SDMA for 60GHz Gigabit Wireless Networks

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***Abstract*—With the opening of the 60 GHz spectrum for WLANs, there has been a great deal of interest in academia and industry on how best to exploit the more than 5 GHz of available bandwidth. One goal in the wireless community has been delivering gigabit data rates to end users. For this, a variety of approaches have been studied in the past. In this paper, we present two SDMA (Spatial Division Multiple Access) algorithms that exploit the peculiar propagation properties of this part of the frequency. We show that in typical indoor environments, one access point can deliver over 8 gbps total throughput while using only 640 MHz of the bandwidth. We generalize the algorithms to the case when multiple channels are available and show that with seven channels, we get aggregate throughput of over 31 gbps.**

I. INTRODUCTION

Providing gbps/user wireless connectivity in indoor environments is an exciting problem that has received much attention in the recent past. Techniques such as MIMO (Multiple Input Multiple Output) and MIMO/SDMA have been extensively researched and have been shown to provide very high data rates in the WLAN. In this paper, we consider the same problem of providing gbps data rates but at the 60 GHz ISM band. Unlike lower frequency bands (typically between 2 and 6 GHz), the 60 GHz band has unique propagation properties. This band is very well absorbed by oxygen, and reflections are severely attenuated. Thus, as noted in [8], [1], the propagation at this frequency can be considered *ray-like* with a measured path loss exponent of 2.1 [2]. Also, multipath signals are severely attenuated making MIMO a poor choice for 60 GHz [4]. Various authors [11], [4] have therefore suggested using SDMA with highly directional smart antennas as the best architecture of such WLANs. In this paper, we compare two SDMA algorithms that are designed for this particular frequency band and show that we can achieve multi-gbps data rates indoors.

The remainder of the paper is organized as follows. The next section describes related work on 60 GHz. Section III presents the system model we use and section IV presents the two algorithms we study. Results are described in section V where we first focus on achievable throughput for one channel and then study how the use of multiple channels affects throughput, section V-A. Finally, conclusions and future work are described in section VI.

II. RELATED WORK

The propagation characteristics of 60 GHz has been studied by several authors [13], [2], [3], [7] who have noted its ray-like propagation properties and almost complete lack of significant multipath. Indeed, [13] compares the LoS (Line of Sight) path to first-order reflections in typical indoor environments and notes that the strongest reflections (from windows) were almost 10 dB below the LoS path. If the surface is not polished, then the reflected component is much weaker. The penetration losses are also severe with many building materials such as concrete causing a 35 dB reduction in signal strength. The conclusion of these studies is that using SDMA with highly directional antennas will yield the highest throughput.

SDMA has been studied over the past decade and numerous algorithms have been developed. However, all previous works look at a much lower frequency (2-5GHz) where multipath components are significant. Thus, a great deal of previous work [9], [12], [6] develops MIMO/SDMA algorithms to identify the strongest multipath components in a room and combine them to achieve high data rates. In our system, since multipath is negligible, these previous algorithms are not applicable.

III. SYSTEM MODEL

Smart antenna systems typically consist of M antenna elements placed in some geometry such as linear or circular or rectangular. These antenna elements are connected to $k \geq 1$ *beamforming* modules. A beamforming module is responsible for appropriately phase shifting and weighting the input/output of each antenna element in order to beamform in some given direction. Generally, the beamforming modules occur after the analog-to-digital converter on the receiver side and before the digital-to-analog converter on the transmitter side.

We consider a room with the AP (Access Point) located in the center of the ceiling. The AP and users are all assumed to be equipped with a smart antenna system where the antenna elements are arranged in a *linear* geometry with $d = \lambda/2$ inter-element spacing. The AF (Array Factor) of such a system is given by [5],

$$AF = \sum_{i=1}^{M} e^{j(i-1)kd(\sin\theta - \sin\theta_0)}$$

where $k = 2\pi/\lambda$, d is the inter-element spacing, θ_0 is the direction we are beamforming in and θ is the direction in which we are computing the array factor. The *gain* in any direction is then computed as,

$$E\frac{4\pi U(\theta,\phi)}{\int_0^{2\pi}\int_0^{\pi} U(\theta,\phi)\sin\theta d\theta d\phi}$$

where E is the efficiency (assumed to be 1), and θ, ϕ are measured as shown in Figure 1. U is the radiation intensity derived from the the array factor [5].

