TÉCNICO LISBOA

Mestrado em Engenharia Electrotécnica e de Computadores

Redes Móveis e Internet das Coisas

Formulas

Propagation Models		
1	Antenna Apperture and Gain	$A_{eff} = \eta \cdot A_{phy} = \frac{\lambda^2}{4\pi} G$
2	Log-distance Model	$P_r\,[dBm] = P_t\,[dBm] - PL_0 + G_t\,[dBi] + G_r\,[dBi] - 10 \cdot \alpha \cdot log_{10}\,(d/d_0\,)$
3	Friis Free Space Model	$P_r = P_t \cdot \frac{G_t \cdot G_r \cdot \lambda^2}{(4 \cdot \pi \cdot d)^2}$
4	Two-Ray Model	$P_r = P_t \cdot \frac{G_t \cdot G_r \cdot (h_t \cdot h_r)^2}{d^4}$ $d_c = \frac{4 \cdot \pi \cdot h_t \cdot h_r}{\lambda}$
5	Fresnel Zone Radius	$r(F_n) = \sqrt{\frac{n \cdot \lambda \cdot d_1 \cdot d_2}{d_1 + d_2}}$

Maximum Channel Capacity		
6	Shannon-Heartley Theorem	$C = B \cdot log_2\left(1 + \frac{S}{N}\right)$
7	Nyquist Rate (applicable in baseband)	$C = 2 \cdot B \cdot log_2(M)$

Modulation Performance (B)		
8	ASK	$B = (1 + r) \cdot R_b$
9	M-PSK, QAM	$B = \left(\frac{1 + r}{log_2(M)}\right) \cdot R_b$
10	M-FSK	$B = \left(\frac{(1 + r) \cdot M}{log_2(M)}\right) \cdot R_b$

Modulation Performance (BER)		
11	BASK	$BER_{ASK} = Q\left(\sqrt{\frac{E_b}{N_0}}\right)$
12	BFSK	$BER_{BFSK} = Q\left(\sqrt{\frac{E_b}{N_0}}\right)$
13	DPSK	$BER_{DBPSK} = 0.5 \cdot e^{-\frac{E_b}{N_0}}$
14	BPSK	$BER_{BPSK} = Q\left(\sqrt{\frac{2 \cdot E_b}{N_0}}\right)$
15	QPSK	$BER_{QPSK} = Q\left(\sqrt{\frac{2 \cdot E_b}{N_0}}\right)$
16	M-PSK	$BER_{MPSK} = \frac{2}{log_2(M)} \cdot Q\left(\sqrt{\frac{2 \cdot E_b \cdot log_2(M)}{N_0}} \cdot sin\left(\frac{\pi}{M}\right)\right)$
17	QAM	$BER_{QAM} = \frac{4}{log_2(M)} \cdot Q\left(\sqrt{3 \cdot \left(\frac{E_b}{N_0}\right) \cdot \frac{log_2(M)}{M - 1}}\right)$
18	Q function	$Q(k) = P(X > \mu + k\sigma) = \frac{1}{\sqrt{2\pi}} \int_k^{+\infty} e^{-\lambda^2/2} d\lambda$

Probabilities	
19	$\sum_{i=1}^{+\infty} i \cdot (1-p)^{i-1} \cdot p = \frac{1}{p}$

