High Data Rate WLAN

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***Abstract*—This paper considers the problem of providing gbps/user data-rate in indoor environments. The technology that we study uses the 60GHz spectrum whose special propagation properties make it ideal when combined with antenna array technology. We present two algorithms. The first algorithm is SINR threshold based which uses dynamic spectrum allocation and adaptive modulation. We show data rates of 2Gbps per user even when 10 users are present in a small room. The second algorithm dynamically assigns users to channels without using a fixed SINR threshold. The results show that it can achieve up to 4Gbps/user for the 10 users case. We obtain a bandwidth efficiency of up to 12 b/s/hz.**

I. INTRODUCTION

We study the problem of providing very high data rates to indoor wireless users in the 60GHz ISM band. The 60GHz band offers more than 5GHz of bandwidth that can support multiple gbps links within a cell. Furthermore, 60GHz signals do not propagate well through obstructions and indeed, the reflected and diffracted components are significantly attenuated [3], [5]. This frequency is also absorbed by oxygen [7] and thus does not propagate well to large distances. In comparison to the 5GHz ISM band, the additional frequency related free space path loss is 22dB at the same distance. All of these features make it ideal for our application since it can *maximize spatial reuse within a room*.

In our architecture, we use multiple *distributed* smart antennas connected to a single AP (Access Point) in a room. Each antenna allows fast electronic beamforming in any direction with the ability to form nulls in some number of directions [4]. By using space division multiple access (SDMA), we can reuse the frequency channels (since 60GHz signals attenuate rapidly) within the room to increase the bandwidth efficiency.

In this paper, we present two algorithms for dynamic spectrum allocation. The performance is measured via detailed simulation in Matlab.

The remainder of the paper is organized as follows: In the next section we summarize previous work. Section III explains the resource allocation problem in our context. Section IV then presents our two algorithms. The experimental design for evaluating the algorithms is given in section V with results described in section VI.

II. RELATED WORK

60GHz ISM band has a LOS dominant signal path due to absorption, greater signal diffusion (i.e., less specular reflection) and lack of diffraction around obstacles [10], [5], [9]. The benefit of this particular propagation model, as noted in [10] and others is the significant lack of interference from other simultaneous, spatially separated transmitters. [3] and [2] report on large-scale propagation for 60GHz can be modeled as free space (a measured path loss exponent of 2.1 in buildings). Small RMS delay spread for 60GHz indicates little multipath [15]. A measurement of the relative strength of the reflected components with respect to the LOS component was studied by [16]. They show that, in general, the strongest reflected components are at least 10dB below the LOS component. Indeed, in many cases the reflected components are even weaker if the surface is not polished. Second-order and higher-order reflections are highly attenuated and negligible. Penetration losses through walls in the building are very high with many examples of over 35dB.

Broadly, the technologies proposed for high-speed WLANs are TDMA (usually for 19 and 25GHz) that gives 400Mbps data rate, MIMO (for 2.4, and 5GHz) that can give rates of up to 1Gbps/AP and SDMA/OFDM/TDMA for all of these various frequency bands, [6]. As we have noted previously, however, MIMO [11] requires a rich multipath environment which makes it ideal for 2.4 and 5GHz but not for 60GHz. For 2.4 and 5 GHz, there has also been research on MIMO/SDMA systems [14]. SDMA with smart antennas for indoor environments has been studied. However, unlike previous models [13], [1], we use *distributed* smart antennas within the room to create multiple mini-cells in the room that are adaptive (i.e., re-positioned and re-configured spatially as users move).

III. RESOURCE ALLOCATION PROBLEM

The problem we are studying is that of allocating resources to users such that each user reaches Gbps data rate using 60GHz ISM band. By intelligently placing multiple spatially distributed smart antennas, we can provide full coverage in indoor environments. In addition, smart antenna arrays can focus bit energy to the intended direction while nulling the interferes thus higher signal to interference and noise ratio (SINR). In this paper we assume that users have omni-directional antennas.