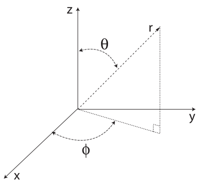

Fig. 1. Coordinate system used.

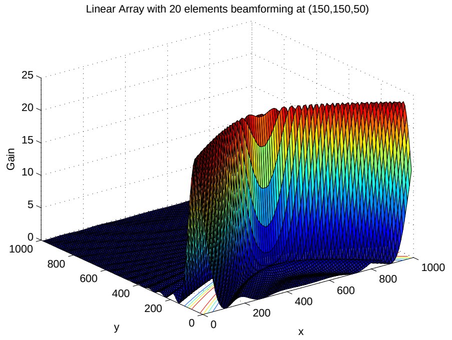

Fig. 2. Gain for a 20-element linear antenna array pointing to (1.5m, 1.5m, 0.3m).

Assume that the AP's antenna has 20 elements and is located in the center of the ceiling of a room of dimension 10m × 10m × 3m, pointing along the y-axis. The beam pattern we get for θ_0 pointing towards coordinates (1.5m, 1.5m, 0.3m) is shown in Figure 2. It is noteworthy that the beam covers a strip across the room. This occurs because the beam formed by a linear array exhibits rotational symmetry about the antenna axis. The implication of this type of beam for SDMA is clear – users located within some angular region, even if they are across the room from one another, cannot be separated by beamforming. We use this constraint in developing the SDMA algorithms in the next section.

IV. SDMA ALGORITHMS

The problem of creating SDMA schedules can be viewed as follows. Given some number of users N in the room at random locations, we need to find a transmission schedule such that average throughput is maximized. A transmission schedule consists of one or more time slots. In each time slot, one or more users may be active. The users that are active simultaneously are located such that the AP can form *distinct* beams towards each of them. Obviously, for each such user, a separate module at the AP is used for beamforming. Thus, if the AP has k modules, then during a given time slot no more than k users (who are angularly far apart) can be active. In this paper, we let k be arbitrary and find the maximum throughput. The value of k for this maximum throughout is then recorded. *Interestingly, the best value of k is seen to be independent of the number of nodes N but is determined by the room geometry*.

We present a static and a dynamic SDMA algorithm in the following two sections. The static algorithm is computationally simple which makes it attractive for a deployed system. However, the static algorithm has a somewhat lower throughput compared to the dynamic algorithm.

A. Static SDMA

Given a room, we can split it into discrete regions utilizing the property shown in Figure 2. Each region is covered by one beam and the region boundaries are 3 dB below the maximum gain seen in the center of the region. For the example room we are using in this paper, we can split the room in 21 regions as illustrated in Figure 3. Thus, if we form a beam towards region 1 using one module and beamform towards region 3 using another module, the interference seen in region 1 due to the transmission to region 3 (and vice versa)will be quite small because of the significant angular separation. This allows us to form beams towards multiple regions simultaneously in order to maximize throughput.

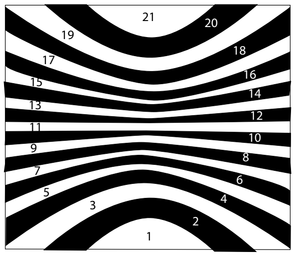

Fig. 3. The 21 regions formed in the room.

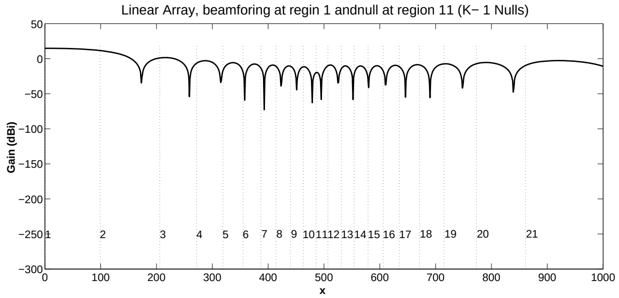

Fig. 4. Beamforming towards region 1 and nulling center of region 11.

