Exclusive Region Scheduling Performance in 60GHz Networks

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***Abstract*—The main problem with 60 GHz Wireless Personal Area Networks is the limited range due to high path loss. Directional antennas are used to address this issue and provide a sufficient gain for communication. A scheduling scheme is employed to increase the total throughput and reduce interference. We investigate a scheduling scheme with the concept of Exclusive Regions (ER). The effect of different antenna beamwidths on the number of concurrent flows, average SINR and total throughput is researched. With Exclusive Regions, the interference between all flows is calculated to determine which ones can transmit simultaneously. Furthermore, we use two variants of the scheduling scheme and study the effect on the metrics.**

I. Introduction

The need for wireless high speed data connections has increased significantly over the years. Unfortunately, the available radio frequencies are becoming more and more limited. The most recent development in Wireless Personal Area Network (WPAN) is the use of the 57-66 GHz frequency band (60 GHz for short). This frequency band is intended to be a free band, in similar fashion to the 2.4 and 5 GHz band. It offers an order of magnitude more available bandwidth that can contain Gigabit speeds. One of its most promising applications is replacing thousands of kilometers of cables connecting components in e.g. cars, that can be replaced by a handful of antennas. However, due to high oxygen absorption at this frequency, the path loss for 60 GHz is very high. It is because of this reason that the use of directional antennas is required, so that at medium distances communication is still possible.

Fig. 1 illustrates a scenario of a 60 GHz WPAN. Here, devices in the network communicate with each other directly. without having to send the data to a central access point. In a WPAN, the PCP (Personal Basic Service Set Central Point) provides scheduling and timing to all devices in the network using beaconing.

Directional antennas bring a new method of communication over conventional omni-directional data links. They are the most practical solution to handle the path loss problem. As an example, with directional antennas a much higher gain is achieved which can be used to combat the high path loss. Additionally, the probability of interference with neighbouring nodes is reduced. The research performed on directional MACs for mmWave networks by Cai et al. [1] was the primer for this paper. The proposed REX MAC optimises the network throughput by allowing a lot more concurrent transmissions than would be possible in an omni-directional network. The use of three-dimensional spatial multiplexing can offer a further increase in concurrent connections[2].

In this project, we are going to investigate the performance of 60GHz communication. Therefore, our problem statement is: *"How well can a 60GHz network perform with use of directional antennas?"*

In our research, we are going to investigate the effect of varying beamwidth on the throughput, Signal-to-Interference-plus-Noise Ratio (SINR) and number of concurrent flows in a 60GHz network. We only investigate 60 GHz networks where all terminals have directional antennas.

The approach of our project will be as follows: We will develop a Matlab model for simulating the behaviour of multiple transmitter and receivers operating simultaneously. This model will consist of a variable number of transmitters and receiver pairs in a room of a certain size, where all transmitters and receivers will have the same directional antenna. We will implement a scheduler that tries to schedule as many concurrent flows as possible, in this way maximising the total throughput. For the model, we highly rely on [1].

We will use Matlab to investigate the mentioned properties that tell us more about the performance of the network and compare them with a normal TDMA schedule. The number of concurrent flows will be determined by the scheduler. On

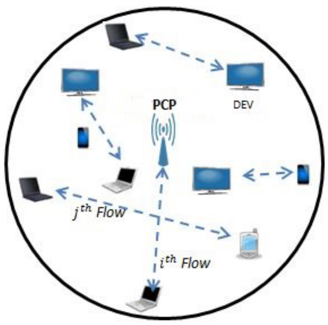


Figure 1: Illustration of a mmWave WPAN.

the other hand, the SINR will be calculated by dividing the received power by the power of the interfering nodes and the power of the noise. From the SINR we can than calculate the maximum achievable data rate for a link.

The model will use the same parameters as in [1]. However, we diverged from that paper when it comes to the scheduler. Aside from implementing the scheduler from the paper, which is based on a minimum-flow-first heuristic, we also implemented a scheduler that uses a maximum-flow-first-heuristic. We will explain both methods in section III-C. The results will also reflect the differences between these two schedulers.

Before we investigate our results, we will first elaborate more on the problem formulation, model and implementation.

II. Problem Formulation

In this section, we will discuss some important properties and formulas regarding 60 GHz networks. We will use these formulation for our model and implementation.

