Initial Access Strategies for Mm-wave Systems

A Project Report

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ADIT RAVI

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THESIS CERTIFICATE

This is to certify that the thesis titled **Initial Access Strategies for Mm-wave Systems**, submitted by **Adit Ravi**, to the Indian Institute of Technology, Madras, for the award of the degrees of **Bachelor of Technology and Master of Technology**, is a bona fide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Prof. Radhakrishna Ganti
Research Guide
Professor
Dept. of Electrical Engineering
IIT-Madras, 600 036

Place: Chennai

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ABSTRACT

KEYWORDS: LaTeX; Thesis; Style files; Format.

In this project we discuss a comprehensive set of metrics and a final measure to compare various mmwave initial access systems and strategies. While comparisons are often made on the basis of one or two parameters and usually qualitatively, we attempt to give a quantitative and wholesome aspect to the comparison. This framework is then used to compare three initial access strategies including one newly formulated strategy which is a modification of an existing method.

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CHAPTER 1

Introduction and Motivation

The ever expanding growth of intensive data-using applications and the consequent desire for ubiquitous data among mobile users has led to numerous measures for efficiently using spectrum (Chia *et al.*, 2009). This motivation has spurred research in the direction of the millimeter wave band of spectrum (60 GHz) that is as yet unlicensed. Millimeter waves are a possible solution to providing small cell backhaul in tiered networks. Among the advantages of millimeter wave are the availability of many GHz of underutilized spectrum (Chia *et al.*, 2009) and controlled interference between systems due to the directed nature and low range of the links formed. However, to function, mmwave systems require a large directional gain to compensate for path loses that are very high at these frequencies of operation in addition to losses due to absorption by certain air molecules at these wavelengths (Rappaport, 2002).

While there are a few different ways to achieve high directional gains in antenae, the possibility of phased arrays of antennae become particularly attractive in the mmwave scenario. For once since the wavelength of operation is smaller, the size of these antennae are in the range of a few millimeters thereby lending themselves to compact and easy packing (Li *et al.*, 2013). Moreover such antenna arrays are simple in terms of their physical structure and are less susceptible to misalignment and maintenance breakdowns as compared to dish antennas.

Millimeter wave phased array antenna can therefore use numerous antenna elements in one array and steer the beam resulting from the array in arbitrary directions using phased sending of signals. These are referred to as beamforming techniques.

Since beamforming and directionality are integral to the successful operation of mmwave systems, it is necessary to perform them in as efficient a manner as possible. To achieve this there are numerous beamforming methods that employ analog as well as digital phase multipliers that ensure directivity of the antenna beam (Sun *et al.*, 2014). There are also possiblities of hybrid analog and digital beamforming methods (Alkhateeb *et al.*, 2013).

Besides the problem of beamforming, another challenge that was relatively less important in LTE communication systems becomes crucial in mmwave systems. This is the problem of initial access. Since in LTE systems directionality is not a feature, the initial access is performed to simply exchange housekeeping data for setup of the communication link (Access, 2008). However, in the case of mmwave systems, due to the requirement of directionality, the base station must 'find' the direction of the user so that the beam may be pointed towards him/her. Likewise, the user must also find the direction of the base station so that the full beam forming gain both on the sender and receiver's side (directional listening) may be done.

As can be imagined, this process is not trivial as it involves a search across the angular space surrounding each device. There have been a few methods (Hur *et al.*, 2011), (Barati *et al.*, 2015), (Cordeiro *et al.*, 2010) suggested to perform this operation effectively and each method shows good performance according to certain parameters.

In this work, we study mmwave systems and initial access methods with the view of not only creating a novel protocol to perform this action but also a comprehensive framework to quantitatively assess and thereby optimally choose the appropriate mmwave system best suited to the required outcomes. Described in subsequent chapters is the framework used for evaluation, the rationale behind using each measure and combining them in the way mentioned. We also leave tractable weights of importance that may be set so that some measure is given more importance than others in the final combined cost function. We combine measures and metrics that are redundant or those that have importance only when compared with some other metric to obtain dimensionless indices which can then be combined according to the required importance given to each.

CHAPTER 2

Problem and Framework

2.1 Problem Definition

We consider a point-to-point multiple-input multiple-output (MIMO) wireless system in a 2-D space. Each of these communicating devices will have an antenna array to transmit and receive signals. Let the number of antenna in an array be N i.e. N_{BS} for the base station and N_{UD} for the user device array. The choice of N will have an effect on certain measurables and characteristics of the system as shown in **??**. Hence its choice may be constrained by design limitations and requirements.

Given an array with N elements, we define a codebook W to be a set of beams which can be chosen from and used to carry the signal in certain respective directions. The design of this codebook must enable more successful of and quick initial access. We must also set a minimum gain threshold G_{min} for a link to be established. This would naturally depend on factors such as range, channel fading etc. Most importantly we need to have an initial access strategy that is able toproduce desirable results acccording to the measurables we consider. In this project, a framework to assess various initial access and codebook forming strategies and compare them is presented. Also, this framework may be used to design an optimal system that performs well in terms of the measurables mentioned in the framework for a given set of contraints.

2.2 Notations and Basic Concepts

A MIMO system consists of an array of antennae to provide directionality to the signals transmitted by it. This is done by shifting the phase of the signal fed to various antenna elements so that they interfere constructively in a certain direction and destructively in others.

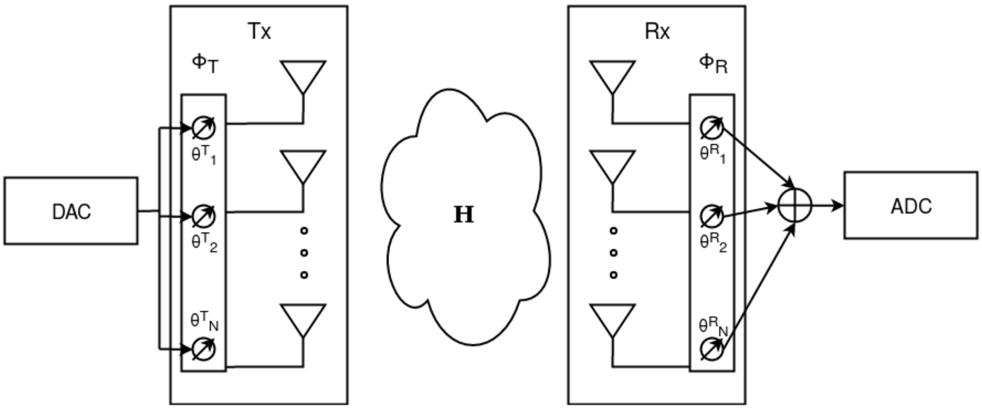

Figure 2.1: A block diagram of the system.

