Master's thesis

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Channel Evaluation with Distributed Base Stations for Wireless Sensor Network Support

Master's thesis in Signal Processing and Communications
Supervisor: Nils Torbjörn Ekman
July 2020

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Wireless Communications, July 23rd, 2020
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Abstract

This paper compares the quality of a channel within a rectangular space given the variables: number of base stations, number of antenna elements, base station locations, and richness of scattering in the environment. Increasing and distributing the number of base stations results in less loss due to distance from the transmitter, while increasing the number of antenna elements within the base station decreases the amount of small scale fading in the channel. When the decrease in loss between the two base stations is compared, the corner oriented station provides a less lossy channel than the sidewall oriented station. As the richness of the environment increases, the difference in quality between sidewall and corner base stations decreases. The final results show that distributed base stations and increasing numbers of antenna elements will provide fewer losses due to distance and interference, but the location difference between sidewall and corner is close to negligible when it comes to the recommendation of the best location for these base stations with a rich scattering environment. Increasing the number of antenna elements in a base 2 scheme will decrease the fading seen by $3dB$.

Acknowledgement

Moving to Norway has been an amazing and trying adventure in my life, and I would not change it for the world. I have had fantastic support from so wonderful people and they have all been crucial to helping me succeed in not just getting a Masters' in Electronic Systems, but realizing I can do anything I set my mind to. To all of my amazing and wonderful family and friends, including those I have made along the way, I could not do it without you.

I would especially like to thank my mother, this entire process has not been easy. She has been endlessly supportive and I could not ask for more. I wish my stepfather was still with us so I could thank him for believing in me and show him what I am capable of achieving.

Many thanks to Nils Torbjörn Ekman and Jens Abraham for answering my many questions and being infinitely patient. They taught me to look at problems with new perspectives and figure out how to break them into solvable pieces. I have had an excellent chance to better myself as an engineer and realize how much more I still have to learn.

Contents

1 Introduction

In a fading dip, no one can hear you scream.

— **Nils Torbjörn Ekman**
(Professor, NTNU)

The goal of a receiver is to provide the best channel for the area it serves. In the rapidly evolving world of 5G wireless communications, localized system support in commercial and industrial environments is becoming more sought after as a solution to improve the interconnectivity of systems and improve integration. This demand requires the development of stable channels, long-lasting sensors, and easy to integrate hardware. With this in mind the application of Multiple In, Multiple Out (MIMO) communication systems is assessed with distributed base stations for the coverage of an industrial environment in an effort to provide a solution for best wireless channel support for low energy sensors. The factors mainly assessed in this thesis are the number of antenna elements and the placement of multiple base stations within a facility. The goal is to understand how these setups provide room coverage to different levels of scattering scenarios.

The results and data presented in this document are purely simulation and geared towards the first steps in measuring the channel coverage of a base station within a real-world environment. At the time of writing this thesis COVID-19 was a global pandemic, making the possibility to get measurements with the type of hardware necessary to simulate these environment impossible. The hope is that in the future this theory can be further explored for its viability in real world settings.

The presented hypothesis is that base stations placed in the corners of a facility or room with a rich scattering environment will provide a more uniform channel over having base stations placed along the walls and result in less severe fading dips due to path loss and phase interference. The corner base stations are expected to provide better diversity for both large and small scale fading.

1.1 Thesis Structure

Chapter 1

Contains a brief overview of what can be expected from this paper and the motivation behind where this research is applicable and can be used in real-world settings. This section also contains a short overview of what the results were from the analysis of the simulation and the measurement acquisition.

Chapter 2

Gives a more in-depth analysis of the problem that the research is investigating and the different factors that must be considered when approaching a solution or innovated approach to solving the issue. Here the expected environmental and technological factors that must be considered are laid out for a better understanding of the starting point for this investigation.

Chapter 3

Provides a review of the theory that is considered essential to understanding the topics presented in this paper and the implementation of the base station arrays. This provides an overview of MIMO, uniform linear arrays, reflections, scattering objects and maximum ratio combining. A basic background in communications and electronics is assumed as a given for the reader.

Chapter 4

Covers the construction of the simulations and the measurement set up for gathering empirical data. For this, the assumptions for simulations on wall materials, room size, frequencies and environmental variables are detailed along with the different options for the simulation.

Chapter 5

In the analysis section the results from the simulation are discussed and plotted. Both normalized path combinations as well as paths with free space path loss (FSPL) are presented with their respective results.

Chapter 6

The overall conclusions from the different approaches to providing coverage using the different scenarios offered are explained and the best possible base station configuration. It is also discussed if this path is worth being explored further and if it offers a vast enough improvement over the current options that are offered to provide the same or similar solutions. Future work options are also presented at the end of this section.

2 Problem Statement

2.1 Motivation

Industrial settings are becoming more interconnected, and requiring better options for quick and easy information transfer from a variety of sources. The reliability required in these systems is extremely high. Connecting a network of sensors that could have hundreds to thousands of nodes would be time-consuming and difficult if everything is hardwired. Wireless sensors provide a quicker and low footprint monitoring system that would be easier to install and quicker to integrate than its hardwired counterpart. One area that is growing to help provide support for better communication with low power wireless sensors is the Industrial Internet of Things (IIOT). Within IIOT the goal is to provide access to a large amount of data and sources in one convenient access point.

One of the main obstacles that prevent these systems from being fully realized is the power consumption that decreases the life span of battery-limited devices. It is crucial to find ways to increase energy efficiency (EE) for these nodes, and using MIMO technology is one method that would be a prime candidate for this task. [10].

2.2 Environment

Large factories and warehouses are often built out of similar materials and have a variety of reflective surfaces. These buildings can range from hundreds to thousands of square meters in area, filled with shelving, supply lines, large equipment, and workers. Industrial environments contain many scattering objects, leading to dense multipath scenarios for the sensor nodes. Often the ceilings are multiple stories high and have exposed piping, circulation equipment, lighting and power management. These different objects and materials will introduce more scattering to the channel and cause a richer signal channel propagation environment. This type of setting can be ideal for a system that can utilize the multipath propagation to create a better channel.

