Communications and Wireless Networks Lab1 - path loss and modulation

1. Results for d=[50:50:600]

1.1. P_rx derived from the path loss model

Distance (m)	P_rx (W)	P_rx (dBm)
50	3.957859e-10	-64.025397
100	9.894647e-11	-70.045997
150	4.397621e-11	-73.567822
200	2.473662e-11	-76.066597
250	1.583143e-11	-78.004797
300	1.099405e-11	-79.588422
350	8.077263e-12	-80.927358
400	6.184154e-12	-82.087197
450	4.886245e-12	-83.110247
500	3.957859e-12	-84.025397
550	3.270958e-12	-84.853251
600	2.748513e-12	-85.609022

1.2. Empirical and theoretical average noise power

Distance (m)	Empirical Noise Power BPSK (W)	Empirical Noise Power QPSK (W)	Empirical Noise Power QAM16 (W)	Empirical Noise Power QAM64 (W)
50	2.524614e-03	2.519776e-03	2.519485e-03	2.515800e-03
100	1.009845e-02	1.007910e-02	1.007794e-02	1.006320e-02
150	2.272152e-02	2.267798e-02	2.267536e-02	2.264220e-02
200	4.039382e-02	4.031641e-02	4.031176e-02	4.025279e-02
250	6.311534e-02	6.299440e-02	6.298712e-02	6.289499e-02
300	9.088609e-02	9.071193e-02	9.070146e-02	9.056878e-02
350	1.237061e-01	1.234690e-01	1.234548e-01	1.232742e-01
400	1.615753e-01	1.612657e-01	1.612470e-01	1.610112e-01
450	2.044937e-01	2.041018e-01	2.040783e-01	2.037798e-01
500	2.524614e-01	2.519776e-01	2.519485e-01	2.515800e-01
550	3.054782e-01	3.048929e-01	3.048577e-01	3.044117e-01
600	3.635443e-01	3.628477e-01	3.628058e-01	3.622751e-01
Distance (m)	**Empirical Noise Power BPSK (dBm)**	**Empirical Noise Power QPSK (dBm)**	**Empirical Noise Power QAM16 (dBm)**	**Empirical Noise Power QAM64 (dBm)**
50	4.021949	4.013619	4.013118	4.006760
100	10.042549	10.034219	10.033718	10.027360
150	13.564374	13.556044	13.555543	13.549185
200	16.063149	16.054819	16.054317	16.047960
250	18.001349	17.993019	17.992518	17.986160
300	19.584974	19.576644	19.576143	19.569785
350	20.923910	20.915580	20.915078	20.908721
400	22.083749	22.075419	22.074917	22.068560
450	23.106799	23.098469	23.097968	23.091610

Distance (m)	Empirical Noise Power BPSK (dBm)	Empirical Noise Power QPSK (dBm)	Empirical Noise Power QAM16 (dBm)	Empirical Noise Power QAM64 (dBm)
500	24.021949	24.013619	24.013118	24.006760
550	24.849803	24.841473	24.840971	24.834614
600	25.605574	25.597244	25.596743	25.590385

The theoretical noise power is 1.000000e-12 W (-90.000000 dBm).

1.3. SNR and SNR_dB

Distance (m)	SNR BPSK	SNR QPSK	SNR QAM16	SNR QAM64
50	396.100230	396.860690	396.572066	397.039737
100	99.025057	99.215173	99.143016	99.259934
150	44.011137	44.095632	44.063563	44.115526
200	24.756264	24.803793	24.785754	24.814984
250	15.844009	15.874428	15.862883	15.881589
300	11.002784	11.023908	11.015891	11.028882
350	8.083678	8.099198	8.093307	8.102852
400	6.189066	6.200948	6.196439	6.203746
450	4.890126	4.899515	4.895951	4.901725
500	3.961002	3.968607	3.965721	3.970397
550	3.273556	3.279840	3.277455	3.281320
600	2.750696	2.755977	2.753973	2.757220

