Minimum Time Length Link Scheduling under Blockage and Interference in 60GHz Networks

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***Abstract*—In this paper we tackle the problem of minimum time length link scheduling in 60GHz wireless networks, under both traffic demand and Signal to Interference and Noise Ratio (SINR) constraints. A constrained Binary Integer Programming (BIP) problem is formulated by incorporating a flexible interference model for directional transmissions and a Markov chain based blockage model. We then propose two effective solution algorithms, including a Greedy Algorithm (GA) that finds the maximum instant throughput for each time slot, and a Column Generation based algorithm (CG) that iteratively improves the current link schedule. The performance of the proposed algorithms is validated with simulations.**

I. INTRODUCTION

Recently, millimeter wave (mmWave) communications in the 60GHz band has attracted intensive attention from academia and industry. For two main reasons, mmWave communications have a great potential for dealing with the wireless capacity crisis caused by the smartphone revolution: it has a huge amount of bandwidth (i.e., up to 7GHz in many countries) and the vast spectrum is license-free. Many emerging bandwidth-demanding services such as HD videos, online gaming, and database synchronization can be accommodated. Several standard organizations have been working on developing standards for 60GHz networks [1] and mmWave communications have been recognized as a core technology for the future 5th generation wireless systems (5G) [2].

Although the 60GHz band is attractive for its capability of supporting high data rates, many challenges should be addressed to make 60GHz networks applicable. The wireless signal propagating in 60GHz channels suffers from an attenuation that is much higher than that in 5GHz channels [3]. To overcome the high attenuation, beamforming should be used to increase the signal's effective power, while the small wavelength does allow integration of many antenna elements with a small form factor. It has been shown in [4] that the highly directional links, especially in the outdoor environment, can be treated as "pseudowired," i.e., the probability of collision even in a dense 60GHz network is usually small. Although the pseudowired feature is attractive from the perspective of spatial reuse, extremely narrow transmission beamwidths will make it hard for network coordination and control [5], which all require the nodes in a neighborhood to be able to hear from each other. In indoor 60GHz networks, the beamwidth is usually wider than that in outdoor networks due to smaller transmission distances. The interference among neighboring links should be considered in this case.

In addition, mmWave signals in the 60 GHz band usually do not diffract around or penetrate obstacles. A line-of-sight (LOS) path between the transmitter and receiver is usually required for a successful transmission. When the LOS path is blocked (e.g., by a human body), relay nodes can be used to forward data for a hidden receiver [6] or wall reflections can be utilized. The blockage may appear or disappear occasionally due to the movement of objects between the transmitter and receiver or the movement of the transmitter or receiver themselves [7], [8]. A flexible link model that considers both narrow and wide beamwidths and dynamic blockages will be desirable for the design of 60GHz network protocols.

In this paper, we investigate the problem of link scheduling in 60GHz networks. We focus on the downlink of a 60GHz network consisting of one Piconet coordinator (PNC) and multiple devices (DEV). The PNC is the central coordinator and schedules the downlink transmissions, based on the traffic demand of the devices (e.g., the amount of packets backlogged in its buffer for each of the devices, or the amount of traffic requested by the devices for the next scheduling period) as well as the status of the 60GHz links. We adopt a directional link model from the literature, which incorporates the beamwidth as well as the beam directions to allow flexibly modeling interference among the directional links. We also model blockage of the LOS path with a discrete-time Markov chain model. A successful transmission requires unblocked LOS path as well as a good Signal to Interference plus Noise Ratio (SINR). By tuning the parameters of the interference and blockage models, both indoor and outdoor 60GHz links can be modeled.

We formulate the link scheduling problem as a constrained Binary Integer Programming (BIP) problem, aiming to determine the minimum time length schedule, i.e., to minimize the time length needed to satisfy the traffic demand of all the links. We develop two effective algorithms to solve the formulated BIP problem: a greedy algorithm (GA) to maximize the instantaneous throughput of each time slot, and a column generation-based algorithm (CG) to identify a better schedule to replace the previous schedule at each time slot. We validate the proposed algorithms with simulation and comparison with a benchmark scheme.

