Exam in
SSY305 Kommunikationssystem

Department of Signals and Systems

Exam date: March 17, 2016, 14:00–18:00
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Teaching Staff

Erik Ström (examiner), 772 5182
Katharina Hausmair, 772 5183
Amina Piemontese, 772 1885

Material Allowed material is

- 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. Photo copies, printouts, other students' notes, or any other material is not allowed.
- A paper-based dictionary, without added notes (electronic dictionaries are not allowed).

Grading A correct, clear and well-motivated solution gives a maximum of 12 points per problem.

An erroneous answer, unclear, incomplete or badly motivated solutions give point reductions down 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 at 19:00 on the course web page.

Results Results are posted on Ping-Pong no later than March 30, 2016. The grading review is on April 13 and April 20, 2016, 12:00–13:00 in room 6414 in the ED-building.

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

Total Score	0–39	40–59	60–79	≥ 80
Grade	Fail	3	4	5

PLEASE NOTE THAT THE PROBLEMS ARE NOT NECESSARILY ORDERED IN 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 transmission of equally likely independent bits with pulse-amplitude modulation with symbol alphabet $\mathcal{A} = \{\pm c, \pm 3c, \ldots, \pm(M-1)c\}$ over an AWGN channel with noise power spectral density $N_0/2$, where $N_0 = 1.10 \times 10^{-20}$ W/Hz. The average received power is $P = 1.74 \times 10^{-12}$ W and the transmitted pulse is chosen to maximize the symbol rate over the channel, while avoiding inter-symbol interference. The channel frequency response is

$$H(f) = \begin{cases} 1, & |f| \leq B \\ 0, & \text{otherwise} \end{cases}.$$

   (a) What is the data rate and symbol error probability if $M = 2$ and $B = 5 \times 10^6$ Hz? (2p)

   (b) Suppose we change M such that the data rate is increased with a factor 2 compared to the case in (a). Assume that P and B are the same as in (a). What is the symbol error probability? (3p)

   (c) Suppose we change B such that the data rate is increased with a factor 2 compared to the case in (a). Assume that P and M are the same as in (a). What is the symbol error probability? (3p)

   (d) Consider transmission of 1500-byte long data frames with a Stop-and-Wait link layer protocol. What is the effective data rate for the layer above the link layer if the physical layers in in (a), (b), and (c) are used?

   Assume that the propagation delay and processing delay is together 0.5 ms, the ACK frame is 25 byte long, and the protocol overhead (header, trailer) in the data frame is 50 byte. The time-out is set to maximize the effective data rate. Assume that ACKs are always transmitted error-free. (4p)

2. Consider a link-layer protocol in which framing is done with the flag field FLAG = [01111110] (just as in HDLC). The PDU is formatted as [FLAG bs([HDR SDU CRC]) FLAG], where the HDR field is a 4-bit link layer header, the CRC field contains the error check bits corresponding to the bit pattern [HDR SDU] and the generator polynomial $g(x) = x^3 + x + 1$, and bs(X) is the bitstuffed version of the field X. When the physical layer is idle (i.e., has no PDU to transmit), it will send a pattern of alternating ones and zeros to maintain synchronization with the receiving physical layer.

   (a) Suppose [HDR SDU] = [111111011010111]. Compute the CRC field. (3p)

   (b) Perform bitstuffing on the field [HDR SDU CRC], i.e., compute bs([HDR SDU CRC]) (3p)

   (c) Suppose the receiving link layer entity observes the bit stream

   $\cdots$010101 0111111000000000001111110010101111110000000001001111110
   0111111011111001110111111001010101$\cdots$

   Compute the SDUs that the receiving link layer entity delivers to its upper layer. (6p)

3. (a) Explain why a minimum frame length is required in CSMA/CD systems and how it is calculated. What would be the consequence if the frames are too small? (4p)
   (b) What is the purpose of the network layer in the OSI reference model? (2p)
   (c) Give an example of an internet layer protocol in the TCP/IP reference model. (2p)
   (d) What is the purpose of the channel decoder block in Shannon's model for digital communications? (2p)
   (e) Consider a reservation scheme for a LAN with 100 stations. The reservation protocol is designed such that all nodes with data to send are guaranteed a transmission opportunity per cycle. In which case is the efficiency the best, (i) when only one node has data to send, or (ii) when all 100 nodes have data to send? Motivate. (2p)