Consider fig 2.2. If we calculated the signal at point x in the diagram, we would have to sum the contribution of every antenna element at that point. Each element i is fed a signal $Ae^{-j\omega t}$ multiplied by a phase shifting factor $e^{j\theta_i}$. Also,

$$\begin{aligned} r_i &= \sqrt{r^2 + (i-1)d^2 - 2r(i-1)dcos\phi} \\ &\approx r - (i-1)dcos\phi \end{aligned} \tag{2.1}$$

Therefore, the signal at point x due to antenna element i is (assuming exponential attenuation)-

$$\begin{aligned} s_i(r, \phi, t) &= Ae^{-\frac{r}{r_0}} e^{j(kr_i - \omega t + \theta_i)} \\ &= A(r, t)e^{j(\theta_i - (i-1)dkcos\phi)} \end{aligned} \tag{2.2}$$

Adding up the contribution of all the antenna elements we have-

$$s(r, \phi, t) = A(r, t) \sum_{i=1}^{N} e^{j(\theta_i - (i-1)dkcos\phi)} \tag{2.3}$$

Consider now a MIMO system with a transmitter having an M_T element array and a receiver having an M_R element array. The transmit and receive antennae are operated as phased array beamformers. As signal to be transmitted by the transmitter array will first be multiplied by a beamforming vector $\mathbf{f} = \frac{1}{\sqrt{M_T}}[e^{j\theta_0^T},\ e^{j\theta_1^T}, \ldots e^{j\theta_{M_T-1}^T}]^T$. These signals are then transmitted through the channel $\mathbf{H}$ and recevied after multiplication by a combiner $\mathbf{z} = [e^{j\theta_0^R}\ e^{j\theta_1^R} \ldots e^{j\theta_{M_T-1}^R}]^T$.

Within the channel we consider multipath fading, signal dispersion and absorbtion

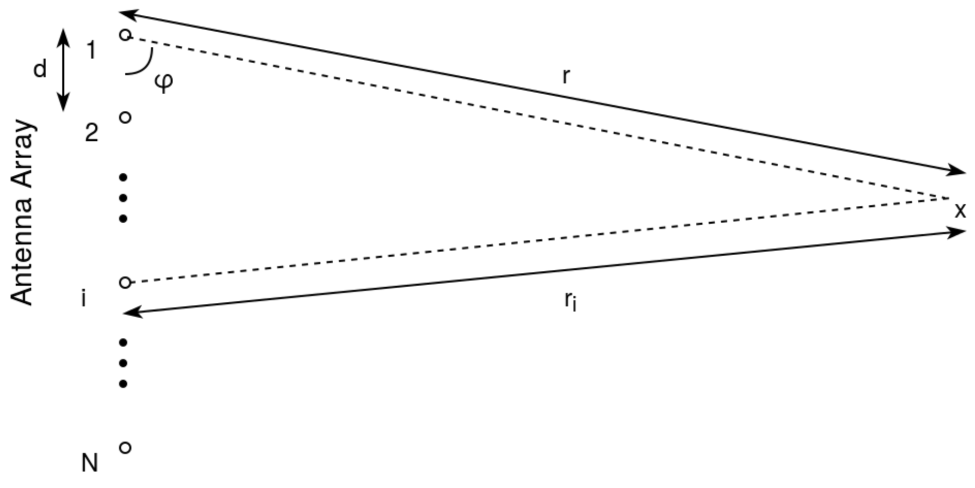

Figure 2.2: Directed beam using a MIMO array

and take the path loss to be as follows from [ref!]

$$PL(R) = 32.5 + 20log_{10}(f) + 10\alpha log_{10}(R) + (A_O + A_R)R \tag{2.4}$$

where R is the link distance, f is the carrier frequency, α is the path loss exponent and A_O and A_R are the oxygen and rain absorbtion coefficients respectively. For the purpose of our calculations we use $\alpha = 2.2$ corresponding to the urban model of [ref!]. A_O is taken to be 16 dB/km and A_R to be 0.2 dB/km as given in [ref!]. Using this path loss model, we can calculate the relationship between the range of the system and the signal strength.

The MIMO channel with the above mentioned fading is typically modeled as a superposition of numerous paths with one being LOS and the others formed due to reflections. Here we assume a sufficiently narrowband of frequency, therefore assuming no variation in frequency. Hence, this can mathematically be expressed as-

$$\mathbf{H} = \sum_{l=0}^{L-1} \mathbf{H}_l \tag{2.5}$$

where L is the total number of such paths and $\mathbf{H}_l \in \mathcal{C}^{M_R \times M_T}$ is the channel response corresponding to path l-

$$\mathbf{H}_l = \Theta_l^R \beta_l (\Theta_l^T)^\dagger \tag{2.6}$$

where $\Theta_l^R = [e^{jkdcos\theta_l^R}, e^{jkdcos\theta_l^R}, \ldots e^{jkdcos\theta_l^R}]^T$ and $\Theta_l^T = [e^{jkdcos\theta_l^T}, e^{jkdcos\theta_l^T}, \ldots e^{jkdcos\theta_l^T}]^T$

while β_l is the fading factor.