2.3 Wireless Local Area Networks

Wireless local area networks (WLANs) have many faces, in one of their recent incarnations they are also referred to as cyber-physical systems (CPSs) [8]. The highest priority of these sensor networks is having as long of a lifetime as possible while providing high-quality signals with minimal bit error rate. In a setting where accuracy is crucial a bit error rate of 10^{-6} can provide the accuracy needed[9]. To make this a reality, sensors are optimized for the best power preservation while using enough power to transmit. One of the best ways to decrease the power demand for these devices is to provide a stronger and more uniform channel for transmission. Energy spent during transmission is a huge power drain and decreasing this aspect can help preserve lifetime of the sensor nodes and decrease the need for replacement and maintenance.

Currently, this is one of the problems with implementing CPSs. IoT systems that are commonly used in the home or office settings are more geared to lower transmission distances and could take advantage of the multiple Wi-Fi access points within a space, depending on the technology. In an industrial facility distances between sensors and their base station could be hundreds of wavelengths. Having more obstacles made of metal, concrete, and other reflective materials also increase the multi-path propagation of the signals from sensors, leading to the risk of creating fading dips and signal interference. These environments often tend to be noisy as well with interference possible from other sensors in the network, wireless devices and electromagnetic signals from the hardware itself. MIMO for the support of WLANs and CPSs is seen as an area of interest to help find a solution to the problem of improving spectral efficiency (SE) as well as energy efficiency (EE) in these networks [8].

2.3.1 Theorized Solution

Small scale and large scale fading is a part of the channel that can be decreased with the addition of more hardware on the receiving side to create a more uniform channel for the environment. By setting up antenna element arrays on each side, or in each corner of a coverage space both the small scale and large scale fading of the channel will be decreased. Comparing the orientation of these arrays, the corner arrays will provide a more noticeable decrease in loss since they have the chance for more reflective paths to reach them, the walls to the corner widening the aperture of the antenna array.

3 Theory

3.1 MIMO

MIMO systems are defined by having multiple transmitters and multiple receivers. Usually, this is with a larger number of base station (BS) antennas than there are users such that $M >> K$ where M is the number of BS antennas, and K is the number of single-antenna users or nodes [3]. With having more antenna elements for the BSs of a system it creates small scale spatial diversity, helping to compensate for small scale fading in the channel. This will increase the probability that the transmitter will have at least one strong path of communication to the receiver. This effect is known as channel hardening, where the spatial diversity in the antennas causes an averaging effect that will cause an overall more even channel environment. This is one of the factors that drive the development of MIMO and massive MIMO, being able to increase the quality of coverage in highly populated spaces.

MIMO systems are currently being deployed in areas with chaotic environments and are being integrated into cellular support in the 5G field. Even when one user, or node, is taking advantage of having these multiple receivers (Single User MIMO, (SU-MIMO)) there is still an increase in the quality for that user.

3.1.1 Channel Hardening

Channel hardening arises when the number of receiving antennas and the multipath propagation is large enough, that the channel across space will have less small scale fading dips and become more uniform[4]. With the increased number of antennas, the occurrence of fast fading decreases within a setting, and the channel begins to act in a more deterministic manner. The hardening effect is not only for fading but also affects the difference in losses between frequencies. When the channel is highly diverse then the delay spread is also decreased, resulting in less fading over frequency[6]. These aspects lead to a higher degree of reliability in the environment for the coverage, causing the fading to mainly be comprised of large scale fading instead of small scale or fast fading.

3.2 Uniform Linear Antenna Arrays

A uniform linear array (ULA) is composed of M antenna elements that lie on a line, the spacing between each sensor is identical, Δ between each of the neighboring sensors. The location of each element in the array can then be defined as:

$$q_m = (m-1)\Delta, m = 1, ..., M \tag{3.1}$$

with M being the total number of elements and the first element being positioned at the beginning of the array.

3.2.1 Antenna Patterns

The number of antenna elements in a ULA impacts the shape of the antenna pattern that the ULA will have. As the number of antenna elements increase, the number of sidelobe will also increase. With this increase in sidelobes the main lobe of the antenna pattern becomes more narrow. This can be seen in Figure 3.1, with each additional element added to the array, the beam form changes and narrows. [1]

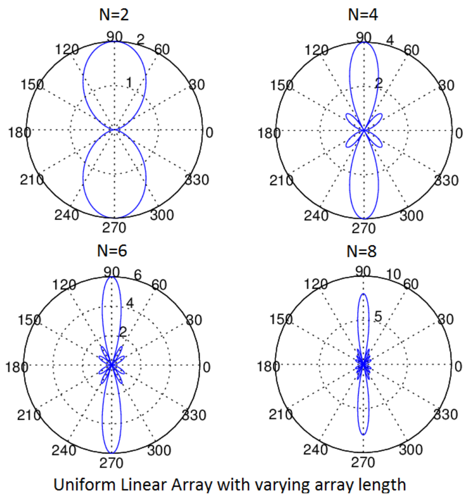


Fig. 3.1: Ideal patterns for a ULA with composed of 2,4,6 and 8 elements.

3.3 Channel Fading

3.3.1 Large Scale Fading

Large scale fading is the path loss of a signal and derived for measuring loss over hundreds of wavelengths. The equation used to describe the loss based on the distance between antennas is given by the free-space path loss (FSPL) equation [11]. In a 2D plane, this would be the loss seen in the electric field, so unlike the equation that is standard for both the electric field and magnetic field, this is not squared to take into account the two perpendicular waves, but just the electric field.

$$FSPL = E_L = \frac{(4\pi d)}{\lambda} \tag{3.2}$$

The ratio is between the power transmitted and the power received, this is commonly expressed is dB in the form of

$$FSPL_{dB} = 10 \times \log(FSPL) \tag{3.3}$$

which will be the subsequent conversion method to dB for any losses shown in this paper. This method of finding the path loss is well used and once known can be easily integrated into budget estimations. The other main large scale fading is obstacles in the path between antennas. Usually this is considered over large distances, and most equations used for this do not scale for indoor environments.

3.3.2 Small Scale Fading

Small scale fading is due to interferences with multipath propagation and small fading dips that can occur and change rapidly throughout a room. There are several different deterministic and statistical models created to describe these fading types in different settings and with different dominating attributes.

Rayleigh Fading

The Rayleigh fading model is a statistical fading model commonly used for wireless devices. It is one of the models used to describe situations where the signal between node and user is expected to have a large number of paths and reflections. Often this is used in outdoor settings, such as in locations with lots of buildings creating reflections of cellular signals. Rayleigh fading is described by the fact that there is no single path, such as the line of sight, that dominates as the majority of the power or signal that reaches the receiver. This can be the case when there are many reflected or scattered paths that have similar lengths to the line of sight, or if no line of sight component is present within the channel [11][9].