The remainder of this paper is organized as follows. The system model and problem formulation are given in Section II.

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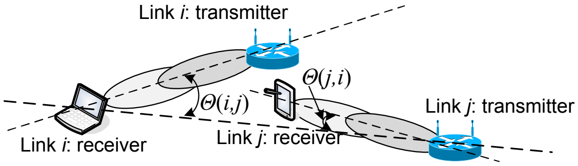

Fig. 1. Directional link gain model.

The proposed solution algorithms are presented in Section III and evaluated in Section IV. Section V reviews related work and Section VI concludes the paper.

II. SYSTEM MODEL AND PROBLEM FORMULATION

We consider the downlink of a 60GHz network consisting of one PNC and N DEVs [1] with directional transmissions. Assume slotted time with unit length time slots. The PNC collects the traffic demand (e.g., the backlog or requests) and link statistical data from the DEVs. It then determines the link transmission schedule and transmits data to the DEVs in each time slot, until the traffic demands are all served. With feedback (i.e., ACKs) from the DEVs, the PNC can learn the state of each link by end of the current time slot and update the remaining traffic demands.

In order to account for the potential co-channel interference (CCI), we model directional antenna gain of a link j as $h_{jj}\Gamma(\theta)$, where h_{jj} is the maximum gain, θ is the angle offset from the peak gain direction, and $\Gamma(\theta) \leq 1$ is a non-negative, non-increasing function of θ with $\Gamma(0) = 1$. The antenna gain from the transmitter of link i to the receiver of link j is $h_{ij}\Gamma(\theta(i,j))\Gamma(\theta(j,i))$, where h_{ij} is the maximum channel gain, and $\theta(i,j)$ and $\theta(j,i)$ are the angles between the two links, as shown in Fig. 1. We assume the transmission on an unblocked link j will be successful if and only if the SINR exceeds a fixed threshold γ, which can be expressed as

$$\frac{|h_{jj}|^2 P_t}{\sum_{i=1,i\neq j}^{N} |h_{ij}|^2 \Gamma(\theta(j,i))\Gamma(\theta(i,j))P_t + \sigma^2} \geq \gamma, \forall\, j. \tag{1}$$

where P_t is the PNC transmit power and σ^2 is the noise power.

To account for the blockage of the LOS path, we model each 60GHz channel as a discrete-time two-state Markov chain. Let G denote the good state (unblocked) and B denote the bad state (blocked); $\Pr(g|b)$ and $\Pr(b|g)$ are the transition probabilities from G to B and from B to G, respectively; $\Pr(g|g) = 1 - \Pr(g|b)$ and $\Pr(b|b) = 1 - \Pr(b|g)$.

At each time slot, the PNC may or may not receive an ACK from a DEV, depending on whether the PNC transmits to the DEV and the channel state of the link. Define the link state variable s_j as:

$$s_j = \begin{cases} 1, & \text{link } j \text{ is in the good state} \\ 0, & \text{otherwise,} \end{cases} \quad \forall\, j, \tag{2}$$

and index variable k as

$$k = \begin{cases} 1, & \text{an ACK is received by the PNC} \\ 0, & \text{otherwise.} \end{cases} \tag{3}$$

Let $U^m(k|s_j)$ be the probability that when link j is activated at time slot m, the ACK status is k conditioned on that the state of link j is s_j. Assuming error-free ACKs, we then have

$$\begin{cases} U^m(1|s_j) = s_j \\ U^m(0|s_j) = 1 - U^m(1|s_j) = 1 - s_j, \end{cases} \quad \forall\, m. \tag{4}$$

It can be easily seen that $U^m(k|s_j)$ is either 1 (i.e., ACK received) or 0 (ACK missing).