Distance (m)	SNR BPSK (dB)	SNR QPSK (dB)	SNR QAM16 (dB)	SNR QAM64 (dB)
50	25.978051	25.986381	25.983221	25.988340
100	19.957451	19.965781	19.962621	19.967740
150	16.435626	16.443956	16.440796	16.445915
200	13.936851	13.945181	13.942021	13.947140
250	11.998651	12.006981	12.003821	12.008940
300	10.415026	10.423356	10.420196	10.425315
350	9.076090	9.084420	9.081260	9.086379
400	7.916251	7.924581	7.921421	7.926540
450	6.893201	6.901531	6.898371	6.903490
500	5.978051	5.986381	5.983221	5.988340
550	5.150197	5.158527	5.155367	5.160486
600	4.394426	4.402756	4.399596	4.404715

1.4. Empirical BER

Distance (m)	Empirical BER BPSK	Empirical BER QPSK	Empirical BER QAM16	Empirical BER QAM64
50	0.000000e+00	0.000000e+00	0.000000e+00	1.000000e-05
100	0.000000e+00	0.000000e+00	3.333333e-06	1.344333e-02
150	0.000000e+00	0.000000e+00	1.396667e-03	6.754000e-02
200	0.000000e+00	0.000000e+00	1.288667e-02	1.269833e-01
250	0.000000e+00	2.666667e-05	3.736333e-02	1.753567e-01
300	3.333333e-06	5.233333e-04	6.851667e-02	2.106833e-01
350	4.333333e-05	2.260000e-03	1.006367e-01	2.403667e-01
400	2.700000e-04	6.596667e-03	1.324333e-01	2.602533e-01

Distance (m)	Empirical BER BPSK	Empirical BER QPSK	Empirical BER QAM16	Empirical BER QAM64
450	8.933333e-04	1.362667e-02	1.596600e-01	2.791367e-01
500	2.503333e-03	2.264667e-02	1.852367e-01	2.914067e-01
550	5.403333e-03	3.451000e-02	2.063067e-01	3.040667e-01
600	9.776667e-03	4.892667e-02	2.260267e-01	3.154767e-01

1.5. Empirical and theoretical throughput

Distance (m)	Empirical Throughput BPSK (bps)	Empirical Throughput QPSK (bps)	Empirical Throughput QAM16 (bps)	Empirical Throughput QAM64 (bps)
50	3.125000e+05	6.250000e+05	1.250000e+06	1.800000e+06
100	3.125000e+05	6.250000e+05	1.233333e+06	0.000000e+00
150	3.125000e+05	6.250000e+05	0.000000e+00	0.000000e+00
200	3.125000e+05	6.250000e+05	0.000000e+00	0.000000e+00
250	3.125000e+05	5.583333e+05	0.000000e+00	0.000000e+00
300	3.083333e+05	5.833333e+04	0.000000e+00	0.000000e+00
350	2.583333e+05	0.000000e+00	0.000000e+00	0.000000e+00
400	9.583333e+04	0.000000e+00	0.000000e+00	0.000000e+00
450	1.666667e+04	0.000000e+00	0.000000e+00	0.000000e+00
500	0.000000e+00	0.000000e+00	0.000000e+00	0.000000e+00
550	0.000000e+00	0.000000e+00	0.000000e+00	0.000000e+00
600	0.000000e+00	0.000000e+00	0.000000e+00	0.000000e+00