A. Problem Space

The problem space is initially a 2D indoor environment where 60GHz communication is used. We will assume a fixed amount of nodes N that is placed in the room in a uniform and random manner. Also present is a global scheduler that is connected to all the nodes and has information on the intended transmissions of each node. Each node has an electronically steered directional antenna, which is capable of beamforming in any direction.

We consider the network graph where each node $n_i \in N$ that is communicating with $n_j \in N$ has an edge $(i,j) = e_k \in E$. All nodes are generated in pairs, namely a transmitter and receiver that want to establish a connection together. These nodes have their antennas directed at each other. Nodes will be reused by the scheduler. This means that means that a node will participate in multiple transmissions, with a variety of nodes. The walls of the room may cause reflections and interfere with other signals. At first, we will make the assumption that the room in our simulations has no walls or ceilings. Integrating this into the model can be considered for further work.

B. Antenna Gain

One way of modelling the gain of the directional antennas is with the flat-top model [3], which assumes a constant gain within the main lobe and zero gain outside the lobe. In our research, we will use the circle-cone antenna model. This is a simplified antenna model with a constant gain G_m in the main lobe, and a lower constant gain G_s in the area outside the main lobe [1]. For an antenna with radiation efficiency η and beamwidth θ the gain of the main lobe is given by $G_m = \eta\frac{2\pi}{\theta}$ and the gain in the side lobe by $G_s = (1-\eta)\frac{2\pi}{2\pi-\theta}$.

C. Evaluation Formulas

The received signal power P_R of the edge $e_k = (i,j) \in E$ is modeled according to the path loss model

$$P_R(j) = G_R(j)G_T(i)P_T(i)\left(\frac{\lambda}{4\pi d_{i,j}}\right)^2, \tag{1}$$

where the $G_R(i), G_T(j)$ are the receiver gain and transmitter gain respectively. $P_T(i)$ is the transmitter power, λ the wavelength and $d_{i,j}$ the distance between node i and j.

Signal to Noise and Interference Ratio (SINR) is calculated by dividing signal power received from a paired transmitter by sum of interference and noise. In the model for this research, the interferers are all transmitters that are not paired with a particular receiver. Interference is then calculated as the sum of all power received from interferer.

Normally, interference power is smaller than received power from the intended transmitter. This happens because the receiver and intended transmitter are facing each other; therefore at each others main lobe, while the interferers are generally not in the direction of main lobe. SINR for receiver j is given by

$$SINR(j) = \frac{P_R(j)}{\sum\limits_{n,n\neq j} P_R(n) + N_0} \tag{2}$$

The noise power in the system N_0 is modeled as Johnson-Nyquist thermal noise.

$$N_0 = k_B T W \tag{3}$$

with k_B is Boltzmann constant (1.380×10^{23}), T is room temperature (290 K) and W is the frequency bandwidth used in transmission. In this research we use bandwidth of 500 MHz, resulting the noise power N_0 equal to 2.0019×10^9 Watt. Let W be the available bandwidth, then according to Shannon's theorem the achievable channel bit rate R is given by

$$R = W\log_2(1 + SINR). \tag{4}$$

Using these formulas, we can evaluate the performance of a directional 60GHz MAC protocol and the effect of varying beamwidth. By modelling the problem we are able to simulate the REX scheduling algorithm in a realistic scenario. The throughput, SINR and number of flows are measured to evaluate the effects.

III. Model

Having defined what our problem statement is and named some basic formulas we are going to work with, we can now elaborate on the used model and implementation. As an example, it was needed for our implementation to define the nodes which were going to communicate with each other, as well as the deciding rules for our scheduler. For this, we again relied on [1].

In the simulation, no modulation scheme is used. Therefore, the channel bit rate calculated from Shannon's theorem (Eq. (4)) is equal to theoretical data rate.

A. Nodes

Nodes are necessary to model the network itself and are modeled by a Node object. This object can be both the Transmitter or the Receiver, having the same properties (i.e. antenna gain). To model the connection between two devices these nodes are generated in pairs. A random position within the modeled room is generated for each node, the heading for

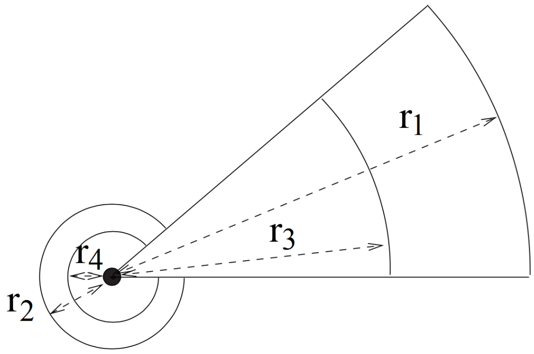


Figure 2: Exclusive region used with directional transmitter and receiver [1].

both nodes of a pair is calculated such that they point towards each other. These node pairs form the basis for the rest of the model. As an example, using the positions of the nodes we can easily calculate the angle of the antennas.