An allocation is a four tuple consisting of a radio, frequency-channel and a time slot assigned to each user. If the interference between users is low, then they can be allocated in the same frequency-channel and time slot thus yielding a higher bandwidth efficiency. However, if the user-to-user interference is high, they will need to be allocated to different frequency channels or to different time slots.

Now, let us introduce the notation which we will use through out the paper. Assume there are A directional antennas each with M beamforming modules. Recall that each beamforming module is capable of forming a beam in a given direction and nulls in other directions. *Each beamforming module is connected to one radio*. Thus, $a_{ij}, i = 1, 2, \cdots, A, j = 1, 2, \cdots, M$ denotes the jth module of antenna i. Note that from one antenna we can support M downlinks to M users simultaneously on the same channel so long as each user is separated in angular direction allowing each beamforming module to point the main beam at its user and place a null at the other user. However, user-to-user interference in uplink transmissions may be high when users use omni-directional antennas. There are $C \geq 1$ frequency channels available within the room that can be allocated to different links. We denote a given frequency channel by $c_l, l = 1, 2, \cdots, C$ and time slot by $t_p, p = 1, 2, \cdots, P$. Finally, assume that there are N users $u_k, k = 1, \cdots, N$ in all. An *allocation* is a set of N tuples $< u_k, a_{ij}, c_l, t_p >$ such that each of the N users has an assignment.

Let $U^{l,p}$ denote the set of users who are all assigned to channel c_l and time slot t_p. We need to ensure that the minimum data rate of the user in each set $U^{l,p}$ can achieve *at least* a 1Gbps rate. Given this constraint, we then maximize total system throughput.

IV. ALLOCATION ALGORITHMS

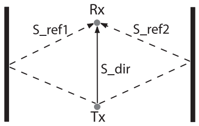

Fig. 1. Signal power consists of direct signal and first order reflections.

Data rate is highly dependent on the signal to interference and noise ratio which can be computed by $SINR = \frac{S}{I+N}$ where S is the signal, I is the interference and N is the noise. Because of high attenuation of 60GHz, there are only two significant contributions to the received power. One is the direct signal, S_{dir}, and the other is first order reflection, S_{ref} which is shown in figure 1. These signals reach the user via different paths (by reflecting on different obstructions). For example, in the figure, there are two obstructions that cause two first order reflections S_{ref1} and S_{ref2} (dotted line). The signal power at the receiver side becomes $S_{dir}+S_{ref1}+S_{ref2}$. In general, it can be calculated using the follow equations:

$$S = S_{dir} + \sum S_{ref} \tag{1}$$

$$S_{dir}[db] = P_t[db]+G_t[db]+G_r[db]-10log_{10}(\frac{\lambda}{4\pi d})^2-TL[db] \tag{2}$$

$$S_{ref}[db] = P_t[db]+G_t[db]+G_r[db]-10log_{10}(\frac{\lambda}{4\pi d})^2-RL[db] \tag{3}$$

where P_t is the transmission power, G_t,G_r are the transmitter and receiver antenna gain respectively and TL is the transmission loss if the transmitter and receiver do not have line of sight (LOS). TL depends on the material of the obstruction. If there are multiple obstructions, TL will be the sum of all transmission losses. RL is the reflection energy loss which is also material dependent. Note that interference I is the sum of unwanted energy from all interferes. This unwanted energy reduces the SINR. Let I_{jk} indicates the interference between u_j and u_k (if u_j and u_k are in different frequency channel, $I_{jk} = 0$).

