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PART I: RESEARCH/REPORT

PROPAGATION CHANNEL MODELING IN THE AGE OF 5G

Key Terms: mmWave, 5G, channel modeling, ray tracing, power delay profile.

Abstract

This report examined how two different channel modeling approaches will be used to meet the challenges of 5G millimetre wave (mmWave) propagation. The two models, the geometry-based stochastic channel model (GSCM) and the site-specific (i.e. map-based) deterministic channel model based on ray tracing are discussed in detail. After brief introductions to the models, there will be examples of a standard model of each type: the 3GPP model for the stochastic model and the METIS project model for the deterministic model. After outlining the standard models, there will be a brief literature review of how those models have been validated, a brief discussion about the limitations of the models, and a brief discussion on future work of the models. Concluding the report will be a recommendation on how each model should be used, based on their respective strengths and weaknesses.

Introduction

This report will discuss two approaches to channel modeling: geometry-based stochastic channel modeling and site-specific (i.e. deterministic) channel modeling based on ray tracing. The focus will be on how each have been and will continue to have to be modified to meet the needs of fifth generation (5G) communication systems. Fifth generation (5G) communications demands will present new challenges for channel modeling. Due to a shortage of bandwidth in the sub-6 GHz bands, applications and services for the anticipated 5G communication systems will have to exploit the millimeter-wave (mmWave) range up to 100 GHz.

Although mmWave bands potentially offer significant performance improvements in wireless networks, they still face many technical challenges related to the propagation characteristics peculiar to mmWave bands. For example, mmWave signals encounter severe path losses and high atmospheric and rain attenuation, making the deployment of mmWave systems very challenging, particularly for outdoor communications [1].

In addition, mmWave signals cannot penetrate most solid materials such as buildings. Furthermore, the significantly larger sizes of buildings relative to mm wavelength signals will result in sharp shadow zones that lead to insignificant diffraction mechanisms that can be neglected in the mmWave system analysis. The multipath nature of mmWave channels is thus expected to be sparse, as opposed to the rich-scattering nature demonstrated by conventional microwave channels. As a result, it would not be possible to directly use microwave propagation models for mmWave systems. An in-depth understanding of the mmWave propagation phenomena is essential for the design and analysis of future (5G and beyond) wireless networks [1].

Due to the high losses expected from mmWave propagation links, engineers must try to achieve a higher propagation gain using technologies such as large array antenna systems [2]. Evaluating the gains of large antenna systems presents a different challenge for channel modeling of propagation phenomena. Furthermore, the target is to model the received power level, determined by the path loss and shadowing, accurately enough for system level simulations [3].

A third challenge will be to achieve spatial consistency and mobility. For the sake of interlink consistency, it is preferred to base the path loss and shadowing determination on a geometrical environment description instead of mere distance and LOS probability as was the case in 4G channel models. A fourth challenge will be to account for diffuse versus specular scattering. In order to get reliable and comparable results, the evaluation of 5G communication systems is preferably performed with a single, but scalable, channel model. Thus, the channel model should be consistent across a wide range of environments, network topologies, and frequencies [3].

The main stream in spatial channel modeling has been the geometry-based stochastic channel model. However, site-specific (also known as map-based) channel propagation models are an alternative attracting increasing interest as technology advances into the mmWave range. Site-specific channel models generate multi-path channel parameters such as diffraction, reflection, and scattering. A customized 3D digital map is used to organize a realistic cell layout. Given the peculiarities of mmWave propagation phenomena, new site-specific models considering the location of streets and buildings must be developed in order to take the elevation dimension and the resulting changes in radio propagation into account [4].

Geometry-based stochastic channel modeling (GSCM)

The stochastic approach of characterizing channel behaviour uses probability distribution functions of the channel parameters to develop general yet sufficiently accurate channel models. The models are not based on a definition of the environment in the form of, e.g., maps or layouts in a coordinate system [3]. Stochastic channel models can be nongeometrical or geometry-based. Geometry-based channel models are developed based on predefined distributions of the channel parameters and the distribution of effective scatterers with their geometric information such as angles of departure and arrival and delay. The parameters are obtained from an extensive set of channel measurements. Millimetre-wave channel measurement data is needed for parametrization of models suitable for 5G planning [1].

The 3GPP standard channel model

The 3rd Generation Partnership Project (3GPP) is an umbrella for a number of standards organizations which develop protocols for mobile telecommunications. They have been responsible for the development and maintenance of: GSM, UMTS, LTE, 5G NR, and their related standards. [5]. The 3rd Generation Partnership Project (3GPP) unites seven telecommunications standard development organizations (ARIB, ATIS, CCSA, ETSI, TSDI, TTA, TTC), known as “Organizational Partners” and provides their members with a stable environment to produce the Reports and Specifications that define 3GPP technologies. The three Technical Specification Groups (TSG) in 3GPP are: Radio Access Networks (RAN), Services & Systems Aspects (SA), and Core Network & Terminals (CT) [5]. The 3GPP report discussed in this report will be TR 38.900 V14.2.0 “Study on Channel Model for Frequency Spectrum Above 6 GHz” (Release 14). The 3GPP standard will be described in this report, despite the existence of METIS and other standards for stochastic channel modeling, because the 3GPP report is the one most often referenced in the literature reviewed for this report.

The 3GPP Technical Report 38.900 contains a detailed channel model for the frequency band from 6 to 100 GHz. It is applicable for bandwidth up to 10% of the carrier frequency (with a limit of 2 GHz), and accounts for the mobility of one of the two terminals. Finally, it provides several optional features that can be plugged into the basic model, in order to simulate spatial consistency, blockage, and oxygen absorption. This model supports different scenarios: urban microcell, urban macro cell, rural macro cell, and indoor office [6].

The channel model is a 3D statistical spatial channel model whose design is an evolution of the 3GPP SCM model. It is based on measurement campaigns of propagation at mmWave frequencies conducted by several 3GPP partners. Given a certain scenario, the 3D positions, velocities and indoor/outdoor state of User Terminals and Base Stations, the model assigns a LOS/NLOS condition to each link according to scenario-specific probability distributions. This condition affects both the pathloss computation and the generation of fading parameters. For the pathloss, different formulas are provided, according to the scenario, and an additional O2I component can be added, with the possibility of modeling different kinds of building penetration losses (glass, concrete, wood) [6].

Parameters for TR 38.900 Channel Model, by scenario of interest [5]

Urban micro – Street Canyon and Urban macro Scenarios

- Cell layout
- BS antenna height
- UT Location: Indoor/Outdoor, LOS/NLOS, UT height
- Indoor UT ratio
- UT mobility (horizontal plane only)
- Minimum BS – UT distance (2D)
- UT distribution

Indoor – Office

- Layout: Room Size and intersite distance
- Same parameters as urban micro, but different settings

Rural Macro

- Carrier frequency
- Same parameters as urban macro, but different settings

Urban Micro – Open Square

- Same parameters as urban micro, but different settings

Other Attenuation Factors

Outdoor to indoor attenuation for different materials

Oxygen absorption

ALGORITHM FOR MODEL DEVELOPMENT [5]

Part 1: General Parameters

Step 1: Set scenario, network layout and antenna parameters

Step 2: Assign propagation condition (NLOS/LOS)

Step 3: Calculate pathloss

Step 4: Generate correlated large-scale parameters (DS, AS, SF, K)

Part 2: Small Scale Parameters

Step 5: Generate delays

Step 6: Generate cluster powers

Step 7: Generate arrival and departure angles

Step 8: Perform random coupling of rays

Step 9: Generate XPRs

Part 3: Coefficient Generation

Step 10: Draw random initial phases

Step 11: Generate channel coefficient

Step 12: Apply pathloss and shadowing

5G GSCM channel modeling validation

Martinez, et al. (2016), introduced multiuser consistency, non-stationarities across the base station array and inclusion of spherical wave modeling as key features for modeling massive MIMO channels with GSCMs [7]. They did not, however address mmWave propagation.

Muhammad, et al. (2017) developed a geometry-based stochastic channel model to statistically characterize the effect of all the first-order reflection paths between the transmitter and the receiver. Based on the geometric model, a closed-form expression for the power delay profile contributed by all the first-order reflection paths was obtained and then used to evaluate their impact on outdoor mmWave propagation characteristics. The authors developed an approximate but accurate closed-form expression for the PDP contributed by all the first-order reflection paths and derived a semi-analytical expression for the average number of the first-order reflection paths. Numerical results demonstrated that the approximate expressions are very close to expected values under all the considered system settings [1].

Limitations of geometry-based stochastic channel modeling for mmWave channels

To a certain extent, GSCMs for mmWaves have accounted for the inherent characteristics of the mmWave channels and have also added channel properties for 5G communication technologies, such as massive MIMO and hybrid beamforming. Nevertheless, as GSCMs they are concentrated on modeling point-to-point BS-UE links with a regular cell size, like their sub-6 GHz ancestors, and cannot support all modeling requirements for new 5G applications due to the lack of channel measurement campaigns for the various link types [2].