20	$\sum_{i=0}^{+\infty} i \cdot (1-p)^{i} \cdot p = \frac{p-1}{p}$

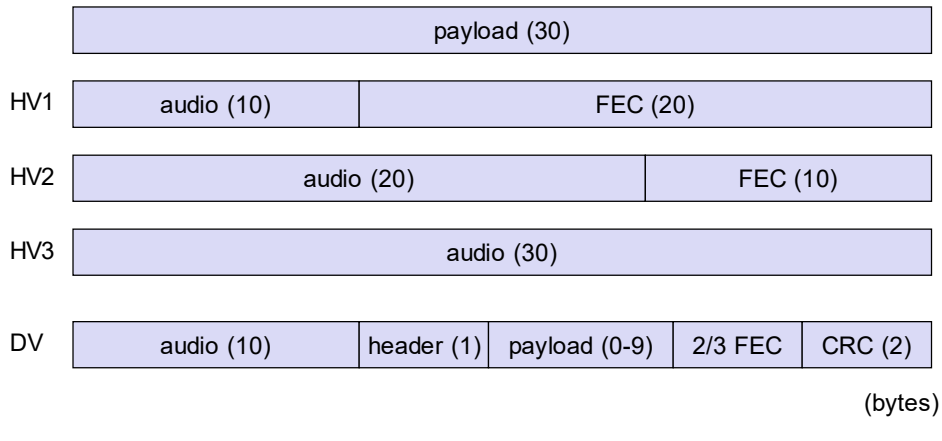
TABLE OF THE Q FUNCTION

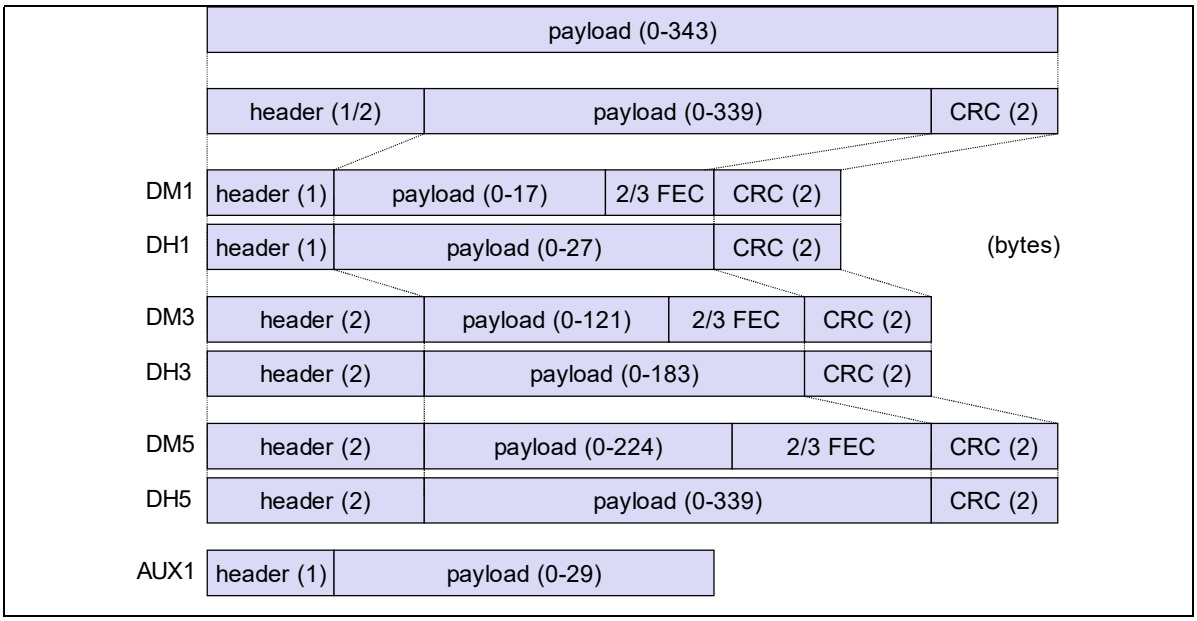
0	5.000000e–01	2.4	8.197534e–03	4.8	7.933274e–07
0.1	4.601722e–01	2.5	6.209665e–03	4.9	4.791830e–07
0.2	4.207403e–01	2.6	4.661189e–03	5.0	2.866516e–07
0.3	3.820886e–01	2.7	3.466973e–03	5.1	1.698268e–07
0.4	3.445783e–01	2.8	2.555131e–03	5.2	9.964437e–06
0.5	3.085375e–01	2.9	1.865812e–03	5.3	5.790128e–08
0.6	2.742531e–01	3.0	1.349898e–03	5.4	3.332043e–08
0.7	2.419637e–01	3.1	9.676035e–04	5.5	1.898956e–08
0.8	2.118554e–01	3.2	6.871378e–04	5.6	1.071760e–08
0.9	1.840601e–01	3.3	4.834242e–04	5.7	5.990378e–09
1.0	1.586553e–01	3.4	3.369291e–04	5.8	3.315742e–09
1.1	1.356661e–01	3.5	2.326291e–04	5.9	1.817507e–09
1.2	1.150697e–01	3.6	1.591086e–04	6.0	9.865876e–10
1.3	9.680049e–02	3.7	1.077997e–04	6.1	5.303426e–10
1.4	8.075666e–02	3.8	7.234806e–05	6.2	2.823161e–10
1.5	6.680720e–02	3.9	4.809633e–05	6.3	1.488226e–10
1.6	5.479929e–02	4.0	3.167124e–05	6.4	7.768843e–11
1.7	4.456546e–02	4.1	2.065752e–05	6.5	4.016001e–11
1.8	3.593032e–02	4.2	1.334576e–05	6.6	2.055790e–11
1.9	2.871656e–02	4.3	8.539898e–06	6.7	1.042099e–11
2.0	2.275013e–02	4.4	5.412542e–06	6.8	5.230951e–12
2.1	1.786442e–02	4.5	3.397673e–06	6.9	2.600125e–12
2.2	1.390345e–02	4.6	2.112456e–06	7.0	1.279813e–12
2.3	1.072411e–02	4.7	1.300809e–06		