For our analysis, we make the following simplifying assumptions. We assume that the array size of both the base station and the user are the same i.e. $M_T = M_R = N$. Without loss of generality, we choose the orientation of the arrays to be such that $\theta_l^R = \theta_l^T = \theta_l$. Finally, we assume that only one path exists in our channel and therefore $\mathbf{H} = \Theta_l^R \beta_l (\Theta_l^T)^\dagger$. We assume that there is additive gaussian noise ($\mathbf{v}[n]$) added to each antenna elemnt and as a result, the final received scalar signal $r[n]$ after combining is given by-

$$r[n] = \mathbf{z}^\dagger(\mathbf{H}s[n])\mathbf{f} + \mathbf{z}^\dagger\mathbf{v}[n] \tag{2.7}$$

Therefore, we can see that there exists a correct path between the transmitter and the receiver and finding this is the objective of the initial access procedure. Mm-wave systems can vary the beamforming direction θ continuously in the range $[0, \pi)$ and search for the path. However, in practical situations, we must discretise the angle space (aka beamspace) to search through the possibilities. A set of all the possible beamforming vectors corresponding to this discrete and finite set of angles is known as the **codebook**.

Each possible beamforming vector corresponds to an angle and is known as a beam. A codebook is therefore a matrix $\mathbf{W}$ such that the i^{th} column is the beamforming vector corresponding to the i^{th} angle in the set of discrete angles to be searched through. There are many factors that should be taken account while designing a codebook. We choose the codebook construction given in [ref] due to its simplicity (it only uses beamforming weights of the form j^p where $p \in \mathcal{Z}$) and also since it covers the range of angles effectively by minimizing gain loss i.e. the maximum drop in gain with respect to the maximum gain of the system as shown in fig 2.3.

We construct a codebook $\mathbf{W}$ with K beams for an antenna array consisting of N elements, as follows-

$$\mathbf{W}(n,k) = \begin{cases} (-j)^{mod(n,K)}, & n = 0,\dots,N-1 \text{ and } k = 0; \\ j^{floor\frac{n\times mod(k+K/2,K)}{K/4}}, & n = 0,\dots,N-1 \text{ and } k = 1,\dots,K-1 \end{cases} \tag{2.8}$$

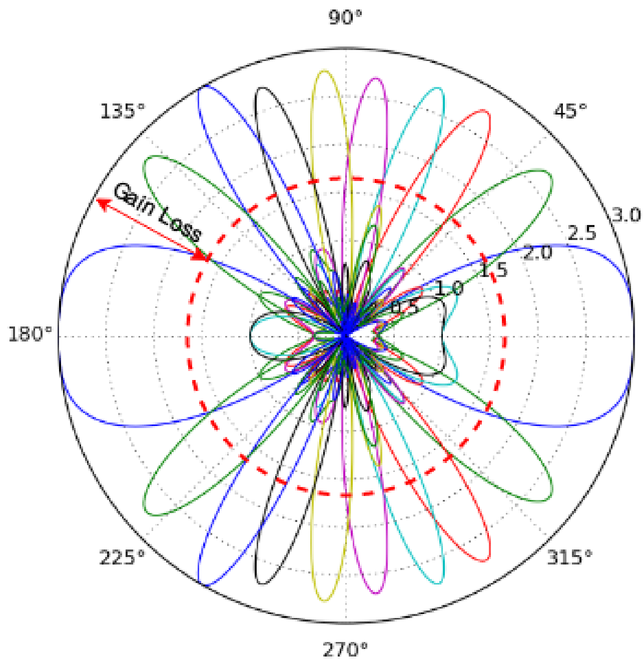

Figure 2.3: Gain Loss of Codebook ($N = 9,\ K = 9$)

2.2.1 The Steps Involved in Initial Access

The initial access process can be thought of as a sequence of three steps-

1. The user searches for and finds the direction in which the base station is present. In this step, the base station transmits a pre-decided signal and the user receives.
2. The base station listens and the user transmits directionally in the direction of the base station as found in step 1. At the end of this step, the base station finds out the direction in which the user is present.
3. The base station and user exchange data to setup the link. In this step the full directional gain is used.

Among the three steps mentioned above, the first step is the most complex since the search space is much larger than the second step. The initial access strategy mentioned in this project deal mainly with the first step and the time taken to establish the link after the end of the first step is negligible compared to the time taken in this step.

Since new users continuously arrive in the range of base stations, the time slot of a base station is divided as shown in fig 2.4. In a total slot of duration T that repeats itself, the first step is given a section of duration t_1 and the second step a duration of t_2. The remainder of the time slot is used for step 3 and communication.