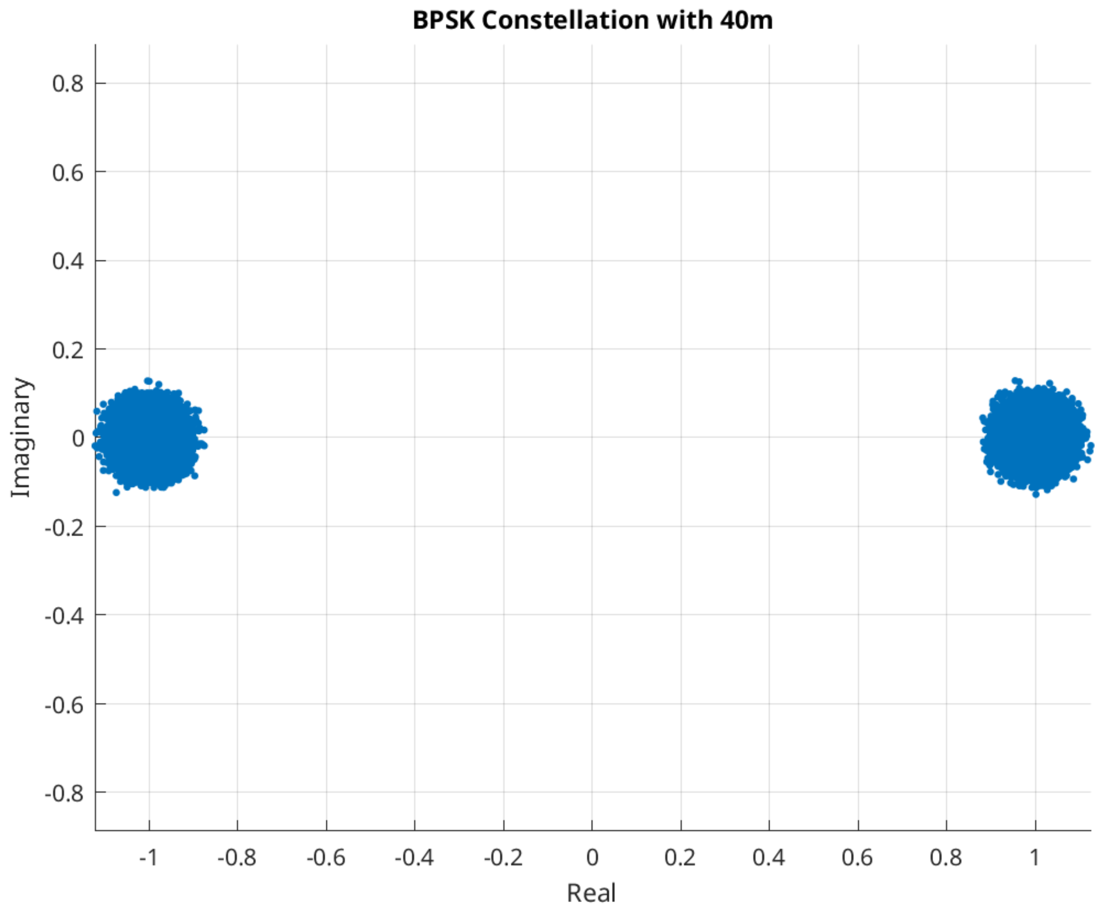
Distance (m)	Theoretical Throughput BPSK (bps)	Theoretical Throughput QPSK (bps)	Theoretical Throughput QAM16 (bps)	Theoretical Throughput QAM64 (bps)
50	3.125000e+05	6.250000e+05	1.250000e+06	1.801480e+06
100	3.125000e+05	6.250000e+05	1.233444e+06	5.769577e-18
150	3.125000e+05	6.250000e+05	4.666117e+03	6.220776e-116
200	3.125000e+05	6.250000e+05	3.672676e-17	2.307495e-230
250	3.125000e+05	5.617650e+05	8.841164e-61	0.000000e+00
300	3.083610e+05	7.700500e+04	6.269957e-118	0.000000e+00
350	2.627669e+05	7.335248e+01	6.880506e-179	0.000000e+00
400	1.061081e+05	1.987612e-06	2.033946e-241	0.000000e+00
450	8.755430e+03	9.144717e-19	8.261434e-297	0.000000e+00
500	1.382491e+01	1.005250e-34	0.000000e+00	0.000000e+00
550	1.210173e-04	6.123502e-56	0.000000e+00	0.000000e+00
600	2.675918e-12	4.486416e-82	0.000000e+00	0.000000e+00

