FACULTY OF INFORMATION TECHNOLOGY AND ELECTRICAL ENGINEERING

REPORT

LABORATORY WORK FOR WIRELESS COMMUNNICATIONS I

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ABSTRACT

This is a report for a laboratory work for course Wireless Communications I, 521395S. This report covers the work and results of group number 6, whose members are Jiska Parrila and Sakari Veteläinen. The work consists of performing simulations related wireless communication topics in MATLAB and Simulink and analysing and explaining their results as well as calculating certain properties of analyzed signals. The tasks in the laboratory work were split evenly among the group members who would write down their answers as they progressed with their tasks. Once all the tasks were done, they were composed into this report.

Key words: Wireless communication, simulation, signal analysis

TIIVISTELMÄ

Tämä on raportti laboratoriotyölle joka tehtiin osana kurssia Langaton Tietoliikenne I, 521395S. Tämä raportti kattaa tehdyn työn ja sen tulokset ryhmälle 6, jonka jäsenet ovat Jiska Parrila ja Sakari Veteläinen. Työ koostuu langattoman kommunikoinnin aiheisiin keskittyvistä MATLAB ja Simulink simulaatioista ja niistä saatujen tulosten analysoinnista sekä selittämisestä ja joidenkin analysoitujen signaalien ominaisuuksien laskennasta Laboratoria työn tehtävät jaettiin tasan ryhmän jäsenten kesken. Molemmat jäsenet suorittavat tehtävänsä omaan tahtiin jonka ohessa kirjoittavat vastaukset niihin. Nämä vastaukset koostettiin lopulta tähän raporttiin.

Avainsanat: langaton tietoliikenne, simulation, singaalianalysointi

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FOREWORD

The answers here are produced as part of the course Wireless Communication I 521395S at University of Oulu. For all the answers, the course book [1] has been used extensively and it is the primary information source for this report. The lecture videos and slides are also used excessively [2] for formulating some of the answers. As is usual for anyone learning a new subject, the answers may contain errors or be lacking in detail. Therefore they should not be considered to be a reliable source for this topic but more of a show case of learning process.

Oulu, October 29, 2021

Jiska Parrila
Sakari Veteläinen

LIST OF ABBREVIATIONS AND SYMBOLS

AWGN	Additive white Gaussian noise
BER	Bit error rate
BPSK	Binary phase shift keying
DPSK	Differential phase shift keying
Eb/No	Energy per bit per noise
LOS	Line of sight
MIMO	Multiple-input and multiple-output
MPSK	M-ary phase shift keyinh
MRC	Maximal ratio combining
QPSK	Quadrature phase shift keying
SC	Selection combining
SER	Symbol error rate
SNR	Signal noise ratio
TED	timing error detector

1. INTRODUCTION

The following chapters contain the answers to the laboratory tasks that must be completed for this course. Each chapter covers one task and all its subtasks. The chapters are in the same order as they were introduced in the laboratory work assignment. Each of the task chapters contains the original questions as quotes, followed by the answers. Tasks 1, 5 and 6 were answered by Sakari Veteläinen and tasks 2, 3, 4 and extra 1 were answered by Jiska Parrila.

2. SIGNAL PROPAGATION

2.1. TWO-RAY MODEL

"Open the provided Matlab file TwoRayModel.m and familiarize yourself with the simulation parameters. Run the code.

1. Add the figure to your report. Explain the three sections of the two-ray model plot using relevant theory. Read the critical distance from the plot and verify by calculating it."

As we can see in the first sector in Figure 2. when distances are short (d < h_t) the path loss is flat and proportional to $1/(d^2 + h_t^2)$. Power falls of inversely proportionally to distance of the transmitter and receiver $1/l^2$, where the distance $l = \sqrt{d^2 + (h_r^2 - h_t^2)}$. In the second sector when d > h_t the LOS signal and reflected signal are alternately constructive and destructive causing these maxima and minima in the wave pattern due to different travel distances causing phase difference. This phenomenon is known as small scale or multipath fading.

In the last sector when the distance is longer than critical distance d_c the antennas received power starts to drop proportionally to d^{-4}. Now there is only destructive interference because phase difference is at least π. Critical distance can be approximated from $d_c = \frac{4h_th_r}{\lambda}$. From Figure 2. we can read that that the critical distance of the simulated model = log(d) ≈ 3.1 so the distance equals to $10^{3.1} \approx 1259\ m$. When using the approximate equation of critical distance with simulated values, we get a result of approximately 1201 m.

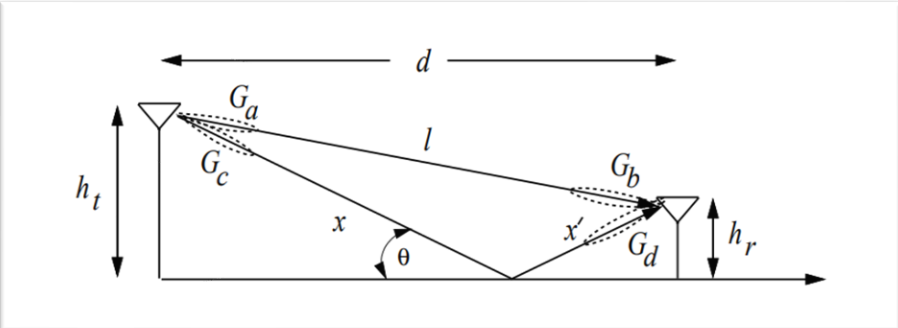

Figure 1. Two-ray model.

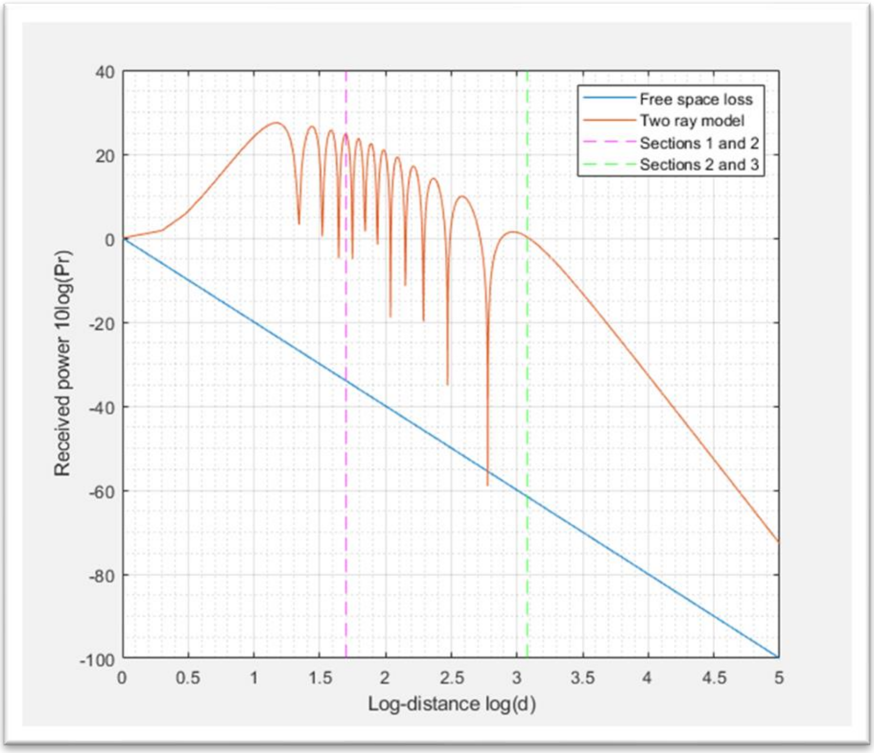

Figure 2. Simulated two-ray model. Received power with function of distance when frequency was set to 900 MHz.

"2. Set the simulation frequency to 9 GHz, run the simulation, and add the figure to your report. Explain the changes to the plot and why the changes happen. Read the critical distance from the plot and verify by calculating it."

Received power of the first sector in Figure 3. drops because path loss is inversely proportional to frequency or proportional to wavelength. In the middle sector the minima and maxima alternate more frequent simply because the frequency is higher. Critical distance in the last sector increases as the wavelength decreases. Critical distance d_c read from Figure 3. is around 12.59 km and by calculating from the equation d_c equals to pretty much exactly 12 km.

"3. What kind of environments is the two-ray model suitable for?"

The critical distance could be useful for example designing cellular systems. If the propagation would follow the critical distance, it could be set for the radius of cell to avoid intercell interference. However, the model is quite dated and propagation in cellular systems rarely follows a two-ray model. Model could still be used for radio channels and cellular networks in flat non-urban areas or over bodies of water with distances of 1-10 km.

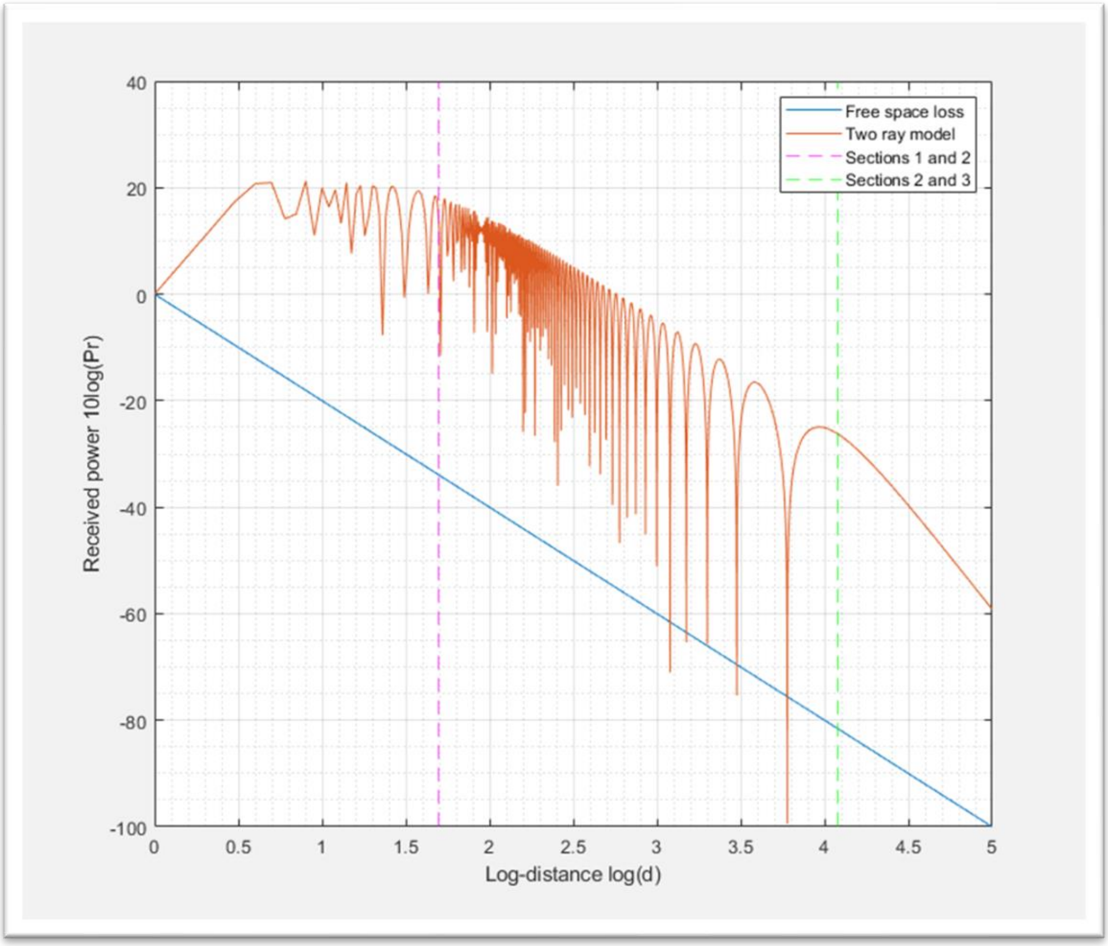

Figure 3. Simulation with frequency of 9 GHz.

