Exam in
SSY305 Communication Systems

Department of Electrical Engineering

Exam date: March 16, 2023

Teaching Staff

Paolo Monti (examiner), 031-772 6027
Morteza Barzegar Astanjin, 070-798 2924

Material Allowed material:

- Chalmers-approved calculator.
- L. Råde, B. Westergren. Beta, Mathematics Handbook, any edition.
- One A4 page with your own handwritten notes. Both sides of the page can be used. Photocopies, printouts, other students' notes, or any other material is not allowed.
- A paper-based dictionary, without added notes (electronic dictionaries are not allowed).

Students are required to solve the exam problems individually. Cooperation, in any form or with anyone, is strictly forbidden.

Grading A correct, precise, and well-motivated solution gives at most 12 points per problem. An incorrect answer, unclear, incomplete, or poorly motivated solutions give point reductions to a minimum of 0 points. No fractional points are awarded. Answers in any other language than Swedish or English are ignored.

Solutions Are made available at the earliest on **March 17** EOB on the course web page.

Results Exam results are posted on Canvas no later than **March 30**. The grading reviews will be on **March 31** according to a process that will be explained on the course webpage.

Grades The final grade of the course will be decided by the project (maximum score 46), quizzes (maximum score 6), and final exam (maximum score 48). The project and exam must be passed (see course-PM for rules). The sum of all scores will decide the grade.

Total Score	0–39	40–68	69–79	≥ 80
Grade	Fail	3	4	5

PLEASE NOTE THAT THE PROBLEMS ARE NOT NECESSARILY ORDERED BASED ON THEIR DIFFICULTY
Good luck!