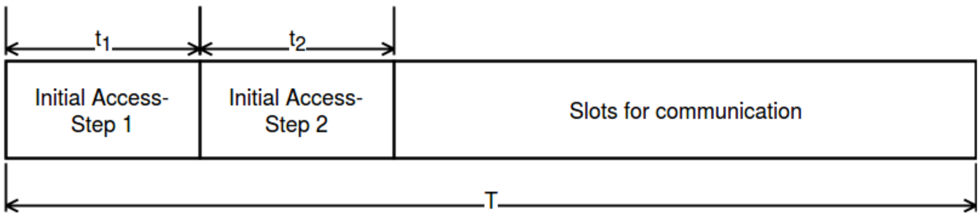

Figure 2.4: Time slots for initial Access

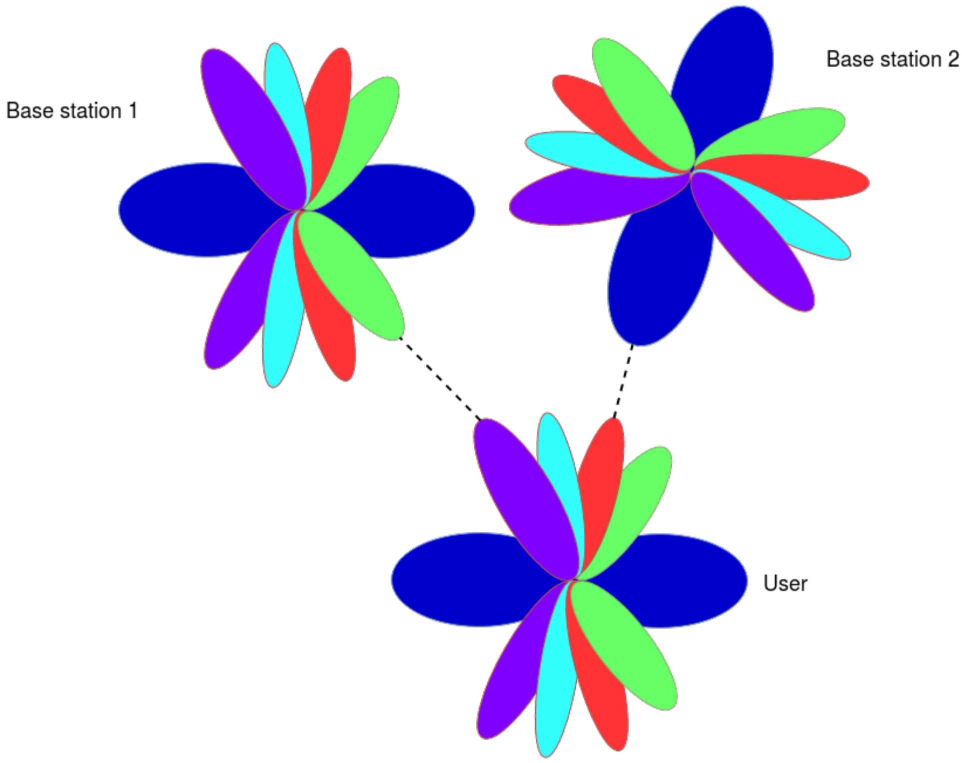

Figure 2.5: Illutstration of SDMA

2.2.2 Multiple Base Stations

In a MIMO system, we can use beamsteering to simultaneously receive or transmit multiple signals at the same frequency but in different directions. In other words, we can have Space Division Multiple Access (SDMA). Consider fig 2.5 for illustration, where there are two base stations and one user. The user can communicate with both the base stations using different beams at the same time. In this project we take a rectangular area $\mathcal{B}$ where base stations are uniformly distributed. The number of base station $N(\mathcal{B})$ in the area follows a Poison distribution-

$$P(N(\mathcal{B}) = n) = \frac{(\lambda|\mathcal{B}|)^n}{n!}e^{-\lambda|\mathcal{B}|} \tag{2.9}$$

Here, we assume that the user is present in the sub area $\mathcal{A}$ as shown in the figure 2.6 or in other words, in an area with sufficient density of base stations. By these assumptions, we calculate the average number of base stations (n_{BS}) for whom the user is in range to be-

$$n_{BS} = \frac{\pi r_{link}^2}{|\mathcal{B}|} N(\mathcal{B}) \tag{2.10}$$

where r_{link} is the maximum range of the link.

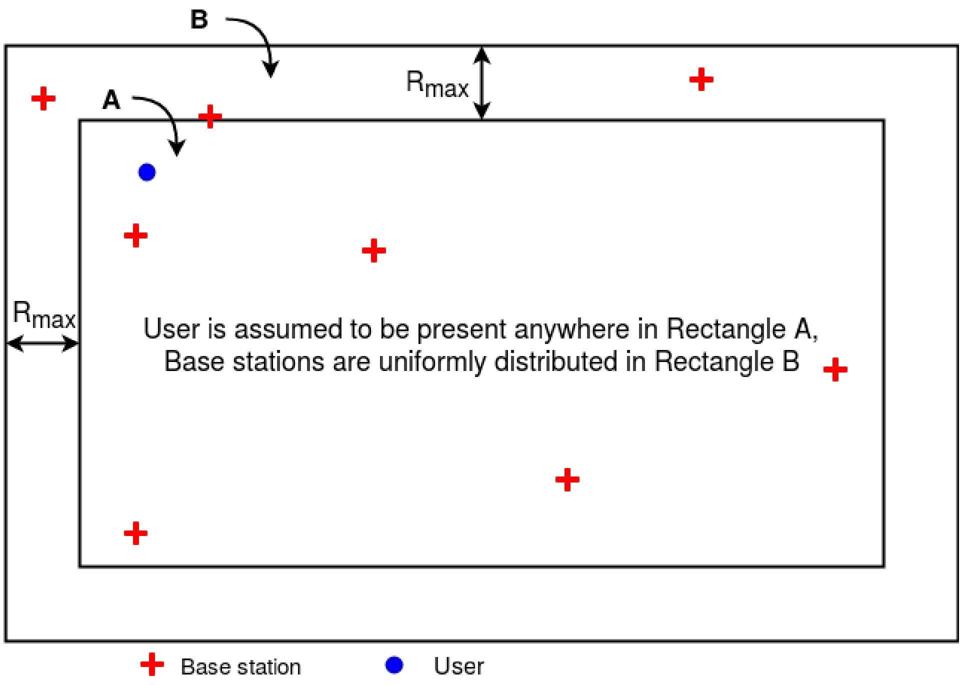

Figure 2.6: Distribution of base stations

CHAPTER 3

Method

In this chapter we first discuss the framework developed by combining various relevant measures and metrics to evaluate the performance of initial access strategies and system configurations. Then, we go on to describe in brief two existing initial access strategies and finally the new strategy proposed. Comparisons are made among the mentioned strategies and their various configurations in the subsequent chapters using the framework developed here.

3.1 Description of Framework

While designing an initial access strategy for an Mm-wave system and the system configuration in general there are numerous variables to take into account. These include the number of antenna array elements (N), number of beams in the codebook (K, 2.8), the minimum link strength required (α), whether alternative modes of communication are available between the two devices we are trying to link, the type of beamforming to be used (analog or digital) and whether there is any additional location information available to either devices. These are some of the common variables that are available to a designer and a choice must be made based on numerous outputs/measurables that need to be optimized as well as constraints that need to be met. Some common metrics of the efficacy of an initial access system are- the probability of failure, the directivity of the antenna, the range of communication, the error rate of the link once established, the rate of communication, and the time delay or the time taken to setup the link.

Previous works that introduce or compare initial access strategies for mm-wave systems use numerous metrics for evaluating them. In (Hur *et al.*, 2011), the authors compare initial access strategies using *Beamforming Gain* defined as-

$$G_{BF} = \frac{E[|r_{BF}[n]|^2]}{E[|r_{SISO}[n]|^2]}$$

Further they also use the computational complexity of the search operation to compare methods. In (Li *et al.*, 2016), the **expected initial access time delay** is used as a metric. This intuitive metric is incorporated into our assessment system. Besides this, they also use **the average user-perceived downlink throughput**. This is a measure directly related to the overhead that the initial access method uses. We don't use this measure in the current framework since we assume a uniform overhead for all the compared methods. However, to measure the data throughput we evolve a different measure called the effective data rate that measures the same outcome. In (Wang *et al.*, 2009), the measures used are **directivity** and **gain loss**.