Rician Fading

The Rician statistical fading model is very similar to the aforementioned Rayleigh model, except for the Rician model it is expected that there is a dominant signal component that is being received at the BS. This dominant component is commonly a line of sight path or a strong single bounce reflection [11][9].

3.4 Reflections and Scattering

3.4.1 Reflections

Reflections can occur on any surface, sending all or a portion of the power reflected off the surface. This is dependent on the relative permittivity of the reflecting material, ϵ_r as well as the medium through which the wave was originally traveling. Materials will have different conductivities at different frequencies as well[9].

If a material is a perfect conductor then the energy or power that is in the wave is reflected perfectly with a 180 phase shift regardless of the angle of incidence. It is also known that the angle of incidence is the same as the angle of reflection, $\theta_i = \theta_r$ [11].

3.4.2 Scattering Elements

Scattering is another method of propagation that commonly enriches a channel environment. These scattering elements receive the signal from a radiating source and then reflect it in all directions or with directivity in certain directions. When these materials repropagate the signal, they will attenuate the retransmitted signal. These attenuating factors change given the permittivity and conductivity of the scattering material.

3.5 Maximum Ratio Combining

To best take advantage of having diversity in the BS antenna elements a method for combining the received signals at each antenna is necessary. For this thesis the method being used to combine the signals once at the antenna elements is maximum ratio combining (MRC), a basic as to how this is preformed is shown in figure 3.2. For this application since there is no signal to use a correlation or a match filter, the recombination compensates instead for phase offset. Each of these antennas sees a

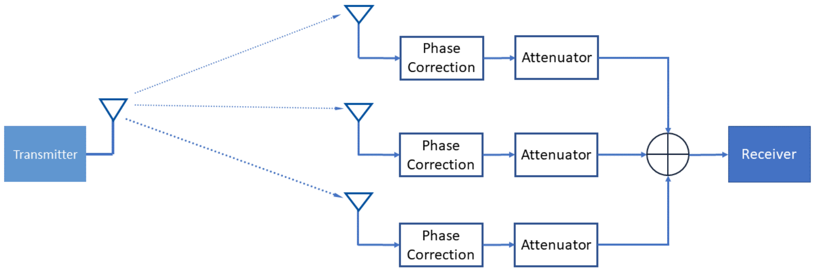


Fig. 3.2: Simplified flow chart showing theory behind MRC.

channel defined as h_n, with n being the antenna and h_n defined as some loss and phase associated with it at arrival at the antenna in the form of $Ae^{j2\pi\theta}$. To get the received signal the final channel of h must be acquired through the summation of all h_n. To compensate for the phase the channel is multiplied by its complex conjugate as shown in 3.4. [7]

$$H = \sum_{n=1}^{N} \frac{h_n \times h_n^*}{|h_n|^2} \tag{3.4}$$

The channel H being the channel between the receiver when a signal from a sensor node is combined across all BS elements.

4 Simulation Methodology

The methodology presents a deterministic simulation that is an ideal 2D ray-tracing program in an attempt to characterize the coverage of a rectangular space with reflections and scattering elements. The main factors considered constant across the simulation are shown in table 4.1 with the main variables that are changing for comparison are listed in table 4.2. The different functions in this chapter are input parameters, layouts, reflections, scattering, radiation patterns, and data analysis. This simulation and its results are to be a precursor to measurement campaigns in an industrial setting to get a far more accurate understanding of these environments discussed in chapter 2. The code that this methodology described is on GitHub at https://github.com/ajlandau/MIMOthesis.

4.1 Input Parameters

To have continuity with the data there are main environmental variables specified for all of the simulations. These variables are the base layer of the entire simulation. This allows not just for continuity between antenna numbers but also is necessary to have proper summation and manipulation of the matrices for the different paths generated.

The frequency chosen for this simulation is based on the antenna array intended for use during the corresponding measurement campaign. This frequency is also explored for use in 5G networks and IoT. For the node spacing, it is necessary to have enough data points to get the statistics of the coverage within the room, a rule of thumb is having at least 10 points within a 5λ radius. The element spacing relates to the spacing of the center points of the BS antennas in the ULAs. For this simulation patch antennas are half λ in width and for some nod to realism, a gap of 5mm is added so they are not directly touching. The room size chosen was to be large enough to have both far-field and near field effects and be large enough to get a variety of coverage areas and patterns. The edge tolerance is considered since it is unexpected that the nodes would be placed directly on the wall, but also so there

Tab. 4.1: Constant variables for simulations.

Parameters	Values
Frequency	5.9GHz
Node spacing	$\frac{\lambda}{0.5}$
Element spacing	$\frac{\lambda}{2} + 0.005$
Room Size	30×20meters
Edge tolerance	1 meter
Wall offset	0.3 meters
Point attenuation	0.8

Tab. 4.2: Target specification and simulated results.

Parameters	Values
BS Location	Sidewall or Corner
Number of BS Antenna Elements	$2, 4, 8, 16, 32, 64$
Scattering Points	$10, 20, 30$

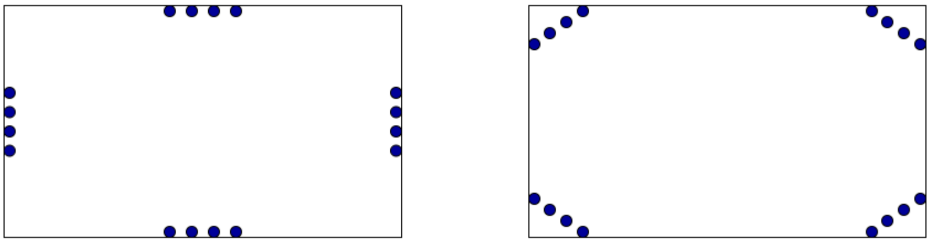
are no nodes directly against the BS. The point attenuation is considered for the scattering elements as described in section 3.4.2.