Table over the Q-function

x	Q(x)	x	Q(x)	x	Q(x)	x	Q(x)	x	Q(x)	x	Q(x)	x	Q(x)	x	Q(x)
0.00	5.0000E-01	0.76	2.2360E-01	1.52	6.4260E-02	2.28	1.1300E-02	3.04	1.1830E-03	3.80	7.2350E-05	4.56	2.5580E-06	5.32	5.1880E-08
0.01	4.9600E-01	0.77	2.2060E-01	1.53	6.3010E-02	2.29	1.1010E-02	3.05	1.1440E-03	3.81	6.9480E-05	4.57	2.4390E-06	5.33	4.9110E-08
0.02	4.9200E-01	0.78	2.1770E-01	1.54	6.1780E-02	2.30	1.0720E-02	3.06	1.1070E-03	3.82	6.6730E-05	4.58	2.3250E-06	5.34	4.6470E-08
0.03	4.8800E-01	0.79	2.1480E-01	1.55	6.0570E-02	2.31	1.0440E-02	3.07	1.0700E-03	3.83	6.4070E-05	4.59	2.2160E-06	5.35	4.3980E-08
0.04	4.8400E-01	0.80	2.1190E-01	1.56	5.9380E-02	2.32	1.0170E-02	3.08	1.0350E-03	3.84	6.1520E-05	4.60	2.1120E-06	5.36	4.1610E-08
0.05	4.8010E-01	0.81	2.0900E-01	1.57	5.8210E-02	2.33	9.9030E-03	3.09	1.0010E-03	3.85	5.9060E-05	4.61	2.0130E-06	5.37	3.9370E-08
0.06	4.7610E-01	0.82	2.0610E-01	1.58	5.7050E-02	2.34	9.6420E-03	3.10	9.6760E-04	3.86	5.6690E-05	4.62	1.9190E-06	5.38	3.7240E-08
0.07	4.7210E-01	0.83	2.0330E-01	1.59	5.5920E-02	2.35	9.3870E-03	3.11	9.3540E-04	3.87	5.4420E-05	4.63	1.8280E-06	5.39	3.5230E-08
0.08	4.6810E-01	0.84	2.0050E-01	1.60	5.4800E-02	2.36	9.1370E-03	3.12	9.0430E-04	3.88	5.2230E-05	4.64	1.7420E-06	5.40	3.3320E-08
0.09	4.6410E-01	0.85	1.9770E-01	1.61	5.3700E-02	2.37	8.8940E-03	3.13	8.7400E-04	3.89	5.0120E-05	4.65	1.6600E-06	5.41	3.1510E-08
0.10	4.6020E-01	0.86	1.9490E-01	1.62	5.2620E-02	2.38	8.6560E-03	3.14	8.4470E-04	3.90	4.8100E-05	4.66	1.5810E-06	5.42	2.9800E-08
0.11	4.5620E-01	0.87	1.9220E-01	1.63	5.1550E-02	2.39	8.4240E-03	3.15	8.1640E-04	3.91	4.6150E-05	4.67	1.5060E-06	5.43	2.8180E-08
0.12	4.5220E-01	0.88	1.8940E-01	1.64	5.0500E-02	2.40	8.1980E-03	3.16	7.8880E-04	3.92	4.4270E-05	4.68	1.4340E-06	5.44	2.6640E-08
0.13	4.4830E-01	0.89	1.8670E-01	1.65	4.9470E-02	2.41	7.9760E-03	3.17	7.6220E-04	3.93	4.2470E-05	4.69	1.3660E-06	5.45	2.5180E-08
0.14	4.4430E-01	0.90	1.8410E-01	1.66	4.8460E-02	2.42	7.7600E-03	3.18	7.3640E-04	3.94	4.0740E-05	4.70	1.3010E-06	5.46	2.3810E-08
0.15	4.4040E-01	0.91	1.8140E-01	1.67	4.7460E-02	2.43	7.5490E-03	3.19	7.1140E-04	3.95	3.9080E-05	4.71	1.2390E-06	5.47	2.2500E-08
0.16	4.3640E-01	0.92	1.7880E-01	1.68	4.6480E-02	2.44	7.3440E-03	3.20	6.8710E-04	3.96	3.7470E-05	4.72	1.1790E-06	5.48	2.1270E-08
0.17	4.3250E-01	0.93	1.7620E-01	1.69	4.5510E-02	2.45	7.1430E-03	3.21	6.6370E-04	3.97	3.5940E-05	4.73	1.1230E-06	5.49	2.0100E-08
0.18	4.2860E-01	0.94	1.7360E-01	1.70	4.4570E-02	2.46	6.9470E-03	3.22	6.4100E-04	3.98	3.4460E-05	4.74	1.0690E-06	5.50	1.8990E-08
0.19	4.2470E-01	0.95	1.7110E-01	1.71	4.3630E-02	2.47	6.7560E-03	3.23	6.1900E-04	3.99	3.3040E-05	4.75	1.0170E-06	5.51	1.7940E-08
0.20	4.2070E-01	0.96	1.6850E-01	1.72	4.2720E-02	2.48	6.5690E-03	3.24	5.9760E-04	4.00	3.1670E-05	4.76	9.6800E-07	5.52	1.6950E-08
0.21	4.1680E-01	0.97	1.6600E-01	1.73	4.1820E-02	2.49	6.3870E-03	3.25	5.7700E-04	4.01	3.0360E-05	4.77	9.2110E-07	5.53	1.6010E-08
0.22	4.1290E-01	0.98	1.6350E-01	1.74	4.0930E-02	2.50	6.2100E-03	3.26	5.5710E-04	4.02	2.9100E-05	4.78	8.7650E-07	5.54	1.5120E-08
0.23	4.0900E-01	0.99	1.6110E-01	1.75	4.0060E-02	2.51	6.0370E-03	3.27	5.3770E-04	4.03	2.7890E-05	4.79	8.3390E-07	5.55	1.4280E-08
0.24	4.0520E-01	1.00	1.5870E-01	1.76	3.9200E-02	2.52	5.8680E-03	3.28	5.1900E-04	4.04	2.6730E-05	4.80	7.9330E-07	5.56	1.3490E-08