2.2. RAY TRACING IN URBAN ENVIRONMENT

"Open the matlab file OuluRaytrace.m. Instead of using run to run the code, use run and advance to run the code one section at a time.

1. Add to your report screenshots of the line-of-sight coverage, non-LOS ray trace and the first line of sight trace. (If you are using Windows, you can use shift + windows key + s to take a screenshot of a part of the screen and directly paste it)

2. How and why does the received power change when the receiver antenna moves?"

In the first scenario (Figure 5.) where receiver is located behind a corner without line-of-sight to transmitter it receives only one reflected ray of signal with power of -63.8dBm (Table 1). After receiver moves to LOS in Figure 6., it starts to receive multiple rays which raises the received power to -42.6 dBm. Change in received power comes mainly from the presence of LOS rays because these rays have zero obstacles in their way that would cause signal attenuation. Antenna also receives higher number of rays with only one reflection which in itself would be enough to significantly better the result.

"3. Is there a significant change in received power with nine reflections enabled? Why? Why not?"

When the maximum number of reflections is raised to 9, we can only see small 1.2 dBm increase in received power. It can be seen from Figure 7. that the rays received through the multiple reflections are attenuated so much that they are of little use compared to the rays passing through the LOS.

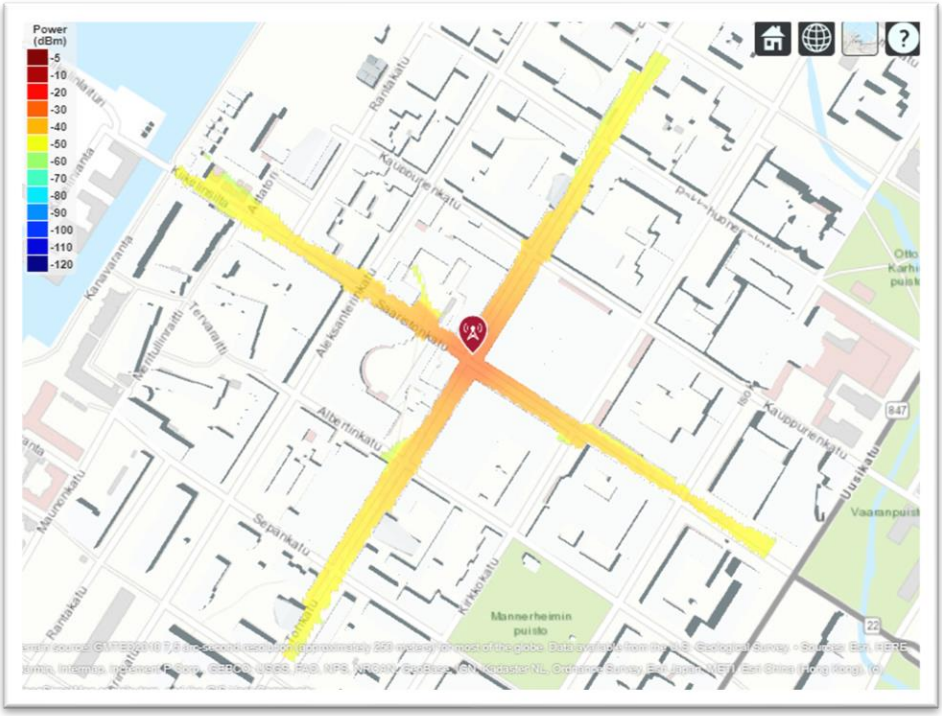

Figure 4. LOS coverage of antenna.

Figure 5. At first, the antennas have no LOS to each other.

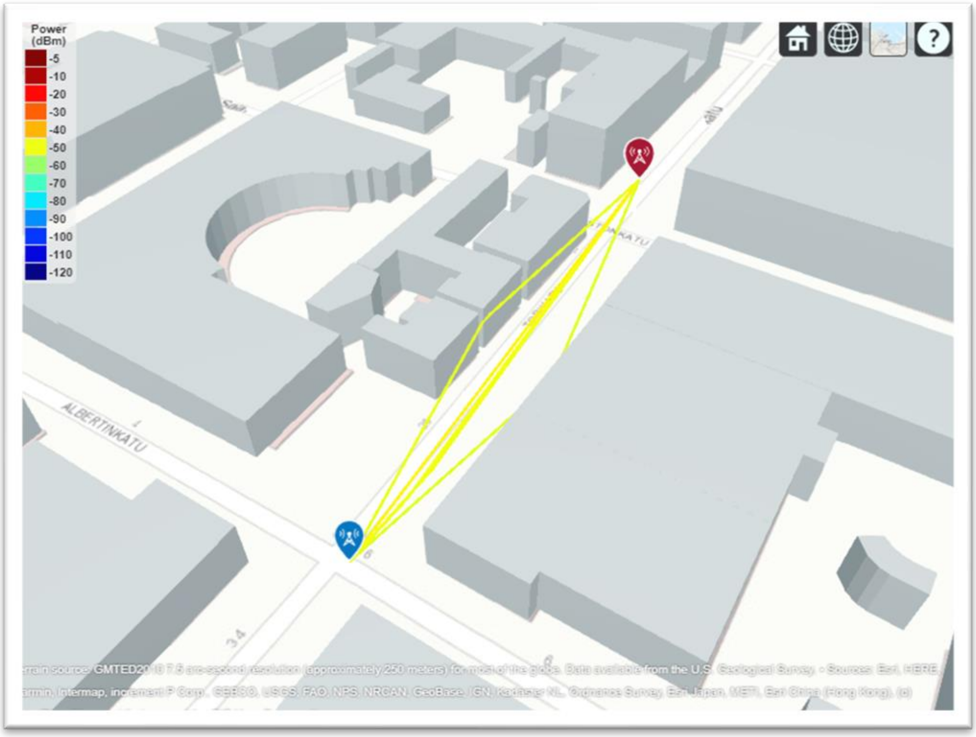

Figure 6. Now receiving antenna moves to LOS of transmitting antenna. Number of reflections is limited to 1.

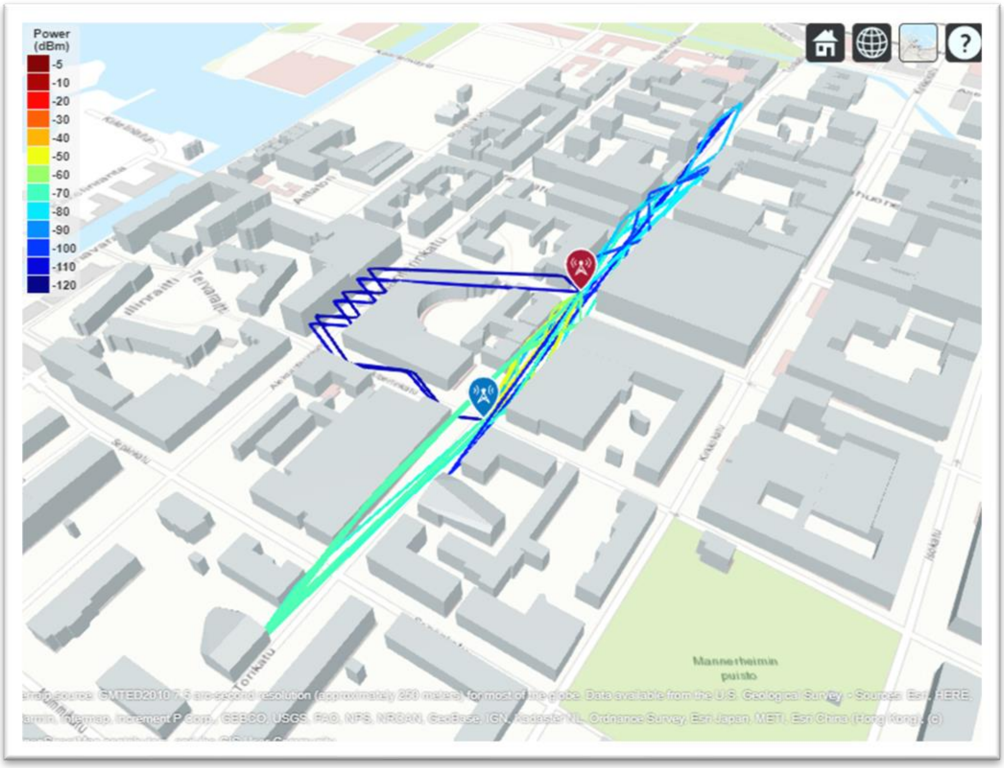

Figure 7. Maximum number of reflections is set to 9.

Table 1 Received power in simulation.

Signal path	Power
Non-LOS received power	-63.8344 dBm
LOS received power	-42.6025 dBm
Nine reflections received power	-41.4018 dBm

3. MPSK IN AWGN CHANNEL

"In this laboratory work, the objectives are to study the performance of BPSK and 8PSK modulated signal in AWGN channel using Simulink model file. The performance metrics in this laboratory work are considered BER (bit error rate) and SER (symbol error rate)."

3.1. BPSK IN AWGN CHANNEL

"In both tasks, you will use the Matlab Simulinkfile MPSK_in_AWGN.slx. Double click on the MPSK_in_AWGN to open it. Get yourself familiar (double click on the block) with the communication blocks used in the schematic. The parameter "M" will be set later. Make sure that MPSK_in_AWGN.slx and MPSK_control.m are in the same folder. Open MPSK_control.m, read the code and run it. Copy the table below (or similar) into your report and write down the BER results into the report."

Table 2 shows the BER rates for the simulation.

Table 2 Simulink simulation BER results with different error to noise ratios.

Eb/No (dB)	BER
0	0,08001
1	0,05851
2	0,03904
3	0,02324
4	0,01236
5	0,00578
6	0,00231
7	0,00077

"1. Plot BER you just recorded while Eb/No changes from 0 dB to 7 dB at 1 dB step. If you are not familiar with using Matlab, you can (should) use the file named plot_help for plotting. Open the file plot_help and read more instructions from there.

2. Compare and print out (you can use plot_help again) the simulated BER of BPSK (task 1) with the theoretical BER. You can generate theoretical BER by using BER toolin Matlab. To open BERtool, type to the Matlab prompt"

Figure 8. shows the BER rate of the simulated signal as well as the theoretical BER rate. It can be seen that they match closely with one another.