Millimeter-wave frequencies down to subgigahertz frequencies for 5G evaluations should preferably be modeled *continuously* across the wide frequency range. Existing empirical GSCM path loss models can be extended into mmWaves, but they can only be parametrized for *discrete* frequency bands above 6 GHz [3]. Likewise, all channel characteristics for 5G models should be geometry specific and vary continuously as either (or both) ends of the radio link is (are) moving. Full consistency is very difficult to achieve with traditional GSCMs, however, where neither cluster locations nor visibility regions are defined [3].

Scattering caused by rough materials and small objects (diffuse) versus large smooth surfaces (specular) results in different propagation channel characteristics. While GSCMs may handle diffuse scattering, by modeling the diffuse tail of propagation paths by introducing appropriate sub-paths around dominant components, without a geometrically defined environment, modeling of realistic specular paths is not possible [3]. Finally, a fixed antenna array size can no longer be assumed for GSCMs, because very large arrays may experience a nonstationary propagation channel with variation in large-scale effects like shadow fading across the array [3].

Future work in geometry-based stochastic channel modeling

There will always be room for channel coefficient refinement and future validation, given the general nature of the model. As technology and scenarios, i.e. the landscape under investigation, evolve assumptions will change and the model will have to be recalibrated. Hybrid (e.g. 3GPP) models that exploit the strengths and minimize the weaknesses of stochastic and deterministic models may be the future of stochastic modeling.

Site-specific (i.e. map-based), deterministic channel modeling

Site-specific channel modeling based on ray tracing uses a simplified 3D geometric description of the propagation environment and deterministic modeling of propagation in terms of rays. The walls of buildings are modeled as rectangular surfaces with specific electromagnetic material properties. The significant propagation mechanisms such as diffraction, specular reflection, diffuse scattering, or blocking, are accounted for. For each specific link between Tx and Rx there are pathways which contribute significantly to the received power [3]. It is necessary to incorporate accurate site-specific layout information into the propagation prediction tool. Since a geometrical optics-based model is used, only objects that are much larger than a wavelength at mmWave frequencies are used [8].

The deterministic site-specific approach based on ray tracing solves many of the problems that the stochastic generalized approach does not. The ideal that all 5G channel characteristics should be geometry-specific and vary continuously with radio link motion is met because all propagation parameters are tied to transmitter/receiver location with respect to the environment through ray tracing. Smaller or larger motion resulting in a displacement of transceivers is accounted for when determining propagation characteristics such as path loss, shadowing, or angular parameters. The coordinate-based deterministic approach enables consistency with respect to all possible transceiver location combinations on the 3-D map. [3]. Diffuse scattering is handled by dividing larger surfaces into tiles. For the specular scattering, straightforward ray tracing is used in modeling the corresponding paths reflected from smooth surfaces. [3].

Very large arrays may experience nonstationary propagation channel with variation of large-scale effects like shadow fading across the array. The proposed model, being based on a map with coordinates, supports determination of propagation channels between any locations, and thus there is no need to assume a confined physical size for antenna arrays. Furthermore, the proposed model supports spherical waves inherently. Each interaction point and antenna element have coordinates, and both the phase and the attenuation are affected by Euclidean distances between interaction points and antenna elements [3]. Millimeter-wave frequencies down to sub-gigahertz frequencies for 5G evaluations are modeled consistently across the wide frequency range, as the model is based on frequency-dependent propagation mechanisms like reflection and diffraction. As an additional frequency-dependent effect, the surface roughness may be accounted for as a function of wavelength [3].

Among the most important requirements of 5G channel models are the seamless and realistic modeling across a wide frequency range and the spatially consistent modeling of numerous radio links. The coordinate-based description of the modeled environment with a stochastic element of random objects together with the deterministic ray tracing principle is the key to achieve consistent but versatile radio channel realizations as the model output [3].

Ray tracing theory

Ray tracing is a method for approximating the propagation of a wave in an environment using discrete rays. The discrete rays are traced either by determining all possible specular images of Tx/Rx or by launching rays into different directions. In both cases the possible pathways and their corresponding interactions, such as reflections, diffraction and diffuse scattering, are determined. For accurate simulation results multiple rays need to be launched from the transmitter using a dense angular grid. In the case of specular images, the complexity grows exponentially with the number of interactions. Ray tracing requires knowledge of the environment as well as knowledge on the material parameters of the objects. The approach is inherently environment-specific and as such deterministic. The approach supports different transmitter and receiver locations, i.e., macro-, microcellular, or D2D and it is spatially consistent [9].

A ray tracing algorithm predicts multipath impulse responses based on site-specific layout information. An object or group of objects called a “scene” is described in terms of its geometry and light scattering properties (i.e. colour). The computer attempts to recreate a photograph of the scene for a fixed observer and one or more light sources. The graphics ray tracing is a geometrical optics model for light. The geometrical optics-based model is used to predict multipath power delay profiles and path loss. Ray tracing represents the high frequency limit of the exact solution for electromagnetic fields and can give quick approximate solutions when the exact solution cannot be found. It is a physically tractable method of predicting the delay spread and path loss of radio signals and lends itself well to rapid parallel computing [8].

The METIS Project map-based channel model with ray tracing

The map-based model is intended for cases where accurate and realistic spatial channel properties are required, for example when studying massive MIMO and advanced beam-forming techniques. It is also suitable for realistic modeling of pathloss in the case of D2D and V2V. the model is based on ray tracing using a simplified 3D geometric description of the propagation environment. The significant propagation mechanisms, i.e. diffraction, specular reflection, diffuse scattering, and blocking are all accounted for. Building walls are modeled as rectangular surfaces with specific electromagnetic material properties. The complexity is scalable as different components, like specular paths and diffuse scattering, may be turned on or off. A simplified diffraction modeling is also provided in order to further reduce the complexity [9]. The METIS report is described in this report because the site-specific model for the 3GPP report is part of a stochastic-deterministic hybrid model and is based on the METIS site-specific model.

The model applies to the following propagation scenarios that provide the necessary geometry data: [9]

Urban micro cell

Urban macro cell

Indoor Office

Indoor Shopping Mall

Highway

Festival (open air)

Stadium

The model parameters are:

Object density

Object height

Object width

Scatterer absorption coefficient

Specular / diffuse power ratio

Angle dependency factor

Angle dependency exponent

Angle dependency factor (HH)

ALGORITHM FOR MODEL DEVELOPMENT [9]

Part 1: Creation of the environment:

Step 1: Define the map in global xyz coordinate system.

Step 2: Define the xyz coordinates of shadowing/scattering objects

Step 3: Define point-source distributions for diffuse scattering over planar surfaces i.e. exterior and interior walls, floors, ground, etc.

Steps 1 – 3 are performed only once. After this step the procedure is fully deterministic.

Part 2: Tx and Rx locations:

Step 4: Define a single location or a trajectory, in xyz coordinates, for each transmitter and receiver antenna element.

Part 3: Determination of propagation pathways:

Step 5a: Starting from the Tx and Rx locations, identify all possible secondary nodes visible to the Tx/Rx node either with a LOS path or via a single specular reflection.

Step 5b: Repeat Step 5a for each identified secondary node treating them as Tx nodes.

Step 5c: Repeat Step 5a for each identified tertiary node treating them as Tx nodes, but find pathways only to the Rx location. Pathways not terminating to the Rx location are discarded.

Step 6: Determine the arrival and departure directions for each path k in the form of wave vectors from the geometry.

Part 4: Determination of propagation channel matrices for path segments:

Step 7: Determine shadowing due to objects for path segments. Each blocking object is approximated by a rectangular screen.

Step 8: Direct LOS

Step 9: Reflection

Step 10: Diffraction

Step 11: Scattering

Part 5: Calculation of the radio channel transfer function:

Step 12: Determine the complex impulse response between Rx antenna element u and Tx antenna elements s with a true motion of transceivers.

The complexity may be reduced by means of accounting only for diffracted paths, which are within a lower order of Fresnel zones with respect to the corresponding specular or direct path [9].

5G site-specific channel model validation

Kyosti, et al. (2017) generated and compared outputs of a proposed site-specific model with a modified IMT-Advanced urban micro model that belongs to the GSCM family. For the indoor validation, the agreement between the map-based model outputs and the measurement results was found to be acceptable. For the outdoor validation, the model was able to predict the most significant paths in the LOS case, but succeeded only partially in the NLOS locations. For V2V validation, predicted path loss samples agreed well with the measured ones and the resulting path loss exponents were both close to the free space loss, which was to be expected for the LOS condition [3].

Shadowing had 1.5 dB higher variation in the predicted case, validating that the model was capable of reconstructing channel conditions with realistic path losses in the specified V2V case. For the simulation, it was concluded that the second moments of angular and delay parameters are not a perfect metric for describing a propagation environment. The authors found that the GSCM seriously overestimated the capacity of MU-MIMO and the spatial separability of UEs by m-MIMO BS arrays in urban street canyon environments, especially in NLOS condition [3].