B. Exclusive regions

In the next context interferers are transmitters that do not play a part in the connection between two nodes. Exclusive regions are areas where a interferer T is not allowed to be when a receiver R is in another connection. Namely, if T would be that close to R, interference at R would be such that the original message for R would suffer from it too much. Shortly, exclusive zones determine where interferers can be before the signal gets interrupted. The notion of Exclusive Regions is introduced in [1] and is an important aspect for determining whether two connection can coexist.

As said before, for simultaneous connections the interferer T must be outside the Exclusive Region. The formula of the radius of this ER is such that if an interferer is further then r away, it is assured that the interference power is less or equal to the background noise, $I_{j,i} \leq N_0W$, where the interference power is

$$I_{j,i} = k_1 G_0 G_T(j) G_R(i) P_T(j) d^a_{j,i}, \tag{5}$$

which is a similar formula as Eq. (1), having $k_1 = \left(\frac{\lambda}{4\pi}\right)^2$.

When the interference power is less than or equal to the background noise, both flows won't suffer significantly from the fact that another flow coexists. If flows with mutual interference less than that of the background noise transmit simultaneously, the throughput of each flow can also be higher than that of a serial TDMA transmission [1].

To model the directional antennas we use the same Exclusive Region method used in [1]. For directional to directional communication, this method uses a number of Exclusive Regions as seen in Fig. 2. Four zones can be identified. For simultaneous connections, the interferer T must be outside one of these four zones. Which zone this is depends on the position of both the antenna of T and the antenna of R. As can be seen, the calculation of the ER radius r follows from the inequality $I_{j,i} \leq N_0W$ and Eq. (5).

First, if both the interferer and the receiver are inside each others beamwidth, Exclusive Region r_1 is used. The radius r_1 is given by

$$r_1 = \left(\frac{k_1 G_0 G_{T_m} G_{R_m} P}{N_0 W}\right)^{\frac{1}{\alpha}}, \tag{6}$$

where (again) $k_1 = \left(\frac{\lambda}{4\pi}\right)^2$, G_0 the cross correlation between concurrent transmissions and α is the pathloss exponent which are all assumed to be constant.

Second, if an interferer is outside the radiation angle of the receiver with its radiation beamwidth toward the receiver, exclusive zone r_2 is used. Its radius is given by

$$r_2 = \left(\frac{k_1 G_0 G_{T_m} G_{R_s} P}{N_0 W}\right)^{\frac{1}{\alpha}} \tag{7}$$

Third, if an interferer is within the radiation angle of the receiver, but the receiver is outside the radiation angle of the interferer exclusive zone r_3 is used:

$$r_3 = \left(\frac{k_1 G_0 G_{T_s} G_{R_m} P}{N_0 W}\right)^{\frac{1}{\alpha}} \tag{8}$$

Last, if both the interferer and receiver are outside of each others radiation beamwidth, Exclusive Region r_4 is used:

$$r_4 = \left(\frac{k_1 G_0 G_{T_s} G_{R_s} P}{N_0 W}\right)^{\frac{1}{\alpha}} \tag{9}$$

In the model these formulas are used by the scheduler to determine whether a flow can be established or not.

C. Scheduler

The purpose of the scheduler is to find a schedule where as many flows as possible can be concurrently active, while still not interfering with each other. Using the previously defined Exclusive Regions, it is possible to find out which flows cannot be active at the same time. The problem that is left is finding a schedule which maximises the throughput of the network, given the restrictions of Exclusive Regions.