Define scheduling index variables x_j^m as

$$x_j^m = \begin{cases} 1, & \text{link } j \text{ is activated in time slot } m \\ 0, & \text{otherwise,} \end{cases} \quad \forall\, j, m. \tag{5}$$

The probability that the state of link j is s_j at time slot $m+1$, denoted as $\lambda_{s_j}^{m+1}$, can be derived as

$$\begin{aligned} \lambda_{s_j}^{m+1} = {} & x_j^m \sum_{s_j'=0}^{1} \left\{ s_j' k \Pr(s_j|s_j') + (1-s_j')(1-k)\Pr(s_j|s_j') \right\} \\ & + (1 - x_j^m) \sum_{s_j'=0}^{1} \lambda_{s_j}^m \Pr(s_j|s_j'), \end{aligned} \tag{6}$$

where $\Pr(s_j|s_j')$ is the channel state transition probability. We set the channel state at time 0 with the stationary distribution, as

$$\lambda_{s_j}^0 = \begin{cases} \frac{\Pr(b|g)}{\Pr(b|g)+\Pr(g|b)}, & s_j = 1 \\ \frac{\Pr(g|b)}{\Pr(b|g)+\Pr(g|b)}, & s_j = 0, \end{cases} \quad \forall\, j. \tag{7}$$

Define time slot index variable t^m for all m as

$$t^m = \begin{cases} 1, \text{at least one link is activated at time slot } m \\ 0, \text{otherwise.} \end{cases} \tag{8}$$

Let $V_j^m(\lambda_{s_j}^m)$ be the expected amount of traffic delivered by link j from time slot m to a future time slot M. We have

$$\begin{aligned} V_j^m(\lambda_{s_j}^m) = {} & \sum_{s_j=0}^{1} \lambda_{s_j}^m \sum_{k=0}^{1} U^m(k|s_j)[k r_j t^m + V_j^{m+1}(\lambda_{s_j}^{m+1})], \\ & \forall 1 \leq m \leq M-1, \end{aligned} \tag{9}$$

where r_j is the number of packets that can be delivered by link j if the transmission on link j is successful, i.e., the SINR of link j is higher than a threshold and the link is not blocked.

The expected amount of traffic delivered by link j from time slot 1 to time slot M can be derived as

$$V_j^1(\lambda_{s_j}^1) = \sum_{m=1}^{M} c_j^m t^m, \forall\, j, \tag{10}$$

where

$$\begin{aligned} c_j^m = {} & \sum_{s_j=0}^{1} \lambda_{s_j}^1 \sum_{k=0}^{1} U^1(k|s_j) \left(\sum_{s_j=0}^{1} \lambda_{s_j}^2 \sum_{k=0}^{1} U^2(k|s_j) \cdots \right. \\ & \left. \cdots \left(\sum_{s_j=0}^{1} \lambda_{s_j}^m \sum_{k=0}^{1} U^m(k|s_j) k r_j \right) \right). \end{aligned} \tag{11}$$

Assuming the traffic demand is D_j for each link (i.e., each DEV) j, we aim to minimize the total amount of time slots used to serve the traffic demands under SINR and blockage constraints. The problem can be formulated as

$$\min: \ \tau = \sum_{m=1}^{M} t^m \tag{12}$$

$$\text{s.t.} \ V_j^1(\lambda_{s_j}^1) \geq D_j, \forall\, j \tag{13}$$

$$t^m \geq t^{m+1}, \forall\, m. \tag{14}$$

Note that the SINR constraint is implicitly expressed in the formulated problem in that the c_j^m's are generated by the feasible x_j^m set, for all j, m, that satisfies the SINR constraint of the links. Further, M can be set to a sufficiently large value so that there is always a feasible solution. As we will show later, with the proposed algorithms, the value of M doesn't affect the solution and objective value as long as it is sufficiently large. The traffic demands will be served in a certain amount of consecutive time slots (for which $t^m = 1$); when the traffic demands are all cleared, we have $t^m = 0$ for all the future time slots, as given in constraints (8) and (14).