0.25	4.0130E-01	1.01	1.5620E-01	1.77	3.8360E-02	2.53	5.7030E-03	3.29	5.0090E-04	4.05	2.5610E-05	4.81	7.5470E-07	5.57	1.2740E-08
0.26	3.9740E-01	1.02	1.5390E-01	1.78	3.7540E-02	2.54	5.5430E-03	3.30	4.8340E-04	4.06	2.4540E-05	4.82	7.1780E-07	5.58	1.2030E-08
0.27	3.9360E-01	1.03	1.5150E-01	1.79	3.6730E-02	2.55	5.3860E-03	3.31	4.6650E-04	4.07	2.3510E-05	4.83	6.8270E-07	5.59	1.1350E-08
0.28	3.8970E-01	1.04	1.4920E-01	1.80	3.5930E-02	2.56	5.2340E-03	3.32	4.5010E-04	4.08	2.2520E-05	4.84	6.4920E-07	5.60	1.0720E-08
0.29	3.8590E-01	1.05	1.4690E-01	1.81	3.5150E-02	2.57	5.0850E-03	3.33	4.3420E-04	4.09	2.1570E-05	4.85	6.1730E-07	5.61	1.0120E-08
0.30	3.8210E-01	1.06	1.4460E-01	1.82	3.4380E-02	2.58	4.9400E-03	3.34	4.1890E-04	4.10	2.0660E-05	4.86	5.8690E-07	5.62	9.5480E-09
0.31	3.7830E-01	1.07	1.4230E-01	1.83	3.3620E-02	2.59	4.7990E-03	3.35	4.0410E-04	4.11	1.9780E-05	4.87	5.5800E-07	5.63	9.0100E-09
0.32	3.7450E-01	1.08	1.4010E-01	1.84	3.2880E-02	2.60	4.6610E-03	3.36	3.8970E-04	4.12	1.8940E-05	4.88	5.3040E-07	5.64	8.5030E-09
0.33	3.7070E-01	1.09	1.3790E-01	1.85	3.2160E-02	2.61	4.5270E-03	3.37	3.7580E-04	4.13	1.8140E-05	4.89	5.0420E-07	5.65	8.0220E-09
0.34	3.6690E-01	1.10	1.3570E-01	1.86	3.1440E-02	2.62	4.3960E-03	3.38	3.6240E-04	4.14	1.7370E-05	4.90	4.7920E-07	5.66	7.5690E-09
0.35	3.6320E-01	1.11	1.3350E-01	1.87	3.0740E-02	2.63	4.2690E-03	3.39	3.4950E-04	4.15	1.6620E-05	4.91	4.5540E-07	5.67	7.1400E-09
0.36	3.5940E-01	1.12	1.3140E-01	1.88	3.0050E-02	2.64	4.1450E-03	3.40	3.3690E-04	4.16	1.5910E-05	4.92	4.3270E-07	5.68	6.7350E-09
0.37	3.5570E-01	1.13	1.2920E-01	1.89	2.9380E-02	2.65	4.0250E-03	3.41	3.2480E-04	4.17	1.5230E-05	4.93	4.1110E-07	5.69	6.3520E-09
0.38	3.5200E-01	1.14	1.2710E-01	1.90	2.8720E-02	2.66	3.9070E-03	3.42	3.1310E-04	4.18	1.4580E-05	4.94	3.9060E-07	5.70	5.9900E-09
0.39	3.4830E-01	1.15	1.2510E-01	1.91	2.8070E-02	2.67	3.7930E-03	3.43	3.0180E-04	4.19	1.3950E-05	4.95	3.7110E-07	5.71	5.6490E-09
0.40	3.4460E-01	1.16	1.2300E-01	1.92	2.7430E-02	2.68	3.6810E-03	3.44	2.9090E-04	4.20	1.3350E-05	4.96	3.5250E-07	5.72	5.3260E-09
0.41	3.4090E-01	1.17	1.2100E-01	1.93	2.6800E-02	2.69	3.5730E-03	3.45	2.8030E-04	4.21	1.2770E-05	4.97	3.3480E-07	5.73	5.0220E-09
0.42	3.3720E-01	1.18	1.1900E-01	1.94	2.6190E-02	2.70	3.4670E-03	3.46	2.7010E-04	4.22	1.2220E-05	4.98	3.1790E-07	5.74	4.7340E-09
0.43	3.3360E-01	1.19	1.1700E-01	1.95	2.5590E-02	2.71	3.3640E-03	3.47	2.6020E-04	4.23	1.1680E-05	4.99	3.0190E-07	5.75	4.4620E-09
0.44	3.3000E-01	1.20	1.1510E-01	1.96	2.5000E-02	2.72	3.2640E-03	3.48	2.5070E-04	4.24	1.1180E-05	5.00	2.8670E-07	5.76	4.2060E-09
0.45	3.2640E-01	1.21	1.1310E-01	1.97	2.4420E-02	2.73	3.1670E-03	3.49	2.4150E-04	4.25	1.0690E-05	5.01	2.7220E-07	5.77	3.9640E-09
0.46	3.2280E-01	1.22	1.1120E-01	1.98	2.3850E-02	2.74	3.0720E-03	3.50	2.3260E-04	4.26	1.0220E-05	5.02	2.5840E-07	5.78	3.7350E-09
0.47	3.1920E-01	1.23	1.0930E-01	1.99	2.3300E-02	2.75	2.9800E-03	3.51	2.2410E-04	4.27	9.7740E-06	5.03	2.4520E-07	5.79	3.5190E-09
0.48	3.1560E-01	1.24	1.0750E-01	2.00	2.2750E-02	2.76	2.8900E-03	3.52	2.1580E-04	4.28	9.3450E-06	5.04	2.3280E-07	5.80	3.3160E-09
0.49	3.1210E-01	1.25	1.0560E-01	2.01	2.2220E-02	2.77	2.8030E-03	3.53	2.0780E-04	4.29	8.9340E-06	5.05	2.2090E-07	5.81	3.1240E-09