Limitations to ray tracing-based site-specific channel modeling

Although ray tracing is a very accurate way of simulating radio wave propagation, it suffers from two main drawbacks: 1) knowledge of the environment is required, and 2) the computational burden is high [9]. The attention to detail is particularly costly when a large investigation area is considered [1, 4]. In addition, such results be valid only for the specific propagation setting and may not be applicable to general propagation environments [1].

Alternatives to a ray tracing-based site-specific channel model

Monserrat, et al. (2015) proposed a propagation model for urban macrocell scenarios that is much simpler than ray tracing but still allows for a proper characterization of real environments. Relative to ray tracing, the proposed model is equivalent to a single-ray approach, provided that the total loss is computed as a summation of three terms representing free space loss, the diffraction loss from rooftop to the street, and the reduction due to multiple screen diffraction past rows of buildings. Compared to the IMT-A model and the 3GPP model with 3D extension, the proposed map model showed significant improvements in path loss prediction [4].

Future work to be done in site-specific channel modeling

Since the site-specific model is intended to account for all radio channel characteristics which are important for any 5G mobile communications scenario, the model must be validated by measurements. Work is ongoing or planned to validate diffuse scattering properties, the number of interactions needed to provide realistic delay spreads, and the distribution of scatterers for different environments [9].

Investigations are also needed for determining frequency-dependent diffuse/specular power ratio. Although it is currently done with surface roughness assumptions, the roughness model is not well suited for the wide frequency range expected for 5G. The larger portion of diffuse power would result in a richer multipath channel [3].

Conclusions

This report examined two types of channel model that will be used for 5G RF system planning. Fifth generation systems are expected to serve at least higher data rates in mobile broadband, ultrareliable, and low latency transmission. They are expected to support different link types. The size of cells may decrease; traditional macro- and microcells are going to be complemented by pico- and femtocells composed of ultra-dense networks, moving base stations, and peer-to-peer type of D2D connections between user terminals. The various types of links will coexist in the same area. New antenna topologies, like m-MIMO, with tens or hundreds of closely packed elements, and very large arrays with possibly physical dimensions of tens of meters, may be used. Those features set new requirements for channel modeling [3].

Although the existing mmWave GSCMs have exploited the essential features of the mmWave channel, they are limited by a link type such as traditional BS-UE. Many types of applications, however, will appear with different link types. On the other hand, site-specific mmWave channel models that use ray-tracing serve as a way to model the irregular layouts of small cells and to support new applications' link types, including D2D, V2X, and A2X. They allow researchers to accurately evaluate novel technologies in the mmWave range [2]. For now, it looks like a hybrid model that exploits the respective strengths of the models should produce the optimum results. The site-specific model can be used for smaller areas, when all the site-specific details are known. For more general cases, and where the survey area is too large to be computationally practical, the stochastic model should be used.

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Part 2: Simulation

Introduction

With 5G as the imminent next big thing, it's important for us to look at the 4G LTE technology we are currently using and examine its functions and advantage over older wireless technology.

4G LTE was a revolutionary advancement on mobile standard. Jumping from 3G UMTS with 2Mbps to up to 1Gbps with 4G LTE standard.

This is possible due to Integration of enabling technologies with sophisticated mathematical algorithms such as: OFDM, turbo Coding, as well as adaptive usage of resources and bandwidth.

The key feature on what separates LTE from the previous 2G and 3G network is the turbo coding and OFDM.
Turbo coding allows for high performance error correction, in which a maximum coding rate can be established even with a high amount of noise.
OFDM is a digital modulation scheme which can encode data into multiple sub carriers in a channel that can carry different informations, and each individual sub carrier can be modulated with modulation scheme such as QAM

In this project we have simulated a 4G LTE system complete with a transmitter using QAM and OFDM modulation with turbo coding.
The LTE system is modified from the LTE system example from behind the science [7]

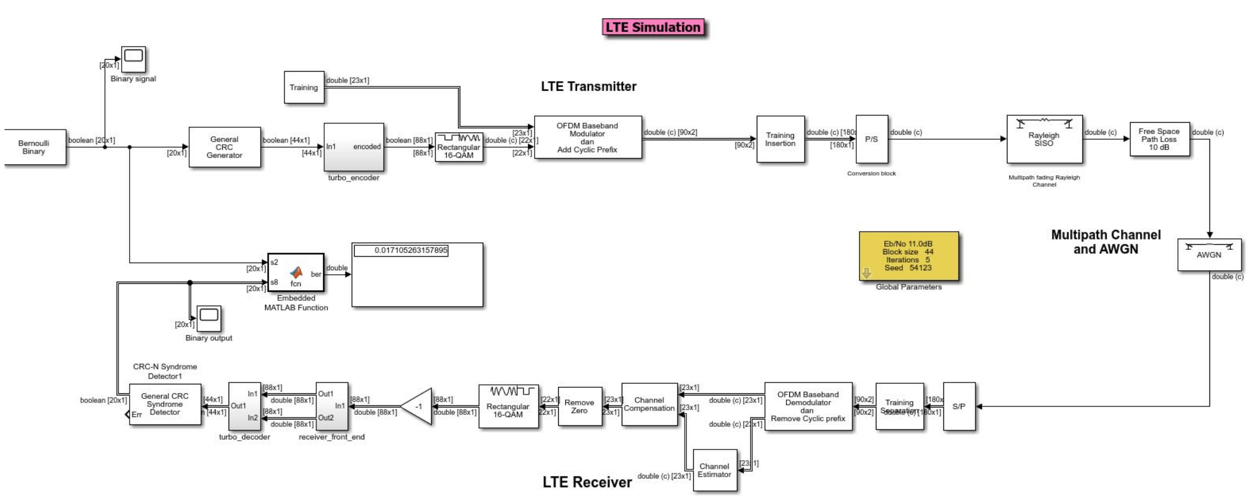

Figure 1 Overview blocks of the LTE simulation in simulink

The simulation, like a real LTE system consists of three parts, the LTE transmitter, the Channel, and the LTE receiver.
To see the performance of the system, the simulation will output a Bit Error Rate(BER) value at the end so we can see the effect the channel has on the system.
For the channel we will apply different types of noise and interference and loss such as multipath fading,pass loss, and Additive white Gaussian noise (AWGN).

The system will run for 0.003 seconds as a standard since through testing increasing the time span past this point does not alter the result in any significant way.

Theory, Observations and Results

We will separate the simulated system into 3 sections: The transmitter,the channel, and the receiver.

LTE Transmitter

The transmitter transmits the binary signal through multiple modulation schemes so it is fit to transmit through the channel with high performance and without losing the necessary information.

Bernoulli Binary Generator

First we need to generate the signal that we want to transmit. We will generate a random signal with simulink's Bernoulli Binary block. We will set the probability of zero to 0.5 so there is an even distribution of 1s and 0s in the signal sample at T=1 and 20 samples per frame.

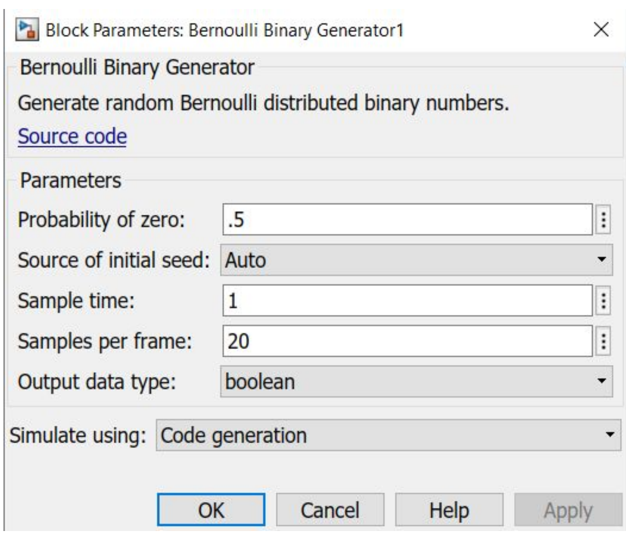

Figure 2 parameter of bernoulli binary generator

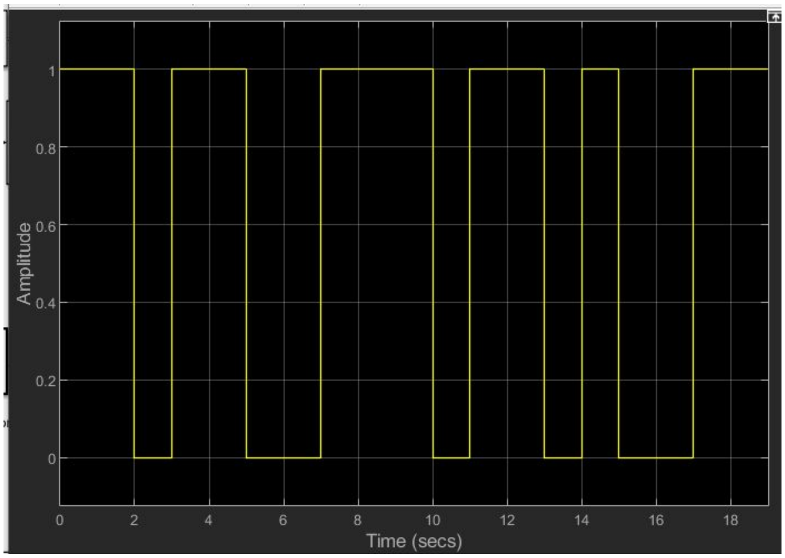

Figure 3 The output of bernoulli binary generator in time domain

General CRC Generator

The Cyclic Redundancy Code (CRC) generator is used for the detection of bits which are received in error.
The CRC generator generates CRC bits for every input frame and appends them to the frame.
The CRC generator works but first divides the input signal into individual frames of equal size. Each frame will be prefixed with the initial states vector and have the CRC algorithm applied to them. Afterwards checksums are applied to each frame and append the end of each frame, then the frames are concatenated and output as the desired length.