4. Consider transmission of data frames over an 802.11 WLAN with DCF (distributed coordinating function). Assume the following (simplified) parameters:

Parameter	**Value**
Slot time T_{slot}	$9\,\mu$s
SIFS	$2T_{\text{slot}}$
DIFS	$3T_{\text{slot}}$
Information frame duration	$100T_{\text{slot}}$
ACK frame duration	$3T_{\text{slot}}$
Maximum value backoff time	15 slots

We define the MAC-to-MAC delay as the time from when an SDU is handed down from the LLC layer to the transmitting MAC layer until the SDU is delivered to the receiving LLC layer. Processing and propagation times are assumed to be negligible. Assume that frames that do not experience collisions are transmitted error-free.

Consider a network with one access point (AP) and three stations (STAs). Assume that all nodes are within radio range of each other and that channel sensing is perfect and instantaneous.

   (a) Suppose STA1 starts to sense the channel at time $t = 0$ and that there are no ongoing transmissions at that time. What is the MAC-to-MAC delay for STA1's first transmitted frame? (2p)
   (b) In addition to the transmission in part (a), suppose STA2 becomes ready to transmit a frame to the AP and starts channel sensing during the interval $0 < t < T_1$, where T_1 is the time when STA1 has completed the transmission of its frame (including receiving the ACK from the AP). What is the minimum and maximum value of the MAC-to-MAC delay for STA2's transmitted frame? (3p)
   (c) In addition to the transmission in part (a), suppose both STA2 and STA3 becomes ready to transmit one frame each and start channel sensing during the interval $0 < t < T_1$. Moreover, suppose the frames from STA2 and STA3 collides at the first transmission attempt, but are successfully transmitted at the first retransmission attempt. What is the minimum and maximum value of the MAC-to-MAC delay for STA3's transmitted frame? (3p)
   (d) For the scenario in part (c), what is the probability for the event that STA2 and STA3 frames collide at the first transmission attempt? (4p)

P1

a) $M = 2$ $\quad B = 5 \cdot 10^6 \ Hz$ $\quad P = 1.74 \cdot 10^{-12} W$ $\quad N_0 = 1.1 \cdot 10^{-20} W/Hz$

for maximum symbol rate $R_s = 2B = 10 \cdot 10^6$ symbols/s

$R_b = R_s \cdot \log_2(M) = R_s = 10 \cdot 10^6$ bits/s

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

$$= Q\left(\sqrt{\frac{2E_s}{N_0}}\right) \qquad E_s = P \cdot T = \frac{P}{R_s} = \frac{P}{2B}$$

$$= Q\left(\sqrt{\frac{2P}{2BN_0}}\right) = Q\left(\sqrt{\frac{1.74 \cdot 10^{-12} \cdot 2}{2 \cdot 5 \cdot 10^6 \cdot 1.1 \cdot 10^{-20}}}\right) = Q(5.6246) = 9.2958 \cdot 10^{-9}$$

b) $R_b = 2 \cdot 10 \cdot 10^6 = 2 \cdot R_s = R_s \cdot \log_2(M) \Rightarrow \log_2(M) = 2$

$M = 4$

$$P_e = 1.5 \ Q\left(\sqrt{\frac{6}{15} \frac{P}{2BN_0}}\right) \qquad E_s = \frac{P}{2B}$$

$$= 1.5 \ Q(2.5154) = 0.0089$$

c) $R_b = 2 \cdot 10 \cdot 10^6 = \log_2(2) \cdot R_s' = R_s' = 2R_s = 4B$

$$P_e = Q\left(\sqrt{\frac{2P}{4BN_0}}\right) = Q(3.9772) = 3.4865 \cdot 10^{-5} \qquad E_s = P \cdot T' = \frac{P}{2B'} = \frac{P}{4B}$$

d) $n_f = 1500$ byte $= 12000$ bit

$t_{prop} + t_{proc} = 0.5$ ms $= 0.5 \cdot 10^{-3}$ s

$n_a = 25$ byte $= 200$ bit

$n_o = 50$ byte $= 400$ bit

$$t_{out\,min} = t_0 = 2(t_{prop} + t_{proc}) + \frac{n_f}{R_b} + \frac{n_a}{R_b}$$