Bluetooth

1 slot = 625us

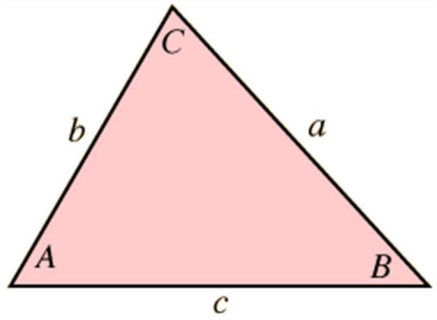
SCO stream throughput = 64 kbit/s





LoRaWAN		
21	Symbol Rate:	$Rs = \frac{BW}{2^{SF}}$
22	Chirp Rate:	$Rc = BW \times Rs = \frac{BW^2}{2^{SF}}$
23	Net Bit Rate:	$Rb = SF \times Rs \times CR$ CR=Code Rate (k/n of the error correcting code)
24	Bit Error Rate (empirical approximation):	$BER = Q\left(\frac{log_{12}(SF)}{\sqrt{2}} \cdot \frac{E_b}{N_0}\right)$

Cellular Networks: 4G (LTE and NB-IoT)		
25	Hexagonal cell area	$A_{cell} = 1.5 \times R^2 \times \sqrt{3}$
26	Frequency reuse factor	$RF = \frac{1}{G}$
27	Reuse distance vs cell Radius and cluster size	$\frac{D}{R} = \sqrt{3G}$
28	Distance between hexagonal cell centers	$d = \sqrt{3} \times R$
29	Cell cluster sizes	$G = I^2 + J^2 + (I \times J)$ st $I, J = 0, 1, 2, etc.$
30	Reuse distance vs distance between adjacent cell centers, cell radius and cluster size:	$D^2 = d^2I^2 + d^2J^2 - 2(dI \times dJ)cos(120º) = d^2\left(I^2 + J^2 + (I \times J)\right) = 3R^2\left(I^2 + J^2 + (I \times J)\right)$
Law of cosines: see below.		