We now discuss the metrics we use in the proposed framework chosen out of the above set and their utility. **Delay caused by initial access**- Defined as the time duration between when initial access is initiated to when the location of the base station is discovered given that the discovery is possible. Though one of the most crucial factors to determine the efficacy of an mm-wave system, this metric by itself is useless without an estimate of the delay in terms of lost data carrying capacity. To estimate this, we need to know the **Data Rate**. The data rate achievable by establishing a link depends not just on the bandwidth given for the link but also the number of possible beams in the codebook. Since MIMO systems can perform SDMA as shown in [ref] and hence the capacity of the channel is increased. If there are n_{BS} base stations within whose range the user falls, a link can be established with at most K of them. Consider the number of links the user actually makes to be L. Therefore,

$$L = \begin{cases} n_{BS}, & n_{BS} \leq K \\ K, & n_{BS} > K \end{cases} \tag{3.1}$$

To find the probability distribution of L, we simply truncate the probability distribution of n_{BS} (Eq 2.10) at K and re-normalize it-

$$P(L = l) = \left(\frac{(\lambda|\mathcal{B}|)^n}{n!} e^{-\lambda|\mathcal{B}|} \right) \div \left(\sum_{n=1}^{n_{max}} \frac{(\lambda|\mathcal{B}|)^n}{n!} e^{-\lambda|\mathcal{B}|} \right) \tag{3.2}$$

Where $n_{max} = \lfloor \frac{K|\mathcal{B}|}{\pi r_{link}^2} \rfloor$.

Therefore, if we assume the data rate along one beam to be R, then the combined data rate of the system would, on an average be $RE[L]$ which turns out to be-

$$RE[L] = R\lambda\pi r_{link}^2 \left(\sum_{y=0}^{n_{max}-1} \frac{(\lambda|\mathcal{B}|)^y}{y!} e^{-\lambda|\mathcal{B}|} \right) \div \left(\sum_{n=1}^{n_{max}} \frac{(\lambda|\mathcal{B}|)^n}{n!} e^{-\lambda|\mathcal{B}|} \right) \tag{3.3}$$

This is the total data rate R_{total}. However, to take into account the error while communicating using the link, we also need to consider the **bit error ratio** (BER). Therefore, the total rate is effectively $R(BER)E[L]$.

Combining the data rate and time delay gives us a useful measure that can be called the **Effective Data Rate** of the system. Consider that a user will be within the range of a base station for an average time t_{range}. Out of this duration, say t_{access} time is required for the link to be established.

This time can be split into the time required for the user to discover the base station's beam direction t_{BU} plus the time required for the base station to discover the user's direction once the user knows the base station's direction t_{UB} i.e. $t_{access} = t_{BU} + t_{UB}$. However, the time taken for the base station to discover the location of the user once the user knows the base station's location is negligible and constant. Hence , $t_{access} \approx t_{BU}$.

Here it is also interesting to observe that since multiple base-stations are being communicated with by the user, the initial access must be done for each of these links. Therefore, if the initial access setup strategy is such that only one link can be setup at a time, the total initial access time will be $E[L]t_{access}$ i.e. the access time delay for one link multiplied by the average number of beams being used at a time $E[L]$. However, if initial access can be done simultaneously for multiple beams at a time, the time is just t_{access}. Taking this into account, we define t_{total} as-

$$t_{total} = \begin{cases} t_{access} & \text{, If simultaneous access is possible} \\ E[l]t_{access} & \text{, otherwise} \end{cases} \tag{3.4}$$

Now, if t_{total} time is required to set up the links, the time remaining to communicate via the link is $t_{range} - t_{total}$. Hence, the 'Effective Data Rate' defined as the average data rate during the time the user is within the base station range is-

$$\begin{aligned} R_{effective} &= R_{total}\frac{t_{range}-t_{total}}{t_{range}} \\ &= (BER)RE[L]\left(1-\frac{t_{total}}{t_{range}}\right) \end{aligned} \tag{3.5}$$

However, in case the initial access for multiple beams cannot be done at the same time, as the links are setup one by one, the data rate available for communication increases. This is accounted for as follows-

$$\begin{aligned} R_{effective} &= \frac{1}{T}\Big(0 + tR + 2tR + \ldots + (\bar{L}-1)tR + (T-\bar{L}t)\bar{L}R\Big) \\ &= \frac{1}{T}\Big(tR\frac{(\bar{L}-1)\bar{L}}{2} + (T-\bar{L}t)\bar{L}R\Big) \\ &= \frac{1}{T}\Big(TR\bar{L} - \frac{tR\bar{L}}{2}(1+\bar{L})\Big) \\ &= R\bar{L}\Big(1-\frac{t}{2T}(1+\bar{L})\Big) \end{aligned}$$

where $t = t_{access},\ T = t_{range}$ and $\bar{L} = E[L]$. Therefore, in case simultaneous access is not possible we have the effective data rate to be-

$$R_{effective} = (BER)RE[L]\Big(1-\frac{t_{access}}{2t_{range}}(1+E[L])\Big) \tag{3.6}$$

t_{access} depends on many variables such as K, N, α as well as the strategy used etc. Hence, the value of $R_{effective}$ can be found for various values of these variables and it will be a component of the cost function we shall define to find the optimum configuration of the system.