III. SOLUTION ALGORITHMS

The formulated problem is a BIP problem. The coefficients of the constraint matrix all take continuous values between $[0, k]$, which indicate that the BIP doesn't satisfy the property of $unimodularity$ [9]. Thus the BIP cannot be reduced into a Linear Programming (LP) problem. It is in fact NP-hard.

Furthermore, it is infeasible to list all the columns of the constraint matrix, since the number of all feasible columns in the constraint matrix is as large as M. An exhaustive search to construct the constraint matrix is impractical. Even if it is possible, a huge memory may be needed to store the constraint matrix. In this section, we introduce two effective algorithms to solve the BIP problem with greatly reduced complexity.

A. Greedy Algorithm

We first propose to solve the BIP problem with an iterative greedy algorithm (GA). The main idea is rather than minimizing $\tau = \sum_{m=1}^{M} t^m$, we maximize the instant throughput of the current time slot. Denote H^m as the set of links whose traffic demands have not been satisfied at the m-th iteration (i.e., time slot m). The problem solved at the m-th iteration, denoted as PL^m, can be formulated as

$$\max: \sum_{j \in H^m} c_j^m x_j^m \tag{15}$$

$$\begin{aligned} \text{s.t.} & \sum_{i \in H^m, i \neq j} |h_{ij}|^2 \Gamma(\theta(j,i)) \Gamma(\theta(i,j)) P_t x_i + \\ & \Bigg(\sum_{i \in H^m, i \neq j} |h_{ij}|^2 \Gamma(\theta(j,i)) \Gamma(\theta(i,j)) P_t + \sigma^2 - \\ & \quad \gamma^{-1} |h_{jj}|^2 P_t \Bigg) \cdot x_j \\ & \leq \sum_{i \in H^m, i \neq j} |h_{ij}|^2 \Gamma(\theta(j,i)) \Gamma(\theta(i,j)) P_t, \forall j \in H^m, \end{aligned} \tag{16}$$

$$x_j^m \in \{0, 1\}, \forall j \in H^m, \tag{17}$$

where constraint (16) ensures that the SINR requirement is satisfied at all the active links [10]. In this paper we use the $Bintprog$ function in Matlab to solve this BIP, which incorporates the Branch-and-Bound technique and is optimal according to the Matlab documentation. Thus the obtained solution is optimal to PL^m.

Algorithm 1: Greedy Algorithm

```
1  $m = 1$ ;
2  while $H^m \neq \oslash$ do
3      Solve PL$^m$ to get $x_j^m$, for all $j$ ;
4      PNC schedules transmission according to $x_j^m$, for all $j$ ;
5      $m \leftarrow m + 1$ ;
6      PNC updates $H^m$ ;
7      for $j \in N$ do
8          for $s_j = 0 : 1$ do
9              Update $\lambda_{s_j}^m$ ;
10         end
11         Update $c_j^m$ ;
12     end
13 end
```

Once the x_j^m's are obtained, the PNC schedules transmissions for the current time slot m according to x_j^m's. With feedback from the DEVs, the PNC will know λ_j^{m+1} and c_j^{m+1}, for all j, with which it can solve PL^{m+1} to obtain x_j^{m+1}, for all j. And so forth, until H^m becomes empty or PL^M is solved.

The iterative greedy algorithm is presented in Algorithm 1, which is executed at the PNC. Denote the last time slot as m_j in which link j was active. In line 11 of Algorithm 1, c_j^m should be updated as

$$\begin{aligned} c_j^m = & \sum_{s_j=0}^{1} \lambda_{s_j}^{m_j} \sum_{k=0}^{1} U^{m_j}(k|s_j) \Bigg(\sum_{s_j=0}^{1} \lambda_{s_j}^{m_j+1} \sum_{k=0}^{1} U^{m_j+1}(k|s_j) \\ & \cdots \Bigg(\sum_{s_j=0}^{1} \lambda_{s_j}^{m_j} \sum_{k=0}^{1} U^{m_j}(k|s_j) k r_j \Bigg) \Bigg), \forall\, j. \end{aligned} \tag{18}$$

B. Column Generation Based Algorithm

Column Generation (CG) is an effective method for solving large-scale LPs. CG decomposes the original problem into a Master Problem (MP) and a Sub-Problem (SP). The SP is solved to identify a single new column or variable at each iteration to enter the MP, which has a much smaller constraint matrix and fewer variables (and thus much easier to solve than the original problem). The current solution will be improved sequentially. The algorithm terminates until the optimal solution or a sufficiently good solution is obtained. More details of CG method can be found in [10], [11].