In this paper, we develop algorithms that dynamically assign users to channel and time slots. The channel as well as time slots can be of variable length. Figure 2 shows an example of an assignment. Multiple users can be assigned to the same channel c_p and time slot t_p , to form a user set denoted as $U^{l,p}$ In the example, users $u1, u2, u3$ are in the set $U^{1,1}$. Note that different users in the same slot may have a different SINR.

	t1	t2	$\cdots$
f1	u1,u2,u3	u7	$\cdots$
f2	u4,u6	u5	$\cdots$

Fig. 2. Example of an assignment

Next we decide how much bandwidth should be allocated to frequency channels 1 and 2 and the length of the different time slots such that the total throughput is maximized while maintaining 1Gbps rate at each user. Let $r_{i,j}$ be the minimum user data rate in set $U^{i,j}$. Then we can calculate the ratio $ratio_{i,j} = \frac{\prod_{k,l} r_{k,l}}{r_{i,j}}$ and calculate the corresponding time length by $time_{i,j} = \frac{ratio_{i,j}}{\sum_{k,l} ratio_{k,l}}$. To maximize the throughput, we find the set which has the maximum data rate (i.e. sum of data rate of all users in the same set) within the same time slot. Then we calculate the minimum bandwidth required for the remaining sets using $W_{min} = \frac{1Gbps}{rate \times timeLen} \times 640MHz$. $Rate$ is the minimum data rate of user in the set and $timeLen$ is the assigned time slot length in second. If the bandwidth for some set is $b < 640MHz$, we reassign the difference $(640 - b)MHz$ to another user set so as to maximize total system throughput.

A. Greedy - SINR threshold based algorithm

In the greedy approach, the idea is that if the total interference at u_i (which is equal to $\sum_j I_{ij}$) initially is large, then u_i is more likely to have high interference with other users. On the other hand, if the total interference is small, then we can allocate it with other users in the same frequency channel since it will have less interference.

Let γ define a SINR threshold - the users' SINR should not fall below this threshold. The following is the algorithm outline:

1) Sort the users in a list by the sum of the interference, i.e. $\sum_j I_{ij}$ for u_i for greedy.
2) Set the current time slot to t_1.
3) Set the current frequency channel to c_1.
4) Set the current group to g_1. Each group is assigned the current time slot and frequency channel.
5) Assume each user i is associated with an interference meter IM_i which indicates the interference after the assignment. This value is initially set to zero.
6) Start with the first user u_p in the list (with smallest total interference value).
7) Pick the antenna (say a_{ij}) with the strongest signal. Note that in each time slot, each antenna can only be assigned to M users since M is the number of modules per antenna. If no antenna is available, increment time slot, increment group count and reset the frequency channel. Assign the current time slot and frequency channel to the current group. Now check the following:
    - Pick the first user assigned in the current group (say u_k)
    - Calculate the $SINR > \gamma$ if u_p is assigned to this group. Note that the interference will be $IM_p + I_{pk}$.
    - Repeat these steps until all users in the group are checked. If all have passed the check, return true, otherwise return false.
8) If the previous step returns true, u_p is assigned to the current group. Update the all IM_i with $IM_i + I_{ip}$ for all i in the current group and IM_p with the sum of interference with the user in the group. Repeat step 6 until all users are assigned.
9) Otherwise, assign the user to a different group.
10) Increment the current group count.
11) Increment the frequency channel count.
12) Assign u_p to the current group. Repeat step 6 until all users are assigned.

B. Greedy Dynamic decision based algorithm

The initial list of users is similar to the previous section. However, we do not set a fixed threshold to determine how high SINR should be for each user to be sharing the same channel. Instead, we compare the benefit of putting them in a group or not and pick the best case. For example, assume we only have one frequency channel and two users (u_i, u_j). Let rs_i and rs_j be the rate if we assigned them to the same frequency channel be rd_i, rd_j otherwise. However, in this case, we only have one channel which means they have to be in different time slots. Assume fixed time slot assignment, i.e. the rate is divided by two. rd_i will be greater than rs_i because of low interference. But $rd_i/2 > rs_i$ may not be true. We therefore compare the total data rate and pick the best case. Let's define this decision making as $F(g_i, u_k)$, where g_i is the group and u_k is the user for whom we need to decide to be in this group or not. It returns 1 if it will be assigned to the same group, otherwise 0.