To this end we will follow the scheduler as proposed in [1], but with some modifications. Given a set of flows F, we define the size of a flow as $T_f : f \in F$. And the set of scheduled flows at timeslot $i \in \mathbb{Z}^+$ is S_i. We assume that flows should not be interrupted after they are started to maximise the throughput. Because some flows are larger than one timeslot, this means that they will have to run across many timeslots before they are completed. Let $er(f,g) : f,g \in F$ be a function that checks whether f interferes with g.

$$er(f,g) = \begin{cases} g & \text{if } f \text{ interferes with } g \\ \emptyset & \text{otherwise.} \end{cases} \tag{10}$$

Let the remaining size $rt_i(f) : f \in F$ be a function in $[0, t(f)]$ which expresses the remaining size of f in time slot i. We assume that every time slot an amount of data is transferred for scheduled flows equal to the Shannon Capacity of the channel after scheduling all the flows.

1) Choose a flow $\arg\min\{t(f) : f \in F\}$, randomly deciding when multiple flows satisfy the minimum.
2) Check whether

$$\{\bigcup_g er(f,g) : \forall g \in S\} = \emptyset \tag{11}$$

and only then add f to the scheduled flows $S_i = S_i \cup \{f\}$.
3) Reiterate steps 1 and 2 until all remaining flows $rt_i(f) > 0$ have been tried.

The difference with the REX paper can be found in that flows are not broken in multiple sections, where one section can be transmitted each time slot. A flow in our definition is a unit of work that must be completed in the simulation, without interruptions. The goal of the scheduler is to minimise the time required to complete all jobs:

$$\min\{i, \text{ s.t. } \forall f \in F, rt_i(f) = 0\}. \tag{12}$$

The result of this minimisation is a maximisation of throughput, which is achieved by maximising SINR and concurrent flows.

We have also implemented another variant of this Scheduler. Let the above scheduler be called Min Flows First, we define the Max Flows First scheduler by modifying step 1 of the algorithm:

1) Choose a flow $\arg\max\{t(f) : f \in F\}$, randomly deciding when multiple flows satisfy the maximum.
2) Idem to Min Flows First.

We will compare the two algorithms in our results section.

Scheduler example: For an example of both scheduler heuristics we refer to figure 3. In this figure you see all the flows that need to be scheduled on the right side of the figure. It also shows how the network is laid out.

The position of the nodes are chosen in such a way, that one pair of vertical nodes is able to communicate concurrently with only one pair of horizontal nodes and vice versa. For instance, E and F can communicate concurrently with a transmission between A and B, but not with H and G. The top time line shows the schedule according to the Min-Flow heuristic, the bottom timeline shows the schedule for the Max-Flow heuristic.

D. Simulation

The simulation performs steps through the timeslots until all flows have been completed. Let $S_i = s_i(S, F)$ be the scheduling function, that returns the new schedule in step i, given an initial schedule.

1) Initialise $i = 1$ and $S_1 = \emptyset$, as no flows have been scheduled yet.
2) Calculate $S_i = s_i(S_i, F)$.
3) Increment $i = i + 1$ and calculate the received flow for each $f \in S$, and calculate $rt_i(f), \forall f \in S$ using Shannon's Theorem (4). Calculate the initial schedule for the new i

$$S_i = S_{i-1} \setminus \{f \in S, rt(f) \leq 0\}.$$

4) If there are any remaining flows to be handled $\{\exists f \in F, rt(f) > 0\}$ restart from step 2, otherwise finish.

IV. Results

For our simulation we use 40 randomly generated nodes, in a 10×10 meter room. The total number of tasks is 500, with varying size from 1 to 10 Gigabytes. Each node will participate in multiple transmissions, where it uses its steerable antenna to aim at the paired node. Each task is a transmission between a random receiver and an other random transmitter. All flows use the transmission power of 10 mW, and k_1 is -51 dB. Let