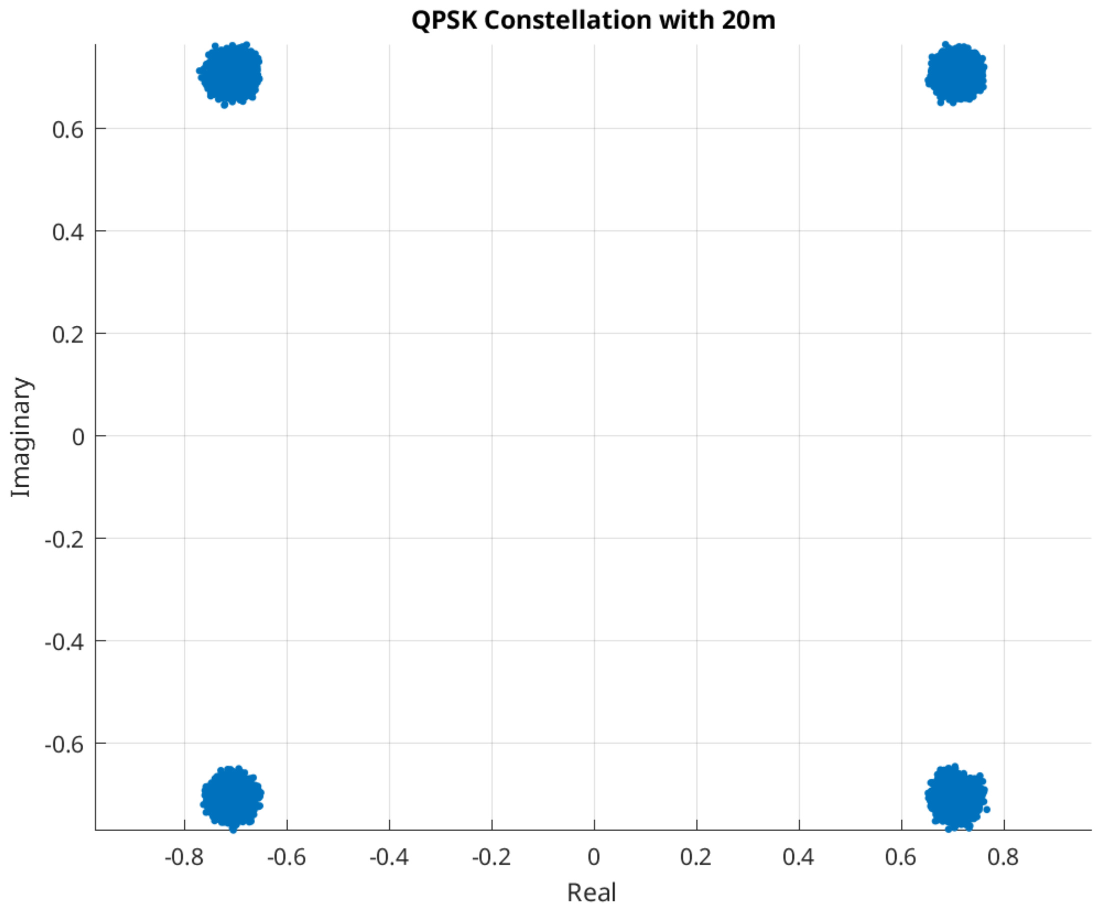
1.6. The optimal modulation scheme for link distance

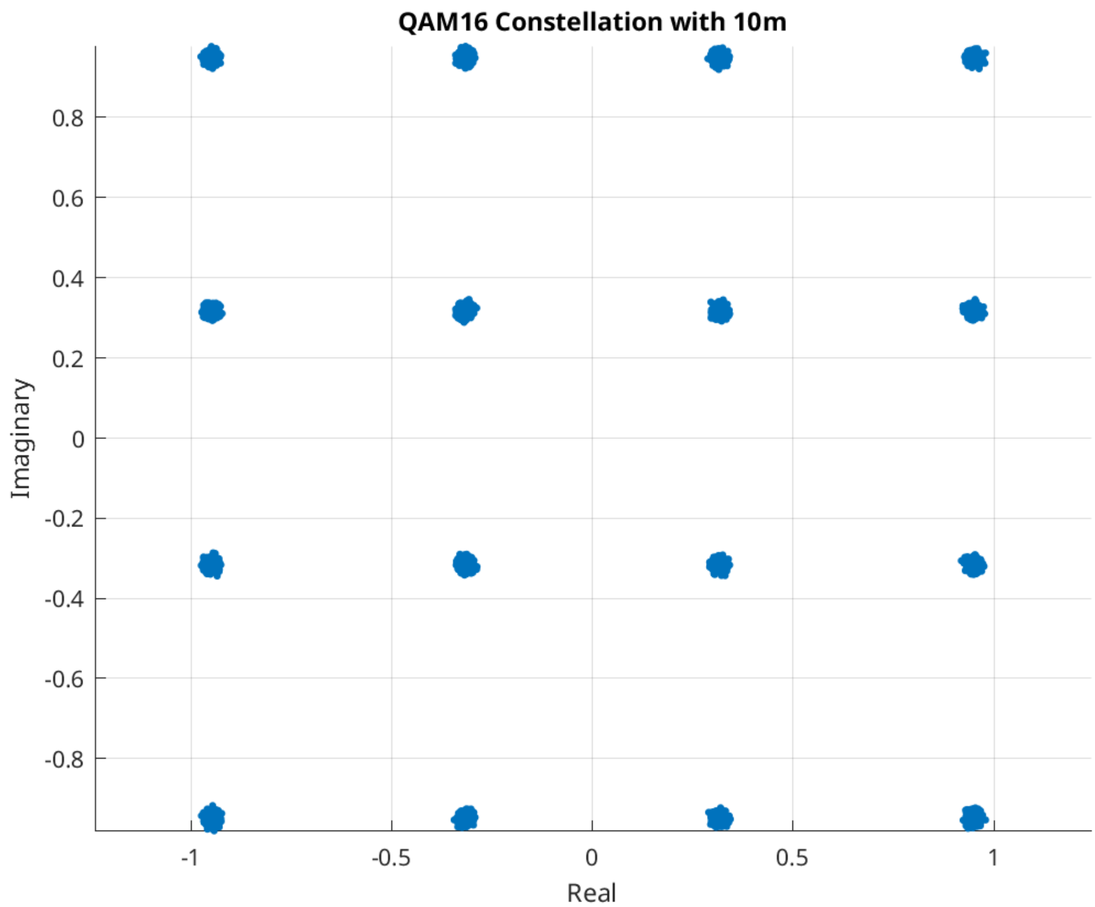
Distance (m)	Optimal Modulation Scheme
50	QAM64
100	QAM16
150	QPSK
200	QPSK
250	QPSK
300	BPSK
350	BPSK
400	BPSK

