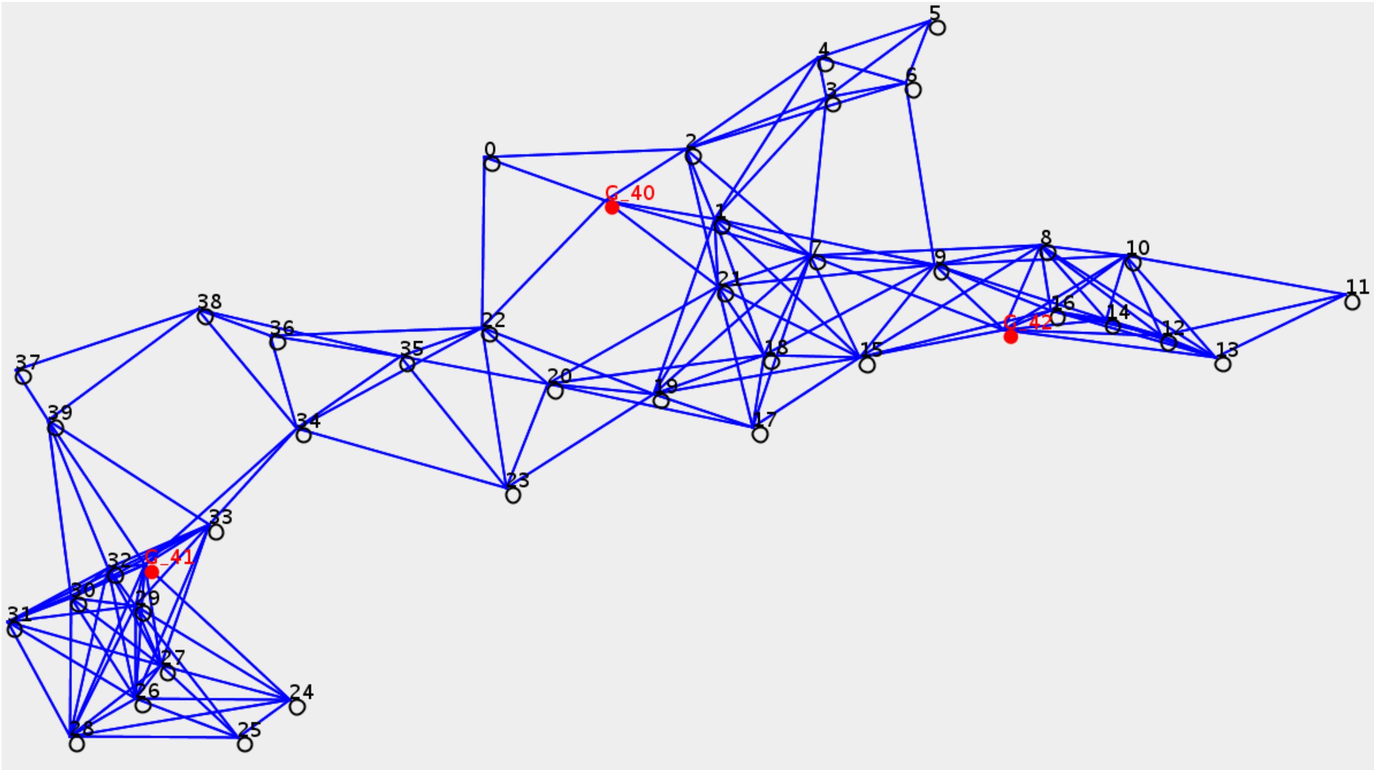

Fig. 5. The Wildhorse network with connectivity shown graphically for 30^0 beam-widths at all nodes.

V. ILLUSTRATIVE NUMERICAL EXAMPLES

For our studies, we use the Wildhorse network consisting of 43 nodes out of which 40 are mesh routers and 3 are gateways to the Internet. Wildhorse is a neighborhood in Davis, CA, US. The node locations in the network correspond to the locations of wireless routers in various residences. Figure 5 shows the Wildhorse network along with graphical connectivity when all the nodes use 30^0 beam-widths.

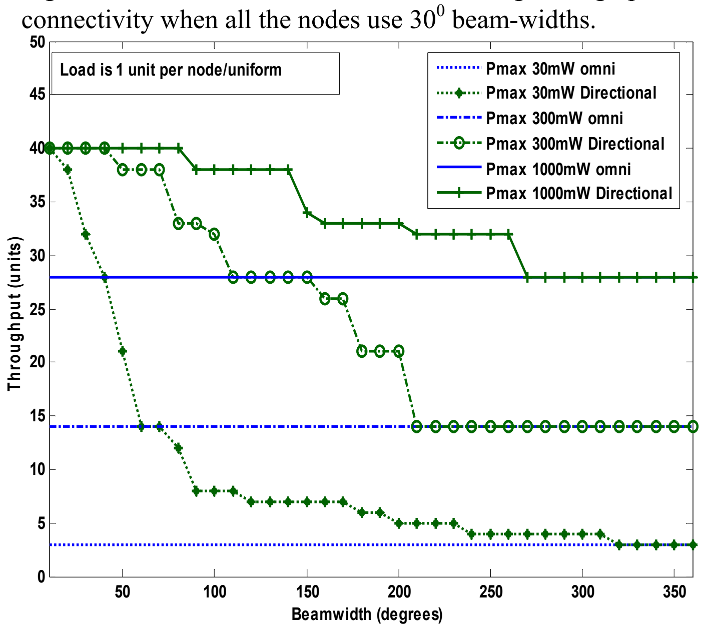

Fig. 6. Throughput with beamforming (light load).