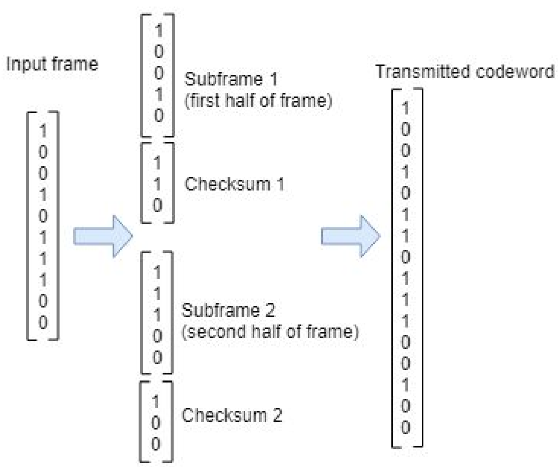

Figure 4 How CRC generator transmit codeword from the input frame from [4]
In our simulation we uses length 24 that corresponds to the 3GPP specifications ,The CRC generator polynomial for parity bits length 24 is
$g_{CRC24A}(D) = [D^{24} + D^{23} + D^{18} + D^{17} + D^{14} + D^{11} + D^{10} + D^{7} + D^{6} + D^{5} + D^{4} + D^{3} + D + 1]$ from [3]

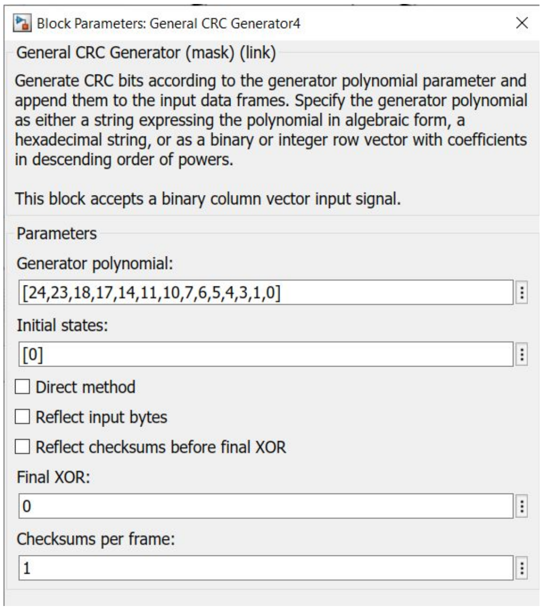

Figure 5 Settings for the CRC generator

Turbo Encoder

We need to process the data bits before they undergo process for primarily two reasons:
First is to make them resistant to attenuation with Channel coding.
Channel coding makes the data resilient to attenuation at the channel, at the cost of reduction in the bit rate.
We use a turbo encoder in the transmitter and turbo coder in the receiver.
The turbo encoder consists of two identical encoders and uses an interleaver that makes the input bits of encoder 2 shifted from the inputs of encoder 1, then it uses punchering and multiplexing to achieve the desired coderate.
The two parallel concatenated decoders exchange information to produce turbo effect

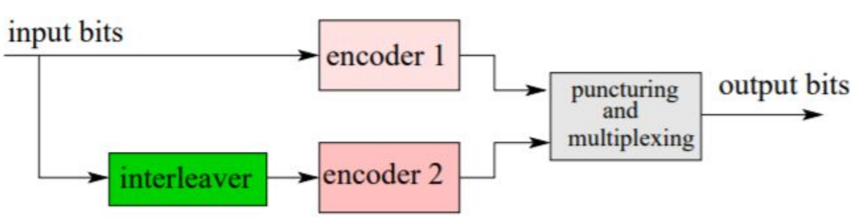

Figure 6 Block diagram for a basic turbo encoder from [5]

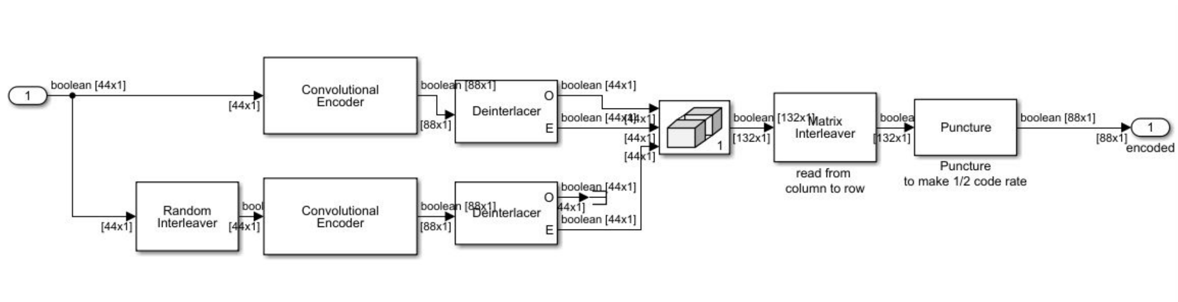

Figure 7 Turbo encoder in our simulation

Our implementation of turbo encoder uses two convolutional encoders that use the trellis polynomial structure, we use a deinterlacer as a mask to separate the encoded input into odd and even elements. We then apply puncturing and multiplexing with a matrix interleaver

Deinterlacer is a mask that multiplies the input to a different string, here we divide the 88x1 into odd and even elements of 44x1 boolean.
Then we concaconcate it in the matrix concatenate block

The puncture is a vector that is able to decrease the coding rate when the vector is multiplied by 0, this is also implemented at the receive so we can undo the changes to the data.
Coding rate is the indication of how much data stream is being used to transmit the usable data, here with a puncture vector of [1 1 0 1 0 1], we are setting the coding rate in half.
We can actually determine the data rate from the MCS table.

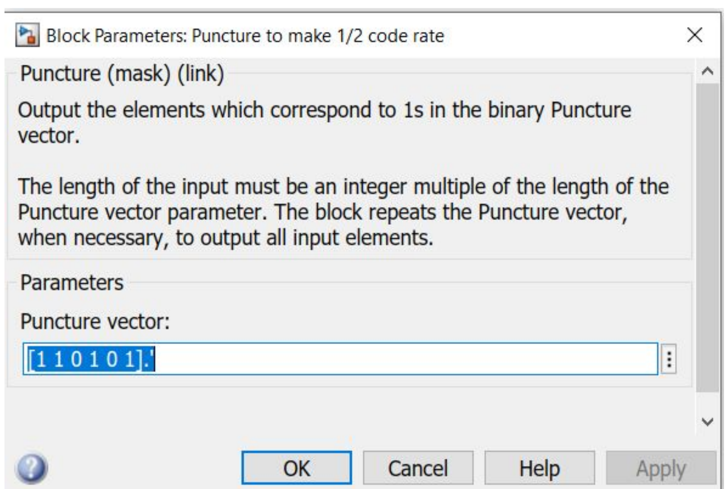

Figure 8 Puncture vector settings

Since we are using the 16-QAM modulation scheme, with a coding rate of ½ we would get 13 Mb/s data rate on 20MHz channel and 27Mb/s on 40MHz channel.
This helps save the bandwidth in the transmission at the cost of losing some quality.