0.50	3.0850E-01	1.26	1.0380E-01	2.02	2.1690E-02	2.78	2.7180E-03	3.54	2.0010E-04	4.30	8.5400E-06	5.06	2.0960E-07	5.82	2.9420E-09
0.51	3.0500E-01	1.27	1.0200E-01	2.03	2.1180E-02	2.79	2.6350E-03	3.55	1.9260E-04	4.31	8.1630E-06	5.07	1.9890E-07	5.83	2.7710E-09
0.52	3.0150E-01	1.28	1.0030E-01	2.04	2.0680E-02	2.80	2.5550E-03	3.56	1.8540E-04	4.32	7.8010E-06	5.08	1.8870E-07	5.84	2.6100E-09
0.53	2.9810E-01	1.29	9.8530E-02	2.05	2.0180E-02	2.81	2.4770E-03	3.57	1.7850E-04	4.33	7.4550E-06	5.09	1.7900E-07	5.85	2.4580E-09
0.54	2.9460E-01	1.30	9.6800E-02	2.06	1.9700E-02	2.82	2.4010E-03	3.58	1.7180E-04	4.34	7.1240E-06	5.10	1.6980E-07	5.86	2.3140E-09
0.55	2.9120E-01	1.31	9.5100E-02	2.07	1.9230E-02	2.83	2.3270E-03	3.59	1.6530E-04	4.35	6.8070E-06	5.11	1.6110E-07	5.87	2.1790E-09
0.56	2.8770E-01	1.32	9.3420E-02	2.08	1.8760E-02	2.84	2.2560E-03	3.60	1.5910E-04	4.36	6.5030E-06	5.12	1.5280E-07	5.88	2.0510E-09
0.57	2.8430E-01	1.33	9.1760E-02	2.09	1.8310E-02	2.85	2.1860E-03	3.61	1.5310E-04	4.37	6.2120E-06	5.13	1.4490E-07	5.89	1.9310E-09
0.58	2.8100E-01	1.34	9.0120E-02	2.10	1.7860E-02	2.86	2.1180E-03	3.62	1.4730E-04	4.38	5.9340E-06	5.14	1.3740E-07	5.90	1.8180E-09
0.59	2.7760E-01	1.35	8.8510E-02	2.11	1.7430E-02	2.87	2.0520E-03	3.63	1.4170E-04	4.39	5.6680E-06	5.15	1.3020E-07	5.91	1.7110E-09
0.60	2.7430E-01	1.36	8.6910E-02	2.12	1.7000E-02	2.88	1.9880E-03	3.64	1.3630E-04	4.40	5.4130E-06	5.16	1.2350E-07	5.92	1.6100E-09
0.61	2.7090E-01	1.37	8.5340E-02	2.13	1.6590E-02	2.89	1.9260E-03	3.65	1.3110E-04	4.41	5.1690E-06	5.17	1.1700E-07	5.93	1.5150E-09
0.62	2.6760E-01	1.38	8.3790E-02	2.14	1.6180E-02	2.90	1.8660E-03	3.66	1.2610E-04	4.42	4.9350E-06	5.18	1.1090E-07	5.94	1.4250E-09
0.63	2.6430E-01	1.39	8.2260E-02	2.15	1.5780E-02	2.91	1.8070E-03	3.67	1.2130E-04	4.43	4.7120E-06	5.19	1.0510E-07	5.95	1.3410E-09
0.64	2.6110E-01	1.40	8.0760E-02	2.16	1.5390E-02	2.92	1.7500E-03	3.68	1.1660E-04	4.44	4.4980E-06	5.20	9.9640E-08	5.96	1.2610E-09
0.65	2.5780E-01	1.41	7.9270E-02	2.17	1.5000E-02	2.93	1.6950E-03	3.69	1.1210E-04	4.45	4.2940E-06	5.21	9.4420E-08	5.97	1.1860E-09
0.66	2.5460E-01	1.42	7.7800E-02	2.18	1.4630E-02	2.94	1.6410E-03	3.70	1.0780E-04	4.46	4.0980E-06	5.22	8.9460E-08	5.98	1.1160E-09
0.67	2.5140E-01	1.43	7.6360E-02	2.19	1.4260E-02	2.95	1.5890E-03	3.71	1.0360E-04	4.47	3.9110E-06	5.23	8.4760E-08	5.99	1.0490E-09
0.68	2.4830E-01	1.44	7.4930E-02	2.20	1.3900E-02	2.96	1.5380E-03	3.72	9.9610E-05	4.48	3.7320E-06	5.24	8.0290E-08	6.00	9.8660E-10
0.69	2.4510E-01	1.45	7.3530E-02	2.21	1.3550E-02	2.97	1.4890E-03	3.73	9.5740E-05	4.49	3.5610E-06	5.25	7.6050E-08	6.01	9.2760E-10
0.70	2.4200E-01	1.46	7.2150E-02	2.22	1.3210E-02	2.98	1.4410E-03	3.74	9.2010E-05	4.50	3.3980E-06	5.26	7.2030E-08	6.02	8.7210E-10
0.71	2.3890E-01	1.47	7.0780E-02	2.23	1.2870E-02	2.99	1.3950E-03	3.75	8.8420E-05	4.51	3.2410E-06	5.27	6.8210E-08	6.03	8.1980E-10
0.72	2.3580E-01	1.48	6.9440E-02	2.24	1.2550E-02	3.00	1.3500E-03	3.76	8.4960E-05	4.52	3.0920E-06	5.28	6.4590E-08	6.04	7.7060E-10
0.73	2.3270E-01	1.49	6.8110E-02	2.25	1.2220E-02	3.01	1.3060E-03	3.77	8.1620E-05	4.53	2.9490E-06	5.29	6.1160E-08	6.05	7.2420E-10
0.74	2.2960E-01	1.50	6.6810E-02	2.26	1.1910E-02	3.02	1.2640E-03	3.78	7.8410E-05	4.54	2.8130E-06	5.30	5.7900E-08	6.06	6.8060E-10
0.75	2.2660E-01	1.51	6.5520E-02	2.27	1.1600E-02	3.03	1.2230E-03	3.79	7.5320E-05	4.55	2.6820E-06	5.31	5.4810E-08	6.07	6.3960E-10