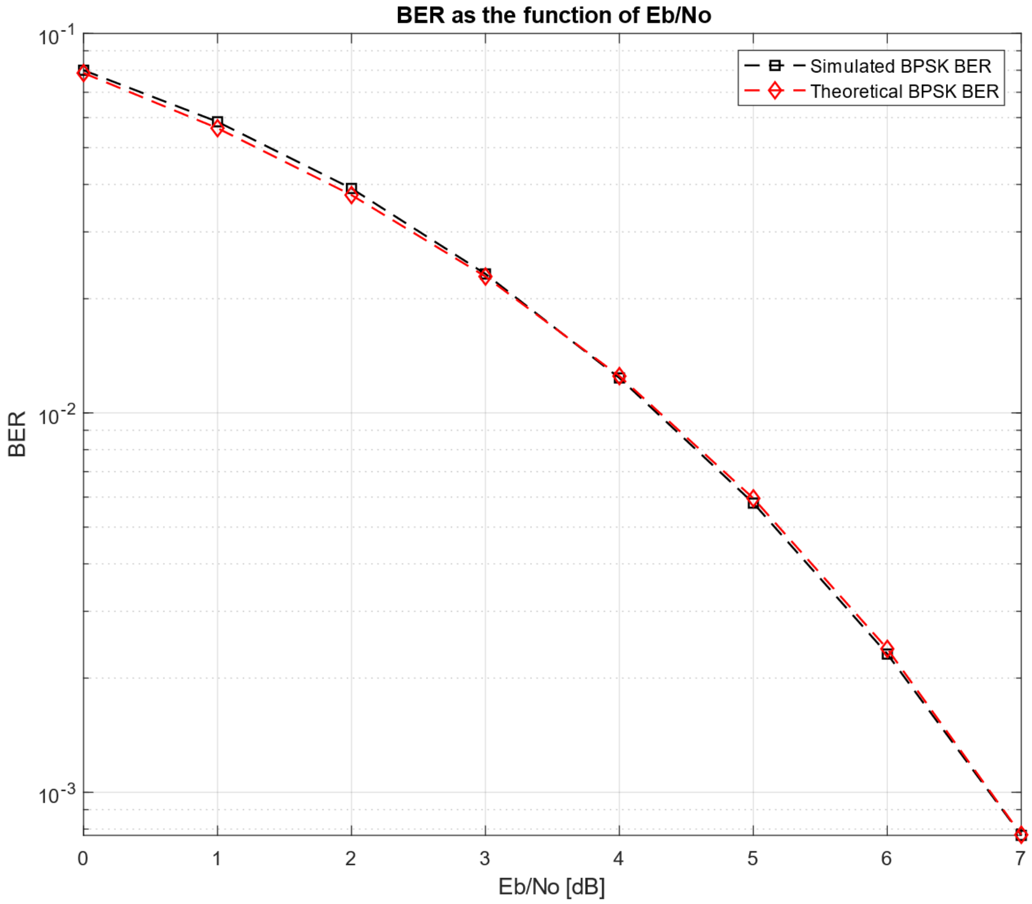

Figure 8. Simulated and theoretical BER values of a BPSK signal over 0 to 7 dB Eb/No.

3.2. 8PSK IN AWGN CHANNEL

"1. Change the modulation order in the code to change the simulation model into 8PSK.

Changing the modulation order for the simulation was done by changing the value of variable M in MPSK_control.m Matlab script.

2. Run the code, write down (copy the table from previous page into your report) and plot BER and SER of 8PSK while Eb/No changes from 0 dB to 7 dB step by 1 dB by using for example plot_help.

3. Compare the BER and the SER of 8PSK and comment on it."

The BER and SER values from the simulation are presented in Table 3. The same signal is seen in Figure 9. and is an 8PSK signal with AWGN mixed into it. The signal uses Gray coding for coding symbols into its constellation. Each symbol encodes three bits. Observing the simulation's numerical BER and SER values, the SER appears to be roughly ~3 times higher than BER at any of the simulated transmission powers. This can be explained as follows; due to Gray coding each adjacent symbol only differs by one bit. The constellation is circular and so the minimum distance between each constellation point is equal. The AWGN noise mixed into the signal has higher likelihood to produce errors that result in a neighbouring symbol to be decoded from the signal by the receiver, as opposed to a more distant symbol. As such, any error in the transmission is more likely cause a one bit error or 1/3 of a symbol. Therefore, for majority of errors, only one bit will be erroneous whilst a whole symbol will be erroneous. As there is no error correcting coding scheme, all three bits that form a symbol must be discarded as it is impossible to tell which of the bits is erroneous, thus explaining the ~3 times higher error rate of SER when compared to BER.

As the energy per bit is increased, the error rate too decreases. This is logical as the SNR improves when more power is used to transmit a signal.

Table 3 Simulink simulation BER and SER results at different error to noise ratios.

Eb/No (dB)	BER	SER
0	0,12470	0,35241
1	0,10074	0,29133
2	0,08085	0,23721
3	0,06094	0,18135
4	0,04709	0,14098
5	0,03239	0,09716
6	0,02024	0,06072
7	0,01185	0,03556

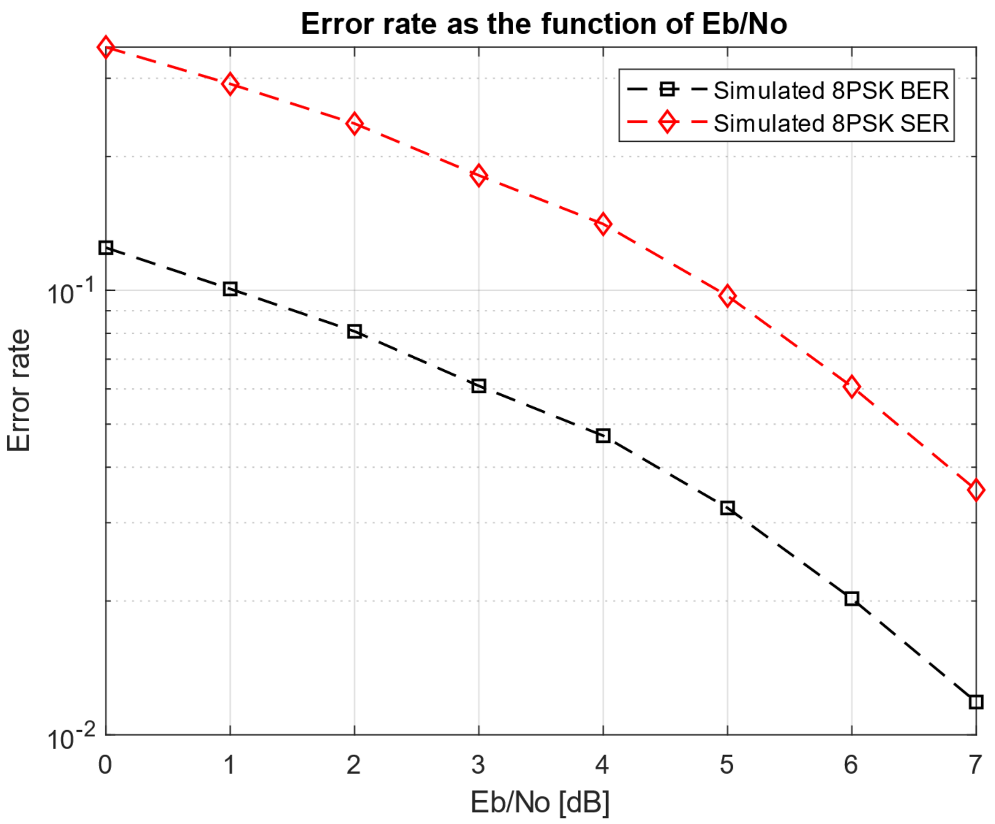

Figure 9. Simulate BER and SER values of a simulated 8PSK signal

"4. Compare the BER of BPSK and 8PSK. Why does the BER change as the modulation order increases and what can be done to compensate for it?"

As can be seen from Figure 10., 8PSK has larger BER than BPSK and it decreases more slowly than BPSK's BER as transmission power is increased. The difference in BER rates is due to the minimum distance between the constellation points of the signals. The larger the M is in a PSK modulation, the smaller the minimum distance d_{min} between the constellation points becomes. Smaller minimum distance means that less noise caused distortion is needed in the carrier signal for a symbol to be erroneously decoded in the receiver.

Figure 10. shows that increasing energy per bit decreases the BER. This is because increasing energy of a transmission signal increases its amplitude. Higher amplitude causes the constellation points to move further from the origin which causes the minimum distance to increase, thus requiring more noise in order to cause an error. Further increasing the transmission energy would yield lower BER but this is not the only way to decrease it. Other techniques to lower the BER include using soft decision techniques at the receiver side which allow more information to be extracted from the signal that help in correcting errors.

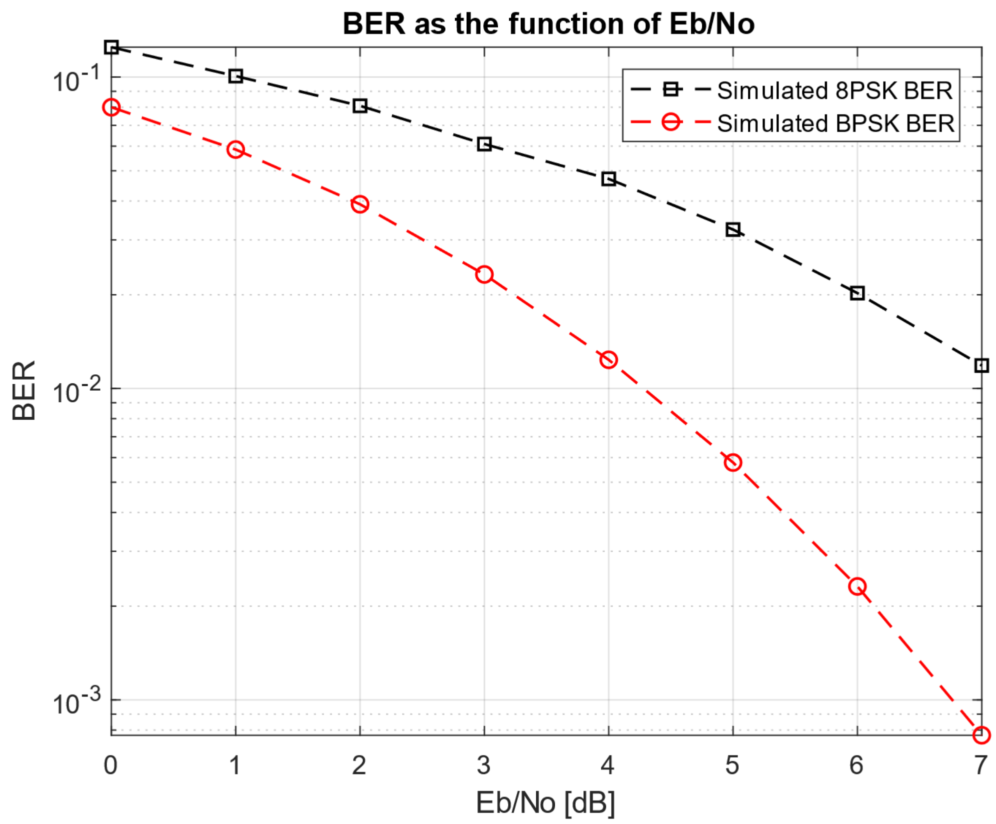

Figure 10. BER of simulated BPSK and 8PSK signals over increasing Eb/No values

"5. Draw the constellation diagram of 8PSK where the symbols arranged with Gray coding. Explain what Gray coding is and how it differs from binary coding."

Gray coding is a channel symbol coding scheme where adjacent constellation points of a modulation only differ by one bit (illustrated in Figure 11.). As stated earlier, this makes it somewhat easier to mitigate error propagation (at least in an AWGN affected signal space). In case of an error, it is far more likely that only one bit is falsely decoded than more due to neighbouring symbols only having a single bit of difference and AWGN "favouring" errors that result in neighbouring constellation points instead of ones that are further away from the transmitted symbol.

Binary coding is another channel symbol coding scheme. It simply enumerates each constellation point in order and does not consider errors in signal transmission whatsoever. This causes the BER of this coding scheme to be higher than that of Gray coding as an error may cause one to three bits to be falsely decoded, depending on at which constellation point the error occurred and to which direction. Running the 8PSK simulation with coding scheme changed to binary and comparing it to a run done with Gray coding agrees with this statement. See Figure 12.