1) Sort the users in a list by the sum of the interference, i.e. $\sum_j I_{ij}$ for u_i for greedy.
2) Set the current time slot to t_1.
3) Set the current frequency channel to c_1.
4) Set the current group to g_1. Each group is assigned the current time slot and frequency channel.
5) Assume each user i is associated with an interference meter IM_i which indicates the interference after the assignment. This value is initially assigned to zero.
6) Start with the first user u_p in the list (with smallest total interference value).
7) Pick the antenna (say a_{ij}) with the best signal. Note that in each time slot, each antenna can only be assigned to M users if M is the number of modules per antenna. If no antenna is available, increment the time slot, increment the group count and reset frequency channel. Assign the current time slot and frequency channel to the current group.
8) If $F(g, u_p)$ returns 1, u_p is assigned to the current group. Update all IM_i with $IM_i + I_{ip}$ for all i in the current group and IM_p with the sum of interference with the user in the group. Repeat step 6 until all users are assigned.
9) Otherwise, it is to assigned to a different group.
10) Increment the current group count.
11) Increment the frequency channel count.
12) Assign the u_p to the current group. Repeat step 6 until all users are assigned.

V. EXPERIMENTAL DESIGN

In order to evaluate the allocation algorithm as well as to answer the larger question of whether gbps/user rates can be provided, we implement a detailed simulation in Matlab. The simulator implements a propagation model for 60GHz and provides signal strength at any location in the simulated indoor space. As input, we specify the architecture of the room including the reflection and absorption properties of all the materials used. For this simulation we use the layout shown in Figure 3. The attenuation data we use in the simulations is based on measurements reported in [8], [16] and is summarized in Table I. We note that in the results reported here, we only use the one room described above. The reason is that since 60GHz signals do not propagate far therefore any large room can be split into smaller parts and each studied separately.

The fixed parameters we use in the simulations include:

Transmit power	10dBm
Noise	-174 dBm/Hz
Path loss	Freespace
Smart antenna gain of main lobe	21dBi
Sidelobe gain	-6.5dBi
Target BER P_b	10^{-5} and 10^{-8}

We use an ideal antenna model derived from [12] in our simulations. The following variable parameters in the experiment are:

- the number of users from 2 and 10. For each run for a given number of users, we place users randomly and uniformly. We also select a random height for each user between 0.5m and 1m above the ground.

- the room has 2 antennas with ranges 1-3 modules each. Thus, the total number of beams we can form is 2-6. We carefully place them in room such that the signal covers the entire room.
- We assume that each user has an omni-directional antenna.
- For SINR threshold based, we define a set of threshold $\gamma_1 = 10, 15, 17, 20, 23, 29$ dB for bit error $P_b = 10^{-5}$ and $\gamma_2 = 12, 18, 19, 23, 26, 32$ dB for $P_b = 10^{-8}$. These threshold values are selected based on the different modulation schemes that yield difference data rates.

Each experiment is repeated 100 times giving us a total of $9 \times 3 \times 6 \times 2 \times 100 \times 2 = 64,800$ runs for SINR based and $9 \times 3 \times 2 \times 100 \times 2 = 10,800$ runs for dynamic decision. Total $75,600$ individual runs.

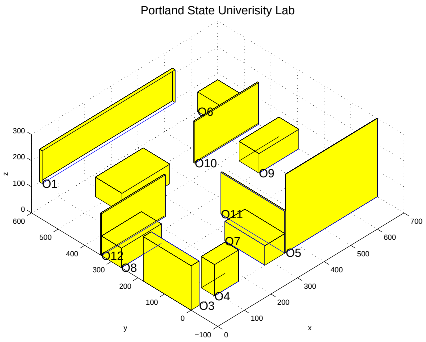

Fig. 3. Laboratory setup used in the simulations.