1. Consider the transmission of 1500 byte long packets over an AWGN channel with noise power spectral density $N_0/2$ using M-ary PAM, where $N_0 = 1.1 \cdot 10^{-20}$ W/Hz. The bits and the symbols making up the packets are assumed to be independent and equally likely. The received signal power is $2 \cdot 10^{-12}$ W, and the packet error probability (P_p) should not exceed 0.1.

   (a) Assuming there is no ISI, give an expression for the packet error probability P_p in terms of the symbol error probability P_e. (2p)

   (b) Assuming P_p is at most 0.1, what is the maximum data rate if $M = 4$? (4p)

   (c) Repeat Part (b) for $M = 8$ and compared the results with the ones obtained in Part (b) with $M = 4$. What conclusions can we derive? (4p)

   (d) Assume using root-raised cosine pulse shapes with roll-off factor $\alpha = 0.1$ and a matched filter receiver. If the transmission should be free of ISI, assuming we would like to target the maximum rate what is the bandwidth of the transmitted signal in Part (b) and (c)? (2p)

   Hint: the symbol error probability for M-ary PAM is

$$P_e = \frac{2(M-1)}{M} Q\left(\sqrt{\frac{6}{M^2-1}\frac{E_s}{N_0}}\right)$$

Solution Problem 1

(a) The symbol energy can be expressed as $E_s = P/R_s$, where P is the received power and R_s is the symbol rate. We assume there is no ISI. Symbol errors are then independent for PAM over a baseband AWGN channel. The packet error probability can be computed as $P_p = 1-(1-P_e)^{n_s}$, where P_e is the symbol error probability and n_s is the number of symbols in the packet.
If we want to compute the value of P_e from P_p, the value of n_s can be derived as $n_s = n_{byte} \cdot 8/\log_2(M)$, where n_{byte} is the number of bytes in a packet and $\log_2(M)$ is the number of bits per symbol. We can now compute the symbol error probability as:

$$\begin{aligned} P_p &= 1-(1-P_e)^{n_s} \Rightarrow \\ P_e &= 1-(1-P_p)^{\log_2(M)/(8n_{byte})} \end{aligned} \tag{1}$$

(b) The data rate R_b (bit/s) can be derived as $R_b = R_s \log_2(M)$. As already seen in the solution of Part (a), $R_s = P/E_s$, then:

$$R_b = R_s \log_2(M) = \frac{P}{E_s} \log_2(M) \tag{2}$$

The only part missing now is E_s, but it can be derived from the general expression of the symbol error probability of an M-ary PAM (see provided *Hint*):

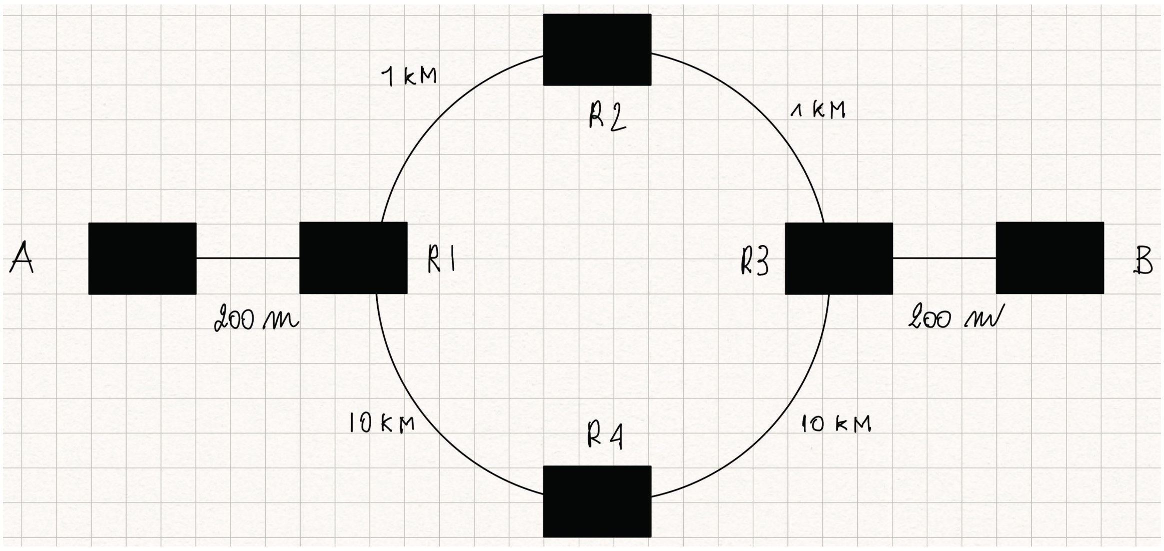
$$\begin{aligned} P_e &= \frac{2(M-1)}{M} Q\left(\sqrt{\frac{6}{M^2-1}\frac{E_s}{N_0}}\right) \Rightarrow \\ E_s &= N_0 \frac{M^2-1}{6}\left[Q^{-1}\left(\frac{M}{2(M-1)}P_e\right)\right]^2 \end{aligned} \tag{3}$$

We can now plug in the numberical values $n_{bytes} = 1500$, $P_p = 0.1$, $N_0 = 1.1 \cdot 10^{-20}$ in Equations (1)–(2) and compute the maximum data rates for $M = 4$ as $R_b = 8.13\,\text{Mbit/s}$.

(c) When $M = 8$ the data rate becomes $R_b = 2.99\,\text{Mbit/s}$.
The lower data rate is because the power efficiency of M-ary PAM decreases with M, i.e., a higher E_b/N_0 is required to reach a given packet error value for $M = 8$ compared to $M = 4$.
Consequently, for a fixed value for the received power, a PAM system with $M = 8$ must operate at a lower data rate to reach the required E_b/N_0 compared to the system with $M = 4$.

(d) In a M-ary PAM system with symbol rate R_s and root-raised cosine pulse shaping with roll-off factor α the value of the bandwidth is $W = R_s(1+\alpha)/2$. Hence, the bandwidth required is 2.24 MHz and 0.55 MHz for $M = 4$ and $M = 8$, respectively.