With our CG based algorithm, the constraint matrix of the MP, denoted as **C**, is firstly initialized with a feasible solution to the original problem. Denote the number of columns of the constraint matrix (which is equal to the objective value of the original problem corresponding to the feasible solution) of the

MP as M'. The MP can be expressed as

$$\min: \ \tau = \sum_{m=1}^{M'} t^m \tag{19}$$

$$\text{s.t.} \ \ V_j^1(\lambda_{s_j}^1) \geq D_j, 1 \leq j \leq N \tag{20}$$

$$t^m \geq t^{m+1}, 1 \leq m \leq M'-1. \tag{21}$$

The constraint matrix of the MP is of the following form.

$$\mathbf{C} = \begin{pmatrix} c_1^1 & c_1^2 & \cdots & c_1^{M'} \\ c_2^1 & c_2^2 & \cdots & c_2^{M'} \\ \vdots & \vdots & \ddots & \vdots \\ c_N^1 & c_N^2 & \cdots & c_N^{M'} \\ 1 & -1 & & \\ & 1 & -1 & \\ & & \ddots & \ddots \\ & & 1 & -1 \end{pmatrix}. \tag{22}$$

Note that the value of M' may change as the feasible solution to the original problem changes at each iteration. Each time when the MP is solved, we can obtain the dual variables (or, the Lagrange multipliers) corresponding to each row of the constraint matrix. Denote the dual variable corresponding to the j-th constraint as u_j, the dual variable corresponding to the $(N+m)$-th constraint as v^m, for all j and $1 \leq m \leq M'-1$, and the reduced cost for the m-th column of the MP as z^m. Then we have

$$\begin{cases} z^1 = 1 - \sum_{j=1}^{N} u_j c_j^1 x_j^1 - v^1 \\ z^m = 1 - \sum_{j=1}^{N} u_j c_j^m x_j^m - (-v^{m-1} + v^m), \\ \qquad\qquad\qquad\qquad 2 \leq m \leq M'-1 \\ z^{M'} = 1 - \sum_{j=1}^{N} u_j c_j^{M'} x_j^{M'} - v^{M'-1}. \end{cases}$$

In order to find a new schedule having the most negative reduced cost (and thus may have the greatest potential in improving the current solution) at time slot m [9], we solve the corresponding Sub-Problem SP^m defined as

$$\min: \ z^m, \tag{23}$$

$$\text{s.t. constraints (16)and (17).}$$

The CG-based algorithm is presented in Algorithm 2, which is also executed at the PNC. In iteration i of the *While* loop, we first solve the Sub-Problem SP^i. If the objective value $z^i < 0$, which means that the optimal solution to SP^i, denoted as $\widehat{x}_j^i$, for all j, may have the potential to improve the current feasible solution to the original problem. Then we find a feasible solution and objective value τ^i of the original problem corresponding to $\widehat{x}_j^i$, for all j, to see if $\widehat{x}_j^i$, for all j, can really improve the current feasible solution. If so, the PNC schedules the link traffic according to $\widehat{x}_j^i$, for all j; otherwise, the PNC schedules the traffic of the links according to x_j^i, for all j, which is the schedule for time slot i in the current solution.

In the step of finding a feasible solution and the corresponding objective value to the original problem, we maximize the instant throughput sum of all the links for the remaining time slots under the SINR constraint, until the traffic demands of all the links are satisfied. The scheduling time for the feasible schedule in each time slot is 1, which is similar to that in GA.