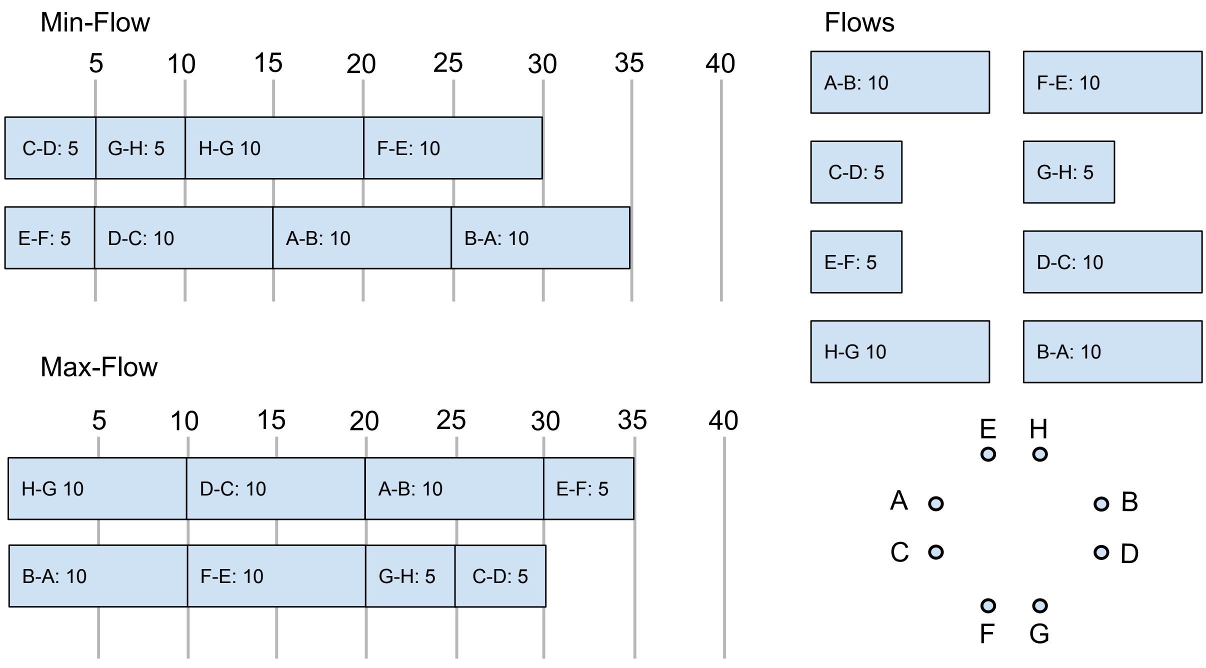


Figure 3: Example of both scheduler heuristics.

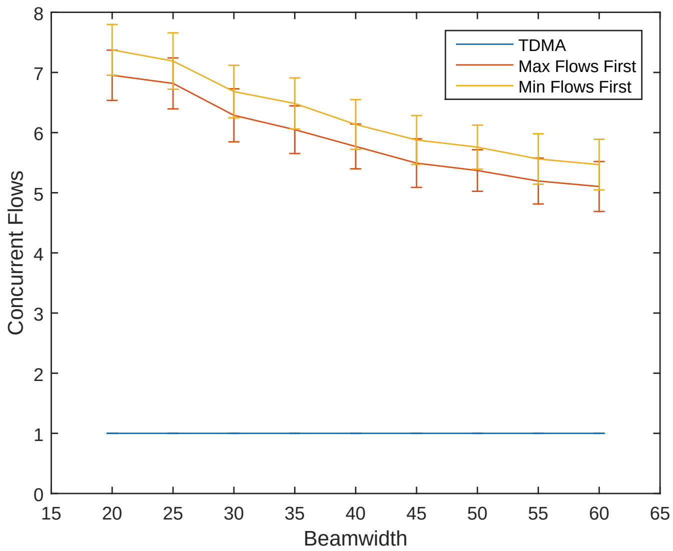


Figure 4: Total number of concurrent flows versus the beamwidth.

$N_0 = -114$ dBm/MHz, $W = 500$ MHz, and $G_0 = 10^{-2}$ as also used in [1].

To investigate the effect of beamwidth θ on the number of concurrent flows, SINR and data rate, we vary $\theta \in \{20, 25, \ldots, 60\}$. For each θ the simulation is ran 50 times, averaging the results to correct for outliers. The simulation uses a step size of 0.25 second on every iteration.

In our simulation we use both schedulers as specified in the previous section, which differ on the flow orderings. The performance of these schedulers is compared with a standard TDMA scheduler, which schedules each flow sequentially.

A. Concurrent Flows

First we consider the number of concurrent flows. This number depends on the Exclusive Regions (ER) and the scheduler. Specifically, when a lot of these Regions overlap, the scheduler will only schedule a small number of flows concurrently.

Fig. 4 shows our result regarding the number of concurrent flows when we change the beamwidth of the antenna. As can be seen, when the beamwidth grows larger, the number of concurrent flows decreases. An explanation for this behaviour are the changes in the ERs when the beamwidth changes. When θ increases, two things happen: First, the mainlobe area in the ER gets wider, thus the transmitted power is delivered to a 'wider' area. At the same time, G_m decreases, because again $G_m = \eta \frac{2\pi}{\theta}$. This results in the mainlobe reaching less far. Secondly, the sidelobe area get smaller. It will now reach further, proportional to the decrease of the mainlobe.