The next metric we define is the **directivity** of the MIMO array. Directivity is defined as the maximum directional gain of the array in question-

$$D = \max_{\Theta}\ \mathbf{f}^{\dagger}\mathbf{\Theta} \tag{3.7}$$

where

$$\begin{aligned} \mathbf{f} &= \frac{1}{\sqrt{N}}[e^{j\theta_0^T},\ e^{j\theta_1^T},\ldots,e^{j\theta_{N-1}^T}]^T \\ \mathbf{\Theta} &= [1,\ e^{jkdcos\theta},\ldots,e^{jkd(N-1)cos\theta}]^T, \quad \theta\in[0,\pi) \end{aligned}$$

We also define **average directivity** as the average gain if the link is established as shown in fig [ref]-

$$D_{avg} = \frac{1}{\pi} \int_L G(\theta) d\theta \tag{3.8}$$

where $L = \{\theta \in [0, \pi) : G(\theta) \geq \alpha\}$

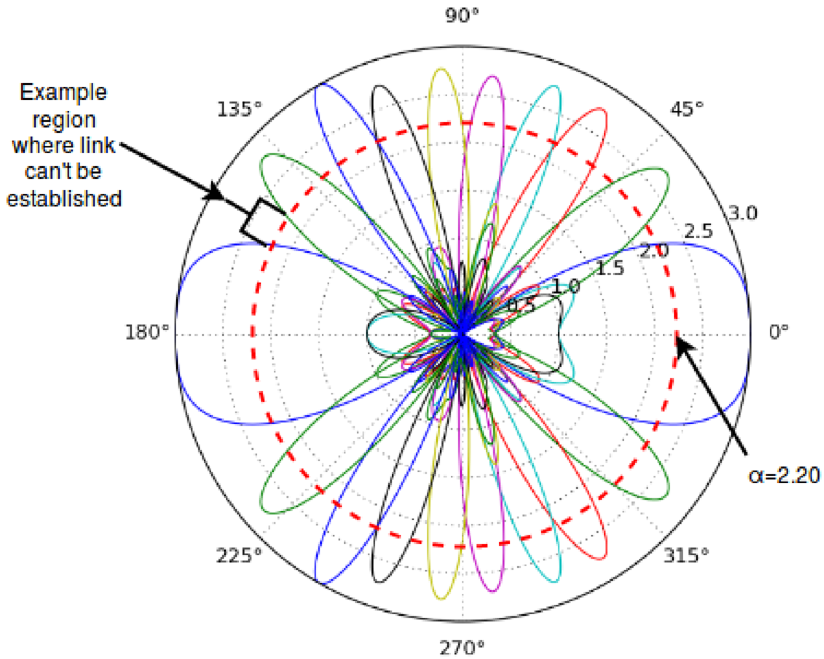

Figure 3.1: Region where initial access fails

As shown in fig 3.1, given a certain link threshold α, there may be certain regions where the beamforming gain lies below the threshold so that forming a link of the required strength is not possible. In a system with both a transmitter and a receiver, the net gain might be lower than the threshold for certain relative positions of the arrays. At these positional configurations, the initial access process is bound to be a failure. The **probability of failure**, for a given configuration of the system, is defined as the ratio of such areas to the total area-

$$p(failure) = \frac{1}{\pi^2} \iint_M d\theta_T d\theta_R \tag{3.9}$$

where $M = \{(\theta_T, \theta_R) \in [0, \pi) \otimes [0, \pi) : G(\theta_T, \theta_R) \geq \alpha\}$

In the case of failure, since the gain of the link is 0, we combine the probability of

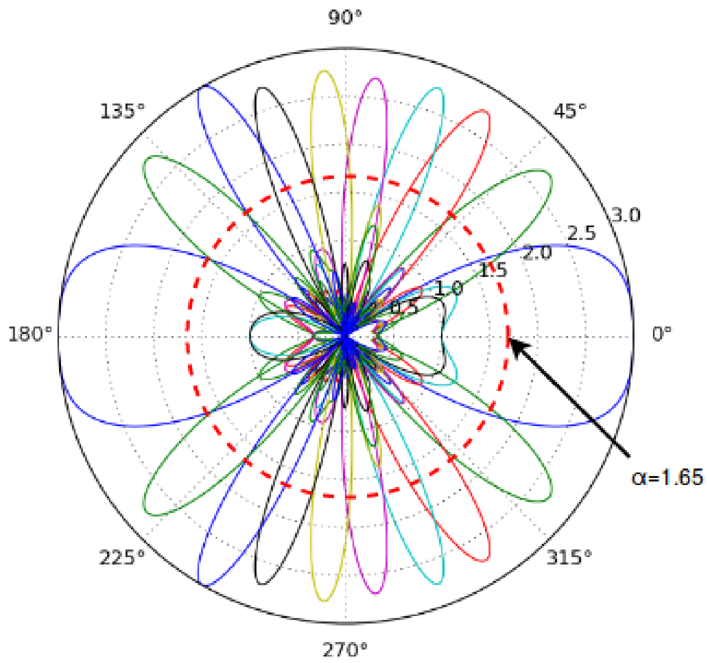

Figure 3.2: For $\alpha < 1.65,\ p(failure) = 0$

failure and the average directivity to get a new measure called the **expected gain**-

$$G_{expected} = (1 - p(failure))D_{avg}^2 \quad (3.10)$$

We note that for sufficiently low link threshold α, the probability of failure is zero 3.2. Also, we note that higher the expected gain, better the system as less power would be required to attain the same intensity of transmission.

Finally we define the **range** (r_{link}) of the system to be the maximum distance between the user and the base station for which a link can be established. This is calculated using the strength of the link, the noise model and the fading model that we have used and averaged over all the directions for each system.

As shown in fig 3.3, we have combined these various measures into three components as described above and now arrive at a function by multiplying each of these components with a factor each and summing them up. To find the optimum system we simply need to assign importance to each of these components in accordance with our requirements and find the point in $(N, K, \alpha, strategy)$ space that maximises this function.