Algorithm 2: Column Generation Based Algorithm (CG)

```
Find an initial feasible solution $x_j^m$ and $t^m$, for all
  $1 \leq j \leq N, 1 \leq m \leq M'$, and compute the objective value $\tau$ ;
Use $x_j^m$, for all $j, m$, to initialize the MP ;
$i = 1$ ;
while $H^i \neq \oslash$ do
    Relax the MP to an LP by allowing $t^m$, for all $m$, to take
      continuous values in [0,1], and solve the relaxed MP to get
      the dual variables ;
    Solve SP$^i$ to get $\widehat{x}_j^i$, $z^i$, for all $j$ ;
    $t^i = 1$ ;
    if $z^i < 0$ then
        Find a feasible solution and objective value $\tau^i$
          corresponding to $\widehat{x}_j^i$, for all $j$ ;
        if $\tau^i < \tau$ then
            Use $\widehat{x}_j^i$, for all $j$, to generate a new column and
              replace the corresponding column in the MP ;
            The PNC transmits data according to $\widehat{x}_j^i$, for all $j$ ;
        else
            The PNC transmits data according to $x_j^i$, for all $j$ ;
        end
    else
        PNC transmits data according to $x_j^i$, for all $j$ ;
    end
    Update $H^i$ ;
    if $H^i = \oslash$ then
        Break ;
    else
        Find a feasible solution to obtain $x_j^l$, $\tau_{new}^i$, for all $j$,
          for all $l = i+1, \ldots, M'$ ;
        $\tau \leftarrow \tau_{new}^i$ ;
    end
    $i \leftarrow i + 1$ ;
    Use $x_j^m$, for all $j$, $1 \leq m \leq M'$ to initialize the MP ;
end
```

IV. SIMULATION STUDY

In this section we used Matlab simulation to validate the performance of the proposed algorithms. Unless otherwise specified, the values of simulation parameters are as that shown in Table I. Each simulated point in the figures is obtained by repeating the simulation 50 times with different random seeds, and 95% confidence intervals are computed and plotted in the figures to guarantee credible results. We compare the performance of our proposed algorithms with that of a benchmark scheme proposed in [10]. The benchmark scheme does not consider link blockages when solving the subproblems in the greedy method, meaning that $c_j^m = 1$, for all j in PL^m, for all m.

In Fig. 2, we compare the performance of the two proposed algorithms with that of the benchmark scheme for different number of DEVs, i.e., N, in the network. It can be seen that as N is increased, the total amount of time needed to satisfy the traffic demands of all the DEVs is also increased, and both proposed schemes always outperform the benchmark scheme. Further, the CG method achieves a slightly higher performance

TABLE I
SIMULATION PARAMETERS

Parameter	*Value*	*Parameter*	*Value*
P_t	1	$\lvert h_{ij}\rvert^2\Gamma(\theta(j,i))\Gamma(\theta(i,j))$	$[0,1], \forall i,j$
σ^2	0.1	D_j	$[50,60], \forall j$
r_j	$10, \forall j$	–	–

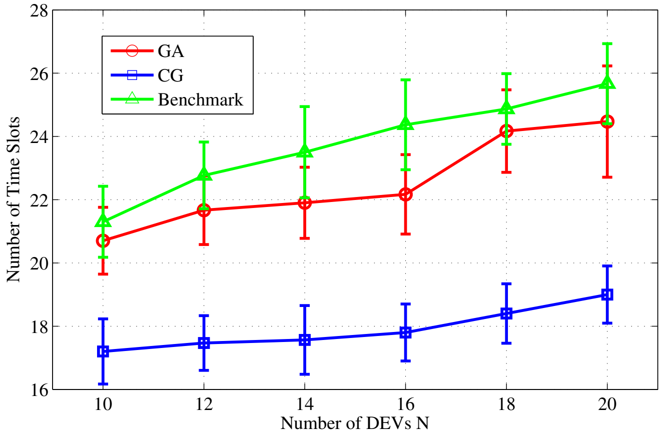

Fig. 2. Number of time slots used to serve the traffic demands when the number of DEVs is increased ($\Pr(s_j = 1|s'_j = 0) = [0.4, 0.6]$, $\Pr(s_j = 0|s'_j = 1) = [0.4, 0.6]$, for all j, and $\gamma = 0.3$).