The variables that change are compared to see what design elements should be evaluated for the best coverage for a room. The largest factor being considered is the coverage of a space given the location of the BSs, comparing the difference between the corner location and the sidewall. Another important factor to investigate is the trade-off between increasing the spatial diversity by adding more antennas and the actual increase in quality or amount of received signal. A base-level simulation will have only the reflected and LOS paths. To add more variety to the simulation scattering objects are added to the space to increase diversity within the room.

4.2 Simulation Layouts

Two main layouts are in the simulation- corner BSs as in Fig 4.1b and sidewall BSs as in fig 4.1a. These two locations would provide different angles of coverage for the room, and overlap of the respected lobe patterns of the BSs. The BSs placed in the corner are assumed to be at a $45°$ from the sidewalls.

The idea behind having distributed BSs in this simulation is to increase the level of spatial diversity on both large and small scale. Having a ULA provides the spatial diversity that occurs between each antenna, which can help account for the small scale fading that would happen within an environment. When there is also a large spatial diversity between the locations of these ULAs there is a decrease in the



(a) Sidewall element layout. (b) Corner element layout.

Fig. 4.1: Two main layouts for simulation of distributed BSs.

amount of large scale fading expected within a space. This is one of the main factors that is considered in the concept of providing a more equalized channel across the entire space or facility, to reduce both of these fading types.

Each time the space is simulated it uses one of the two BS arrangements. The line of sight (LOS), reflected paths, and scattering point paths are then generated between each node in the room to each of the antenna elements. This creates a matrix in the form of:

$$H_n = M_q \times K_{x,y} \quad (4.1)$$

Where H is the type of path, M is the antenna element and K is the sensor node. This is related to a 2D array, where each node has a corresponding set of coordinates saved in the array generated for the layout of the room. Each of these points has the loss and phase data stored as

$$M_n \times K_{x_l} \times Ky_w = A\angle\theta \quad (4.2)$$

Where A is the magnitude of the incoming ray from the node to the BS and θ is the phase of the ray upon arrival at the antenna element M_n. x_l is the location in x along with length of the room with y_w being the location in y along the width of the room. When all the paths between a single node are summed to the antenna, and combined using MRC as described in 3.5 the resulting matrix can be considered a MISO channel when the node is looked at in isolation from the rest of the nodes in the room.

4.3 Antenna Patterns

There are two main methods with which to get antenna radiation patterns. Equations that are used to model the shape of the lobes of the element in the polar domain, and

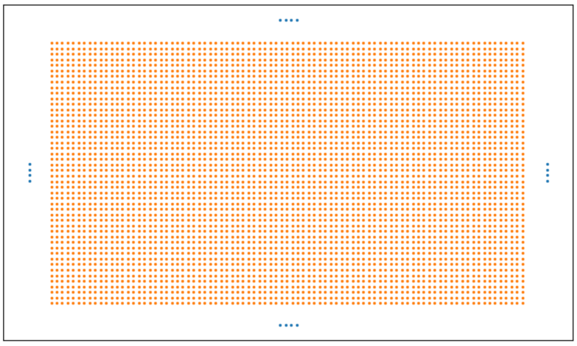


Fig. 4.2: Scaled down room layout example, blue dots show BS elements, orange points show node location.

characterization through real-world measurement. Measurement-based radiation patterns are created by taking measurements in a closed environment at each of the 360 degrees on the circle around the antenna and then used to create a file with the corresponding losses at those approach vectors.

4.3.1 Equation Modeled Radiation Pattern

For common antennas, some patterns are standardized to set equations; these provide a generalized pattern of the gain to be expected given the angle of approach from the sensor node and its reflections. The pattern that is used for this simulation is a square patch antenna, modeled using Equation 4.3 [2]. This pattern is only considered in the front face of the antenna, from $0°$ to $180°$ since the antenna is mounted against a ground plane.

$$E_\theta = \frac{\frac{\sin(kW\sin\theta\sin\phi)}{2}}{\frac{kW\sin\theta\sin\phi}{2}} \cos\left(\frac{kL}{2}\sin\theta\cos\phi\right)\cos\phi \tag{4.3}$$

This equation used to model the radiation pattern for a patch antenna as an element within the BS array shown in figure 4.3. It is assumed that the back of the patch antenna is a ground plane, so there is only one main forward facing lobe to consider with no signal received on the back side of the antenna.

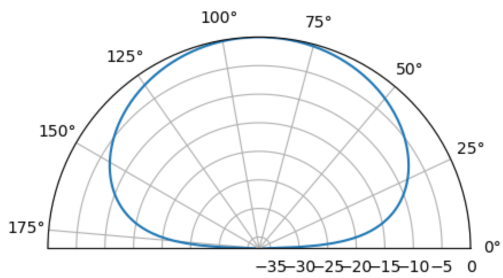


Fig. 4.3: Antenna lobe pattern generated from 4.3

4.4 Reflections

To get the reflections occurring off the walls in the room the BSs' locations are mirrored across the reflecting wall. The reflections are found for each of the walls in the room, for each of the elements. The sidewall BSs have an offset from the wall of 0.3m, given the fact that in real life they would not be perfectly flush to the surface and there would be some chance for reflections off of the wall behind them to be picked up at the antenna array. The visualization of these locations can be seen below in 4.4.

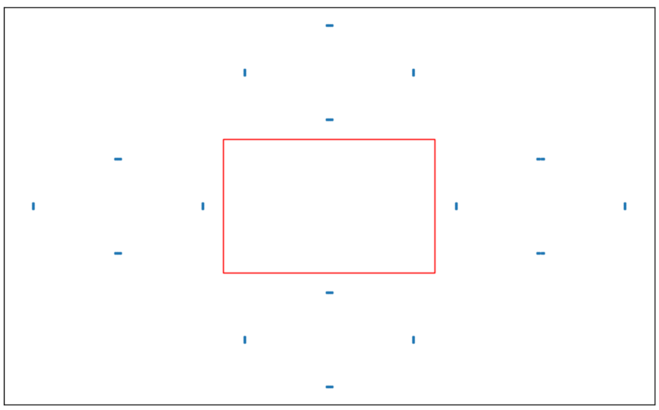


Fig. 4.4: Blue dots show the position of the reflected BS elements, the red rectangle would be the walls in the space.

The antenna pattern described in 4.3 is used for each of the antennas within the BS. No power or paths are received from the back of the antenna. The matrices are stored such that:

$$K_{path} = P_a \times M_n \times K_{x_l} \times Ky_w \tag{4.4}$$

With a representing the path that is taken, be it the line of sight, or reflection.