Table 1 MCS index table

MCS index	Spatial streams	Modulation type	Coding rate	Data rate (Mbit/s) 20 MHz channel 800 ns GI	20 MHz channel 400 ns GI	40 MHz channel 800 ns GI	40 MHz channel 400 ns GI
0	1	BPSK	1/2	6.50	7.20	13.50	15.00
1	1	QPSK	1/2	13.00	14.40	27.00	30.00
2	1	QPSK	3/4	19.50	21.70	40.50	45.00
3	1	16-QAM	1/2	26.00	28.90	54.00	60.00
4	1	16-QAM	3/4	39.00	43.30	81.00	90.00
5	1	64-QAM	2/3	52.00	57.80	108.00	120.00
6	1	64-QAM	3/4	58.50	65.00	121.50	135.00
7	1	64-QAM	5/6	65.00	72.20	135.00	150.00
8	2	BPSK	1/2	13.00	14.40	27.00	30.00
9	2	QPSK	1/2	26.00	28.90	54.00	60.00
10	2	QPSK	3/4	39.00	43.30	81.00	90.00
11	2	16-QAM	1/2	52.00	57.80	108.00	120.00
12	2	16-QAM	3/4	78.00	86.70	162.00	180.00
13	2	64-QAM	2/3	104.00	115.60	216.00	240.00
14	2	64-QAM	3/4	117.00	130.00	243.00	270.00
15	2	64-QAM	5/6	130.00	144.40	270.00	300.00
16	3	BPSK	1/2	19.50	21.70	40.50	45.00
17	3	QPSK	1/2	39.00	43.30	81.00	90.00
18	3	QPSK	3/4	58.50	65.00	121.50	135.00
19	3	16-QAM	1/2	78.00	86.70	162.00	180.00
20	3	16-QAM	3/4	117.00	130.00	243.00	270.00
21	3	64-QAM	2/3	156.00	173.30	324.00	360.00
22	3	64-QAM	3/4	175.50	195.00	364.50	405.00
23	3	64-QAM	5/6	195.00	216.70	405.00	450.00
24	4	BPSK	1/2	26.00	28.80	54.00	60.00
25	4	QPSK	1/2	52.00	57.60	108.00	120.00
26	4	QPSK	3/4	78.00	86.80	162.00	180.00
27	4	16-QAM	1/2	104.00	115.60	216.00	240.00
28	4	16-QAM	3/4	156.00	173.20	324.00	360.00
29	4	64-QAM	2/3	208.00	231.20	432.00	480.00
30	4	64-QAM	3/4	234.00	260.00	486.00	540.00
31	4	64-QAM	5/6	260.00	288.80	540.00	600.00

Rectangular 16-QAM generator

QAM or Quadrature Amplitude Modulation, uses both amplitude and phase to modulate a signal with high efficiency.
We call the default signal the in phase signal component and the signal that is shifted 90 degrees quadrature signal components.
As a result both the phase and amplitude have variation present, allowing us to use it for modulation.
This is better than just amplitude modulation for example, since it uses the available bandwidth for more effectively, we can place multiple QAM signals in the same spectrum where you can just place one with amplitude modulation.

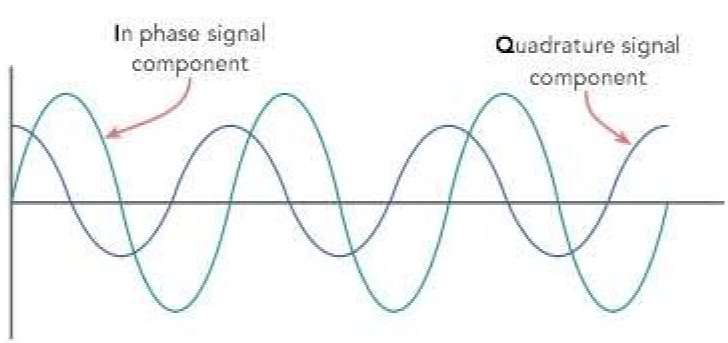

Figure 9 Representation of in phase and quadrature signal component taken from [2]
As a result both the in phase and quadrature

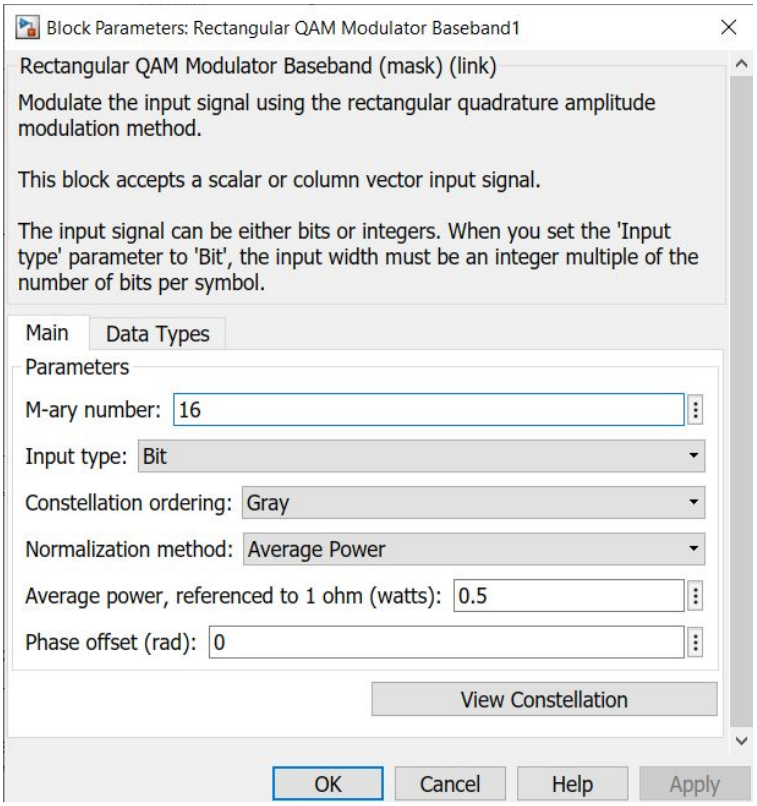

Figure 10 Settings for the QAM modulator

From figure 10 we have set the M-ary number to 16 for 16 bits QAM, and constellation ordering to gray so the binary input follows the scheme in figure 11 below.

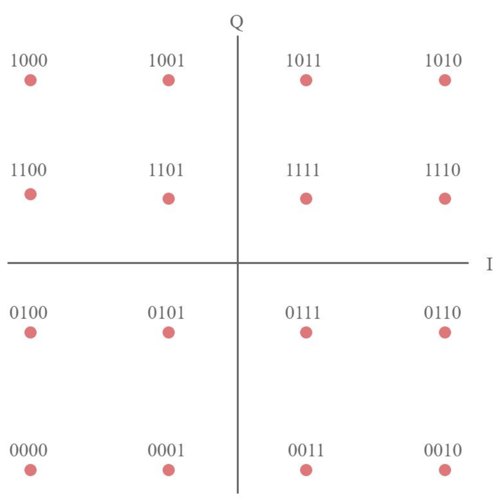

Figure 11 Gray ordering constellation for 16-QAM

With 16-QAM we have 4 variations of amplitude and phase each, in total we can represent 16 bits in a constellation.

Here we input the multiplexed and punctured signal and get the output in QAM constellation

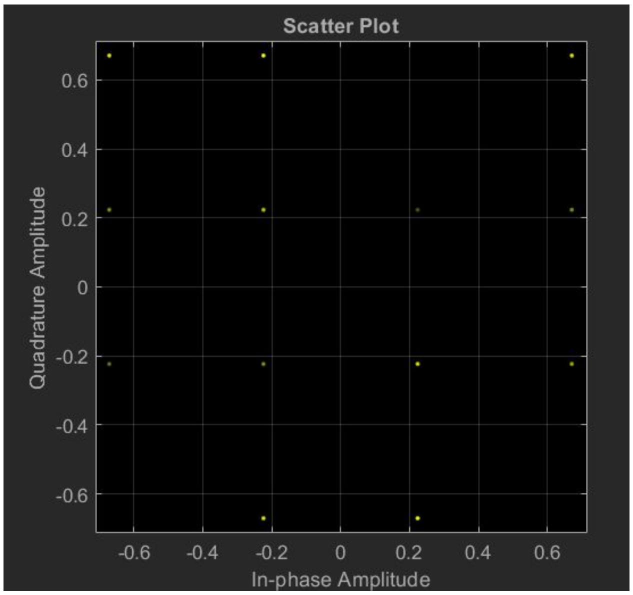

Figure 12 Output constellation from the initial 16-QAM generator

Some dots are blurry in areas of poor signal strength, for example the 0000 and 0010 bits are shown to be dim. This is due to the puncture in the turbo encoder being imperfect, so some parts of the signal are weaker than the others.
Now if we remove the puncture function to increase the coding rate, all the bits on the QAM constellation are more apparent.