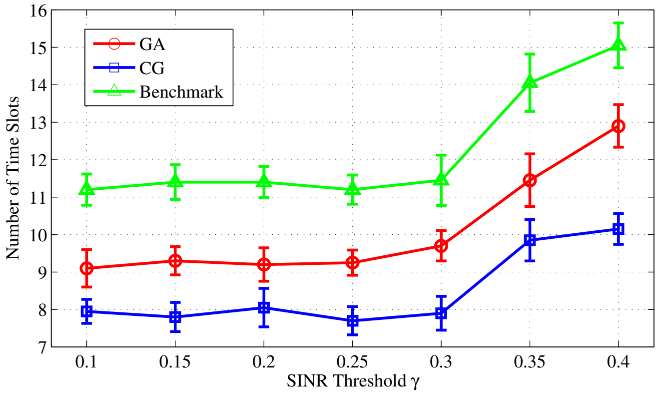

Fig. 3. Number of time slots to serve the traffic demand under various SINR threshold γ (N=10, $\Pr(s_j = 1|s'_j = 0) = [0.7, 0.9]$, and $\Pr(s_j = 0|s'_j = 1) = [0.1, 0.3]$, for all j).

than GA. The main reason is that CG always attempts to find a better schedule at each of the time slot to improve the system throughput. Nevertheless, their performances are close under our simulation settings.

The performance of our proposed algorithms under different SINR threshold γ is shown in Fig. 3. All the algorithms have degraded performance when γ is increased. The reason is that a larger γ means that for a specific link, given a fixed channel gain and transmission power, a lower interference can be tolerated. Fewer concurrent transmissions can be accommodated in the system to leverage spatial reuse and the throughput of each time slot is reduced. Therefore, the number of time slots needed to satisfy the traffic demand is increased as γ grows.

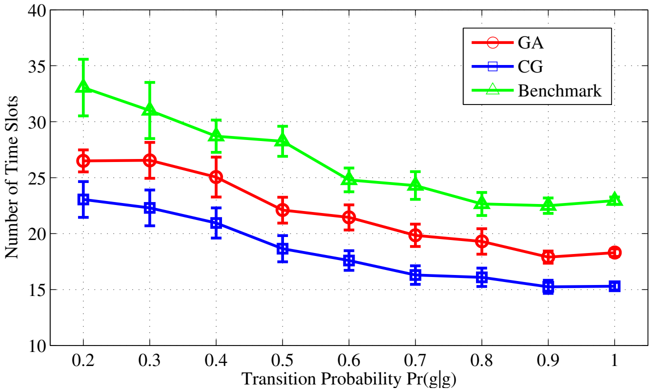

Fig. 4. Number of time slots to serve the traffic demand under various transition probabilities for the 60GHz channels $\Pr(g|g)$ (N=10, $\Pr(g|b) = 0.5$, and $\gamma = 0.5$).

It would also be helpful to examine constraint (16) of problem PL^m in Section III. It can be seen that if γ is increased, the value of the left hand side (LHS) of (16) will also increase, which means that constraint (16) will become tighter. Therefore, PL^m will have a smaller solution space and its optimal objective value may be reduced. The system throughput in each time slot may be reduced as a result and the time length needed to schedule all the traffics will be prolonged.