In the context of interfering flows, having a wider mainlobe areas means that the chance that two antennas are in each others beamwidth increases. This can be explained by the size of the room compared to the mainlobe range $\{r_1 \approx 20m : \theta = 20°\}$ down to $\{r_1 \approx 10m : \theta = 60°\}$. And the room diameter is about 14m. Thus the range that is lost when the beamwidth increases, does not have a significant effect on the number of nodes that can be reached that are 'far' away, i.e. between 10 and 20 meters. However, it does increase the width of the lobe, which causes many more nodes that are within 10 meters distance of the node to be covered. All in all this causes a larger interference with a wider mainlobe.

Compared to TDMA both schedulers have significantly more concurrent flows. As expected TDMA schedules all flows sequentially so the concurrent flows always equal 1. Furthermore, the number of concurrent flows for the Max Flow First algorithm is significantly lower than Min Flow First. We will not go further into explaining this, and leave it as Future Work.

B. SINR

The graph of average SINR vs Beamwidth is shown in Fig. 5a. Although the average SINR per node decreases on average by more than 3dB with increasing beamwidth for the ER schedulers, the variance of the SINR is very large. All in all we cannot say that the decrease is significant, because it falls within the confidence bounds of smaller beamwidths.

We can address two things when analysing what happens with the SINR when decreasing θ. First, the ERs change, having a 'wider' but less 'deep' shape in the mainlobe area. As seen previously this results in less concurrent flows. This then leads to less interfering nodes that can decrease the SINR at a node. One goal of the scheduler is to keep the interference affecting active flows to a minimum, in this way ensuring that the SINR does not decrease significantly.

The other thing what happens when increasing θ is that G_m decreases and G_s increases. Take a flow $f_j \in F$. For the calculation of the SINR for this flow this means that the received power P_r decreases because of a smaller G_m. At the same time, there will be flows that coexist with f_j that cause more interference because G_s has increased. Looking again at Eq. (2), the change of Gain can cause the SINR to decrease because the numerator decreases and denominator can increase.

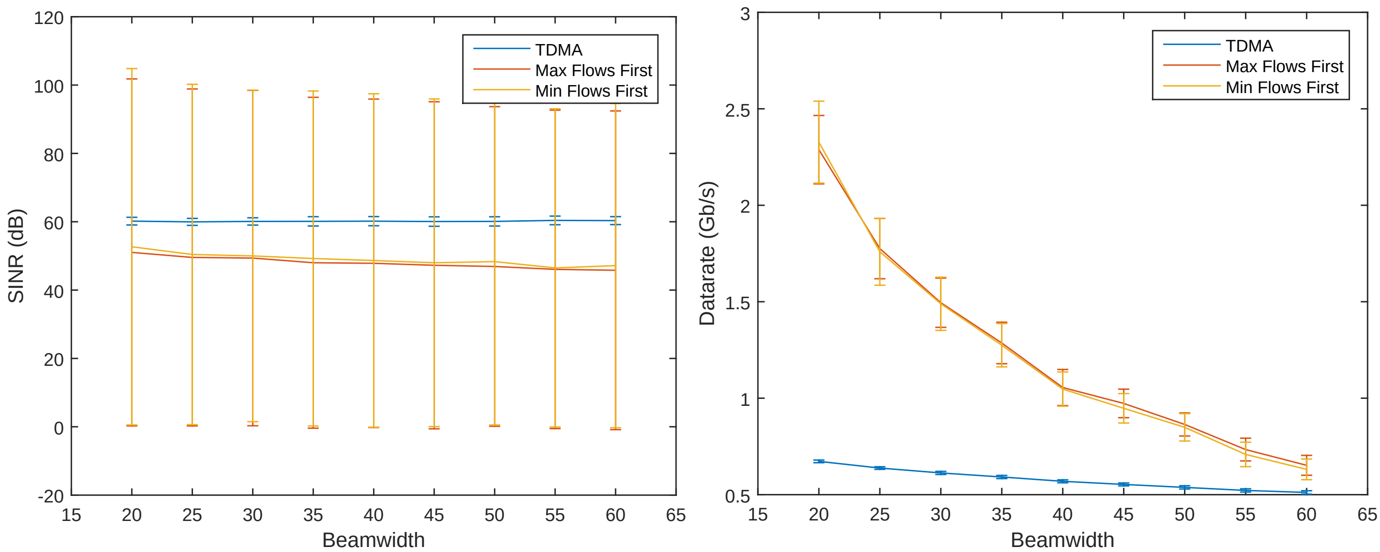
In comparison with the TDMA schedule, the ER schedulers have a lower SINR. This is cause by the multiple concurrent flows that are active and the interference they cause to eachother.