The values of parameters we use are $\eta = 1$, $\beta = 10$ dB, $g_s = -10$ dB, and $N_0 = -90$ dB [13]. Figure 6 shows the throughput versus beam-width for a light load of 1 unit per 50 time slots. The throughput is plotted for different maximum power levels. For each power level, we plot two curves. In one curve, we plot the throughput using omni-directional transmission as a base with which we can compare. In the second curve, we plot the throughput as a function of beam-width. Figure 7 shows the throughput for a heavy load of 5 units per frame of 50 time slots. We observe the general trend that the overall network throughput improves as the beam-width decreases. Also, the throughput increases with increase in maximum power. The improvement with increase in maximum power is because of better connectivity while the improvement obtained by decreasing the beam-width is due to better connectivity and reduced interference in the network which allows more spatial reuse. We also note that the improvement in throughput obtained by decreasing the beam-width is more at lower power levels than at higher power levels.

Figures 8 and 9 compare the performance of our heuristic algorithm versus MILP solutions for maximum power levels of 300 mW and 1000 mW, respectively. In each figure, we plot the throughput versus beam-width for light load as well as heavy load. We observe that our heuristic performs optimally at low loads; and at heavy loads, it has a small but acceptable degradation in performance.

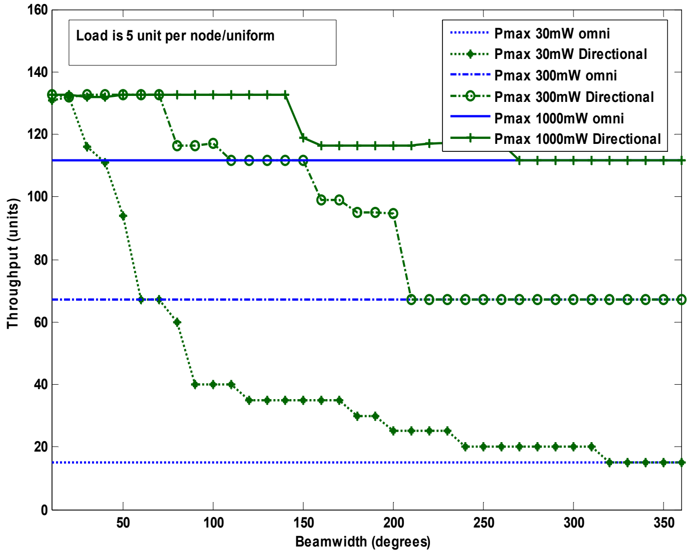

Fig. 7. Throughput with beamforming (heavy load).

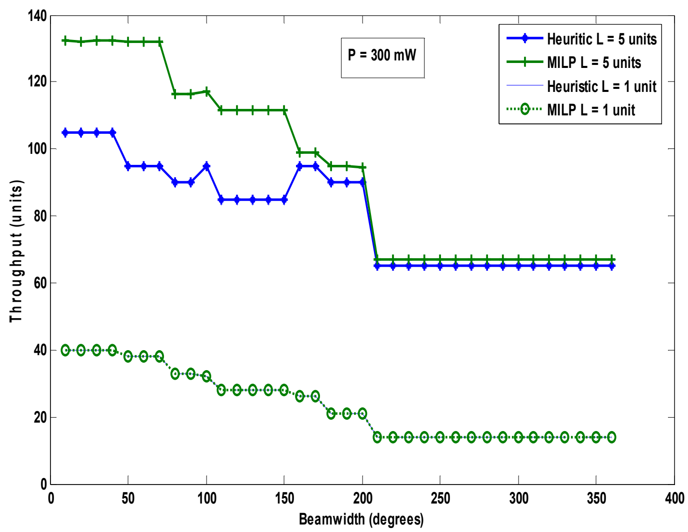

Fig. 8. MILP vs. Heuristic with P_{max} = 300 mW.

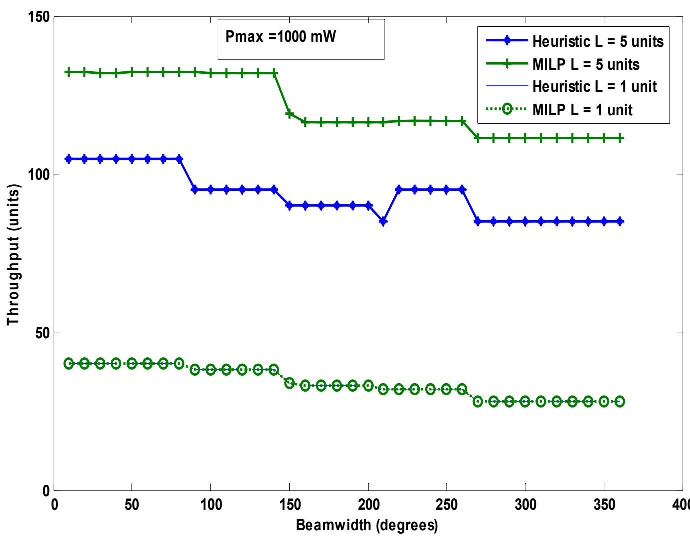

Fig. 9. MILP vs. Heuristic with P_{max} = 1000 mW.

VI. CONCLUSION

This paper has developed a methodology for cross layer design in wireless mesh networks that use directional antennas. We have proposed a novel interference model suitable for directional antennas based on a good antenna model. Based on this model, we designed a MILP-based link-scheduling and power-control algorithm. Then we designed an efficient heuristic to solve the problem quickly. Our heuristic algorithm performs optimally at light loads and degrades only marginally at heavy loads. Thus, this paper has demonstrated how various physical layer models including an antenna model and interference model could be used by a link scheduling algorithm to culminate in a good cross-layer design.

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