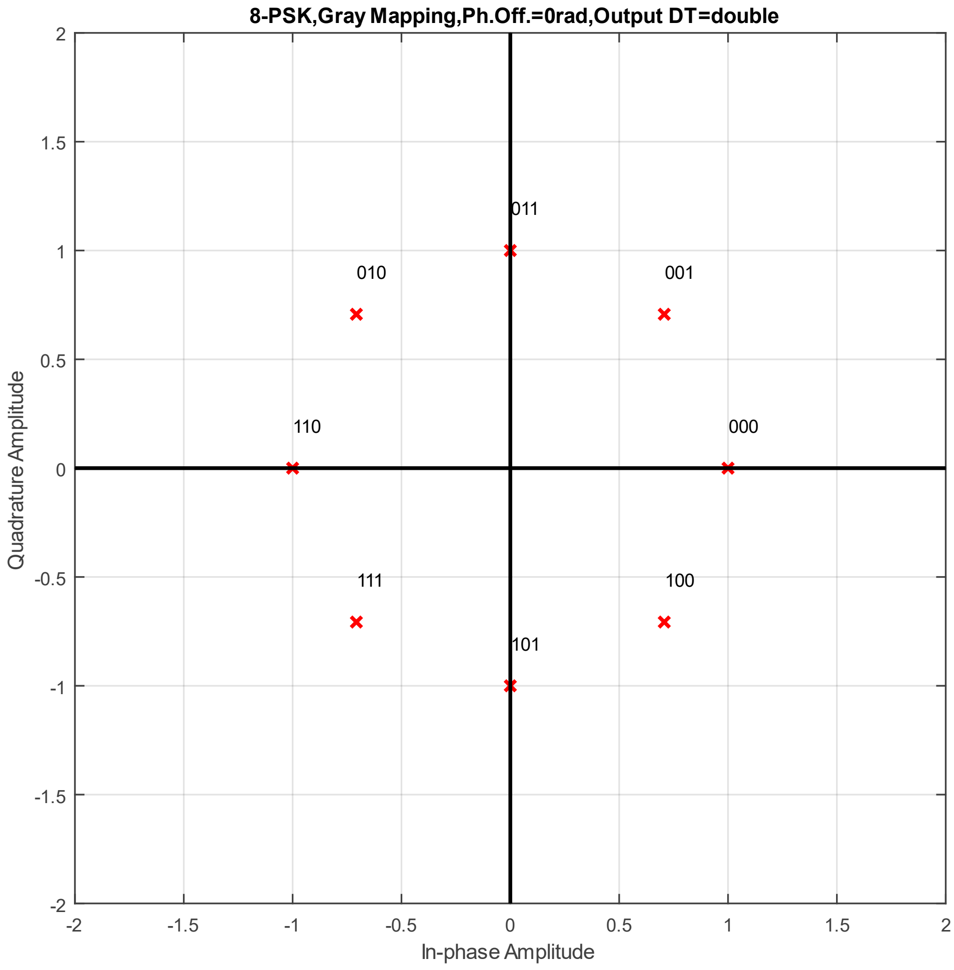

Figure 11. Constellation of an 8PSK signal with Gray coding

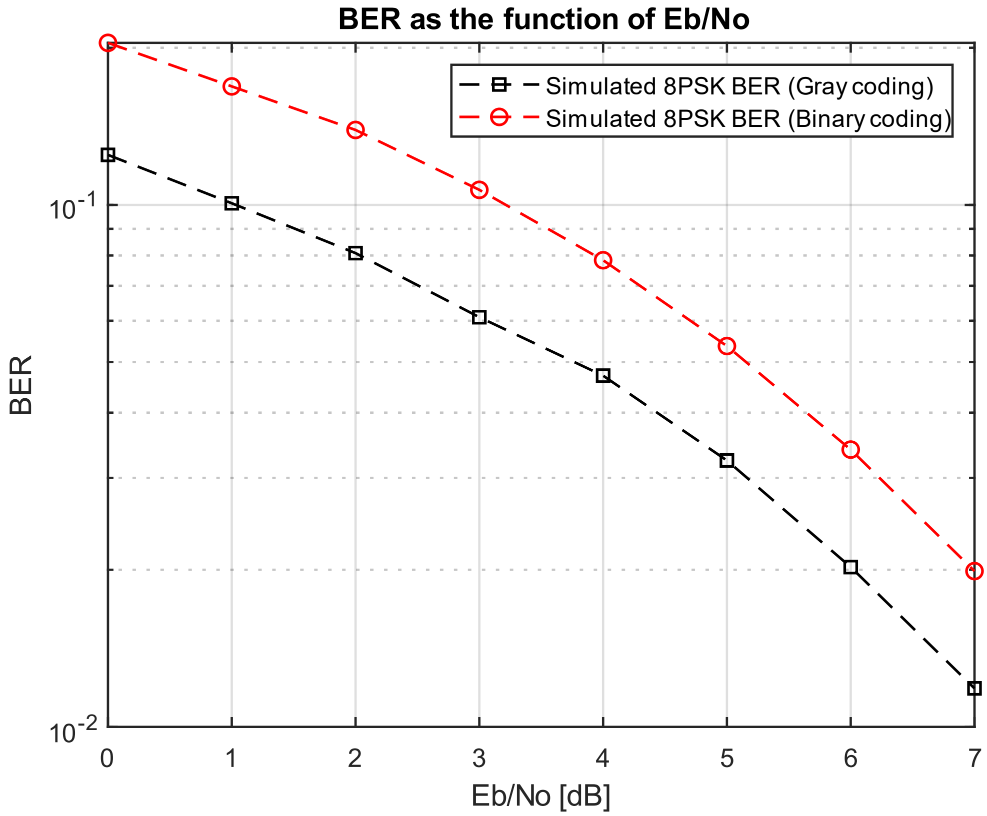

Figure 12. BER of two 8PSK signals. One uses Gray coding, other uses binary coding.

4. DPSK IN RAYLEIGH FADING CHANNEL

"Unlike in chapter 2, here we use MATLAB scripts to simulate differentially coded BPSK (DPSK) modulated signal in Rayleigh fading channel. In this assignment, three m-files have been provided to perform the following tasks (HINT! Read questions very carefully)

1. Calculate (hint: use the value 3 x 10^8m/s for the speed of light) different Doppler shifts when carrier frequency (fc) is 800 MHz and use it as input to the file channel_plot.m for the following cases: a. velocity=27km/h b. velocity=151.2km/h. (hint: second parameter in comm.RayleighChannel function is the Doppler shift value that you should change depending on the situation). Print out the results and comment on it."

The formula to calculate Doppler shift of a signal:

$$f_D = (v / \lambda) \cos \theta = (v / (c / f_c)) \cos \theta \qquad [1, p. 30]$$

Let $c = 3 * 10^8$ m/s
$f_c = 800$ Mhz $= 800\ 000\ 000$ Hz
$\theta = 60°$

Angle θ is chosen arbitrarily to somewhat reflect real life scenarios, to be reasonable in a Rayleigh fading channel and to keep the calculations simple.

Let $v = 27$ km/h $= 7.5$ m/s

$$\begin{aligned} f_D &= (v / (c / f_c)) \cos \theta \\ &= (7.5 / ((3 * 10^8) / 800\ 000\ 000)) \cos(60) \\ &= 20 \cos(60) \\ &= 10 \end{aligned}$$

Let $v = 151.2$ km/h $= 42$ m/s

$$\begin{aligned} f_D &= v \cos(\theta / (c / f_c)) \\ &= (42 / ((3 * 10^8) / 800\ 000\ 000)) \cos(60) \\ &= 112 \cos(60) \\ &= 56 \end{aligned}$$

Figure 13. depicts a single path for two signals in Rayleigh fading channel. It can be seen that a receiver with higher velocity relative to the transmitter suffers more from the fading effect. While both signals appear to have occasional gain in them, majority of the interference causes fading. The downward spikes in the signal received by the faster moving receiver manifest themselves as deep fades in the signal and cause symbol errors.

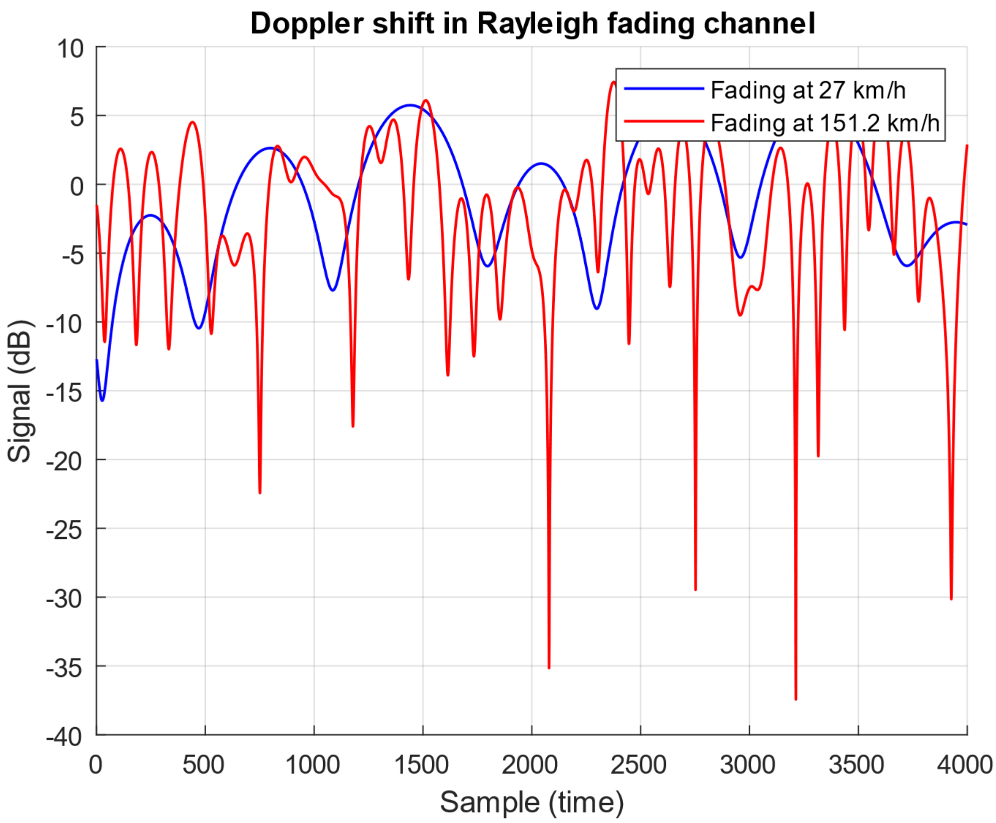

Figure 13. Two signals received in a non-static aerial configuration at different velocities and under the effects of Doppler shift

"2. Plot the BER performance of differentially coded BPSK modulated signal in fading channel using DPSK_fading.m. In this case, use the calculated Doppler shift value in Task (1a). Comment on the result."

As seen in Figure 14., for most transmission powers the theoretical BER matches with the empirical BER at low velocities which imply low Doppler shift. At higher transmission powers, there appears to be a bit of divergence between the two models. For both models, the BER decreases almost linearly as transmission power increases.