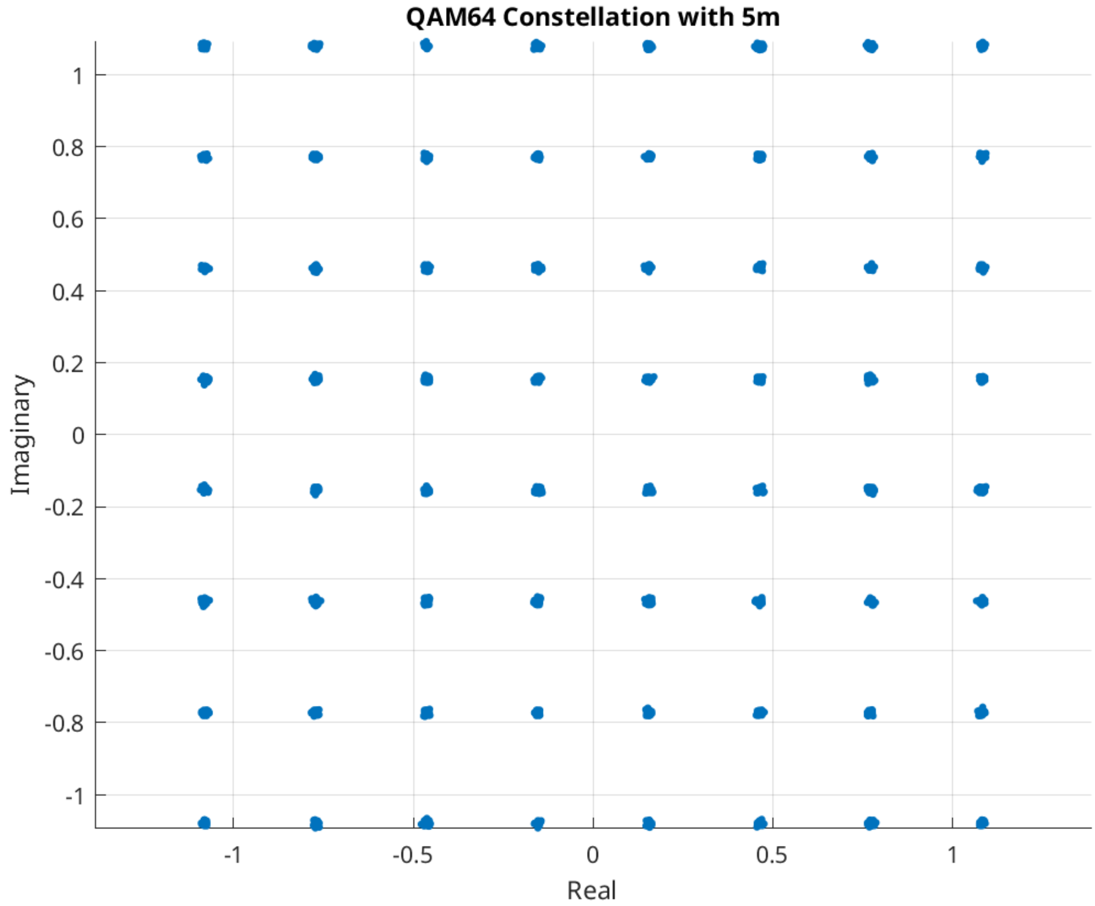
Distance (m)	Optimal Modulation Scheme
450	BPSK
500	BPSK
550	BPSK
600	BPSK