4.5 Scattering Points

As discussed in 3.1 multipath propagation is an important part of the functionality for a MIMO set up to be useful. With scattering points being a component to the simulation this gives an idealistic method to increase the number of paths in the channel. There are two ways that scattering points are added into this simulation, with two or three straight path components. With two paths the ray would go from $node_{xy} \rightarrow scattering\ point \rightarrow antenna\ element$. With three paths the ray would go from $node_{xy} \rightarrow scattering\ point \rightarrow wall\ reflection \rightarrow antenna\ element$. Another factor that is accounted for is that scattering objects will also have absorbing properties and will not reflect the full energy of the path that is received. This is accounted for with a multiplying coefficient such that the scattered value is always $s_{coeff} \leq 1$. For this the paths are considered in two parts, p_1, p_2. With the combination of the losses for these two paths computed as:

$$p_{loss} = (FSPL_{p_1} \times s_{coeff}) \times FSPL_{p_2} \tag{4.5}$$

These paths are then stored in a layout the same as described in equation 4.4, but in this instance a represents a scattering object. Since the two and three 'bounce' paths are generated separately, a would just be the number of scattering elements within the room in order of original generation.

4.6 Assumptions About the Environment and System

For this simulation to be defensible many assumptions must be clarified. In its current state, this simulation is a starting point for further investigation. It is also acknowledged that this is not going to be representative of a real-world environment but instead a proof of concept to better guide the furthering research in the area of providing uniform channel loss for large indoor facilities.

Viewed from Uplink Given that the main use case for this environment will be as an uplink, with the nodes sending information to the BSs assumptions were made about the abilities of the BS and impacted the choice in the mathematics used in the methodology. Sensor nodes will be assumed only to transmit to the BS and that there is no beam-steering by the BS. When no scattering elements are in the simulated space the coverage appears as overlapping patterns of the ULAs given the number of antennas as shown in 3.1.

2 Dimensional For the results that are produced by this simulation, only the length and the width of the room are taken into account for the dimension while ignoring the floor and ceiling aspect. For the scattering objects within the room, they are assumed to be infinitely tall, so there would be no chance of not having a reflection from them.

Ultra-Narrowband The center frequency for this simulation is $5.9GHz$ and the system is assumed to have an ultra narrowband channel (UNB). With a system as described in 2, the goal is to support low power sensor nodes that will have small information packets. UNB results in the representation of the channel to act as a single tap channel.

Ideally Radiating Nodes There is no antenna pattern applied to the sensor nodes in this simulation. For this to be a fairly ideal scenario and look at the abilities distributed BSs to provide coverage, having path loss in specific directions would detract from this assessment. Instead, the sensor nodes radiate equally in all directions, and only the effects of the path propagation will have an attenuation effect.

Only Path Loss The main goal of this simulation is to look specifically at the part of the loss that is dependent on the distance and path of the signal traveled. This loss is only one part of the overall link budget. To have a more thorough investigation of the requirements in this setting more variables such as coding gain, modulation scheme, and other schemes should be included in the simulation or assessed separately.

4.7 Consideration of Methodology Limitations

This model is an ideal ray-tracing simulation and there are many weaknesses in the level of realism that can be expected for the generated outcomes as compared to real-world measurements or a ray launching software. The assumption that the walls will be perfectly reflective will not hold in the real world, which will have a far richer level of absorption and scattering for materials. Often there will be absorbing materials that will prevent one or multiple paths from being completed from node to BS. Within a factory, there will be other sources of electromagnetic radiation that could distort or interfere with the signals.

Another one of the shortcomings in this code is the fact that it takes place in a 2D environment. With the assumption that the reflections will be solely in a horizontal plane, not taking into consideration the floor or ceiling reflections. As stated in 4.5, the scattering objects are essentially infinitely tall, so all of the nodes will see the objects and be scattered by the them.

Fully absorbing objects also need to be added to the simulation. At the moment the best-case scenario is taken into account. Except for the ground plane for the BS antennas, the paths the signals from node to BS take are not blocked, only attenuated.

This simulation provides a look at what a staged environment might be for a measurement campaign, but it does not hold when it comes to the variety of obstacles that are expected in industrial settings. This methodology provides a proving ground to verify the investment in further resources, such as a measurement campaign.

5 Results and Discussion

> *Science is the process that takes us from confusion to understanding.*
>
> — **Brian Green**
> (Theoretical Physicist)

This chapter details the results from the simulation in section 4 and compares the different configurations described in table 4.2. The factors that remained constant for each simulation are detailed in table 4.1. The paths between the sensor nodes and the BS elements are analyzed via two methods, a normalized model and a path loss model. For the normalized path loss, the losses seen are resultant from the angle of approach with the antenna pattern and the attenuation due to the scattering objects. FSPL is a scalable factor that will change with the room size, loss increasing with distance. These will be analyzed separately to describe the effect that the increased distance of the paths has on the constructive and destructive recombination of signals. The main number of antenna elements per a BS will be 8, since the original measurement plan to validate these results would have been does with an array of 8×8 antennas.

5.1 Normalized Path Analysis

For the first step in understanding the signal coverage of a space with multiple BS's, the paths without their lost component are analyzed. This comparison helps to build the foundation of understanding of how the BSs will provide service for the room if they are along the walls vs. in the corners. A CDF was generated from the data for different numbers of antenna elements in 5.1. The dashed lines show the BS sidewall locations, with the solid line antennas showing the BS corner locations. This set up is shown in 4.1a and 4.1b. Each time the number of antennas doubles, the number of paths seen is increased by $3dB$. More paths are expected with the increase in the number of BSs added. For an environment that is prone to severe large scale fading, more antennas per an array could help decrease the losses due to multipath interference.