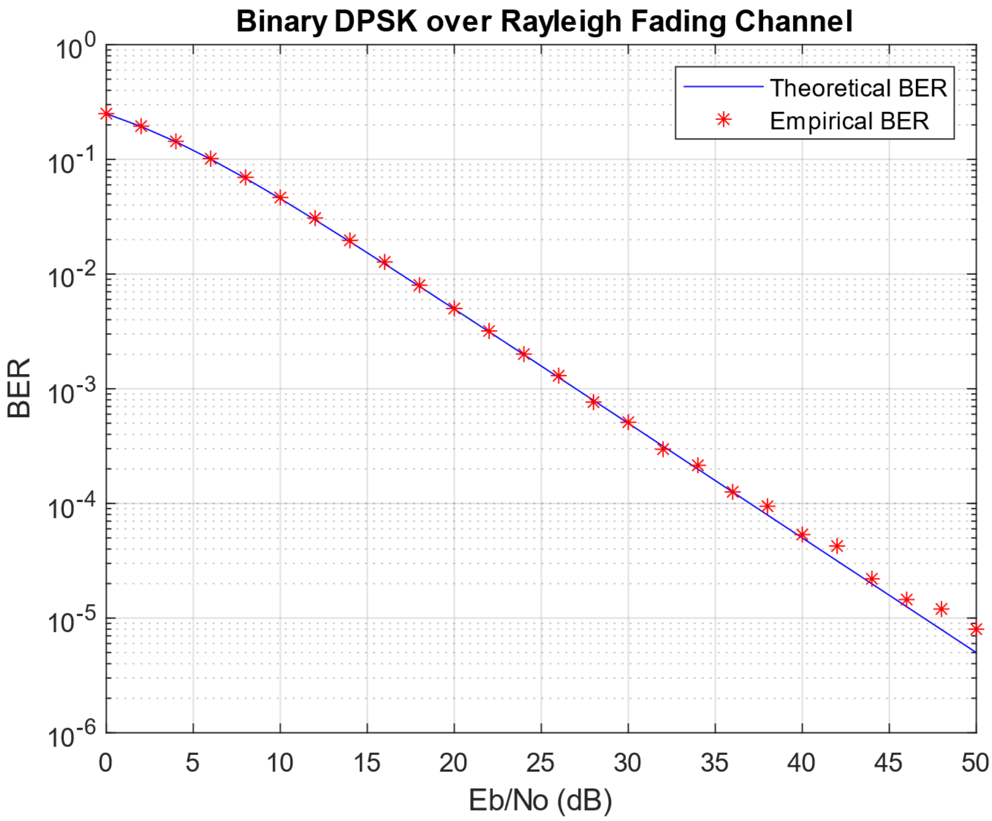

Figure 14. BER of a DPSK signal in Rayleigh fading channel with an aerial moving at 27 km/h

"3. Plot the BER performance of differentially coded BPSK modulated signal in fading channel using DPSK_fading.m. In this case, use the calculated Doppler shift value in Task (1b). Comment on the result and compare it to the result you got on task 2. Why the Empirical saturates comparing to the Theoretical (Hint: look at Goldsmith's book and read "help berfading")?"

The theoretical and empirical BER values are nearly equal up until ~30 dB Eb/No, after which they diverge as shown in Figure 15. The empirical BER rate no longer decreases as the transmission power is increased. This is because DPSK — Differential Phase Shift Keying — is a differential modulation technique, which is susceptiple to an irreducible error floor due to Doppler spread. Doppler spread in this case causes inter symbol interference as the differently timed signals decorrelate with each other's phase, which is used as symbol reference point in differential modulation, creating high levels of noise in the phase.

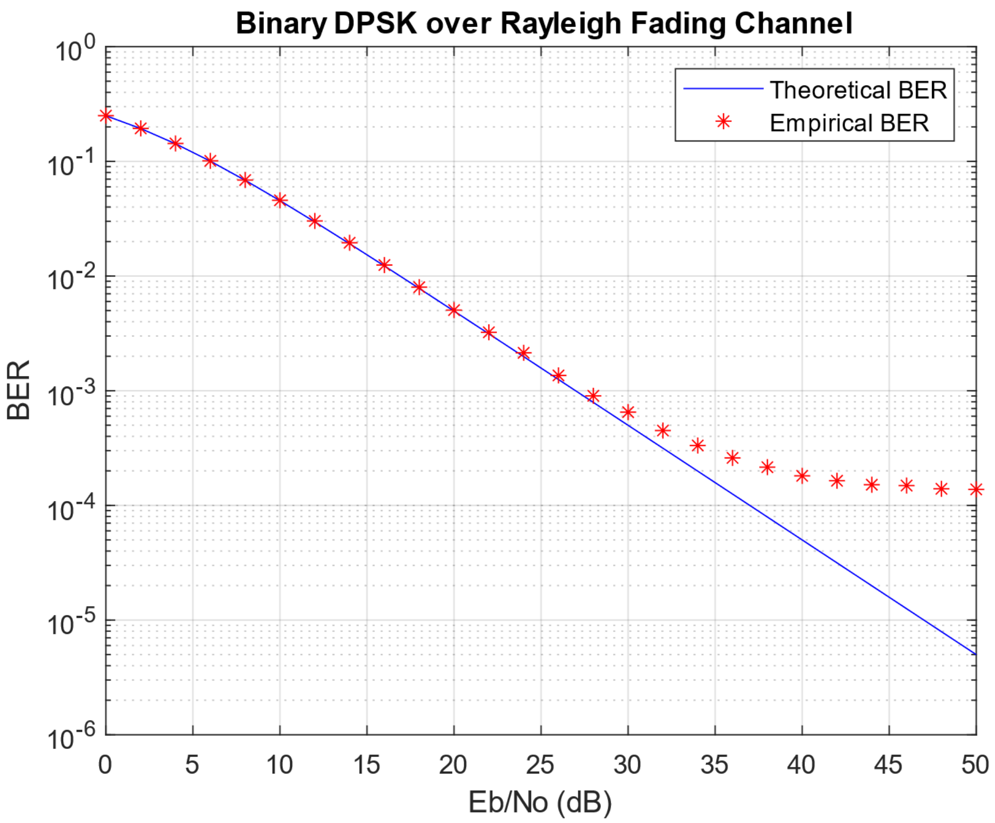

Figure 15. BER of a DPSK signal in Rayleigh fading channel with an aerial moving at 151.2 km/h

"4. Calculate (using equations and numbers, mark every "middle part" of your calculation visible also; in other words: write your thinking visible) and explain the theoretical irreducible error floor for DPSK (hint: look at Goldsmith's book at page 193; copy of that is in the Moodle). Make your calculations using Gaussian Doppler power spectral model and correlation coefficient. You must activate (you will find more info from the MATLAB code) Gaussian Doppler power spectral model on the model DPSK_fading.m. Compare the calculated (by using equations) theoretical result to the result you get from the simulation (empirical result), when the Doppler shift value is the same as Task (1b). HINT! You may find DATA CURSOR - MATLAB Tool useful for finding accurate simulation result values."

Irreducible error floor

$$P_{floor} = ((1 - \rho_C)e^{-K})/2 \qquad [1, p. 193]$$

For Rayleigh fading channel K = 0, thus the equation can be simplified to

$$P_{floor} = (1 - \rho_C)/2$$

Rayleigh channel correlation coefficient

$$\rho_C = exp[-(\pi B_D T)^2]$$

Maximum Doppler is $B_D = f_D$, thus ρ_C becomes

$$\rho_C = exp[-(\pi f_D T)^2]$$

Substituting the variables in simplified P_{floor} yields

$$P_{floor} = (1 - exp[-(\pi f_D T)^2])/2$$

As per the the task 1b, the variables can be defined as follows,

$$Let\ f_D = 56$$
$$P_{floor} = (1 - exp[-(\pi f_D T)^2])/2 = (1 - exp[-(\pi T(56))^2])/2$$

5. DIVERSITY

"This section highlights comparison of transmit vs. receive diversity by simulating coherent binary phase-shift keying (BPSK) modulation over flat-fading Rayleigh channels. For transmit diversity, we use two transmit antennas and one receive antenna (2x1 notational), while for receive diversity we employ one transmit antenna and two receive antennas (1x2 notational) or four receive antennas (1x4 notational).

The simulation covers an end-to-end system showing the encoded and/or transmitted signal, channel model, and reception and demodulation of the received signal. It also provides the no-diversity link (single transmit-receive antenna case) for comparison. Here it is assumed that the channel is known perfectly at the receiver for all systems. We run the simulation over a range of Eb/N0 points to generate BER results that allow us to compare the different systems.

MATLAB files named mimo.m and mrc1m.m have been provided to investigate transmit diversity as well as receive diversity.

TASKS: Go through the MATLAB codes and familiarize yourself with variables used in the m-files. Run simulation by writing down in your MATLAB prompt >> mimo

1. Print out the plot and interpret the results. Remember (again) to write theory enough and explain to results through that theory."

The simulation uses BPSK modulation over different diversity setups. It sends 10 000 packets, each of which are 120 bits long. This operation is carried out at different transmission powers ranging from 2 to 22 Eb/No in increments of 2 dB. It can be clearly seen that increasing transmission and/or receiving diversity leads to reduced BER. The effect increases as transmission power increases. As the simulation does not define any frequency nor bandwidth at which the signal is transmitted, it can be assumed that the diversity is achieved through space diversity.

Let us first consider the receiver diversity. In this simulation receiver diversity makes use of multiple aerials to receive the same carrier signal that has travelled through multiple paths, each with different fading amplitude. In order for each of the aerials to receive the signal with roughly independent fading amplitudes, they must be set sufficiently apart from one another. How distant they must be depends on the transmitter type. Multiple receivers allow combining the signals each of them received, leading to improved SNR. There are different methods for combining the signals. Selection combining (SC) outputs the signal from a branch with the highest SNR, so it chooses the best branch and changes it as needed. Maximal-ratio combining (MRC) the combination is a weighed sum of all the received signals where signals that are likely faded (low SNR) are attempted to be eliminated with the smaller coefficients where as signals that have not faded (high SNR) are stressed with larger coefficients. As per the equation 7.1 in the course's book, it can be seen that increasing the number of receivers improves the SNR when there is no fading. This is called array gain. With fading, the SNR improvement is not as significant but it still exists and is called diversity gain.

Transmit diversity in this simulation makes use of multiple aerials. Only one such signal is simulated and it performs better than one without diversity but worse than the receiver diversity simulated signals. The transmitter does not have prior knowledge of its channel. As in, the transmitter does not know the path gain of the channel and thus can not perform weighing on each of the aerial's transmission energy. Instead it uses Alamouti scheme. Alamouti scheme uses space and time diversity by sending each symbol twice over two symbol periods over a complex signal space. Both aerials have the same transmission energy. During the first symbol period, two symbols s_1 and s_2 are sent simultaneously, one from each aerial. Then, both symbols have their complex conjugate calculated and the complex conjugate of symbol s_2 is negated. The new symbols are then transmitted during the next symbol period from the opposite aerial from which they were originally transmitted. The receiver must have all four symbols over the two symbol periods in its memory in order to calculate their values from them. As can be seen from the simulation graph, this scheme does yield improvements over having no diversity at all and closely matches the theoretical 2nd order diversity, which is a maximum rate for a dual aerial transmitter. Though it does not achieve as good results as MRC techniques. A downside of this technique is the decreased bandwidth as each symbol is effectively sent twice, halving the bitrate.

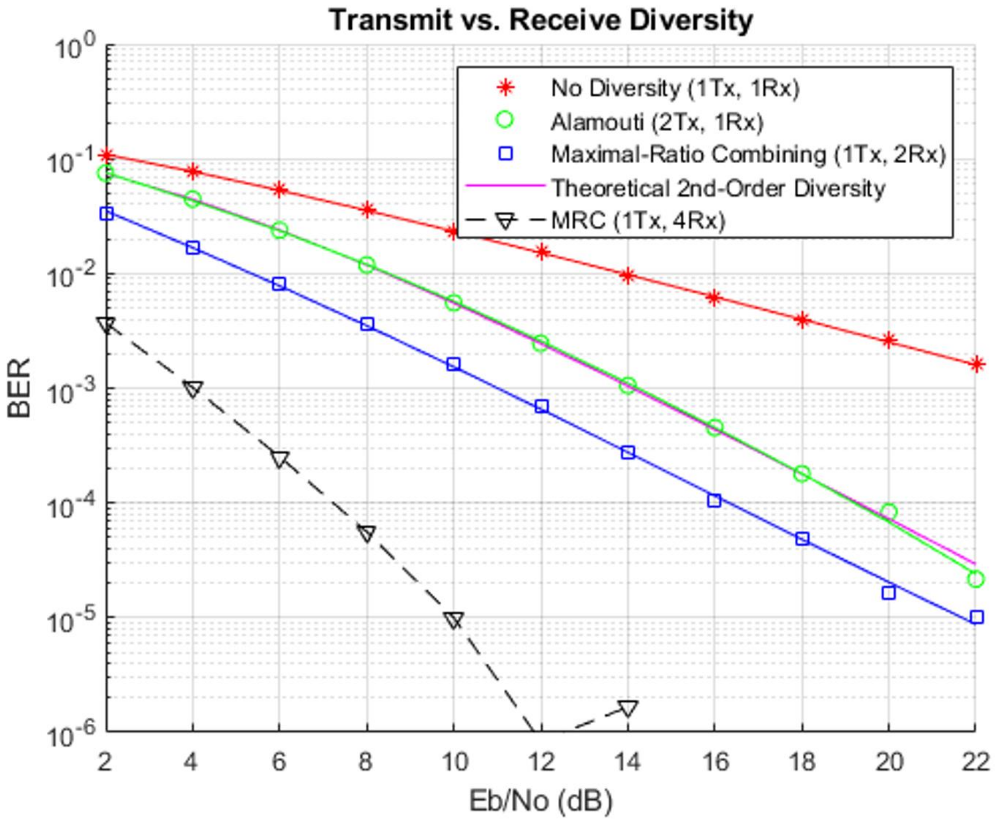

Figure 16. BER of different diversity setups with varying number of aerials and theoretical 2nd-Order diversity.