In order to further reduce interference, we exploit the *nulling* capability of smart antennas. Given M antenna elements, a module can beamform in one direction while forming up to $M-1$ nulls. Thus, if k modules at the AP are used to form k beams simultaneously, each of these modules can simultaneously null the remaining $k-1$ directions to maximize

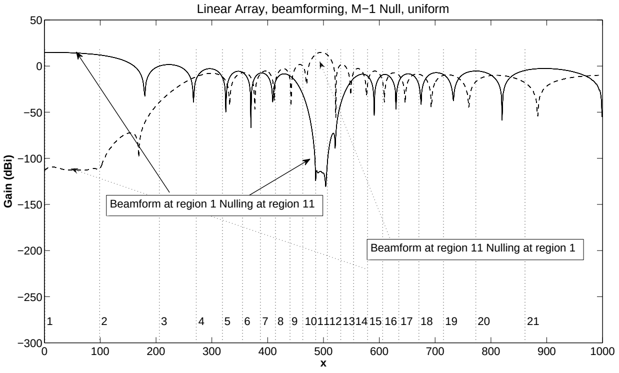

Fig. 5. Beamforming at region 1 and forming multiple nulls towards region 11.

SIR (Signal to interference Ratio) for each user. Note that if $M-1 > k-1$ then we have the ability to form more nulls than there are directions. Thus, we can intelligently form more than one null towards each of the $k-1$ directions in order to improve SIR even further. As an example, in Figure 4 we beamform towards region 1 while we null the center of region 11. As we can see, the gain at the center of region 11 is very small but it increases rapidly as we go to the boundary of this region. If we now form two nulls uniformly located in region 11, then the gain in all of region 11 falls dramatically as seen in Figure 5. Therefore, given $p \leq k$ active modules in any time slot, each module beamforms towards its desired direction and then forms $\lfloor \frac{M-1}{p-1} \rfloor$ nulls uniformly located in each of the remaining $p-1$ regions.

We can now simply describe the static algorithm:

- Let N be the number of users. Find the region that each user falls into. Sort the users according to region number.
- Let ρ take positive integer values.
- A schedule may consist of one or more time slots. In the first time slot, the user in the lowest numbered region is allocated a channel (and a module). If the user is in region number x then a user from region numbers $x+rho$ is also allocated a channel in the same time slot.
- If some users have not yet been allocated a time slot, we remove the users already allocated a slot and run the above algorithm for the remaining set.
- If all users have been allocated a time slot, we are done and the schedule repeats.

We explore the performance of the algorithm for $\rho = 1, 2, 3$. When $\rho = 1$ we allow neighboring regions to be active simultaneously. This results in higher interference and thus lower data rates. If $\rho = 3$ we get the lowest interference but the schedules will be longer since fewer users are packed into one time slot.

B. Dynamic SDMA

The dynamic algorithm performs channel allocation by first sorting users according to their angular locations with respect to the AP. The schedule is then constructed as follows:

Room dimensions	10m x 10m x 3m
AP location	Center of ceiling
Transmit power	10 dBm
Bandwidth	640 MHz
Modulation	Table II
No. antenna elements at AP and user	$M = 20$
No. Modules k at AP	Unlimited

TABLE I
EXPERIMENTAL PARAMETERS.

- In the first time slot, the leftmost user (smallest θ) is allocated a module. The first user outside the 3 dB of the beam formed towards the first user is then allocated a module, and so on. In other words, all users who do not lie within the 3 dB beamwidth of each other's beams are allocated the channel in the first time slot. Each of these users then forms nulls in the direction of the other users in the same slot.
- Of the remaining users who have not been allocated the channel, we perform the above step again. This process is continued until all users have been allocated the channel.

The primary difference between the dynamic and static cases is best illustrated by considering a single user. In the static case, this user will be allocated a static beam in some region. However, if the user is not in the center of the region, the gain will be smaller than if the beam was formed directly at that user, as in the dynamic case. Thus, we expect that the signal strength of the desired signal in the dynamic case will be better than in the static case.

V. RESULTS

For our experiments we used the system parameters given in Tables I and II. The simulations were conducted in Matlab using a detailed propagation model developed for 60GHz utilizing measurement studies described in section II. The metrics we studied are:

1) The *average* total (or aggregate) throughput in one WLAN. This is calculated by randomly placing N users in the room and running the two SDMA algorithms. After finding the SNIR for each user, we find the data rate achieved using Table II. The throughput per slot in the schedule is the sum of the data rates per user in that slot. The data rate is summed over all slots in the schedule and averaged by the number of time slots.
2) The average number of *modules or radios* used at the AP. As we mentioned previously, the number of modules we use is a function of the room geometry and not N since interference is the limiting factor on achievable throughput. We plot the number of modules used as a function of N to show this behavior.
3) The average *delay* is the average number of slots per schedule.