In figure 5.1 when comparing the BSs with the same number of antennas but

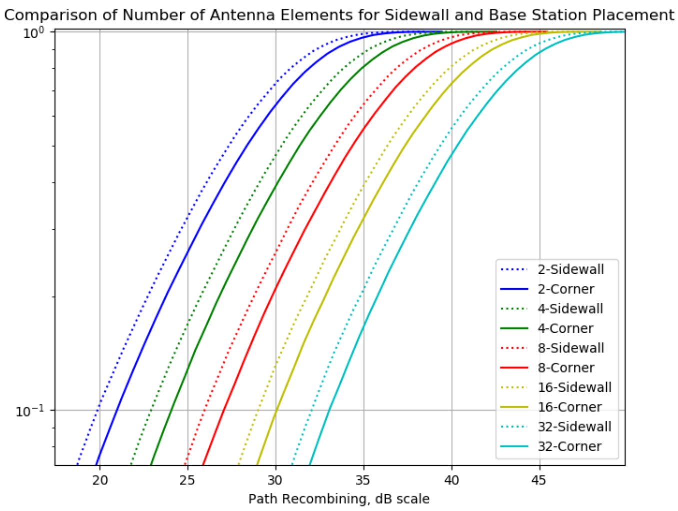


Fig. 5.1: Normalized Path combination comparison of antenna numbers in BSs.

different orientations the corner located BSs always have more paths. This holds with the theory that the total paths, or the 'quality' of paths, being received are better with the corner BSs when it comes to the consideration of phase interference. The main reason why this could be the case is the reflections that reach the corner BSs are both more numerous and also have better angles of arrival. The paths are more likely to arrive in a direction of the radiation pattern that experiences less attenuation. When path loss is not included, and only the effects from the attenuation of the scattering points and the antenna pattern directly affect the amplitude of the paths the performance difference between the corner location and the sidewall location is clear and consistent.

5.2 Paths with FSPL

When FSPL is included in the simulation the losses of the paths will increase. Shorter paths between the node and the antenna elements will dominate the final signal, where the longer paths will add less power to the signal due to the greater path loss experienced with distance. The results show the channel coverage for the space and could also be considered as an example of how the channel would decay as the user moves through the environment. Given the scenario described in section 2 for use in industrial settings, the channel coverage could also apply to moving objects and not just stationary sensor nodes. This allows the understanding of Rician and Rayleigh fading channels (3.3) to be used to increase the comprehension of the coverage within the simulations discussed in this chapter.

5.2.1 Number of Antenna Elements per BS

One of the most crucial factors in a MIMO set up is the number of antenna elements in the BS, with the more antennas added, the decrease in small scale fading decreases at the individual antenna arrays. To look at how this affects the channel in the simulated environment the plot in figure 5.2 is referred to. As the number of elements increases, the amount of fading seen decreases, but the slope of the CDFs does not vary. Regardless of the number of antenna elements in the BS, the corner

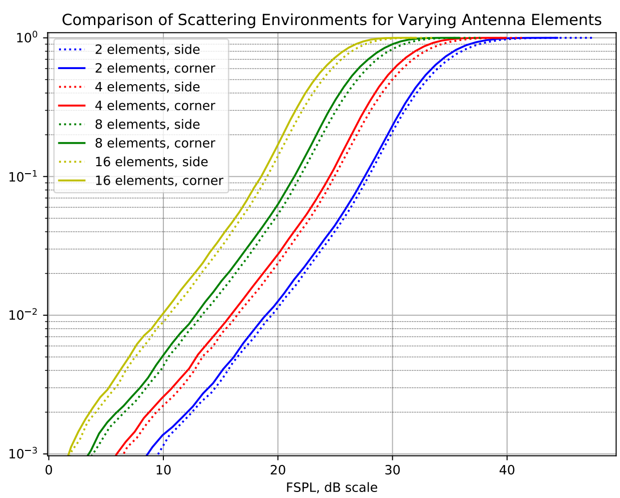


Fig. 5.2: Visualization of Coverage with 30 scattering points for corner BS set up

oriented BS still has a slightly lower amount of path loss. This shows that when FSPL is accounted for in a rich environment then it is mostly the amount of elements in the BSs that impact the channel, not the location. Another feature in these plots is that the slopes of the CDFs are extremely similar, one does not display a smaller range of loss,they experience the same variances and distribution of losses, just slightly off set for more in the case of the side wall orientation. One of the expectations with having two orientations is that one of the set ups would experience a more narrow range of loss and provide a more even channel than the other, so far that is not the case.

5.2.2 Full Room Channel

The full room channel looks at the quality and uniformity of the channel environment for the entire simulated space. Figure 5.3 is a visualization of the channel for the space with 30 scattering points and corner BSs. Figure 5.4 shows the sidewall located BSs with the same scattering layout. The dark points show the locations of the scattering points in the simulated space. Each of these points has a 'physical' radius of 5λ. This results in the values being interpreted as zero for there are no antennas in those locations but locational values for antennas are still generated in the simulation.

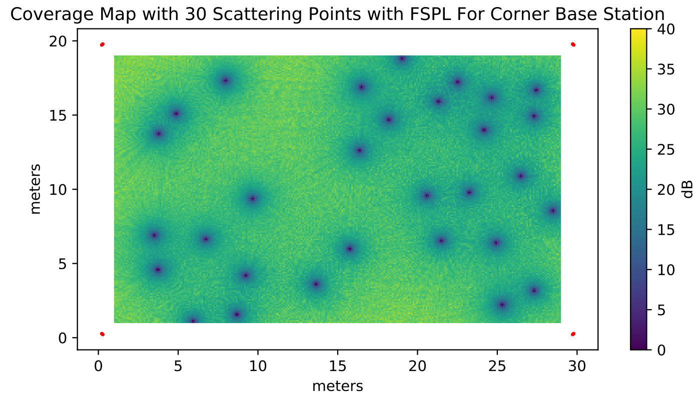


Fig. 5.3: Visualization of Coverage with 30 scattering points for corner BS set up

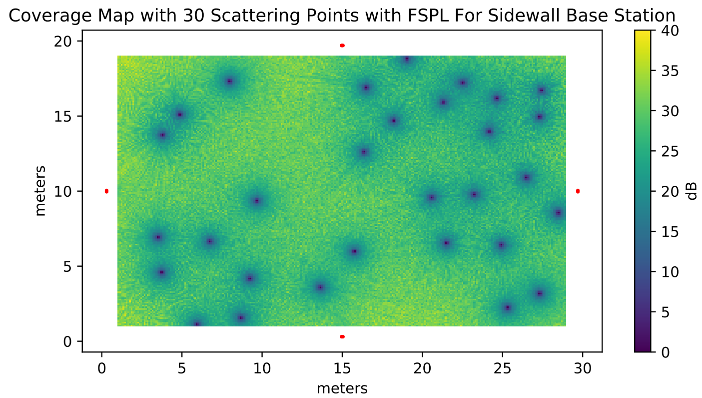


Fig. 5.4: Visualization of Coverage with 30 scattering points for sidewall BS set up