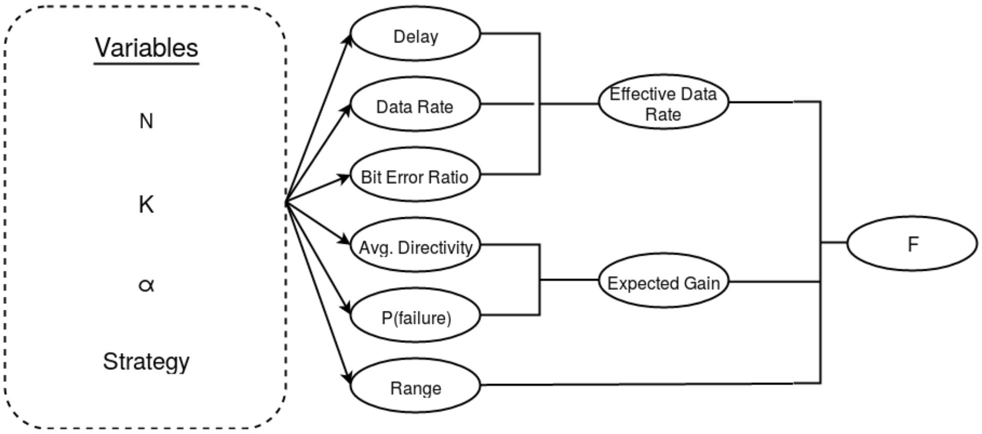

Figure 3.3: Schematic of Metrics Used

$$F(N, K, \alpha, strategy) = a\left(\frac{G_{expected}}{G_{max}}\right) + b\left(\frac{R_{effective}}{rate_{max}}\right) + c\left(\frac{r_{link}}{R_{max}}\right) \quad (3.11)$$

$$(N, K, \alpha, strategy)_{optimum} = \text{argmax}\, F(N, K, \alpha, strategy) \quad (3.12)$$

3.2 Initial Access Strategies

3.2.1 Variable Beamwidth Search

We now describe the initial access method used by [ref]. In this strategy, we use successively narrower beams to find the correct angle of transmission and reception. This method uses an alternative link present between the user and base station for limited feedback. The steps of this method are-

3.2.2 Exhaustive Search

In this method, we search through all the possible beam pairs between the user and the base station. Given a codebook $\mathbf{W}$ with K beams, we go through all the K^2 pairs possible till we find a pair whose link strength is greater than the threshold α.

3.2.3 Modified Exhaustive Search

In this method, we use the observation that the width of all the beams in a codebook are often not the same. And the likelihood of a beam being the correct direction (of transmission or reception) is not the same for all beams. Therefore, we assign a probability weight to each beam and search in the order based on the probability weight so that the more likely beams are searched first and therefore reducing the time required to set up a link.

The probability weight is calculated based on the width of each beam that is above the link threshold. Other factors, such as frequency of past links may be used to update the weight. For example, if we find that the base station is situated such that beams in one direction are unlikely to yield a link because of a blockage, over time the weight assigned to the beam will reduce since other beams will form links while the blocked beam will form much fewer links. However, in this project, since we are assuming no blockages and a uniform distribution of the relative position of the user, we don't include this factor in updating the weights assigned to each beam.

CHAPTER 4

Parameters, Comparison and Results

We now use our framework and parameters described in the previous chapter to decide which configuration and strategy is best suited. Given the cost function F of the form mentioned in equation 3.12, we range the values of the factors a, b and c from 0 to 1 in steps of length 0.1. For each such point (a, b, c), we maximise the cost function F to find the ideal configuration and strategy. Table 4.1 shows the various parameters and the values assumed for the purpose of the simulation. While we use a range of values for K, α and N for the exhaustive search and new method strategy (table 4.2), the sector search approach allows only one comparable configuration and hence all comparison are with that configuration alone.

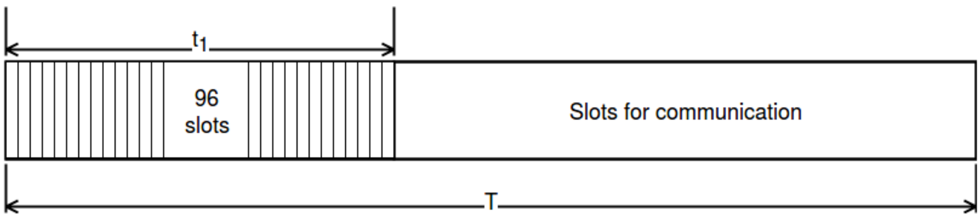

Figure 4.1: Time slots for initial Access

Table 4.1: Values of various simulation parameters

Parameter	Symbol	Value
Oxygen Absorbtion	A_O	16 dB/km
Rain Absorbtion	A_R	0.2 dB/km
Max. Range of Array	R_{max}	0.1 km
Noise	$\mathbf{v}$	$\mathcal{N}(0,1)$
Area in Consideration	$\|\mathbf{B}\|$	0.1π km^2
λ of Poisson Point Process	λ	$1000/\pi$ km^{-2}
Frequency	f	60 Ghz
Distance between Antenna Elements	d	$\lambda/2$
Time frame duration (fig 4.1)	T	1 unit
Time slot for initial access	t_1	0.25 unit
Number of Slots	N_slots	96
Data Rate per beam	R	1 unit

Table 4.2: Ranges of the variables

Variable	Range
N	$\{1, 2, \ldots, 32\}$
K	$\{1, 2, \ldots, 3N + 1\}$
α	$\{0.1N, 0.2N, \ldots, N\}$

Using these parameters and constraints, we simulate the three methods and compare them with each other based on the cost function F. We pick the method and the configuration that has the maximum F as the ideal method for the given set of importance (a, b, and c) that we give to the three terms of the cost function. Ranging each of these weights, a, b, and c, from 0 to 0.9 in steps of 0.1 we get a grid of points. At each point in this grid, we choose the best strategy and configuration. This is shown in fig 4.2. As can be seen, the new method is better than the Sector Search method in certain regions while the sector search is better in other. Comparing exhaustive search and sector search we again find very similar results as shown in fig 4.3. Finally, comparing exhaustive search and the new method we find that the new method, which is a modification of exhaustive search, performs better than it in all cases except for the trivial point $(0, 0, 0)$ (fig 4.4).