$$R_{eff} = \frac{n_f - n_o}{t_0}(1 - P_f)$$

P_f: frame error probability

$$P_f = 1-(1-P_e)^{n_s}$$

n_s: number of symbols in frame

$$n_s = \frac{n_f}{\log_2(M)}$$

for a) $R_b = 10^7$ bit/s $\quad M=2$

$n_s = n_f = 12000$ symbols $\quad P_f = 1.1154 \cdot 10^{-4}$

$t_o = 0.001221\ s$

$$R_{eff} = \frac{n_f - n_o}{t_o}(1-P_f) = 5.2246 \cdot 10^6 \text{ bit/s} = 5.2246 \text{ Mbit/s}$$

b) $R_b = 2 \cdot 10^7$ bits/s $\quad M=4$

$n_s = \frac{n_f}{2} = 6000$ $\quad P_f = 1$

$t_o = 0.0016\ s$

$R_{eff} = 0$ bit/s

c) $R_b = 2 \cdot 10^7$ bits/s $\quad M=2$

$n_s = n_f$ $\quad P_f = 0.3418$

$t_o = 0.0016\ s$

$R_{eff} = 4.7417 \cdot 10^6$ bit/s $= 4.7417$ Mbit/s

P2 FLAG: 01111110

$g(x) = x^3 + x + 1 \triangleq 1011$ degree: 3 → CRC: 3 bits

HDR: 4 bits

a) $[\text{HDR SDU}] = [\underbrace{1111}_{\text{HDR}}, \underbrace{11011010111}_{\text{SDU}}] \triangleq i(x)$

CRC = ?

① $i(x)\,x^3$: 111111011010111$\underbrace{000}$
add 3 bits

② find $r(x)$ by dividing $i(x)\,x^3$ by $g(x)$

```
  111111011010111|000
⊕ 1011
  ---------------------
  010011011010111|000
⊕  1011
  ---------------------
   00101011010111|000
⊕    1011
  ---------------------
     000111010111|000
⊕       1011
  ---------------------
        010110111|000
⊕        1011
  ---------------------
         00000111|000
⊕              101|1
  ---------------------
                010|100
⊕                10|11
  ---------------------
                 00|010
```

→ $r(x) = x \triangleq 010$

[HDR SDU CRC] = [111111011010111010]

b) bit stuffing: insert zero after every instance of five consecutive 1s to prevent occurrence of flag inside the frame

frame = bs([HDR SDU CRC])
= [1111101011010111010]

c) (when physical layer is idle: 0101 ...)

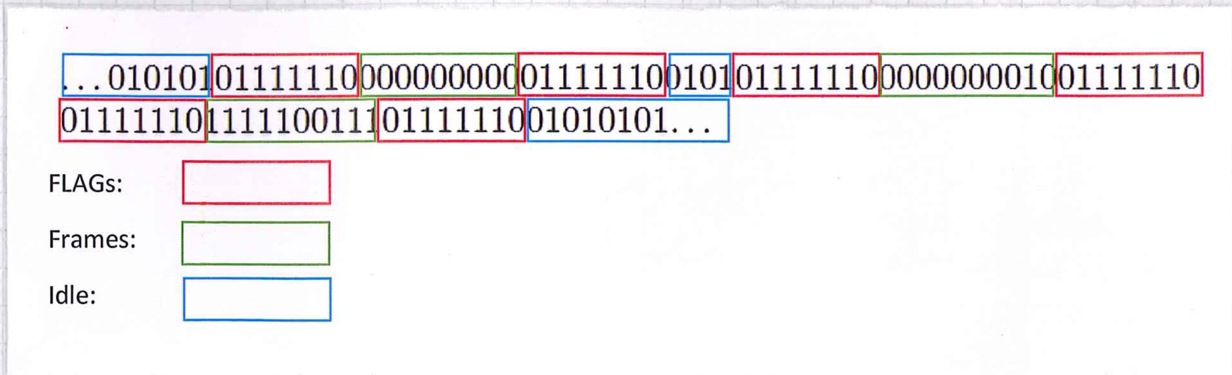
① find flags

② take bitstream in between flags and perform destuffing to obtain frames

③ perform error detection

④ hand SDUs from error-free frames to upper layer

①



② frame1: 0 0 0 0 0 0 0 0 0

frame2: 0 0 0 0 0 0 0 0 1 0

frame3: 1 1 1 1 1 0 0 1 1 1

only frame 3 has 5 consecutive bits

frame3: 1 1 1 1 1 0 0 1 1 1 → 1 1 1 1 1 0 1 1 1

$\uparrow$ remove

③ divide $\hat{b}(x)$ by $g(x)$, if remainder is zero → no error detected

frame 1: $\hat{b}(x) = 0000000000$

000000000 → $\hat{r}(x) = 0$ → no error detected

frame 2: 0000000010 $\quad \hat{r}(x) = 10$ → error detected

frame3:

```
   1 1 1 1 1 0 | 1 1 1
⊕  1 0 1 1
   -----------------
   0 1 0 0 1 0 | 1 1 1
⊕    1 0 1 1
   -----------------
     0 0 1 0 0 | 1 1 1
⊕        1 0 1 | 1
   -----------------
         0 0 1 | 0 1 1
⊕            1 | 0 1 1
   -----------------
               | 0 0 0
```