VI. Results

Our goal is to calculate the data rate in order to compare different algorithms. Therefore, given an allocation, we first compute the SINR and then use table III to find the data rate. The values in this table are based on a 640MHz channel.

Table II shows the summary of average data rate achieved for 6 and 10 users for different bit errors. When the total number of radios increases per antenna, the average data rate also increases in both tables. This is because more frequency channels are reused giving a higher data rate as well as bandwidth efficiency. Thus, the total number of radios available constrains the spatial reuse. Let x bps be the maximum rate for 6 users. The seventh or additional users will require allocating a new time slot resulting in lower data rate on average. For example, if there are 10 users, the maximum data rate will be $\frac{6x+4x}{10 \times 2} = \frac{x}{2}$.

Note that for the SINR threshold based algorithm, it is very important to find the right threshold from the sets $\gamma 1$ or $\gamma 2$ in order to get good performance. Therefore, we examine different threshold values to get the best throughput.

For the dynamic decision algorithm, we try to examine an alternative way to allocate resources to users. Instead of a fixed threshold, we compare different results of assigning users in the same group or not to determine the decision.

Figure 4 shows the average data rate for bit error $P_b = 10^{-}5$ for 1-3 radio per antenna. In general, the more the number of radios, the more spatial reused in the same time slot, thus higher average data rate per user. However, comparing the two algorithms in the figure: SINR based algorithm (top) shows only slight improvement in the number of radios while the dynamic decision algorithm(bottom) shows better performance.

Comparing the dynamic allocation with the SINR based algorithm, it is noticeable that dynamic allocation provides much higher data rate per person and much higher bandwidth efficiency when number of radios per antenna is greater than 1.

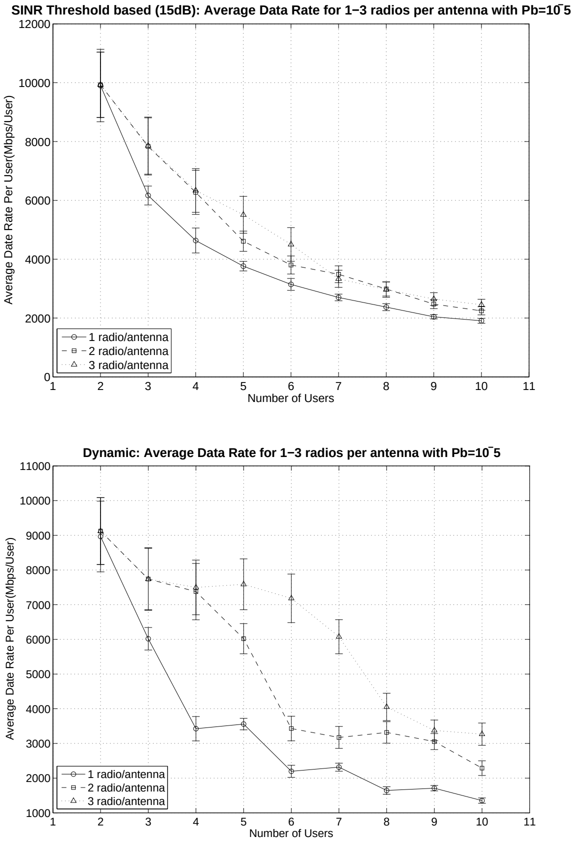

Fig. 4. Left: Average data rate for SINR based algorithm for $P_b = 10^{-5}$. Right: Average data rate for Dynamic decision algorithm $P_b = 10^{-5}$.

We repeat the experiments for low bit error rate, $P_b = 10^{-8}$. The shape of the graph remains basically the same but the data rate drops 1Gbps per person on average. The bandwidth efficiency drops from $12b/s/hz$ for $P_b = 10^{-5}$ to 9 for $P_b = 10^{-8}$.