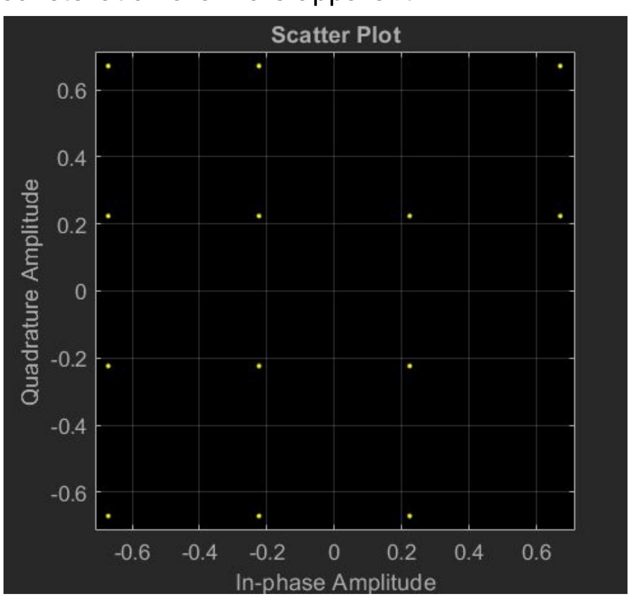

Figure 12 Output constellation from the unpunctured 16-QAM generator

The OFDM modulator

OFDM is a modulation scheme in which a signal data stream is split into different narrowband channels at different frequencies in order to reduce interference. It is used in
With a signal wideband channel you are using the entire band to send a single signal, while with OFDM channel we can use multiple narrow band channels and send multiple signals in the same channel.
The reason we didn't use frequency division multiplexing(FDM) in this case, is due to FDM requires extra overhead with guard band to protect the signals from interfering with

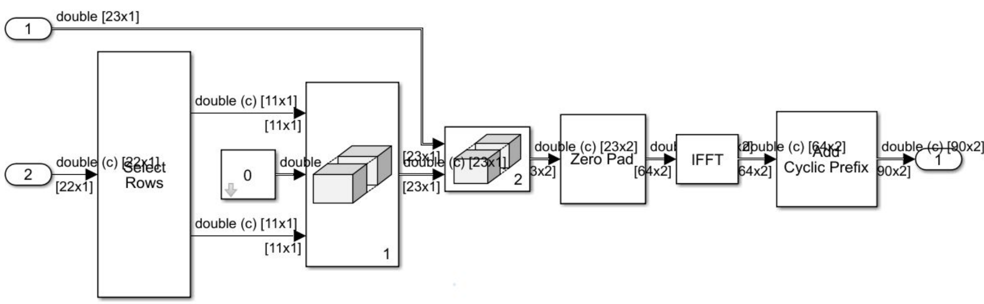

Figure 13 OFDM block diagram in simulink

As shown in figure 13, we first concatenate the 16-QAM data with a PN sequence generated randomly with a polynomial that the receiver also has. We also insert a set of zero values for zero padding to generate a suitable signal length for IFFT, which will be removed at the receiver.
Standard IFFT is performed on the data and goes through a cyclic prefix.

The OFDM module uses Cyclic prefix to help to reduce the ISI caused by the channel when an OFDM signal is being transmitted. A cyclic prefix is the copy of the port portion of the OFDM symbol, it preserves the orthogonality of the grid structure of the signal.
The cyclic prefix of our simulation is only copying the sample of the signal from 39 to 64, so the length is reduced to nyquist rate.

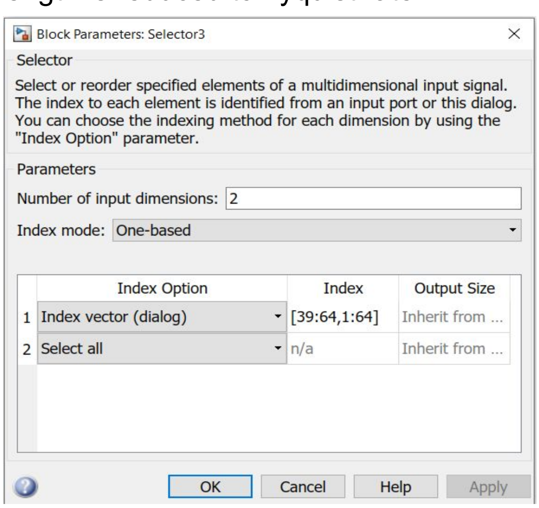

Figure 14 settings for the cyclic prefix

Training block

We will set the first column as the training information, and the second column as the ODFM information, we then concaconate it into a single sample of 180 samples.

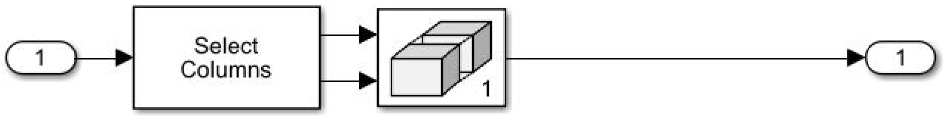

Figure 15 Training block diagram

Transmission Channel

Multipath fading

Multipath fading occurs where there are multiple paths of propagation and the path and constantly changing, this will affect the signal’s relative strength and phase, as well as the path length.

This in turn causes distortion to the signal, as various parts of the signal are inconsistent, causing phase distortion and inter symbol interference. One of the reasons we employ OFDM in this LTE simulation is to minimize the effect of multipath fading.

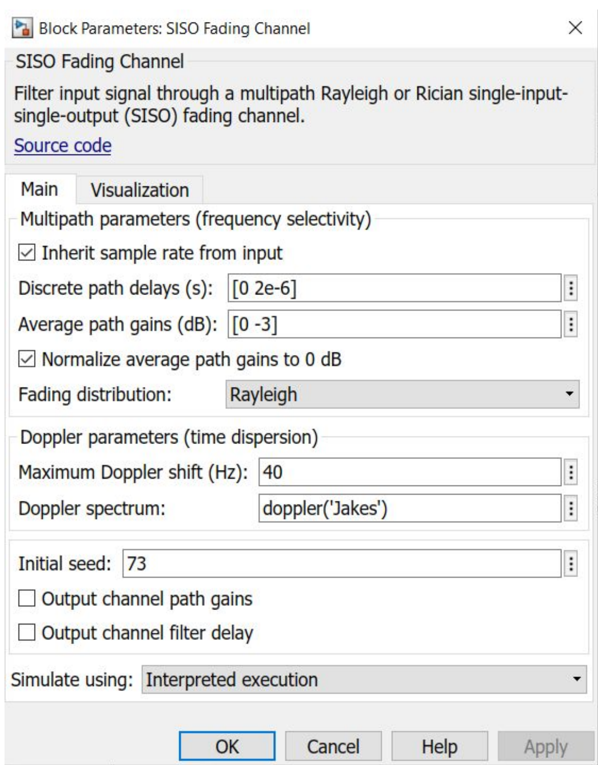

Figure 16 Settings for multipath fading block

The path delay is the measurement of the intensity of multipath in a channel, it is the difference between arrival time of the first multipath component and the last component.
Average path gains is the power gain of the multipath channel, in this case we lose an average of 3dB of power.

Dopper shift is the effect when the frequency shifts from the transmitter relative to the receiver occurs due to movement from the mobile station.
In multipath propagation a signal can be received in multiple routes, this in turn could cause destructive interference that causes fading in the transmission, multipath fading can also be caused by difference in speed of the mobile station and the base station, the transmitter and the receiver in our case.
Setting the maximum doppler shift to 40 ensures there is a realistic amount of doppler shift that emulates a real life cell tower transmitter and a receiver.

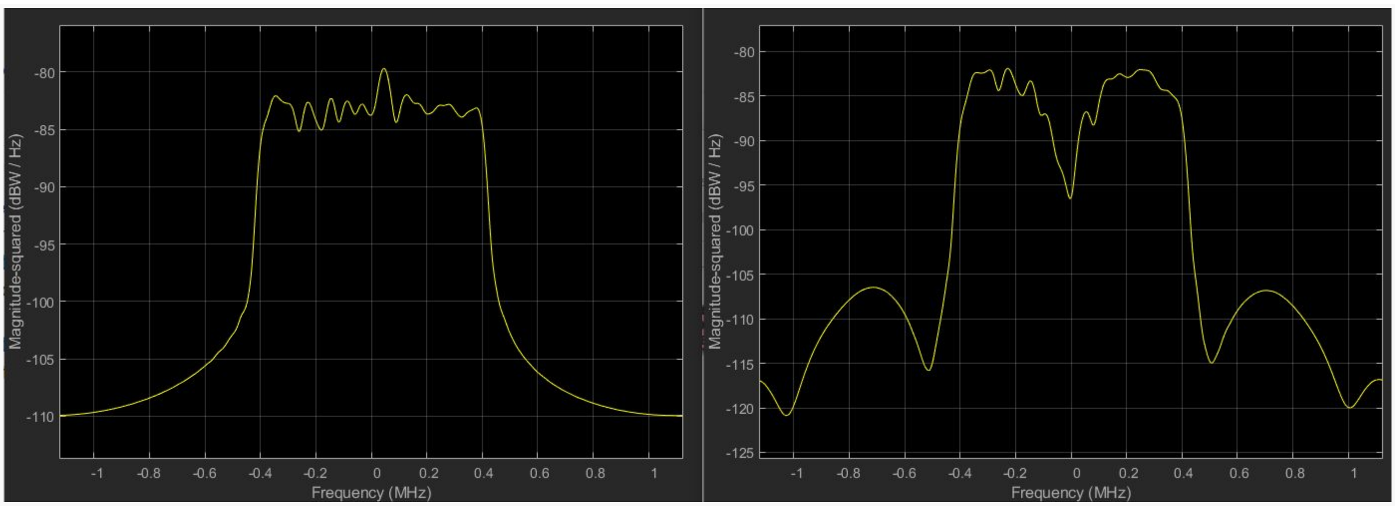

Figure 17 OFDM signal before(left) and after(right) going through multipath fading

As seen on figure 17, multipath fading distorts the OFDM signal, especially near 0Hz for around 0.2 MHz in general, this corresponds to the discrete path delay of 2e-6 seconds in the fading channel configuration.