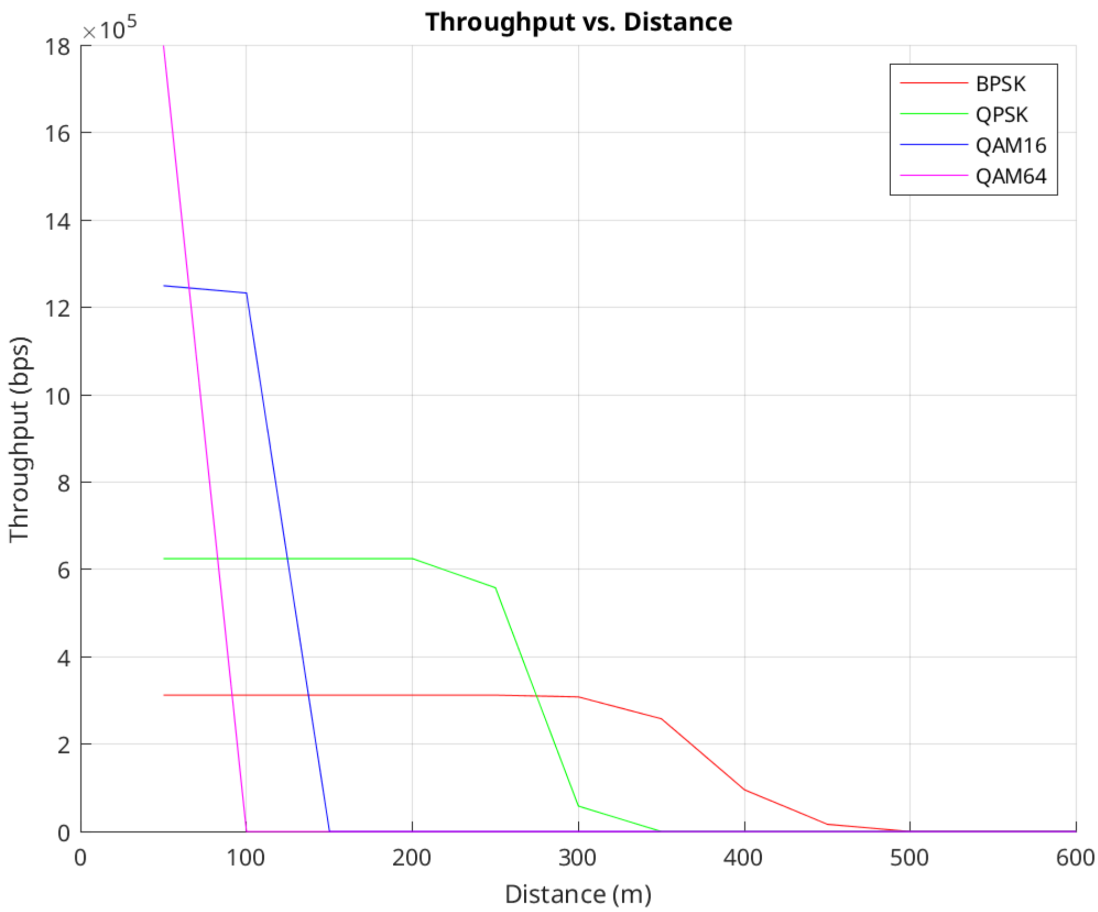
1.7. Figures




QPSK Constellation with 20m
Imaginary
Real
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8


QAM16 Constellation with 10m
Imaginary
Real
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-0.5
0
0.5
1


QAM64 Constellation with 5m
Imaginary
Real
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1
-0.5
0
0.5
1


Throughput vs. Distance
×10^5
Throughput (bps)
Distance (m)
BPSK
QPSK
QAM16
QAM64
18
16
14
12
10
8
6
4
2
0
0
100
200
300
400
500
600