"2. There are five different curves in the plot now. Try to implement a new curve to the plot by altering the code. What technique did you use? How your implementation performed compared to other curves?"

From a long-time programmer's perspective, the simulation code is a mess and takes far too long to run considering the amount of work it is doing. While reading through to see how it works, it was only natural to split it into multiple smaller functions to make it easier to grasp the individual parts of it. Combining the theory from the course's book yields a well covering understanding of what the program is doing. Once it was understood, by far the easiest way to introduce a new, yet uninteresting curve into the simulation, was to call mrc1m with a different number of receivers and introduce the necessary variables to hold the results for plotting. Along with this change, the performance of the simulation program was improved significantly by making the outer loop run in parallel. This made the simulation runtime drop from ~45 seconds to less than 5 seconds. Though this improvement came with the cost of greatly increased memory consumption, measured in several gigabytes.

The number of receivers was chosen to be three; nicely between the already present four and two. As can be expected, the performance of a tri-aerial receiver falls nicely between the two and four aerial ones. (Figure 17.) To make this change just a little more interesting, four more curves were added for MRC receivers with five to eight aerials. This is depicted in Figure 18. The results are as could be predicted; adding aerials decreases the BER but does appear to lead towards diminishing returns as the rate at which BER decreases does not decrease linearly with the number of receivers (Notice the logarithmic y-axis).

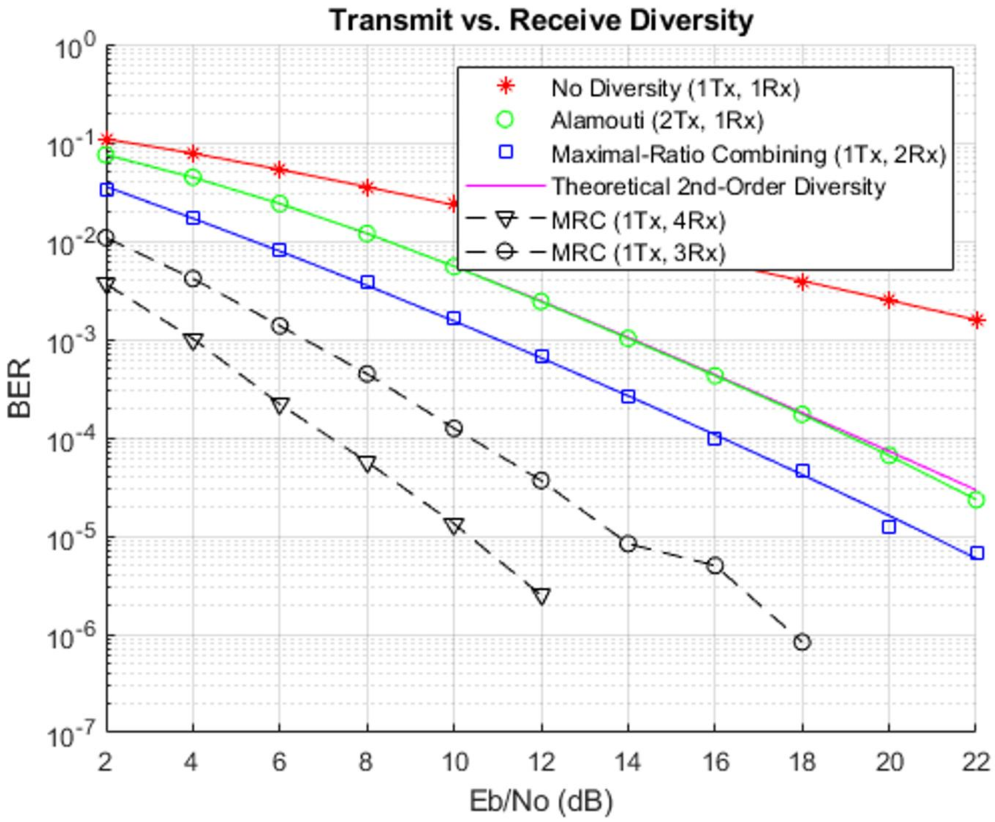

Figure 17. BER of different diversity setups with varying number of aerials.

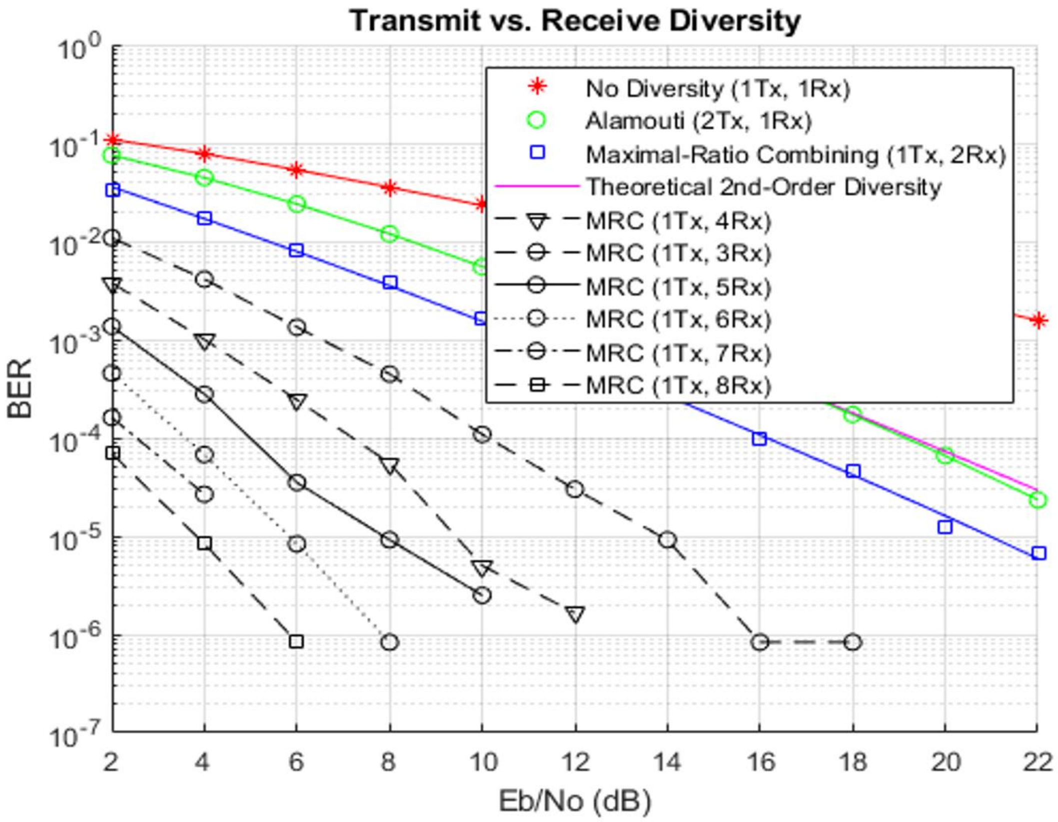

Figure 18. BER of different diversity setups with varying number of aerials.

6. SYNCHRONIZATION

"In this laboratory work, a Simulink file named symbolnframesync has been provided. In this Simulink file, there is a QPSK channel with symbol and frame synchronization.

1. Get familiar with the Simulink file. Explain purpose of every block in it. Why each of them is needed in the simulation? Hint: You can use MATLAB documentation as help."

At the beginning of the model bit frame is generated with the help of Bernoulli binary generator. Data is then modulated by using 4-QPSK which is a nonlinear modulation method. After modulation the shape of the pulse is modified with raised cosine transmit filter to minimize intersymbol interference. Before data is sent to the AWGN channel "Variable Fractional Delay"-block adds delay to the sent signal. The amount of delay is defined by "repeating sequence stair" -block where amount of delay mimics a stair sequence, and that sequence repeats periodically.

After going through AWGN-channel the demodulation process begins. First the data goes through raised cosine receive filter to a symbol synchronizer where pulse is shaped back by downsampling. This synchronizer is based on PLL-algorithm (phase-locked loop) and consists of four key components: interpolator, TED, loop filter and interpolation control. In interpolator time delay is estimated from samples received which are then aligned with the symbol boundaries by "moving" them closer to correct time. A feedback loop that consists of the remaining three components is needed to fine tune the synchronization. TED then estimates if there are any timing errors remaining in this case by zero-crossing method that requires 2 samples per symbol. Estimate is made by examining the sign of the in-phase and quadrature components of signals passed to the synchronizer. Loop filter consists of a proportional gain K_p summed with an integrator gain K_I . It is called a Proportional Integral (PI) or Lead-Lag filter. Lastly to finish the feedback loop to interpolation control provides the fractional interval between previously interpolated sample and correct timing if I understood correctly.

After synchronization QPSK is then demodulated the data packets are detected in preamble detector for frame synchronizer. Inputs to frame synchronizer can vary or be different length than wanted so frame synchronizer outputs frames with specified length which is in this case 200 bits. After all this BER is calculated and displayed for branch with and without symbol synchronizer to show the improvement of the BER with synchronizer.

"2. What can you tell about simulation? Why constellation diagrams are different before and after symbol synchronization. Why synchronization improves the results?"

As we can see from the Figure 19. the constellation has greatly improved after symbol synchronization because in-phase and quadrature components of QPSK are better aligned. Especially the zero-crossing which was the TED method used is very practical solution to estimate timing errors in QPSK.

From Figure 20. and Figure 21 it can be seen that when the SNR drops, the effect of the synchronization starts to diminish. Especially at 0 dB SNR since the signal drowns in noise it becomes very difficult to correctly align in-phase and quadrature components.