Free space Pathloss

Pathloss is the reduction in signal power of a signal going through space

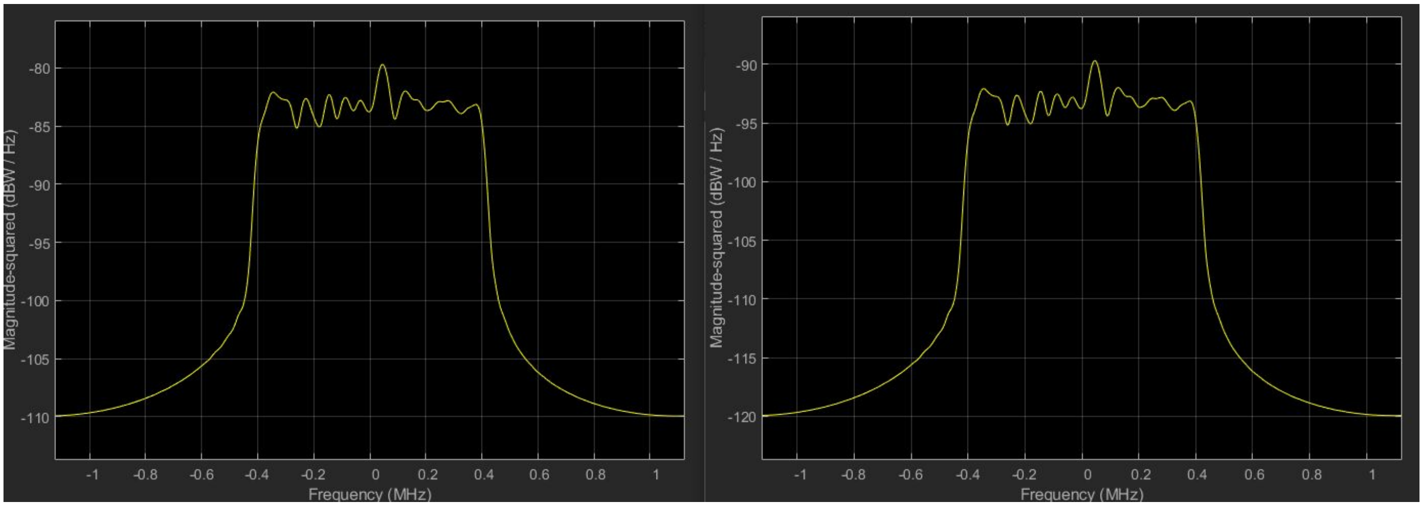

Figure 18 original OFDM narrowband signal before(left) and after pathloss(right) with 10db loss

As seen on figure 18 the signal shape remains the same, while the signal magnitude decreases. This means the pathloss with cause minimal signal loss as long as we account for it in the receiver

Table 2 Pathloss and BER relationships

Pathloss intensity(dB)	BER
1 to 4	0
5 to 7	0.0013
8 to 10	0.0079
15	0.017105

From table 2 it looks to confirm the fact that pathloss does not affect the receiving signal significantly

AWGN

AWGN stands for Additive white Gaussian noise. Addictive due to the fact that it can be addictively added to existing noise, white refers to the fact that it has uniform power across the entire bandwidth, and gaussian refers to the gaussian probability distribution.
We use simulink's own AWGN block and use Es/No as the parameter to adjust the noise.

Eb is the signal energy, while No is the noise spectral density.
Es/No is the energy per bit to noise power spectral density ratio. It is a measurement of the signal to noise ratio(SNR).

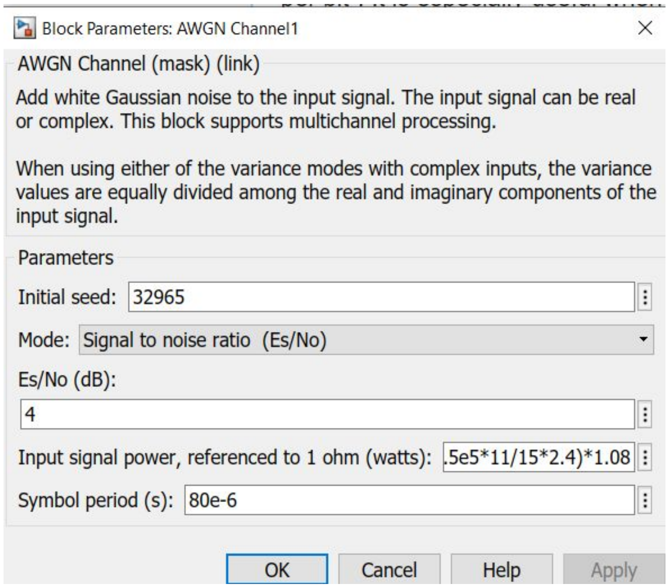

Figure 19 AWGN channel parameters

We use the same seed for a consistent random variable, in which we will change the Es/No and see the effect it has on BER.
The BER is tested with the simulation running for 0.03 seconds.

Table 3 recorded the relationship of pathloss with the BER without the factor of multipath fading

Es/No (db)	BER
1	0.00395
2	0.00341
3	0.00285
4	0.00273
5	0.00262
6	0.00186
7	0.00186
8	0

LTE Receiver

An LTE receiver can be a number of things such as a Mobile station(cell phone,tablets), or a cell tower.
The structure of many elements in the LTE receiver are very similar to the ones in the LTE transmitter but works in reverse to recover the original signal.
So this section will be brief as the inner workings of most of the modules are already explained in the transmitter section.

Training separator

Training separator is the inverse of the training block in the receiver, it separates the OFDM signal from the training information.

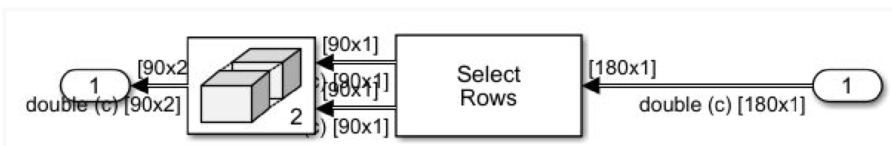

Figure 20 Training separator

OFDM Demodulator

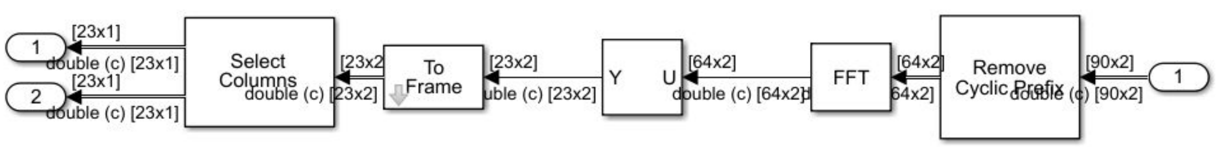

Figure 21 OFDM Demodulator

Inverse the OFDM at the transmitter. We remove the cyclic prefix, perform FFT to inverse IFFT and separate the
The selector removes the extra zero padding added in transmission to create the suitable length of the IFFT.
The select columns block separate the data from 23x2 to two 23x1, so we can feed one column of data to the channel estimator

Channel Estimator

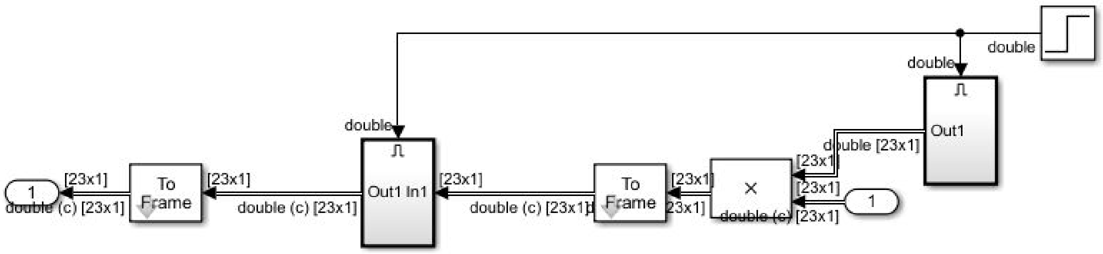

Figure 22 Channel Estimator
Channel estimate multiplies the signal with step function to gather the channel estimation values.