C. Data Rate

The results of our simulation given by Fig. 5b show that the data rate follow the same trend as the number of concurrent flows: As the beamwidth increases, the data rate decreases. This can be explained and follows directly from the number of concurrent flows. A larger number of active flows means that more data is being send simultaneously. This directly leads to a higher total data rate.

The difference between Min Flow First and Max Flow First is negligible. The total data rate for each of these schedulers falls within the other's confidence bounds, and thus cannot be seen as significant.

The ER schedulers perform significantly better than a TDMA scheduler. Even though the SINR is lower on average, the multiple active flows cause a significant increase in total



(a) SINR versus beamwidth.

(b) Total data rate versus beamwidth.

Figure 5: Further simulation results.

data rate. For larger beamwidths less flows can be scheduled concurrently, and thus the difference between TDMA and ER schedulers decreases.

V. Conclusion

In this paper, we have researched the performance of 60 GHz networks. These networks offer an immense bandwidth that can contain Gigabit speeds. However, with this high frequency comes a very high path loss, which can lead to a poor performance of these networks. A proposed solution to increase the performance of these networks is the usage of directional antennas. Directional antennas can be used to partly circumvent the problem of interference due to other transmitting nodes. The directional antennas provide a significant increase in gain that can be used to combat the high pathloss.

In [1] a method was proposed to increase the number of concurrent flows in 60 GHz networks using directional antennas, that increase the performance of the network. This scheduler uses the notion of Exclusive Regions, which we have also elaborated on in this paper. Using [1] as a primer, we looked into the effect of a changing beamwidth of the directional antennas on performance properties like the number of concurrent flows, Signal-to-Interference-Noise-Ratio and data rate.

Conclusions of our research are that the number of concurrent flows is higher when using a smaller beamwidth. As a direct consequence of this, the data rate increases when the beamwidth is small, because there are more concurrent flows and thus more data is being sent simultaneously. The average SINR decreases by more than 3dB as the beamwidth increases. However, that is still within the confidence bounds of smaller beamwidths and thus cannot be seen as very significant. This decrease is causes by the fact that there is a smaller directed gain of the transmitting nodes and a slightly larger omni-directional gain of interferers, even though at larger beamwidths there are less concurrent flows. It is clear from the simulations that a lower beamwidth results in the most important metric, the total data rate, to increase.

A standard TDMA scheduler has a significantly lower data rate than the ER schedulers. This is a strong motivation for the use of directional antennas, because with spatial multiplexing the total data rate can be more than a factor 2 larger.

From our research, we conclude that 60GHz networks can perform well with the use of directional antennas. Our simulation results show that better results are achieved when using antennas with a smaller beamwidth. In other words with higher directionality of the antennas comes a better network performance. Besides this, as named in [1] and the next section, there is much research in this field left to improve the performance of communication in the 60GHz band even more.

VI. Future Work

In this research, we analysed the behaviour of certain properties of 60 GHz networks as result of a changing antenna beamwidth. This is not the only important research topic regarding the performance of 60 GHz networks. It is also possible to improve the maximum total throughput by using 3D spatial multiplexing [2]. By using reflections from the walls and ceiling in the data center the amount of concurrent flows can be increased, because this approach allows new paths to be created that don't interfere with other nodes in the space. Another extension is to incorporate a mobility model in the existing model. In this project, we were unable to focus on this.

For the creation of our scheduler, we followed the REX algorithm proposed in [1], with a Min Flow First and a Max Flow First approach. First, scheduling the minimum flows first (the original approach of [1]) leads to more concurrent flows (see Fig. 4). An other interesting find is that, although this scheduling rule does lead to more concurrent flows, it does not lead to a higher data rate in Fig. 5b. A future study may look into the behaviour of the two scheduling approaches to explain this behaviour. Perhaps by performing an algorithmic analysis of the problem and comparing the approximation ratios of the algorithms.

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