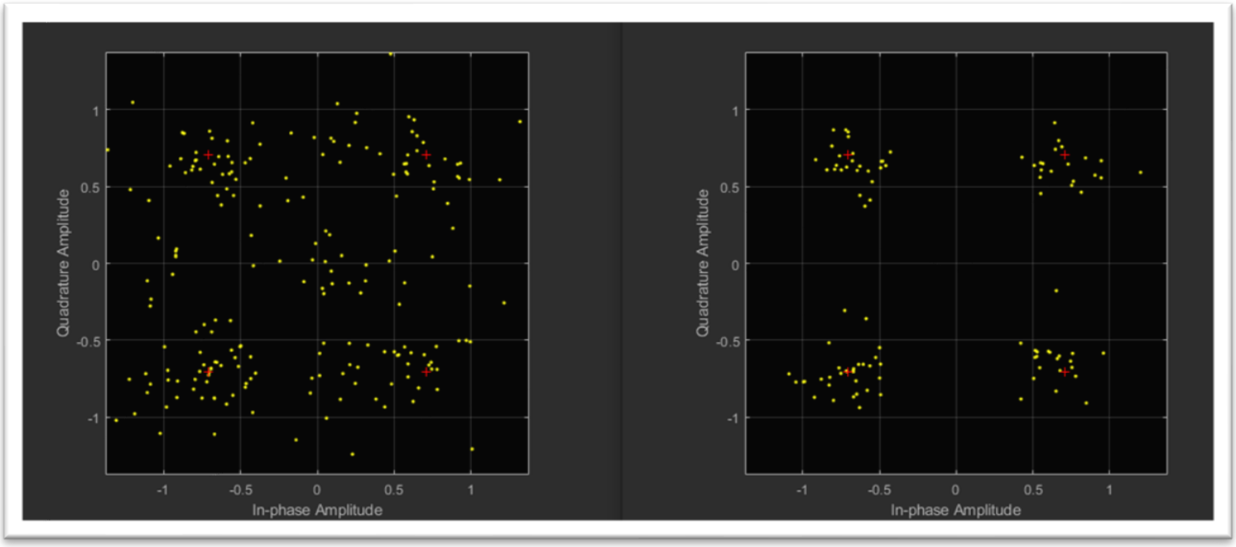

Figure 19. Constellation diagrams before and after symbol synchronization. SNR was set to 10dB.

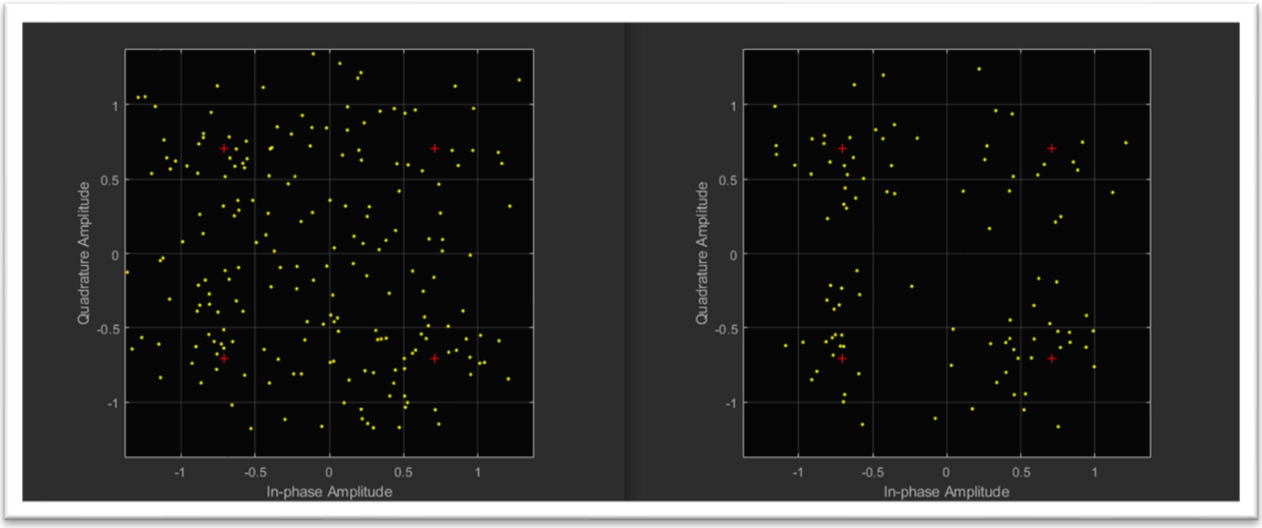

Figure 20. Constellation diagrams with SNR set to 5 dB.

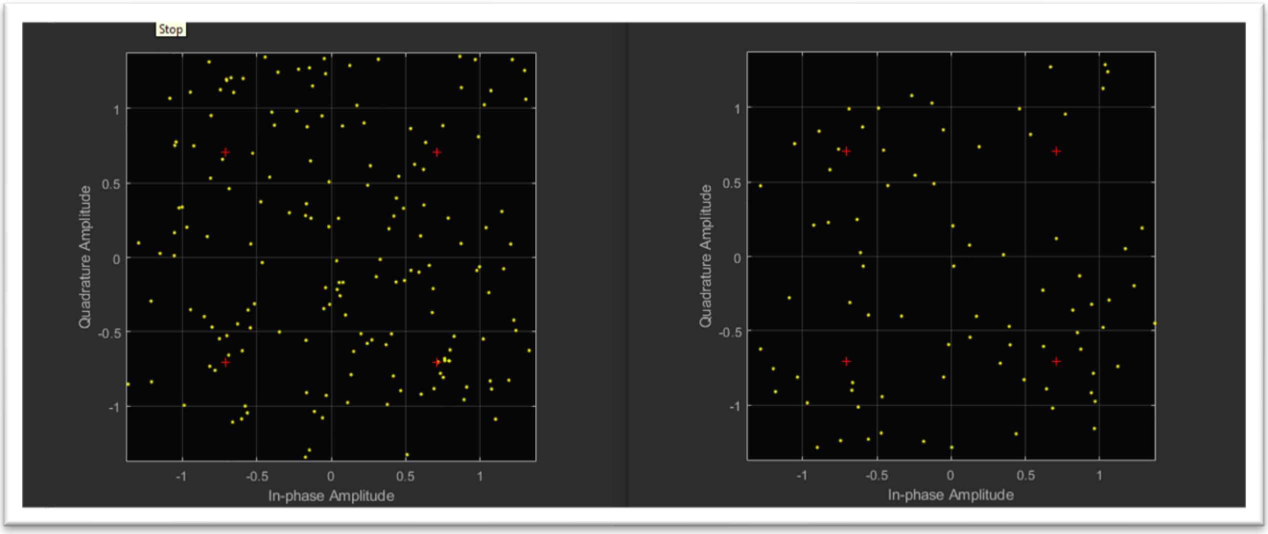

Figure 21. Constellation diagram with SNR set to 0dB. Simulation was stopped near the end of it as the constellation after synchronization would blank in the end.

"3. Run the simulation with SNR values 10dB, 5dB and 0dB. What can you say about the constellation diagrams? what happens to the synchronization as the SNR lowers?
4. Run simulation with the same SNR values as in task 3. Write down BER values from each simulation. What can you say about the BER values in each simulation?"

With 10 dB signal-to-noise ratio the model detected only 31 errors out of 898200 bits which comes up to 3.451E-5 BER as can be seen in Table 4. If we consider BER of 1E-9 acceptable for modern telecommunication systems, with added error correction by coding this model could satisfy those requirements with 10 dB SNR. Using 5 dB SNR the BER with symbol synchronization worsens drastically but is still around nine times better than without it. This could be simply explained by the fact that model has a hard time detecting the sent signal from the noise since SNR is starting to get low. Finally with 0 dB SNR I assume that the signal can only be detected from the noise when it's close to its peak because bit error rates around of 0.43 is almost as good flipping a fair coin.

Table 4 BER values from each simulation.

Signal-to-noise ratio	BER without Symbol synchronization	BER with symbol synchronization
10 dB	0.2496	3.451E-5
5 dB	0.3528	0.04688
0 dB	0.4258	0.4332

7. PERFORMANCE OF CHANNEL CODING METHODS

"In this task, channel coding is studied with the help of a Simulink model. The model displays the stages of encoding and decoding of Hamming code. The codeword is modulated with BPSK and sent through an AWGN channel. In the first part you are asked to study the error correction mechanism of Hamming codes. In the last parts you will see how coding affects BER performance.

1. Open the MATLAB file codingexample_control.m and use run and advance to run the first part of the code to set the simulation parameters. Use step forward in the Simulink model and study the binary numbers in the displays until you get one bit error (indicated in the "Bit errors" display). Is there a difference between the transmitted and received messages? Explain using theory how the error correction works. What happens when you get two or more bit errors? How does the error correction perform?"

First error was found in the model when sending out the 6th 4-bit binary number "1111" which in Hamming (7,4) produced codeword of seven 1-bits (1111111). After the codeword was transmitted with BPSK modulation over the AWGN-channel it had one bit wrong which was then detected and corrected in Hamming decoder. So, although there was an error in received codeword after demodulation we know from the lectures that (7,4) Hamming code can detect 2 errors and correct 1 error, as was shown in the model.

Error detection is based on comparing received parity bits with the calculated parity bits in the decoder. The parity bits are the 3 extra bits added to the data in order shown in Table 5.

Table 5 Position of data and parity bits in the codeword. p_i marks parity bit. d_i marks data bit.

Position	1	2	3	4	5	6	7
	p_1	p_2	d_1	p_3	d_2	d_3	d_4

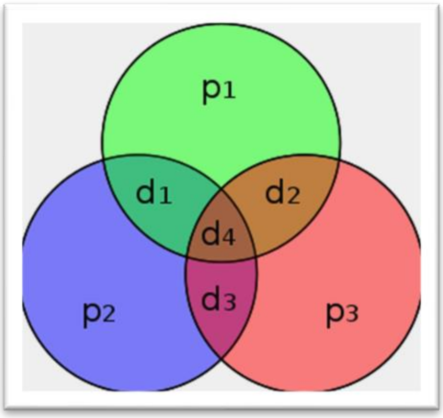

Figure 22. Graphical depiction of Hamming code (7,4)

This positioning of the bits is important because it can not only tell us when error occurred (≤ 2-bit error) but also where it occurred (1 bit error). Due to minimum hamming distance d_{min} being 3 for (7,4) Hamming code, when 2-bits of error happen it can tell that this isn't a right codeword, but it can't differentiate what is the right codeword since its hamming distance to the closest two codewords are the same. If 3 or more errors happen it might interpret it as incorrect codeword or try to correct to incorrect codeword.

“2. Run the second section of the code. Write down the bit error rates at 0 dB and 7 dB. Use theory to comment on the performance. (Hint. why would the bit error rate be worse at a lower value of SNR?)”

Table 6 Simulated BERs for (7,4) Hamming code.

Signal-to-noise ratio	BER without (7,4) Hamming coding	BER with (7,4) Hamming coding
7 dB	7.46E-4	5.86E-4
0 dB	0.0781	0.1162

First, we can see the effect on BER when coding is used in higher level of SNR. The difference derives from the amount of at least 2-bit errors happening while transmitting data. At 0 dB SNR these errors happen more frequently since the signal is harder to differentiate from noise thus the BER value is worse. At low SNR I assume that since hamming coded branch sends 7-bit data, the probability of 2 or more-bit errors happening is greater than 1-bit errors in uncoded branch where only 4-bit data is sent. When inspecting the model there were cases when errors in received signal caused the code to correct to completely wrong dataword resulting in high number of errors at once.

All in all, what can be seen in this simulation is that the extra redundancy backfires at low SNR as the coding gain isn’t enough to compensate for spreading the bit energy over multiple coded bits.

“3. Modify the code to increase the code rate and run the second section again. Pay attention when choosing the message and codeword lengths. Write down the bit error rates at 0 dB and 7 dB. Explain the difference in performance.”

Before we used (7,4) Hamming code which has a code rate of 4/7 ≈ 0.57. To increase the code rate (15,11) Hamming code was chosen since its code rate is 0.733…, with repeating 3 decimal. The results in Table 6 and **Error! Not a valid bookmark self-reference.** are pretty much identical except when simulating with 7 dB SNR the number of errors more than halved in the branch where coding was used. Difference in performance could be explained by the increased code rate R_c which then resulted in improved coding gain $G_c = 10\ log_{10}[R_c d_{min} - \frac{k\ ln2}{Y_b}]$, where Y_b is the SNR.