→ no error detected

(4) remove HDR and CRC

- SDU1: $\underbrace{0\,0\,0\,0}_{HDR}\,0\,0\,\underbrace{0\,0\,0}_{CRC}$ → SDU1 = [0 0]
- SDU2: error was detected → not handed to upper layer
- SDU3: $\underbrace{1\,1\,1\,1}_{HDR}\,1\,0\,\underbrace{1\,1\,1}_{CRC}$ → SDU3 = [1 0]

SDU1 = [0 0] and SDU3 = [1 0] are delivered to the upper layer

Problem 3

a) The minimum frame length in CSMA/CD is
$n_{f,\min} = 2t_{prop}R$ in bit
where t_{prop} in s is the longest possible propagation time between any two stations in the network, and R in bit/s is the data rate.
Using this minimum frame length is necessary to ensure that any collision can be detected by the transmitting station before the transmission of its frame is finished (see Figure 1). If a shorter frame length is used, there is a risk that a station doesn't detect that a collision has happened (see Figure 2).

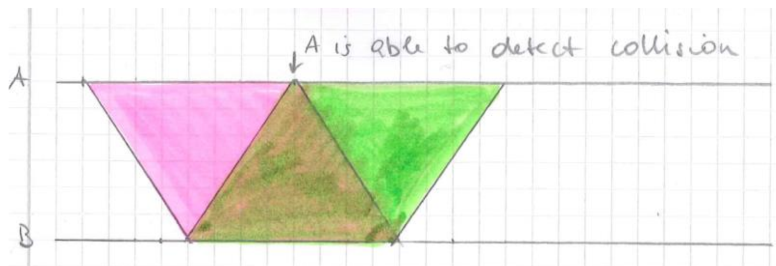


Figure 1: With the minimum frame length station A can detect a collision even if station B starts a transmission directly before it starts receiving station A's frame.

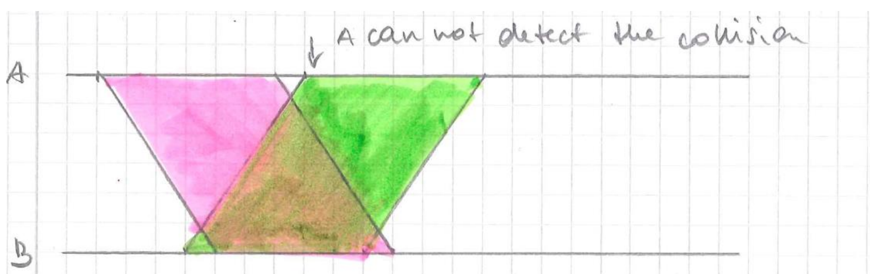


Figure 2: When using a frame length shorter than the required minimum, station a may not be able to detect collisions.

b) The network layer transfers data over several links or networks. This includes:
- the addressing scheme
- segmentation and reassembly of data
- determining routes across networks and message forwarding
- handling of connection setup, maintenance, release and congestion control

c) E.g. Internet Protocol (IP), Internet Protocol Security (IPsec), Internet Control Message Protocol (ICMP), Internet Group Management Protocol (IGMP), etc

d) The channel decoder takes the output of the demodulator (i.e. bits) and exploits redundancy (e.g parity bit, CRC bits, etc.) to estimate the sequence of information bits that were input to the channel encoder. This means that error detection, correction and control are tasks of the channel decoder

e) For a LAN with 100 stations, where all stations are guaranteed a transmission opportunity per cycle, one cycle of the reservation system consist of

- one reservation interval with 100 minislots of length νX time units where $\nu < 1$
- 100 data frame slots of length X time units