2. Consider a data transmission from Host A to Host B over the network depicted below.



We want to design an application layer that uses an ARQ protocol to provide a reliable, in-sequence transmission service of 1000 byte SDUs.
The transmission takes place over UDP, IP, and Ethernet. The application layer protocol header is 25 byte, and the ACK PDU is also 25 byte. We also assume that the IP header is 20 byte, the UDP header is 8 byte, and the Ethernet header and trailer are 22 byte and 4 byte, respectively.

R1, R2, R3, and R4 are store-and-forward routers. The links are full-duplex with a line data rate of 100 Mbit/s. The length of each link segment is indicated in the figure. We assume that the link propagation speed is $v = (2/3)c_0$, where $c_0 = 3 \cdot 10^8$ m/s. The processing time in the hosts and routers is assumed to be negligible.

(a) Sketch the layout of the Ethernet frame carrying the data SDUs of the application layer. More specifically, indicate the order and the length of the different protocol elements (headers, trailers, payloads, etc.) that makes up the frame. (1p)

(b) Repeat Part (a) for the application layer ACK PDUs. (1p)

(c) Suppose the application layer uses a Stop-and-Wait ARQ protocol. What is a good value for the time-out if Route 1 = (A—R1—R2—R3—B) is used? Motivate. (2p)

(d) Assume now the application layer uses Route 2 = (A—R1—R4—R3—B). Is the time-out value computed in Part (c) still a good choice? Motivate. (2p)

(e) Compute the value of the effective rate of the application layer service, assuming to use Route 1 = (A—R1—R2—R3—B) and error-free transmission. (2p)

(f) Suppose R1 drops frames with probability 0.1 and R3 drops frames with probability 0.2. Assume that the frame drops are independent of each other. Note that both data frames and ACK frames are subject to frame drops. What is the effective data rate experienced by the application layer ARQ protocol? Use the route and the time-out value as in point (c). (4p)

Hint: Suppose the success probability of a trial is p, then the average number of independent trials needed until a successful trial is:

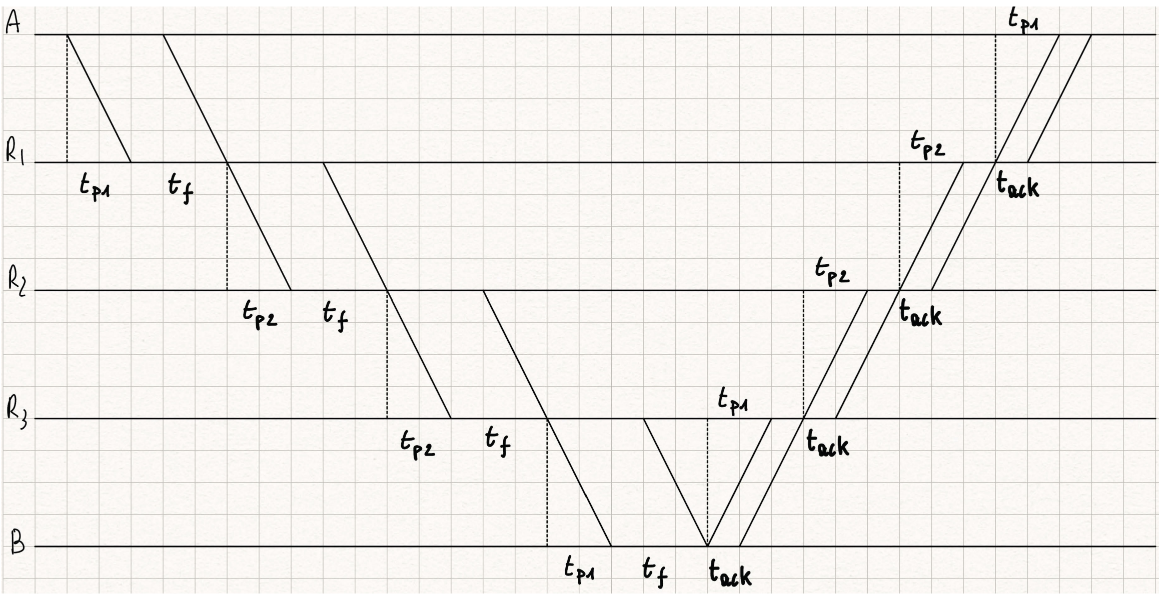
$$\sum_{k=1}^{\infty} kp(1-p)^{k-1} = \frac{1}{p}.$$

Solution Problem 2

(a) The Ethernet frame carrying the application layer data SDU (Data-SDU) can be represented as: |EH|IH|UH|AH|Data-SDU|ET|, where EH, IH, UH, and AH are headers for the the Ethernet, IP, UDP and application protocols. ET represents the trailer for the Ethernet protocol. As a result the Ethernet frame consists of 1079 bytes (i.e., (|22|20|8|25|1000|4|).

(b) The Ethernet frame carrying the application layer ACK PDU can be represented as: |EH|IH|UH|AH|ACK-SDU|ET|. The ACK PDU size is 25 bytes, this implies that ACK-SDU = 0. As a result the Ethernet frame consists of 79 bytes (i.e., (|22|20|8|25|0|4|).

(c) Let's compute the time required to transmit and acknowledge, over Route 1, an Ethernet frame containing the App-SDU data. Let's call this time t_{R1}. If we want to avoid unnecessary re-transmissions, we should set the time out of the SW ARQ protocol (t_{out}) at least to this value. Let's use the diagram below.