Figure 6 plots the average total throughput in the room as a function of N for the static and dynamic algorithms (all figures show the 95% confidence intervals). As the number of users increases, the total throughput in the WLAN also increases, as

Modulation	*Code Rate*	*Min E_b/N_0 for $P_b \leq 10^{-6}$*	*Rate (Mbps)*
64-QAM	3/4, 1/2	22.65 dB	1080, 960
16-QAM	3/4, 1/2	19.1 dB	720, 480
QPSK	3/4, 1/2	16.7 dB	360, 240
BPSK	3/4, 1/2	11.45 dB	180, 120

TABLE II
BIT PER SECOND FOR DIFFERENT MODULATION SCHEMES [10].

is to be expected since more users are active. However, after peaking at 8 gbps at 25 users, the throughput falls somewhat for the dynamic case because of increased interference as more users are allocated in the same time slot. The throughput for the static case (for $\rho = 1, 2, 3$) is much smaller than the dynamic case for $N \leq 35$. The reason is that in the static case we may have two users at the opposite ends of a region's boundary but they will be allocated to the same region (and hence to different time slots in the schedule). In the dynamic case, however, it is likely that these two users will be allocated to the same time slot because they lie outside each other's 3 dB beamwidth. As N increases, however, the static case and dynamic case become similar in performance because the schedule lengths are similar. Figure 7 plots the average length of a transmission schedule for the various schemes.

The performance of the static algorithm for different ρ values is quite different. The reason $\rho = 1$ is the poorest performing algorithm is that by allowing neighboring static regions to be active simultaneously, we are increasing interference. When $\rho = 3$, however, interference is minimized allowing higher data rates. Figure 7 shows the schedule lengths for different schemes. As we can see, the schedule length for $\rho = 1$ is 1 while it is 50% greater for other values of ρ and for the dynamic case. Indeed, while shortening the schedule length helps increase the throughput for the $\rho = 1$ case, the increased interference causes a far greater reduction in throughput.

Figure 8 plots the number of modules at which maximum throughput is obtained for each value of N for each algorithm. As expected, the number of modules used by the static case when $\rho = 1$ is by far the largest. However, for the dynamic case (which has the highest throughput for all values of N), the number of modules used is no greater than 10. This indicates a good separation of beams between nodes assigned to the same time slot.

A. Multiple Channels

The 60GHz ISM band has over 5GHz of available bandwidth allowing us to utilize multiple channels simultaneously within a cell. We therefore modified the static and dynamic SDMA algorithms to examine the potential benefits of doing so. The modification made in each case is the same:

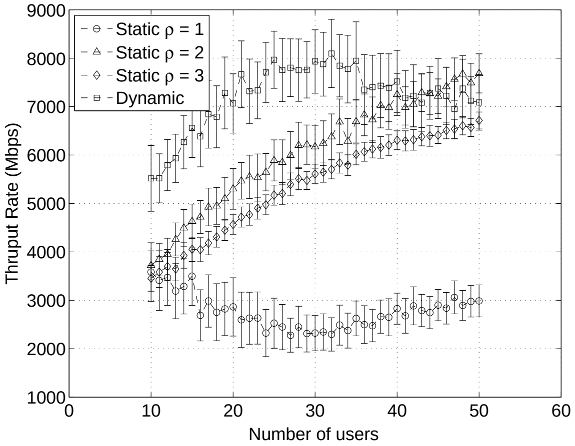

Fig. 6. Average throughput.

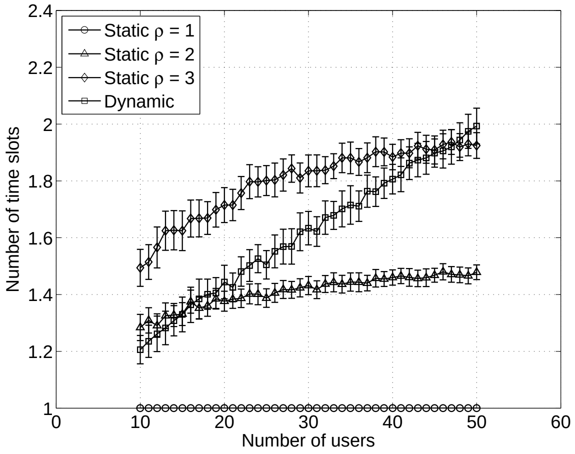

Fig. 7. Average schedule lengths.