Channel Compensator

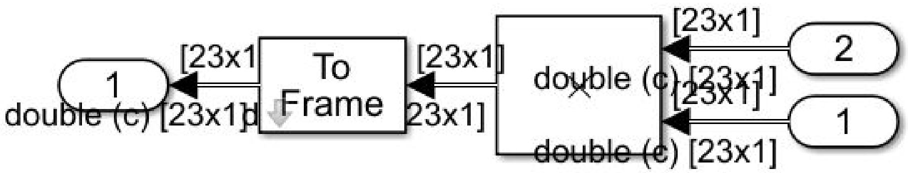

Figure 23 Channel Compensator

Channel Compensation takes the channel estimated value and the OFDM values, we multiply the OFDM information by the channel input response. This is used to inverse the effect of the extra symbol added during the OFDM modulation.

16-QAM Demodulator

THe 16 QAM demodulator is a default simulink block that reverse the 16 QAM modulation, we simply enter the same parameters as the 16-QAM modulator

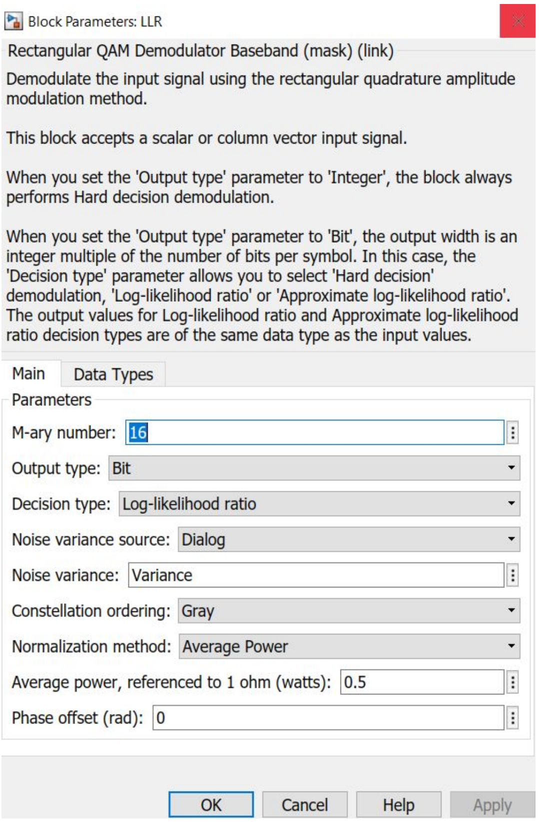

Figure 24 QAM demodulator settings

Front End Receiver

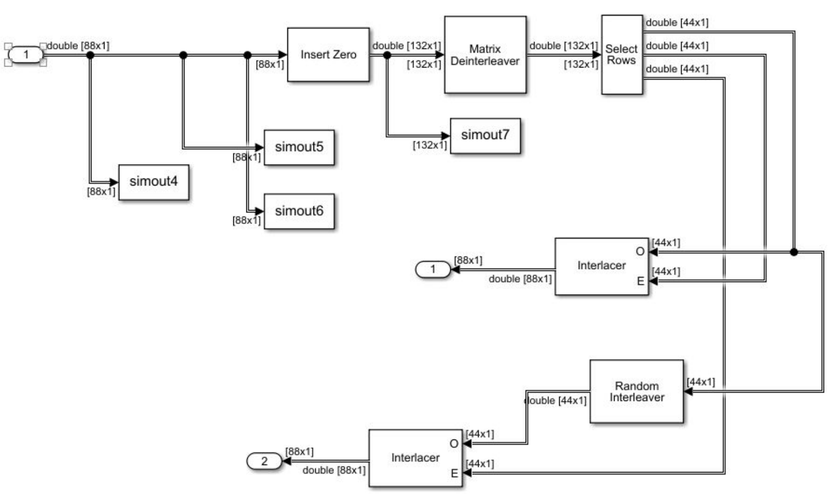

Figure 25 Diagram of Front End Receiver

Front End Receiver is a part of two component decoder works by interleaving and separating the data so we can input it into the turbo decoder. Front end receiver exchanges extrinsic information outputted by one component and becomes the former information for the other components.

Turbo Decoder

The turbo decoder uses two soft input and soft output devices, and uses probability algorithms known as the Viterbi algorithm to estimate the binary state.
The process goes through multiple iterations with both devices exchanging extrinsic information and finally output the decoded binary signal.

The general formula for each iteration is $\underbrace{L_p(b_k)}_{a\ posterior\ \mathrm{LLR}} = \underbrace{L_e(b_k)}_{\mathrm{extrinsic\ LLR}} + \underbrace{L_a(b_k)}_{a\ priori\ \mathrm{LLR}}$ from [5]

Soft input bits go through the Viterbi algorithm and return as Log-Likelihood Ratio(LLR), after each iteration the priori LLR is the LLR of the previous iteration, so the priori LLR on the first iteration is 0. The posterior LLR after enough interaction is then mapped into a binary signal.

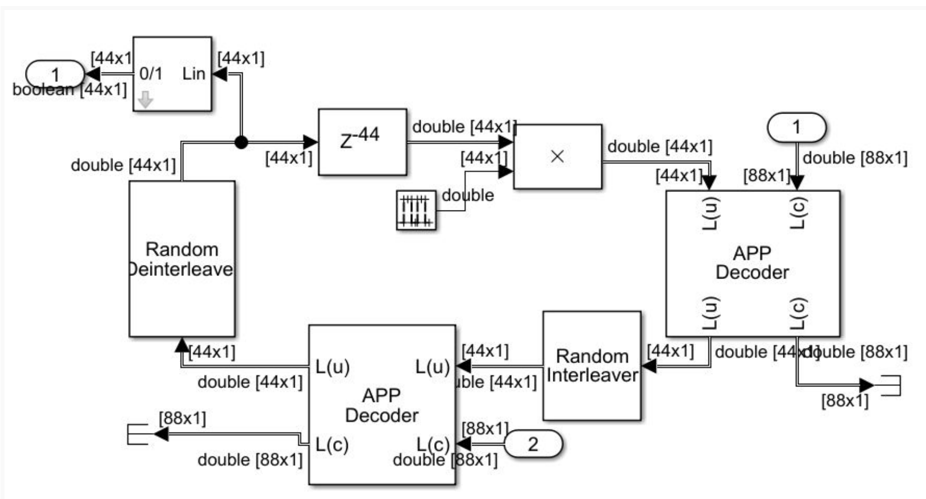

Figure 26 Turbo Decoder

CRC syndrome detector

CRC syndrome detector is a standard simulink block that removes the CRC added by the CRC generator corresponding to the specific polynomial used by the 3GPP standard.

Output

The system outputs the binary sequence as well as the BER of the entire system,
The BER calculation is embedded as

```
function ber = fcn(s2,s8)
y=s2-s8;
z=0;
for i=1:20
    if y(i)~=0
        z=z+1;
    end

end
ber=z/(length(s2)*38);
```

The BER with all system modules at default value is 0.017105, other variations with the channel are given in table 2 and table 3.

The output binary sequence is virtually identical to the input sequence shown in figure 2

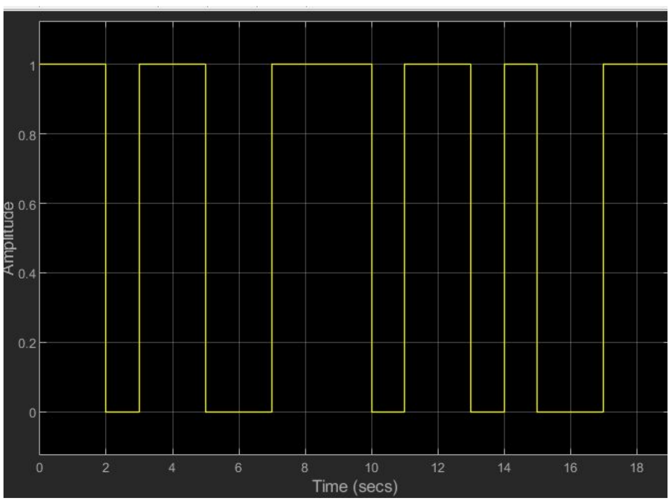

Figure 27 Output binary sequence

Conclusion

In this project we have successfully simulated a functional LTE network.
The key characteristic of a LTE network is it's speed and reliability, which we have accomplished by having low BER despite the high bandwidth of the channel. Without interference in the channel such as multipath fading,path loss, and AWGN, the BER is consistently zero.
Although this is partially due to the fact that this is running in discrete time, while an actual 3GPP LTE system runs in continuous time.

Even with channel interference the largest BER in the system with all the noise and interference turned to maximum is 0.017105, a less than 1% error in signal quality.
This is due to the advanced modulation scheme in LTE such as OFDM that minimize Inter symbol interference. The error detecting capability of CRC coding, and the high performing and effective modulation of 16-QAM to modulate data streams.

In general a real system will encounter more noise and interference than our simulation such as shadowing, shadowing is difficult to account for in a simulation since it's effects are non linear.

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Individual Contribution Summary

Ryan Austin is responsible for all the research and reporting done in part 1 portion of this project.
Zihang Yue is responsible for all the research,coding/simulation,and reporting done in the part 2 portion of this project