The time required by an Ethernet frame containing the Data-SDU to be transmitted at A, traverse R1, R2, R3, and be received at B can be expressed as:

$$t_{f1} = 4 \cdot t_f + 2 \cdot t_{p1} + 2 \cdot t_{p2}. \tag{4}$$

The time required by an Ethernet frame containing the ACK PDU to be transmitted at B, traverse R3, R2, R1, and be received at A can be expressed as:

$$t_{a1} = 4 \cdot t_{ack} + 2 \cdot t_{p1} + 2 \cdot t_{p2}. \tag{5}$$

t_{p1} is the propagation time over links (A—R1) and link (R3—B), while t_{p2} is the propagation time over links (R1—R2) and link (R2—R3). Their value is $t_{p1} = 200/v = 1\ \mu s$ and $t_{p2} = 1000/v = 5\ \mu s$.
t_f and t_{ack} are the transmission time for Ethernet frames containing the Data-SDU and the ACK PDU, respectively. They can be computed as:

$$t_f = n_f/R = 1079 \cdot 8/100 \cdot 10^6 = 86.3 \cdot 10^{-6} \text{ [s]} \tag{6}$$
$$t_{ack} = n_{ack}/R = 79 \cdot 8/100 \cdot 10^6 = 6.3 \cdot 10^{-6} \text{ [s]}, \tag{7}$$

where n_f and n_{ack} are the number of bits of the two Ethernet frames containing the App-SDU and the ACK PDU, and R is the line data rate. As a final result we have the following:

$$t_{R1} = t_{f1} + t_{a1} = 357.3 \cdot 10^{-6} + 37.3 \cdot 10^{-6} = 394.6 \cdot 10^{-6} \text{ [s]} \tag{8}$$

If Route 1 = (A—R1—R2—R3—B) is used we can set $t_{out} = t_{R_1}$.

(d) To answer the question we need to compute t_{R2}, i.e., the time required to transmit and acknowledge, over Route 2, an Ethernet frame containing the App-SDU data. We can use the same reasoning as in Part (b) and compute:

$$t_{f2} = 4 \cdot t_f + 2 \cdot t_{p1} + 2 \cdot t_{p3} \tag{9}$$

$$t_{a2} = 4 \cdot t_{ack} + 2 \cdot t_{p1} + 2 \cdot t_{p3}, \tag{10}$$

where t_{p3} is the propagation time over link (R1—R4) and link (R4—R3), whose value is $t_{p3} = 10000/v = 50\ \mu s$. We can then compute:

$$t_{R2} = t_{f2} + t_{a2} = 447.3 \cdot 10^{-6} + 127.3 \cdot 10^{-6} = 574.6 \cdot 10^{-6} \text{ [s]} \tag{11}$$

A good value of the time-out if Route 2 is used is $t_{out} = t_{R_2}$. Since $t_{R_2} > t_{R_1}$, we can not use t_{R_1} as the time-out. If we do we will trigger unnecessary re-transmissions.

(e) The effective rate of the application layer service when Route 1 is used can be computed as the ratio between total number of bits of App-SDU and the time required for a successfully acknowledged transmission:

$$R_{R1} = \frac{1000 \cdot 8}{t_{R1}} = 20.3 \cdot 10^6 \text{ [bit/s]} \tag{12}$$

(f) Let p be the probability that a transmission trial over Route 1 is successful. We can express p as:

$$\begin{aligned} p = \Pr\{&\text{"Data frame not dropped at R1"} \cap \text{"Data frame not dropped at R3"} \\ &\cap \text{"ACK frame not dropped at R3"} \cap \text{"ACK frame not dropped at R1"}\} \end{aligned}$$

Since the data and ACK frame drops at R1 and R3 are independent of each other, p can be calculated as:

$$\begin{aligned} p = &\Pr\{\text{"Data frame not dropped by R1"}\} \cdot \Pr\{\text{"Data frame not dropped by R3"}\} \\ &\cdot \Pr\{\text{"ACK frame not dropped by R3"}\} \cdot \Pr\{\text{"ACK frame not dropped by R1"}\} \end{aligned}$$

$$\begin{aligned} p &= (1 - 0.1)^2 (1 - 0.2)^2 \\ &= 0.5184. \end{aligned}$$

We can then compute the effective data rate taking into account that on average it takes $\frac{1}{p}$ transmissions attempt a frame is successfully transmitted and acknowledged (check provided *Hint*) as:

$$R_{\text{sw}} = \frac{1000 \cdot 8}{\frac{1}{p} t_{\text{R1}}} = 10.5 \cdot 10^6 \text{ [bit/s]}.$$

3. Consider a forest where several wireless sensors want to transmit their readings to a base station. The sensors are distributed uniformly over a circular area with a radius $r = 15\,\text{km}$ with the base station in the center. The transmitted frames are 80 byte long.

   The physical layer has data rate R bit/s and the propagation speed is $c = 3 \cdot 10^8$ m/s.

   We will consider two medium access protocols: Aloha and slotted Aloha. In the slotted case, synchronization is assumed to be perfect.