> Start with a transmission schedule constructed for the single channel case. If this schedule has m slots and $m \leq 7$ (with 5GHz of bandwidth we can get a total of 7 channels of 640MHz with 80MHz spacing), we shrink the schedule down to one time slot and assign users from each slot of the static schedule to a different channel. Frequently, m is of the order of 2-3 time slots. This means that we will be left with 4-5 free channels. We divide these channels among the users as follows. Take the channel with the largest number of users and split the set in two with one subset retaining the original channel and the other subset being assigned to a new channel. This process is repeated until no channels remain.
>
> In the unusual case that $m > 7$, we shrink the first 7 slots into one slot as above, and repeat the algorithm for the remaining $m - 7$ slots yielding a multi-slot schedule.

A point to note is that the number of radio modules used in this case will equal the *total* number of users in the slot. Therefore, unlike in the single-channel case, the total number of radio modules will be much greater.

Figure 7 plots the average number of time slots as a function of N. As we can see, $m \leq 2$ in most cases. Thus, as per the algorithm above, we will first reduce the schedule length to one slot by assigning separate channels to users in each time slot from the single-channel schedule and then we allocate the remaining 5 channels.

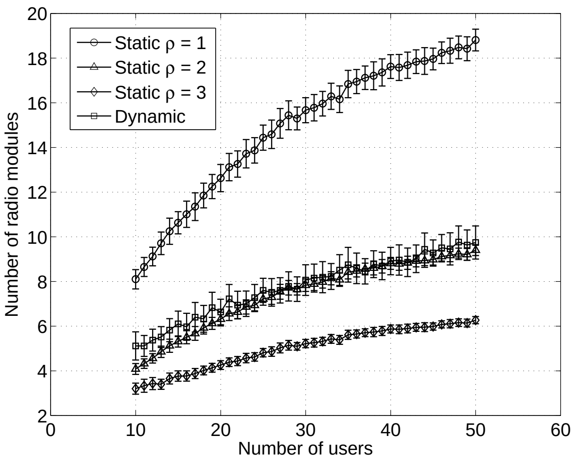

Fig. 8. Number of modules used to maximize average throughput.

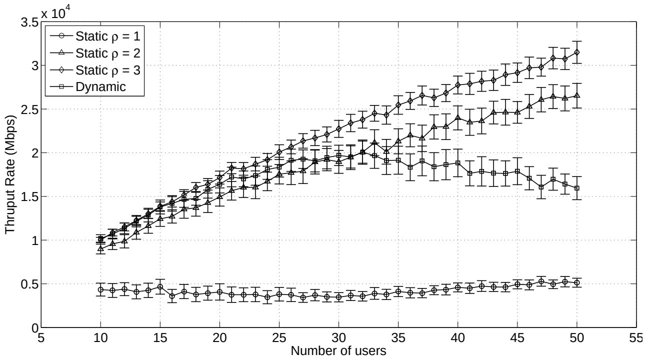

Fig. 9. Average throughput utilizing multiple channels.

Figure 9 plots the average aggregate throughput in the room as a function of N. Note the almost linear scaling of the static algorithm ($\rho = 3$) with N. Indeed, the maximum throughput of 31 gbps is obtained at $N = 50$ users. To understand this performance, consider the following approximate mathematical model. Recall that the static algorithm uses the $k = 21$ statically defined regions to allocate the channels. Let n denote the number of users in the system. These users are randomly uniformly distributed among the k regions. If a region has no users in it, we do not allocate a channel to that region. On the other hand, if a region has two or more users, we allocate two channels to that region and distribute users equally between the two channels. In the static algorithm with $\rho = 3$, we can reuse the channels every fourth region. Thus, channels used in region 1 can be reused in region 4 and so on. The schedule for this model of the static algorithm has a length of one slot. In order to compute the aggregate data rate, we need to find the number of regions r_1 with exactly one user and the number r_2 with more than one user. The aggregate throughput is then written as:

$$S = 7/6\,(r_1 + r_2 \times 2)\ \text{ gbps}$$

Note that we multiply r_2 with 2 since we allocate two channels and the aggregate rate per channel can be as high as 1 gbps.