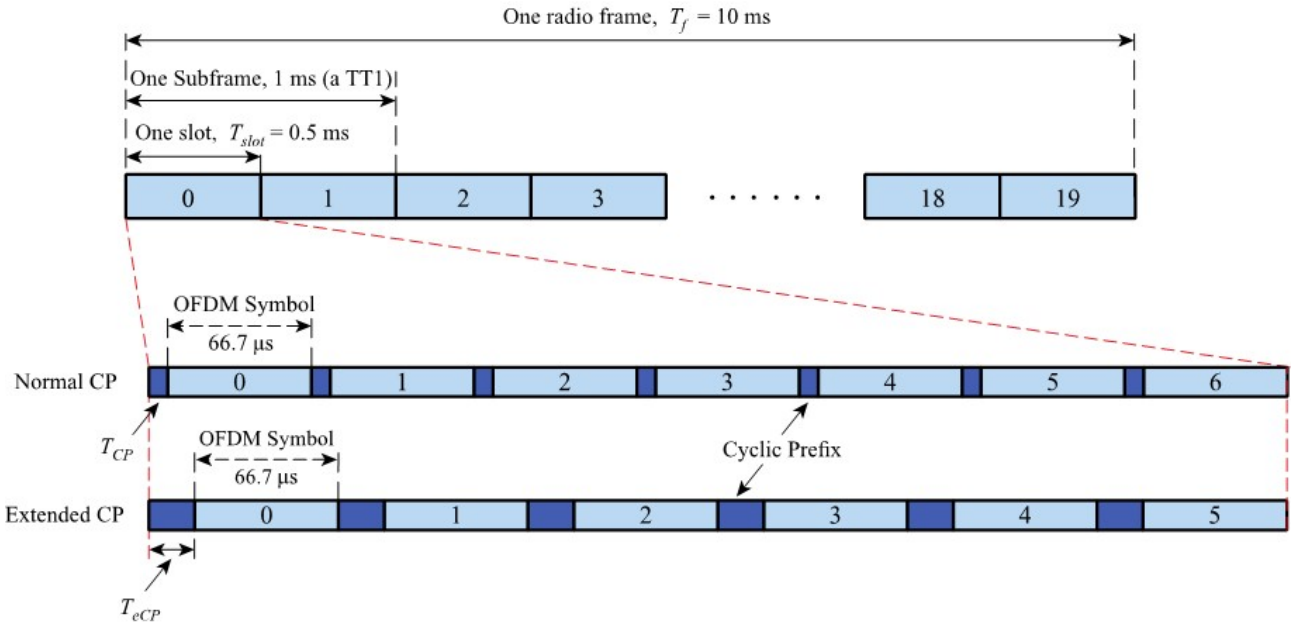
Useful Trigonometry		
		
31	Law of cosines	$c^2 = a^2 + b^2 - 2ab \cdot cos(C)$ $b^2 = a^2 + c^2 - 2ac \cdot cos(B)$ $a^2 = b^2 + c^2 - 2bc \cdot cos(A)$

32	Law of sines	$\frac{a}{sin(A)} = \frac{b}{sin(B)} = \frac{c}{sin(C)}$

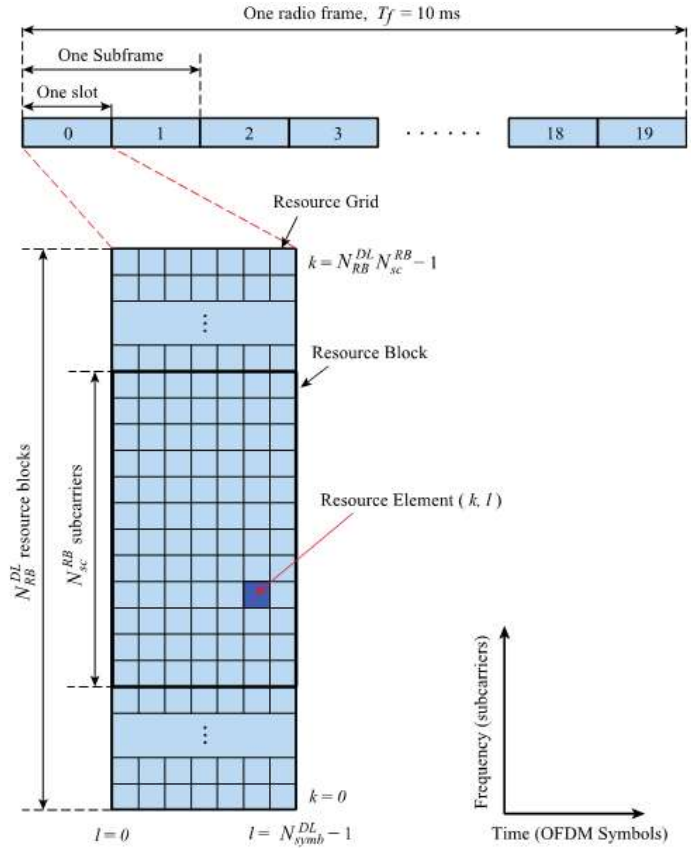
LTE CQI Indices

CQI Index	Modulation	Code Rate × 1024	Efficiency
0	Out of Range		
1	QPSK	78	0.1523
2	QPSK	120	0.2344
3	QPSK	193	0.3770
4	QPSK	308	0.6016
5	QPSK	449	0.8770
6	QPSK	602	1.1758
7	16QAM	378	1.4766
8	16QAM	490	1.9141
9	16QAM	616	2.4063
10	64QAM	466	2.7305
11	64QAM	567	3.3223
12	64QAM	666	3.9023
13	64QAM	772	4.5234
14	64QAM	873	5.1152
15	64QAM	948	5.5547

LTE Frames, Subframes, and Slots



LTE Resource Blocks and Resource Elements



5G Frame Structure for each Numerology

Index: μ	Subcarrier Space: Δf [kHz]	Number of slots per subframe (1 ms): 2^{μ}	Number of slots per frame (10 ms): $10 \cdot 2^{\mu}$	Slot duration: T_{slot} [ms]
0	15	1	10	1
1	30	2	20	0.5
2	60	4	40	0.25
3	120	8	80	0.125
4	240	16	160	0.0625