The maximum throughput when N stations want to transmit is given by

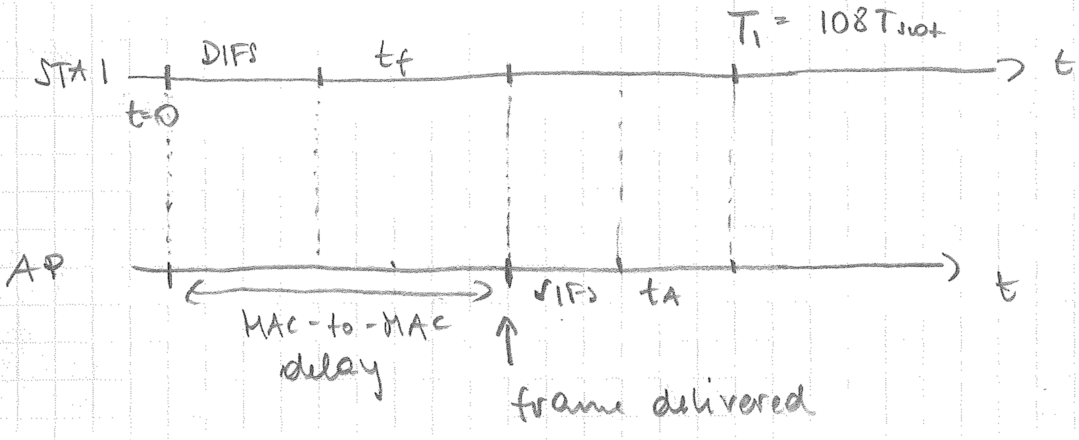
$$\rho_{\max} = \frac{NX}{M\nu X + NX} = \frac{1}{1 + \nu M/N}$$

Since $R_{eff,\max} = \rho_{\max} R$, the efficiency is highest when all 100 nodes have data to send.

$t_{prop} = t_{proc} = 0$

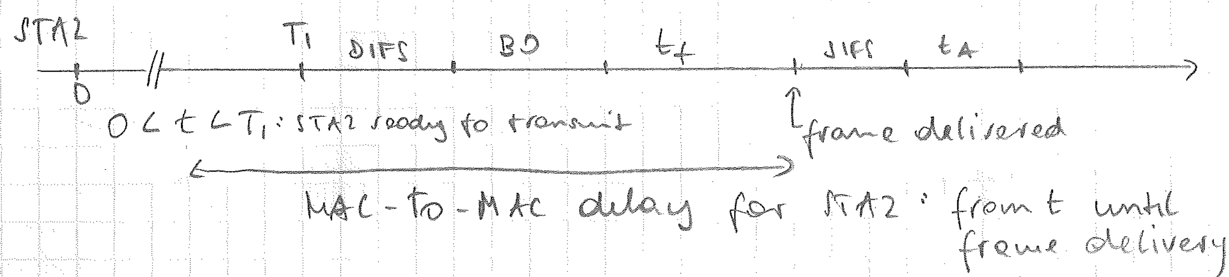
P4

a)



$\Rightarrow t_{M2M} = DIFS + t_f = 3\,T_{slot} + 100\,T_{slot} = 103\,T_{slot}$

b)



BO: back-off : $r\,T_{slot}$ $\quad r \sim \mathcal{U}[0, 2^K-1]$ $\quad K=4$

t : $0 < t < T_1$

$t_{M2M} = T_1 - t + DIFS + BO + t_f$

minimum: for $t = T_1$ and $BO = 0\,T_{slot}$

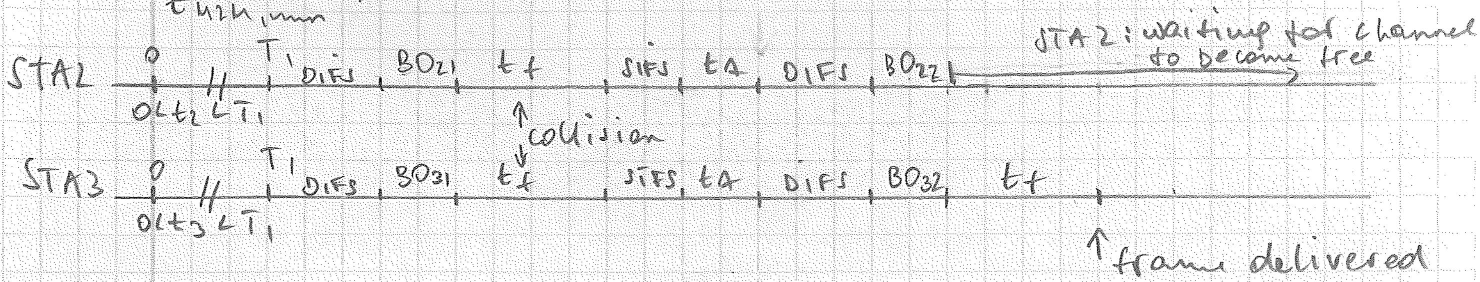
maximum: for $t = 0$ and $BO = 15\,T_{slot}$