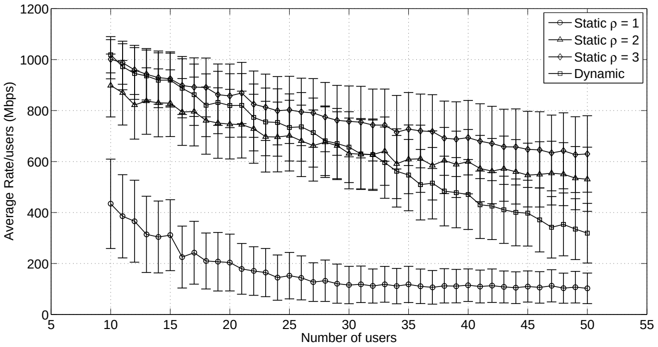

Fig. 10. Data rate per user utilizing multiple channels.

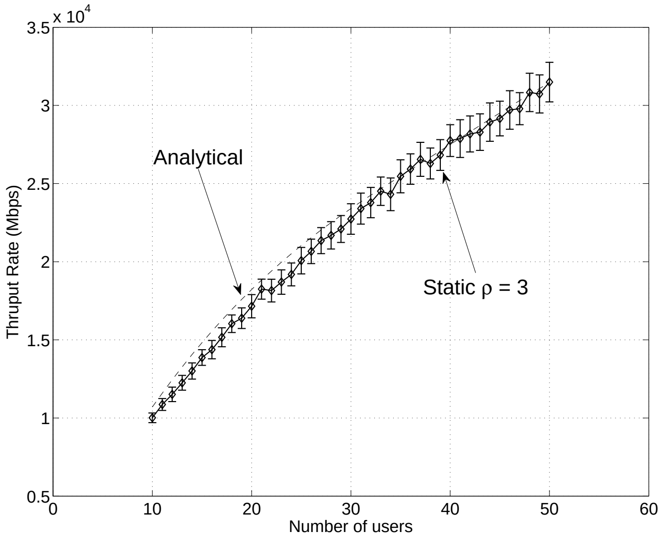

Fig. 11. Analytical model for the static algorithm with $\rho = 3$.

We multiple the expression on the right by $7/6$ since we are using only 6 out of the 7 possible channels (that are used in the simulation).

In order to compute r_1 let us first find the probability $p_1(i)$ of the event when i regions out of k have at least one user. We can write this as,

$$p_1(i) = \frac{\begin{pmatrix} k \\ i \end{pmatrix}\begin{pmatrix} n-1 \\ i-1 \end{pmatrix}}{\begin{pmatrix} n+k-1 \\ n \end{pmatrix}}$$

Out of these i regions some number j will have more than one user. The conditional probability $p_2(j|i)$ of this happening can be calculated using the above formula but substituting k with i, n with $n - i$, and i with j. Then,

$$r_2 = \sum_{i=1}^{k} p_1(i) \sum_{j=1}^{i} j p_2(j|i)$$

We can then obtain r_1 as,

$$r_1 = \sum_{i=1}^{k} i p_1(i) - r_2$$

Figure 11 plots the analytical model versus the simulation for the static algorithm. As we can see, the correspondence is very good. We observe that the above analysis can be carried forward for other values of ρ as well.

A second item of note is that the throughput of the dynamic algorithm is much worse than that of the static algorithm ($\rho = 3$) unlike the case with a single-channel. The reason for this is that in the dynamic algorithm, spatial channels are separated by 3 dB only whereas the separation is much greater with the static algorithm when $\rho = 3$. The impact of this difference in channel spacing in the single-channel case is that we get a shorter schedule for the dynamic algorithm as opposed to the static algorithm, Figure 7. The immediate impact of a shorter schedule is greater aggregate throughput. In the multiple-channel case, all schedules end up being of length one slot and thus the dynamic algorithm loses that advantage. On the other hand, because the dynamic algorithm separates simultaneous spatial channels by only 3 dB, the interference in each channel is significant and starts playing a dominant role. This is why the dynamic algorithm performs poorly compared to the static algorithm.

VI. CONCLUSIONS

This paper examined the problem of channel allocation in 60 GHz indoor WLANs in order to maximize throughput. We exploit the ray-like propagation of this frequency and the absence of significant multipath, to develop novel SDMA algorithms. The performance of the SDMA algorithms is evaluated in a Matlab simulator that contains an accurate propagation model for 60 GHz. We show that, while using only 640 MHz of the bandwidth, we can achieve up to 8 gbps data rate in a typical room. Since there is more than 5 GHz of available bandwidth at 60 GHz, it is easy to see that much higher throughput are achievable by exploiting multiple channels simultaneously. We extend the single-channel algorithm to the multiple-channel case and show that aggregate throughput of over 31 gbps can be obtained for 50 users.

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