Table 7 Simulated BERs for (15,11) Hamming code

Signal-to-noise ratio	BER without (15,11) Hamming coding	BER with (15,11) Hamming coding
7 dB	7.46E-4	2.23E-4
0 dB	0.07682	0.1248

8. EXTRA TASKS

"1. Modify the MATLAB code channel_plot.mto include a Rician fading channel. Use one of the doppler shift values you calculated in section DPSK IN RAYLEIGH FADING CHANNEL Pass the signal through the Rician channel and plot the results of both channels into the same figure. What is the difference between the two types of fading? Add your modified code as an appendix into your report."

The difference between Rayleigh and Rician fading channels is that Rician fading has a dominant, much stronger signal than any other path. [3] Simulating a signal passing through a Rayleigh channel and Rician channel at same velocity to induce Doppler shift is depicted in above figure. The velocity is set to 151.2 km/h for the simulation as this is the higher of the two velocities calculated in task 3.1 and higher velocity produces stronger Doppler shift in the signal. The effects of the Rician channel's dominant signal manifest themselves as a much lesser and more stable fading that does not impose even nearly as drastic deep fades as the Rayleigh channel onto the signal. The differences are visualized in Figure 23.

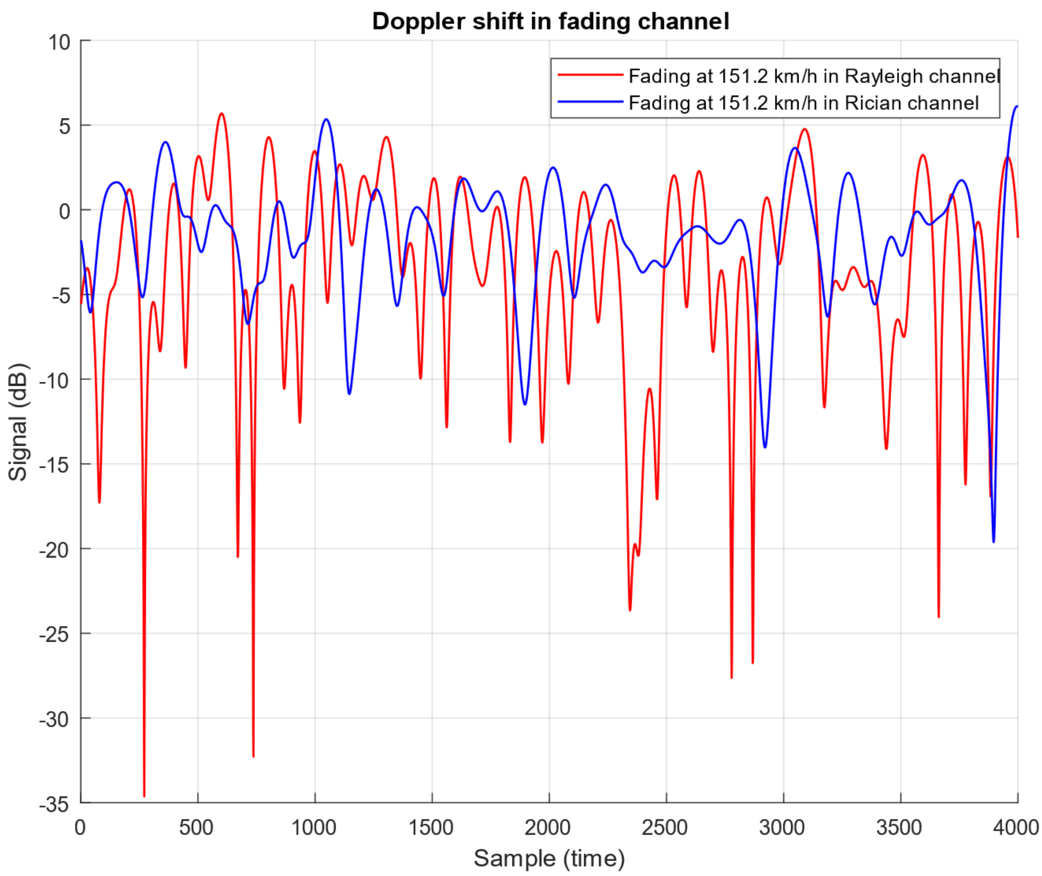

Figure 23. Two signals under the effects of Doppler shift with an aerial velocity of 151.2 km/h. One channel operates in a Rayleigh fading channel, another in Rician fading channel.

9. SELF-EVALUATION AND FEEDBACK

As requested in the laboratory task list, the self-evaluation and feedback will be written in Finnish. Each group member provides their own personal evaluation and feedback.

Sakari Veteläinen, 2555304

Omasta mielestäni työ oli hyvänä tukena oppimiselle luentojen ja harjoitusten lisäksi. Simuloinnit eivät mielestäni olleet vaikeita ja niissä olisi voinut päästä enemmänkin itse koodaamaan. Tekstin tuottaminen ei sinällään ollut hankalaa mutta hieman tuotti vaikeuksia selittää helppojakin asioita englanniksi mitkä on kandivaiheessa opittu suomeksi.

Työ jaettiin parin kanssa aikalailla puoliksi jossa minulla oli päävastuu tehtävistä 1, 5 ja 6. Ainakin ennen arviointia olen tyytyväinen suoritukseeni lukuunottamatta viimeisen tehtävän haparoivaa selitystä BER-arvoille sillä en ollut varma mistä tulokset johtuivat. Nyt jos tekisin tehtävät uudelleen saattaisin käyttää enemmän aikaa aiheeseen perehtymiseen lukemalla teoriaa jonka pohjalta arvioida simulointeja. Nyt tein käytännössä päinvastoin eli etsin simulointien jälkeen niihin sopivaa teoriaa jolloin mahdollisuus vääriin tulkintoihin kasvaa.

Jiska Parrila, 2698850

Ollessaan välikokeiden tai loppukokeen ohella ainut pakollinen tehtävä koko kurssille sanon, että tästä oli hyötyä. Kurssikirjaa on pakko lukea ja sen sisältöä ymmärtää edes jollain tasolla, jotta tehtäviin voi vastata hyväksyttävästi. Aiemmasta tutkinnosta ja siten myös edellisistä langattomiin signaaleihin perehtyvistä kursseista on jo ehtinyt vierähtää jokunen vuosi, eikä tätä aihetta ole ollut tarvetta soveltaa työelämässäkään, joten valtaosa asioista on unohtunut. Signaalimodulaatio ja koodaus olivat jotenkin mielessä. Kaikki muu olikin ainakin muistin mukaan uutta. Signaalimodulaatiosta sain paikattua joitakin harmaita alueita, jotka olivat ennestään epäselviä. Diversiteetti, propagaatio, MPSK ja DPSK jäivät kurssista parhaiten mieleen ja ne ovat kutakuinkin selkeitä ajatus tasolla. Signaalien synkronointi, fading ja shadowing ovat vielä hakevat parempaa ymmärrystä. Liekkö syynä muutamien käsitteiden – kuten coherence time – ymmärtämättömyys. Kanavien suoritustehoon liittyen olen saanut jonkinlaista käsitystä, koska BER ja SER ovat läsnä useammassakin tehtävässä. Loppujaan on kuitenkin itsellenikin epäselvää mistä itselläni johtuu matematiikkaan nojaavien aineiden haastavuus, vaikka matemaattisten konseptien sisäistäminen onnistuukin melko hyvin. Soveltaminen ei niinkään.

Itse työn tekeminen sujui valtaosin hyvin. Vastaukset suurinpaan löytyivät osaan kysymyksistä kurssikirjaa lukemalla, vaikkakin joskus ei heti huomannut tarkistaa painoksen virhelistaa, joka aiheutti päänvaivaa. Kaavojen pyörittelyyn kului turhan paljon aikaa. Ryhmätasolla työ sujui hyvin. Omalle kontolleni otin tehtävät 3, 4 ja 5 ja kaikkien kolmen parissa kurssikirja oli jatkuvana tukena. 3. tehtävä oli verrattain helpoin. 4. tehtäväkin sujui pitkälti ongelmitta sen viimeistä kohtaa lukuunottamatta. 5. tehtävä vaati hyvän tovin tavaamista, mutta lopulta senkin sai kasaan.

Tehtävän alusta aloittaminen ei todennäköisesti muuttaisi omaa toimintatapaani juurikaan. Se on iskostunut päähäni vuosien saatossa ja ehkä jopa urautunut liiankin syvälle, josta johtuen tämän prosessin muuttaminen olisi sangen työlästä. Luonnollisesti toisella suorituskerralla tekeminen olisi helpompaa, koska ensimmäisen toteutuksen aikana kerrytetty tietämys olisi jo mukana. Tästä johtuen vastaukset olisivat mahdollisesti syvällisempiä ja tarkempia, kun kirjan lukeminen toistamiseen synnyttää uusia ajatuksia ja konseptit avautuvat paremmin.

Niin valitettavaa kuin se onkin, en osaa ehdottaa parannuksia tähän harjoitustyöhön. Ainakaan sen teoria osuuksiin. Ymmärrykseni aiheesta ei yksinkertaisesti ole riittävä. MATLAB skriptit toisaalta voisivat olla parempiakin luettavuudeltaan ja jotkin myös suorituskyvyltään. Mikäli aikaa liikenee, niin voisinpa nähdäkin itseni kirjoittamassa näitä ohjelmia paremmiksi.

10.REFERENCES

[1] A. Goldsmith, Wireless Communication, Campridge University Press, 2005.

[2] *Wireless Communication I 521395S Course material*, University of Oulu, 2021.

[3] J.-P. M. Linnartz, "Rician fading," 1996. [Online]. Available: http://www.wirelesscommunication.nl/reference/chaptr03/ricepdf/rice.htm.

11.APPENDICES

Appendix 1 Source code of the modified channel_plot.m

Appendix 1 Source code of the modified channel_plot.m

```
% This is a matlab script created by modifying the channel_plot.m version 1.7.2021
% which was provided as part of the project material.

clear
close all

smplrte   = 10000;
signal    = ones(4000,1);
dpplrshft = 10;

% This matlab code plot power of faded signal, versus sample number.
% If you like, you can take lines from plot_help to decorate plots.
% Version 1.7.2021
chanray1 = comm.RayleighChannel( ...
   'SampleRate',          smplrte, ...
   'MaximumDopplerShift', dpplrshft, ...
   'DopplerSpectrum',     doppler('Jakes'));

dpplrshft = 56;
chanray2 = comm.RayleighChannel( ...
   'SampleRate',          smplrte, ...
   'MaximumDopplerShift', dpplrshft, ...
   'DopplerSpectrum',     doppler('Jakes'));

dpplrshft = 56;     % Redundant but set here for sake of consistency
chanrice1 = comm.RicianChannel( ...
   'SampleRate',          smplrte, ...
   'MaximumDopplerShift', dpplrshft, ...
   'DopplerSpectrum',     doppler('Jakes'));

y1 = step(chanray1, signal);                 % Pass signal through Rayleigh channel.
y2 = step(chanray2, signal);                 % Pass signal through Rayleigh channel.
y3 = step(chanrice1, signal);                % Pass signal through Rician channel.

% Plot power of faded signal, versus sample number.
hold on;
figure(1);
% plot(20*log10(abs(y1)), '-b', 'LineWidth', 1);
plot(20*log10(abs(y2)), '-r', 'LineWidth', 1);
plot(20*log10(abs(y3)), '-b', 'LineWidth', 1);
title('Doppler shift in fading channel');
xlabel('Sample (time)');
ylabel('Signal (dB)');
grid on;                               % Add grid to the diagram
legend(... % 'Fading at 27 km/h in Rayleigh channel', ...
      'Fading at 151.2 km/h in Rayleigh channel', ...
```

```
    'Fading at 151.2 km/h in Rician channel');
hold off;
```