The theoretical data rate that we then see is derived from Table III. This table is calculated using the estimation equation 4 for MPSK and 5 for QAM:

$$P_e = 2Q(\sqrt{\frac{2E_s}{N_o}}sin\frac{\pi}{M}) \tag{4}$$

			Attenuation [-dB] angle of incidence						
Object ID	*Description*	*Material*	10	20	30	40	50	60	70
O1	White Board	Acrylic Glass	6.2	5.5	5.5	5.5	6.0	7.6	13.1
O2	Table	Wooden Chipboard 1.3cm	13.4	10.7	9.5	11.7	7.9	5.5	5.3
O3	Book Self	Wooden Chipboard 1.3cm	13.4	10.7	9.5	11.7	7.9	5.5	5.3
O4	File Cabinet	Acrylic Glass	6.2	5.5	5.5	5.5	6.0	7.6	13.1
O5	Glass Door	Glass Smooth 0.8cm	8.8	9.8	12.1	9.1	5.5	3.4	2.6
O6,7,8,9	Desk	Wooden Chipboard 1.3cm	13.4	10.7	9.5	11.7	7.9	5.5	5.3
O10,11,12	Partition	Wooden Panels 1.9cm	22.0	21.7	18.4	18.2	15.2	9.3	6.5

TABLE I
ATTENUATION VALUES USED FROM [8], [16].

		1 Radio/antenna			*2 Radio/antenna*			*3 Radio/antenna*		
		Rate (Mbps)			*Rate (Mbps)*			*Rate (Mbps)*		
Algorithms	*Bit Error P_b*	*N=6*	*N=10*	*η (b/s/hz)*	*N=6*	*N=10*	*η (b/s/hz)*	*N=6*	*N=10*	*η (b/s/hz)*
SINR based (15dB)	$10^{-}5$	3200	2000	5	3800	2400	6.3	4500	2600	6.8
Dynamic	$10^{-}5$	2600	1500	4.5	4500	2500	8	7100	3400	10.7
SINR based (18dB)	$10^{-}8$	3000	1900	4.6	3400	2000	5.4	3900	2100	5.8
Dynamic	$10^{-}8$	2000	1200	4	3800	2200	6.7	6100	3000	9

TABLE II
SUMMARY OF THE RESULT OF EACH ALGORITHM

where $P_b = \frac{P_e}{log_2 M}$ for $P_e << 1$ and $M > 2$. For $M = 2$ case, $P_b = P_e = Q(\sqrt{\frac{2E_b}{N_o}})$.

$$P_{bc} = \frac{4}{k}(1 - \frac{1}{\sqrt{M}})Q(\sqrt{\frac{3k}{M-1}\frac{E_b}{N_o}}) \tag{5}$$

where $P_b = 1 - (1 - P_{bc})^2$ and $k = log_2(M)$.

Modulation	*Code Rate*	*SINR for $P_b \leq 10^{-5}(10^{-8})$*	*Rate (Mbps)*
256-QAM	0	28.85 (31.25) dB	2560
64-QAM	0	22.7 (25.06) dB	1843
16-PSK	0	20.45 (22.97) dB	1280
16-QAM	0	16.58 (18.89) dB	1228
8-PSK	0	14.73 (17.2) dB	960
QPSK	0	9.4 (11.79) dB	614
QPSK	3/4	7.85 (10.3) dB	460
QPSK	1/2	5.54 (8.22) dB	307
BPSK	3/4	3.08 (5.52) dB	230
BPSK	1/2	2.5 (5.21) dB	153

TABLE III
BIT PER SECOND FOR DIFFERENT MODULATION SCHEMES WITH BLOCK CODE RATE.

VII. CONCLUSION

Our algorithms provide high data rate per user with high bandwidth efficiency for the 60GHz ISM band. Using the special properties of this band, we develop very efficient SDMA algorithms. The algorithms dynamically partition the bandwidth into variable length slots to achieve these high data rates. The experimental results show that the average data rate falls smoothly when the number of users increase, thus showing graceful degradation with loading.

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