Looking at the visualization for the BS orientations it is difficult to discern which of the orientations would be capable of providing better channel coverage for a space with randomized scattering points. Both appear to be uniform and have similar channel qualities. This increase in similarity of coverage is caused by the increased variety of paths within the setting. There is a stronger likelihood that multiple paths will have better angles of approach and less destructive interference with the diversity of the environment. To understand the difference in coverage from placing

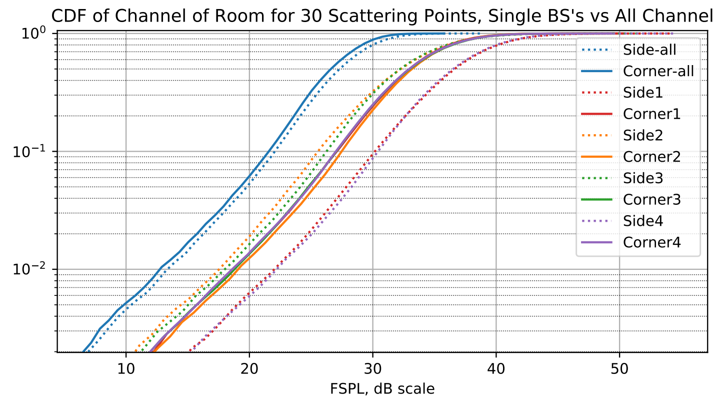


Fig. 5.5: CDF for full room coverage from 5.3 and 5.4 compared to single BS coverage

BSs in different points in the room, a comparison of the CDFs for single BSs vs. using all of the BSs is plotted in 5.5. Here it is shown that the single BSs experience higher losses for the final signal compared to using the BSs combined. This is expected as the increased diversity in paths and with the average distance between a BS and sensor node decreased there is less path loss. The gain from having the combination of BSs to the next closest coverage is $4dB$.

5.2.3 Sectional Room Coverage

The coverage of the space is as dependent on the number of paths as it is on the distance of the sensor node. It can be seen in the previous section that with the dispersion of BSs the large scale fading that would occur with only one BS covering the room is effectively combatted with having large scale spatial diversity. To provide a better understanding of the coverage the BSs provide, different sections of the room were chosen and CDFs of their coverage quality were plotted. These spaces include parts of the corners, along the sidewall and in the center of the space. This shows the variation in the spaces of losses in different sections.

To best understand the differences in operation and verify the intuitive coverage of the space that is provided by the different orientations the 'empty space' scenario is used to generate a set of CDFs for these sections. With lower paths, the effect of having the BSs in different locations is highly pronounced in figure 5.6. The lack of richness in the environment leads to the lobe patterns of the antennas to be the driving force behind where the loss occurs within the space.

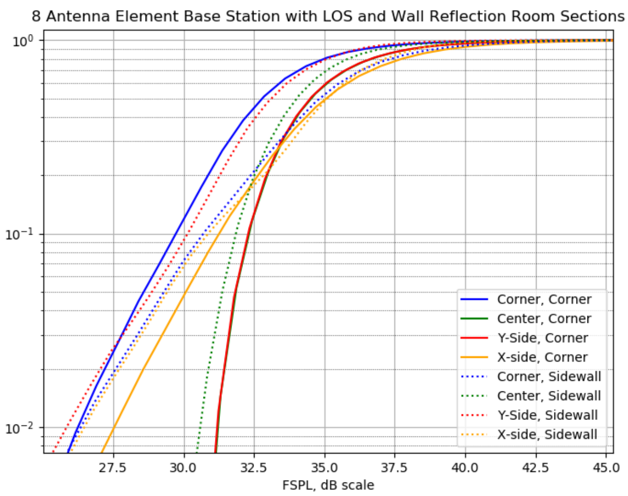


Fig. 5.6: CDF of coverage for an empty room, only LOS and reflected paths.

Here the only paths that are accounted for in the setting are the line of sight components and the reflections on the wall. This is to look at how the path behavior could be expected in an empty room. For the room sections, the coverage is logical in where the BSs perform best. For the corner BS the CDF (blue) coverage out preforms the sidewall BS. The same is true for the sidewall BS, the middle of the walls see better coverage (dotted lines) than the corners can provide. The slopes of the CDF coverage also vary greatly depending on the region they are generated for with new few paths. With this plot, the overall coverage capabilities of the BSs for either position seem to provide a rather uneven environment with sections experiencing variations of $2.6dB$ at $.1$ and $3dB$ at 0.5 for the corner set up, which in this case shows a more varied coverage pattern. When the same BS setups are with

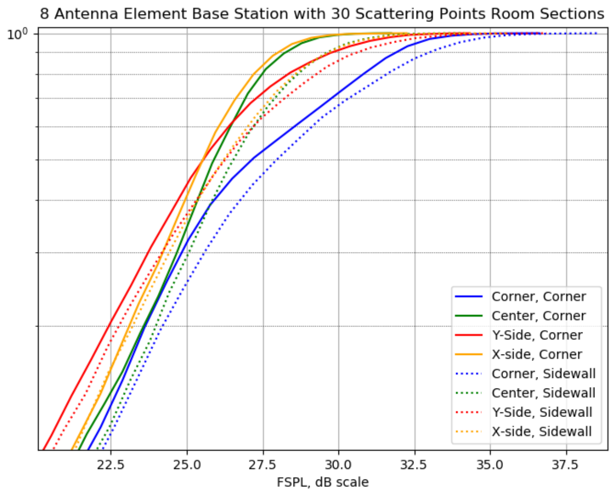


Fig. 5.7: Comparison Graph of 30 point sets for BSs with 8 antennas CDF.

a randomized layout of 30 scattering objects all of the sections of the space begin to trend towards the same CDF. The slopes are notably more similar and also steeper, indicating a more similar coverage across all points tested in the room.

5.2.4 Testing Scattering Points

It is important to verify that the randomly generated points that act as scattering objects within this scenario do not favor the corner room set up or the sidewall set up for BS implementation when it comes to the comparisons for determining the validity of the results. For this purpose, ten random sets of 30 scattering points were created for a room layout that consisted of 8 antennas elements per BS. The overall CDF coverage generated for each set of points and then plotted against the same graph. Figure 5.8 shows that regardless of the layout of the scattering points within the room, the overall trend is consistent with corner orientations preforming slightly better than the sidewall.