2. Questions

2.1. The theoretical optimal modulation with a theoretical modulation table

Using the script below:

```
function [P_rx_W, P_rx_dBm] = ...
    calculate_received_power(d)
    % Constants
    c = 3e8; % Speed of light (m/s)

    % Tx Parameters
    f = 2.4e9; % Frequency (Hz)
    P_tx_dBm = 10; % Transmit power (dBm)
    P_tx = 10^(P_tx_dBm / 10) * 1e-3; % Transmit power (W)
    G_tx = 1; % Transmit antenna gain

    % Rx Parameters
    G_rx = 1; % Receive antenna gain

    % Calculate the wavelength
    lambda = c / f;

    % Received Power (dBm)
    P_rx_dBm = P_tx_dBm + 10 * log10(G_tx) + ...
        10 * log10(G_rx) + ...
        20 * log10(lambda / (4 * pi * d));

    % Convert dBm to Watts
    P_rx_W = 10^(P_rx_dBm / 10) * 1e-3;
end

function [best_scheme] = best_modulation_scheme(d, l)
    % d: distance in meters
    % l: packet length in bits
    % best_scheme: best modulation scheme

    load('SNR_BER.mat');

    [P_rx_W, P_rx_dBm] = calculate_received_power(d);
    noise_power_dBm = -90;
    noise_power_W = 10^(noise_power_dBm/10) * 1e-3;
    SNR = P_rx_W / noise_power_W;

    if SNR > 31
        BER = [0; 0; 0; 0];
    else
        SNR_floor = floor(SNR);
        delta = SNR - SNR_floor;
        BER = SNR_BER(:, SNR_floor) * (1 - delta) + SNR_BER(:, SNR_floor + 1) * delta;
    end

    PDR = (1 - BER) .^ l;

    sample_duration_s = 3.2e-6;
    throughput = [1; 2; 4; 6] .* PDR / sample_duration_s;
    [best_throughput, best_scheme_index] = max(throughput);
    modulation_schemes = ["BPSK", "QPSK", "16-QAM", "64-QAM"];
    best_scheme = modulation_schemes(best_scheme_index);
end

fprintf('| Distance (m) / Packet Length (bits) | 500 | 1000 | 2000 | 4000 | 8000 |\n');
```

```
fprintf('| --- | --- | --- | --- | --- | --- |\n');
for d = 50:50:600
    fprintf('| %d |', d);
    for l = [500, 1000, 2000, 4000, 8000]
        best_scheme = best_modulation_scheme(d, l);
        fprintf(' %s |', best_scheme);
    end
    fprintf('\n');
end
```

We can get the theoretical best modulation scheme table:

Distance (m) / Packet Length (bits)	500	1000	2000	4000	8000
50	64-QAM	64-QAM	64-QAM	64-QAM	64-QAM
100	64-QAM	64-QAM	64-QAM	64-QAM	64-QAM
150	64-QAM	64-QAM	64-QAM	64-QAM	64-QAM
200	QPSK	QPSK	QPSK	QPSK	QPSK
250	QPSK	QPSK	QPSK	QPSK	QPSK
300	QPSK	QPSK	QPSK	QPSK	QPSK
350	BPSK	BPSK	BPSK	BPSK	BPSK
400	BPSK	BPSK	BPSK	BPSK	BPSK
450	BPSK	BPSK	BPSK	BPSK	BPSK
500	BPSK	BPSK	BPSK	BPSK	BPSK
550	BPSK	BPSK	BPSK	BPSK	BPSK
600	BPSK	BPSK	BPSK	BPSK	BPSK

The empirical rate seems to have worse noise than the theoretical result. We can see that the theoretical best modulation switched to QPSK when the distance comes to 200m, but empirical test suggest that we should switch to QPSK when the distance is 150m.

This is due to the noise being amplified in the demodulation process, where the symbols y is divided by channel h. In the theoretical table, we did not consider the effect of channel h.

2.2. What I have learned

I wasn't used to programming in matlab before this lab. This lab helps me to get familiar with the syntax of matlab, and also give me a comprehensive view of what happened during signal transmission.

2.3. Difficulty in this lab

Because I was not familiar with matlab code and the calculations were complicated, I spent much time debugging and experimenting different syntax. For example, I named a file with hyphen `-` and matlab gave me an error.