$\rightarrow t_{M2M,min} = DIFS + t_f = 103\,T_{slot}$

$t_{M2M,max} = T_1 + DIFS + 15\,T_{slot} + t_f = 226\,T_{slot}$

c)
- a collision occurs when STA2 and STA3 choose the same value K for the backoff timer
- the minimum possible MAC-to-MAC delay that STA3 can experience is if STA3 gets to transmit before STA2 in the transmission attempt after the collision
- the maximum MAC-to-MAC delay for STA3 is when STA3 transmits after STA2
- after a collision the maximum size of the contention window is doubled: $r \sim \mathcal{U}[0, 2^{K+1}-1] \rightarrow r \sim \mathcal{U}[0, 31]$

$t_{M2M,min}$:



$BO_{21} = BO_{31}$ $\quad$ $BO_{22} > BO_{32}$

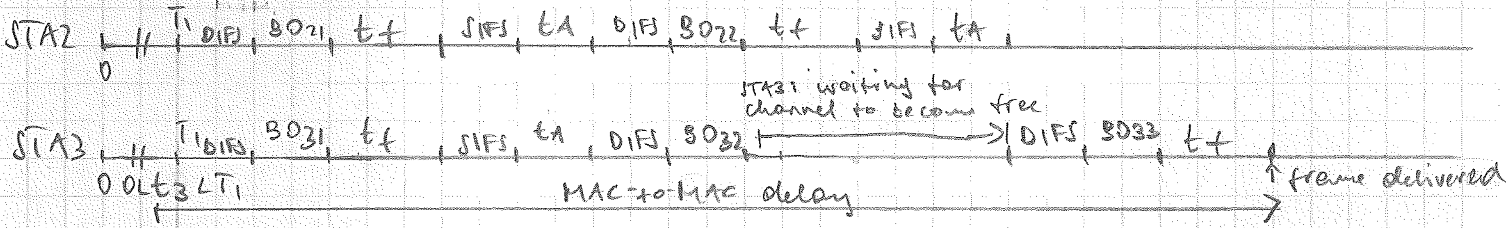
t_3: time when STA3 is ready to start transmitting

$\rightarrow$ for $t_{M2M,min}$: $t_3 = T_1$

$BO_{31} = 0\, T_{slot}$

$BO_{32} = 0\, T_{slot}$

$t_{M2M,min} = 0 + DIFS + 0 + t_f + SIFS + t_A + DIFS + 0 + t_f = 211\, T_{slot}$



$BO_{31} = BO_{21} \Rightarrow \max(BO_{31}) = 15\, T_{slot}$

$BO_{22} < BO_{32} \Rightarrow \max(BO_{32}) = 31\, T_{slot}$

$\max(BO_{22}) = 30\, T_{slot}$

$BO_{33} = BO_{32} - BO_{22} = 1\, T_{slot}$

$0 < t_3 < T_1 \Rightarrow t_3 = 0$

$t_{M2M,max} = T_1 + DIFS + BO_{31} + t_f + SIFS + t_A +$ $\rightarrow$ STA1 + transmission with collision

$DIFS + BO_{22} + t_f + SIFS + t_A +$ $\rightarrow$ STA2 transmission

$DIFS + BO_{33} + t_f$ $\rightarrow$ STA3 transmission

$= T_1 + T_1 + 15\, T_{slot} + T_1 + 30\, T_{slot} + DIFS + T_{slot} + t_f$

$= 3T_1 + 46\, T_{slot} + DIFS + t_f = 473\, T_{slot}$

d) $\text{Prob}\{\text{collision}\} = \text{Prob}\{BO_{21} = BO_{31}\} =$

$$= \sum_{r=0}^{15} \text{Prob}\{BO_{21} = r\}\, \text{Prob}\{BO_{31} = r\}$$

$$= 16 \cdot \frac{1}{16} \cdot \frac{1}{16} = \frac{1}{16} = 0.0625$$