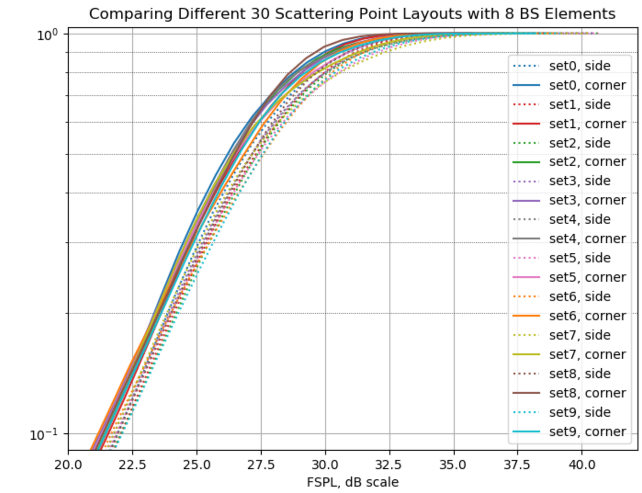


Fig. 5.8: Comparison Graph of 30 point sets for BSs with 8 antennas CDF.

For a closer look at the trends between the CDFs figure 5.9 looks at the CDFs between 0.2 to 0.6 along the y-axis. Here is it notable that regardless of the set of points the received combined signal is always lower with the sidewalls BS than with the corner BSs. On average for the different sets, it is found that the corner BSs have a $1dB$ increase in signal over sidewall implementation. With these plots used for verification, it does not show that a variation in point placement will lead to radically different results and consistently results in the corner BSs provide an increase in path recombination.

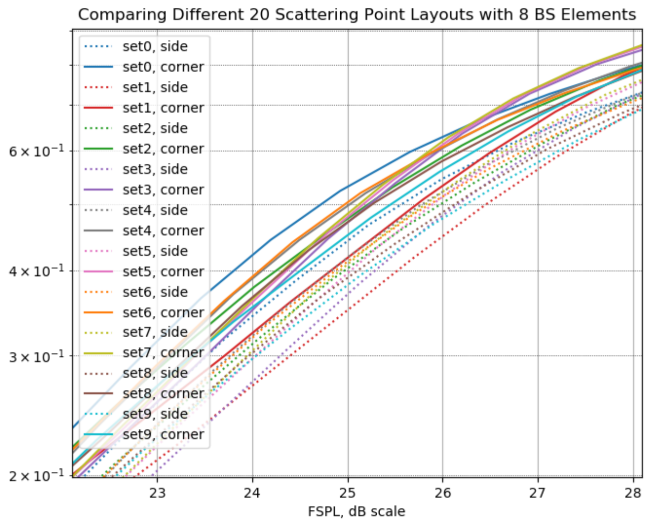


Fig. 5.9: Zoomed in comparison of 8 antenna BSs with different scattering sets CDFs.

When it comes to a scattering scenario of 30 points, there is no set up that was tested that resulted in a simulation where the sidewall BSs performed better than the corner BSs. The performance distance that was originally expected was to see a more clear distinction between the locations, with the corner, oriented BS providing a notably increased coverage for a rich scattering environment.

6 Conclusion

Overall this thesis lays out the groundwork to examine the best placement of BSs for a scattering environment in regards to the phase interference and path losses within a room; this shows just one of many layers of what would be in the link budget for a system. The importance of this is to see that the value expected for the path loss can be made consistent across the room, and result in a link budget with the low variance between sensor nodes. Having a more uniform channel can simplify the planning for a system and allow the set up for the sensor nodes to be more flexible since both small and large scale fading decreases. As the number of scattering elements in the facilities increases, the increased gain of having the BSs located in the corner compared to the middle of the wall decreases. Another effect expected was to see a reduction in loss when having the BSs place in the corner locations compared to the sidewalls, and while this did happen, it was not to the extent expected.

The best way to validate these results would be to perform a real-world measurement campaign discussed in 6.1. It is also clear that regardless of the corner versus sidewall argument, having a distributed system would allow for overall better coverage, but this would require the trade-off of more complexity in software to recombine signals as well as increased complexity of computation. The introduction of more hardware to a system is going to increase the initial price and might not be offset by the increase lifespan seen in the sensor nodes used in the wireless systems.

6.1 Future Work

There are multiple options to continue the research started in this thesis using software or hardware methods. An improvement on the simulation used in this thesis would be introducing more complexity to better estimate real world channels. Regardless of how complex the simulation is, there is no replacement for acquiring real data.

6.1.1 Future Simulations

A starting point to improve the simulations provided would be to reference section 4.6. Increasing the simulation to cover a 3D environment would increase the amount of realism expected from this simulation greatly. Another factor that should be implemented is setting antenna patterns for the sensor nodes with the simulation. Though these tasks are feasible, the best direction would be to do real world measurements.

6.1.2 Future Measurement Campaigns

There is a level of complexity in the real world that cannot be created with a simulation and is invaluable to supporting the assertions made in this thesis. NTNU has an antenna array set up designed by KU Leuven that has a grid of 8×8 dual-polarized antenna elements operating at a center frequency of $5.9GHz$ and $5.1Ghz$ [5]. This antenna system, with some effort, can be relocated to a warehouse facility that would be a viable location to test real-world measurements of these environments. Lund university implemented software in LabView that can save data from the transmission of 'sensor' nodes for their constellation diagrams and SNR. The best option would be to have multiple identical antenna arrays to perform the measurements so that the distributed BS layout is evaluated in a real-world setting. If only one antenna array is available, setting this array in different locations, and taking channel measurements in the sample locations for each BS set up would be another method to get an approximation of the room. The second option is only viable if the room does not change over time.

The goal would be to have this measurement campaign performed in the near future by other Masters students. The evolution of IoT will continue and the methods and options for WLANs and CPSs will become increasingly more relevant in this ever connected world.

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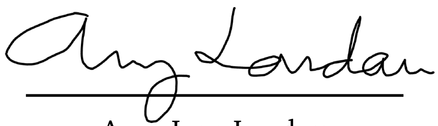
Trondheim, July 23rd, 2020



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