We compare the performance of the three algorithms under different transition probabilities $\Pr(g|g)$ in Fig. 4. Here we set $\Pr(s_j = 1|s'_j = 0) = \Pr(s_i = 1|s'_i = 0) = \Pr(g|b), \Pr(s_j = 0|s'_j = 1) = \Pr(s_i = 0|s'_i = 1) = \Pr(b|g) = 1 - \Pr(g|g)$, for all $1 \leq i \leq N, 1 \leq j \leq N$, and $i \neq j$. According to the channel model, the stationary probability of the channel being in the good state, denoted as $\pi(G)$, and channel being in the bad state, denoted as $\pi(B)$, can be derived as $\pi(G) = \frac{\Pr(g|b)}{\Pr(g|b)+\Pr(b|g)}$, and $\pi(B) = \frac{\Pr(b|g)}{\Pr(g|b)+\Pr(b|g)}$. As can be observed from Fig. 4, when $\Pr(g|g)$ is low, it is of higher probability that a particular link is in the bad state for a specific time slot, and thus fewer links can have successful transmissions, resulting in a lower system throughput at that time slot. As $\Pr(g|g)$ is increased, the possibility that more links have successful transmissions at each time slot grows. Thus the average number of time slots needed to satisfy the traffic demand of all links will decrease.

However, the decrement cannot go indefinitely and the time length needed will converge to a certain threshold regardless of the increase of $\Pr(g|g)$ once it goes beyond a specific value. This is because constrained by the SINR threshold required for successful transmission of each link, there is a limit on the maximum number of links that can transmit concurrently in the network. Even when $\pi(G) = 1$, which means that the channel state of each link is always good, there is always a limit on the maximum number of links of concurrent transmission, and the system throughput of each time slot is bounded. Thus the time length required to schedule the traffic demand of all the links will be always lower bounded.

V. RELATED WORK

There have been considerable work on link scheduling in wireless networks. However, most of the prior work do not consider the specific properties of 60GHz channels and thus may not be applied for 60GHz networks. In [10], [12], the authors solve the problem of spatial TDMA scheduling in ad hoc networks, where each link has its traffic demand and the objective is to find the optimal scheduling of the links to minimize the time length needed to satisfy the traffic demand of all links. However, the channel state of each link is assumed to be static during the entire period, which may not be a valid assumption for 60GHz networks where the channel state may change dramatically due to blockage of the LOS path.

The uncertainty of channel availability in Cognitive Radio Networks is considered in [13]. The problem of deciding which channel to sense and access in order to maximize the throughput of the secondary user is formulated as a Partially Observable Markov Decision Process (POMDP), and a separation principle is proposed to reveal the optimality of myopic spectrum sensing and accessing strategies. However, this paper only considers the case where only one channel can be sensed and accessed at each time slot, and the interference between links of concurrent transmissions is not considered, which is obviously not the case when spatial reuse is considered.

There are also several interesting prior works on link scheduling and interference modeling in 60GHz networks. For example, the authors in [4] find that the interference between links of concurrent transmission can be ignored in outdoor 60GHz networks because of high attenuation of 60GHz channel and the extremely small beamwidths of the directional transmissions. Motivated by this observation, a Graph Coloring method is proposed in [14], [15] as a scheduling algorithm to compute a schedule for given traffic demands, such that the total transmission time is minimized for the 60GHz network. These papers consider "pseudowired" 60GHz links and do not take the potential co-channel interference (CCI) into consideration.

On the other hand, the authors of [16] propose the concept of *exclusive regions*, which is described by the relative geolocation and the antenna angle between the transmitter and receiver, to exclude certain concurrent transmissions in the 60GHz network. To provide a more accurate attenuation model for the 60GHz channel, the authors of [5] conduct extensive urban cellular and peer-to-peer RF wideband channel measurements and find that there are very few unique antenna angles for creating a link, i.e., a directional link is hard to find in 60GHz networks. Motivated by the prior works, in this paper we consider a more general interference and blockage model compared with the previous literature as described in Section II and develop effective link scheduling algorithms.

VI. CONCLUSION

In this paper, we investigated the problem of minimum time length scheduling in 60GHz networks under both traffic demand and SINR constraints. The problem was formulated as a BIP problem that is NP hard. We developed two effective link scheduling algorithms with greatly reduced complexity: (i) a Greedy Algorithm that maximize the instant throughput of each time slot, and (ii) a Column Generation based algorithm that aims to find a better scheduling solution at each time slot to improve the current solution. The performance of the proposed algorithms are validated by simulations.

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