   (a) Suppose to use Aloha to access the medium. What is the best system throughput we can achieve when $R = 3\,\text{Mbit/s}$? Your answer should be in the unit [frames/second]. (3p)

   (b) Now consider slotted Aloha. The slot duration is the frame duration plus a guard interval. What is the smallest guard interval such that transmissions from different slots will not collide at the base station? (3p)

   (c) Repeat Part (a) for slotted Aloha. Use the slot duration from Part (b). (3p)

   (d) Suppose we want to improve the throughput by increasing the data rate R. For which data rate do Aloha, and slotted Aloha have the same throughput value? (3p)

   Hint: Assuming that the sensors generate, on average, G frames/(frame duration). The Aloha system throughput can be expressed as $S = G\exp(-2G)$, where S is measured in frames/(frame duration). G is a free variable we can adjust to maximize the system throughput.

   Similarly, the system throughput for slotted Aloha is $S' = G'\exp(-G')$, where the system throughput S' and the offered traffic G' are measured in frames/(slot duration). Note that S and S' are measured in different units.

Solution Problem 3

(a) With Aloha, the normalized throughput is maximum when $G = 1/2$.
If we set $\frac{dS}{dG} = 0 \rightarrow G = 1/2$, we obtain $S_{max} = \frac{1}{2}e^{-1}$ [frames/frame duration].
We can compute the frame duration t_f as:

$$t_f = \frac{80 \cdot 8}{R} = 213\,\mu s \tag{13}$$

The maximum achievable throughput is

$$\begin{aligned} R_{eff} &= \frac{S_{max}}{t_f} = 862.2\,[\text{frames/s}] && (14) \\ &= 0.55 \text{ Mbit/s.} && (15) \end{aligned}$$

(b) Let us define τ as the maximum propagation time from any sensor to the base station. We have that

$$\tau = \frac{15000}{c} = 50 \cdot \mu s \tag{16}$$

Let us assume that a sensor is located 15 km from the base station. When the sensor starts transmitting at the beginning of a new slot, the frame will reach the base station after $t_f + \tau$. In order to ensure that transmissions from different slots will not collide at the base station, we should set the guard interval to $t_g = \tau$.

(c) With slotted Aloha, the normalized throughput is maximum when $G' = 1$.
If we set $\frac{dS'}{dG'} = 0 \rightarrow G' = 1$, we obtain $S'_{max} = e^{-1}$ [frames/slot duration].
We can compute the slot duration as:

$$t_{slot} = t_f + t_g = 263\,\mu s. \tag{17}$$

The maximum achievable throughput for slotted Aloha is:

$$\begin{aligned} R'_{eff} &= \frac{S'_{max}}{t_{slot}} = 1.397 \cdot 10^3[\text{frames/s}] && (18) \\ &= 0.89\,\text{Mbit/s.} && (19) \end{aligned}$$

(d) If we write the maximum achievable throughput of Aloha and slotted Aloha as a function of R, we obtain:

$$\begin{aligned} R_{eff} &= R \cdot \frac{e^{-1}}{2 \cdot 80 \cdot 8} && (20) \\ R'_{eff} &= R \cdot \frac{e^{-1}}{80 \cdot 8 + \tau R}. && (21) \end{aligned}$$

If we want to have $R_{eff} = R'_{eff} \Rightarrow 640 + \tau R = 2 \cdot 640$, and we obtain

$$R = \frac{640}{\tau} = 12.8\text{Mbit/s.} \tag{22}$$

4. (a) Explain the purpose of the spanning tree algorithm in the context of transparent bridges. (2p)

   (b) Explain how systematic binary block codes can be used for error detection. (3p)

   (c) What is characteristic of an end-to-end protocol? Give an example of a TCP/IP protocol that is an end-to-end protocol. Give an example of a TCP/IP protocol that is not an end-to-end protocol. (3p)

   (d) Define the security goals of confidentiality and integrity. Can One-Time Pad guarantee both goals? Motivate. (3p)

   (e) Given an example of a channelization scheme in which channels can be accessed at all times. (1p)

   (a) In the context of transparent bridges, the purpose of the spanning tree (SP) algorithm is to create a loop-free logical network topology from a physical topology that may have loops. In this way, bridges can create and maintain valid forwarding tables (i.e., tables that ensure a frame reaches its destinations) using backward learning, i.e., by inspecting the destination addresses of data traffic on the attached LANs. The spanning tree algorithm logically disables links (bridge ports) such that the resulting topology is a spanning tree.

   (b) Error detection with systematic binary block codes works as follows. We encode the k first received bits (normally the information bits) to find the corresponding $n - k$ parity bits. These bits are compared with the last $n - k$ received bits. The received bit pattern is a codeword if, and only if, the computed and received parity bit patterns are the same.

   (c) In an end-to-end protocol, the protocol entities reside in the end nodes. End-to-end protocols reside in the transport and application layers, e.g., UDP, TCP, HTTP, etc. Non-end-to-end protocols (single hop protocols) reside in the layers below the transport, e.g., IP, IEEE 802.3, IEEE LLC, etc.

   (d) Confidentiality guarantees that two entities can communicate privately even when an eavesdropper listens to their conversation. Integrity guarantees that a message has not been altered during transmission. One-Time Pad guarantees confidentiality but not integrity, i.e., it is possible for an eavesdropper to change bits in the plaintext by simply flipping corresponding bits in ciphertext.

   (e) FDMA and/or CDMA are two examples of channelization schemes where a channel can be accessed at all times.