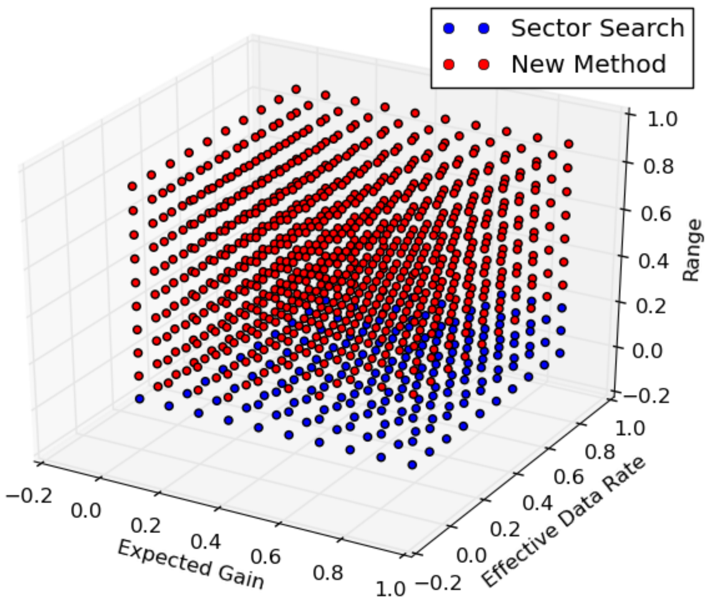

Figure 4.2: Comparison of the New Method vs Sector Search

As expected, for higher importance given to the range of the link, the iterative sector search method is outperformed by the new method.

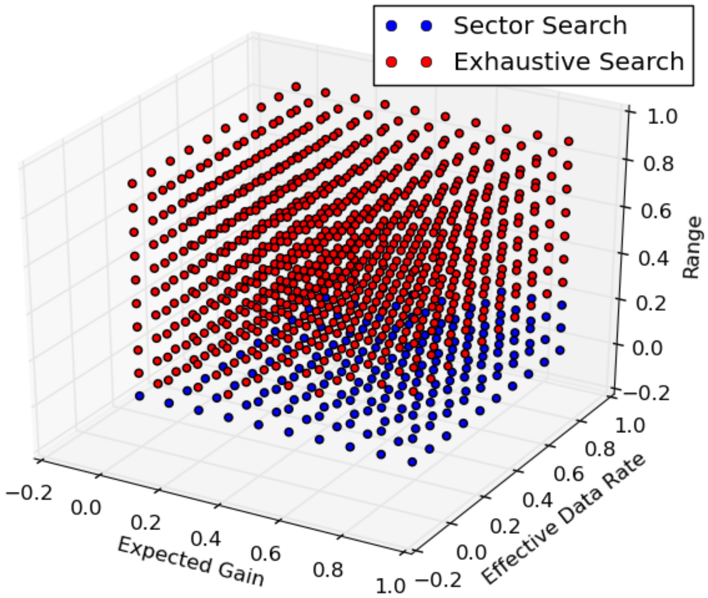

Figure 4.3: Comparison of the New Method vs Sector Search

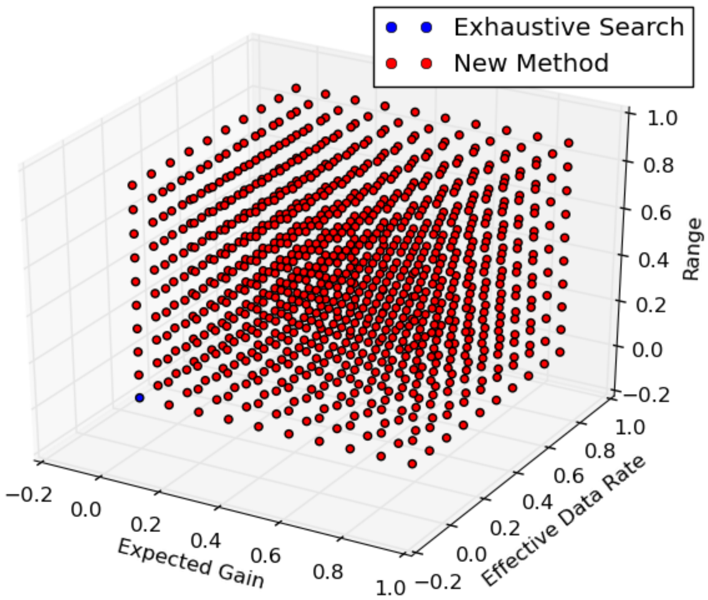

Figure 4.4: Comparison of the New Method vs Sector Search

CHAPTER 5

Limitations, Further Work and Conclusion

Among the many assumptions made in this work some of the most important assumptions that need not have been assumed as well as some other limitations are mentioned in this chapter. We connect these limitations to the future work that can possibly be undertaken to rectify them. The first among the major assumptions was that of a static user. We assume that the user is static for at least some time (the exact value mentioned in the previous section). This may not hold depending on the application of the mmwave system. In the case of backhaul applications such an assumption may be justified but in case of a user with a handheld device, the validity of this assumption needs to be checked. To incorporate this variable, future work could focus on transitional beam steering and initial access methods that use the previous position of the user to give a higher probability weight to neighboring beams.

The second major assumption was that there is no interference between two beams in space. However this is not the case for any practical beamforming codebook or scheme. In practice, any two beams have some overlap area where the signal strength from one beam may be significant in the area of another beam. This can lead to interference and therefore the spatial division multiplexing won't be perfect in such cases. To mitigate the effect of this interference, we can impose limitations on the arrays to use only those sets of beams that have minimal interference at any given point in time. This could be the subject of future work.

The third and relatively less problematic assumption is that only single path exists in the channel. If we were to have multiple paths between the user and the base station, it would hasten the process of initial access. Adding the option of multipath is also relatively simple as it is just a superposition of multiple single path channels and this simulation and framework can easily be extended to the multipath case.

The final major limitation is that in this study we have not considered the effect of variation of the overhead on the performance of the initial access systems. We have assumed a uniform overhead for all the initial access strategies while different strategies may experience different effects due to the varying overhead. This needs to be explored in future work.

In conclusion we have developed a framework to comprehensively evaluate various initial access strategies quantitatively using pre-existing metrics as well as newly formulated ones. We combine all the metrics to come to a cost/reward function that needs to be maximised across all variables to get the optimal performance according to the specific requirements in any context. We use this framework on a variety of initial access methods including a novel method based on prior probability/importance of beams to evaluate the strategies and compare them. The comparison is done by assuming a set context for all three strategies that are compared. This context is explicitly stated in the simulation parameters used and can be varied according to requirements. As a result of the comparison we conclude that different methods perform well for different yardsticks. However, for the majority of cases, the new method proposed in this work outperforms both the iterative sector search as well as the brute-force exhaustive search methods. However this tractable framework can be used to determine the most suitable method on a case by case basis according to the needs and requirements of the system and the context.

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