Humboldt-Universität zu Berlin, Institut für Informatik,

IHP, Leibniz Institut für innovative Mikroelektronik, Frankfurt (Oder)

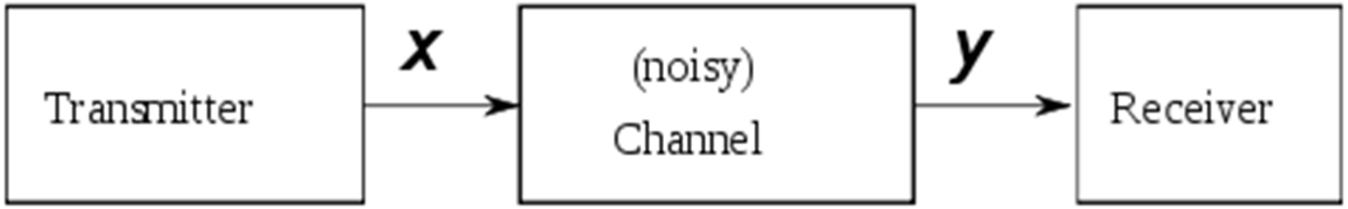
Vorlesung Drahtlose Breitbandkommunikationssysteme

Prof. Dr. Eckhard Grass grass@ihp-microelectronics.com

grass@informatik.hu-berlin.de

http://www.informatik.hu-berlin.de/~grass/bbk

Channel Capacity: Shannon Theorem [Wikipedia]



- The **Shannon limit** or **Shannon capacity** of a communications channel is the theoretical maximum information transfer rate of the channel, for a particular noise level.
- Stated by Claude Shannon in 1948 (with sketchy proof)
- The first rigorous proof by Amiel Feinstein in 1954.
- The Shannon theorem states that given a noisy channel with channel capacity *C* and information transmitted at a rate *R*, then if R<C there exist codes that allow the probability of error at the receiver to be made arbitrarily small.
    - This means that, theoretically, it is possible to transmit information nearly without error at any rate below a limiting rate, *C*.

Link Budget Calculation

Shannon channel capacity:

$$C = B \log_2 (1 + S/N)$$

How to calculate the S/N at the receiver?

-> Need to know how much signal is attenuated at a given distance
-> This can be calculated with Friis equation

Path loss (PL) in free space (Friis equation):

$PL(a) = (4 * \pi * d * f/c)^2$ (direct form)

$PL(log) = 10 * \log_{10}(4 * \pi * d * f/c)^2 = 20 * \log_{10}(f) + 20 * \log_{10}(d) + 20 * \log_{10}(4\pi/c)$

(logarithmic form)

- d: Distance between Sender and Receiver
- f: Carrier Frequency
- c: Speed of light (~ 300 000 km/s)

Noise Power Spectral Density N_o

$$C_{awgn} = W \log_2\left(1 + \frac{\bar{P}}{N_0 W}\right)$$

$N = N_o * W = N_o * B$

$N_o = k*T$ [W/Hz]

k: Boltzmann constant [J/K] (= 1.38×10^{-23} J/K)

T: Temperature [K] (~ 300 K @ room temp.)

$N_o = k*T = 1.38 \times 10^{-23}$ J/K * 300 K

$= 4.14 * 10^{-21}$ J

$= 4.14 * 10^{-21}$ Ws (for room temperature)

Friis Equation: Derivation @ board

- Friis Equation
- Link Budget Calculation

Path Loss Exponent

Path loss (PL) in free space (Friis equation):

$$PL(a)= (4*\pi*d*f/c)^2 \qquad \text{(direct form)}$$

- The additional losses caused by fading, blockage … can be simply modeled by modifying the path loss exponent E_{PL}
- The path loss exponent $E_{PL} = 2$ for free space, line-of sight scenario
- For indoor and urban areas the path loss exponent can range from $E_{PL} = 2…4$
- In some lossy environment, the path loss exponent can reach even $E_{PL} = 6$
- In a specific tunnel scenario the lath loss exponent can be $E_{PL}<2$

Link Budget Calculation

- TX-Power	P_{TX}	
- Friis equation (path loss)	L_{FS}	(=PL)
- Antenna gain TX	G_{TX}	
- Antenna gain RX	G_{RX}	
- RX Losses (cables, connectors, …)	L_{RX}	
- Miscellaneous losses (Implementation losses)	L_M	
- RX-Noise Figure	NF	
- Shannon channel capacity	C	

Received Power (all in dB):

$$P_{RX}\,(dB) = P_{TX} + G_{TX} + G_{RX} - L_{FS} - L_{RX} - L_M$$

Required Signal/Noise at the Receiver

- During transmission and reception noise will be added to the signal
  - Thermal noise (Boltzmann noise)
  - Receiver Noise (Noise Figure)
  - Transmitter Noise caused by non linearities
  - etc.
- The effect for the received signal is that, in the constellation diagram, not a single point but a cloud of points around the expected point are received.
- Due to these noise and distortion impacts, the signal/noise (S/N) ratio to correctly receive an uncoded signal is at least around 6 dB in case of BPSK modulation.
- The required SNR is dependent on the modulation and the transmission type
  - For 64 QAM, the required SNR is at least 4 dB higher than for 16 QAM etc.

Receiver Sensitivity

The receiver sensitivity S_{min} is the minimum input signal power required at the receiver input to provide sufficient SNR at receiver output to do data demodulation for a specific modulation scheme

- S_{min} depends on:
  - Required SNR for desired modulation = SNR_{req}
  - Thermal noise floor at RX antenna = kT_oB
  - Noise Figure of the receiver = N_F

$$S_{min} = SNR_{req} * kT_oB * N_F \quad \text{(all in absolute numbers)}$$

$$S_{min}\,(dB) = SNR_{req}\,(dB) + 10*\log_{10}(kT_oB) + N_F\,(dB)$$

- In some (generic) cases: $SNR_{req} = 0$ dB

SNR <-> E_b/N_o

For the evaluation of the efficiency of a specific implementation, the parameter E_b/N_o is often used.

E_b/N_o = SNR * (B_T/R)

SNR = (E_b/N_o) * (R/B_T)

- SNR = Signal-to-noise ratio
- E_b = Energy required per bit of information
- N_o= thermal noise in 1Hz of bandwidth
- R = system data rate
- B_T= system bandwidth
- (R/B_T) = spectral efficiency

Source: Intersil, Tutorial Link budget Analysis 1998

Required Signal/Noise at the Receiver

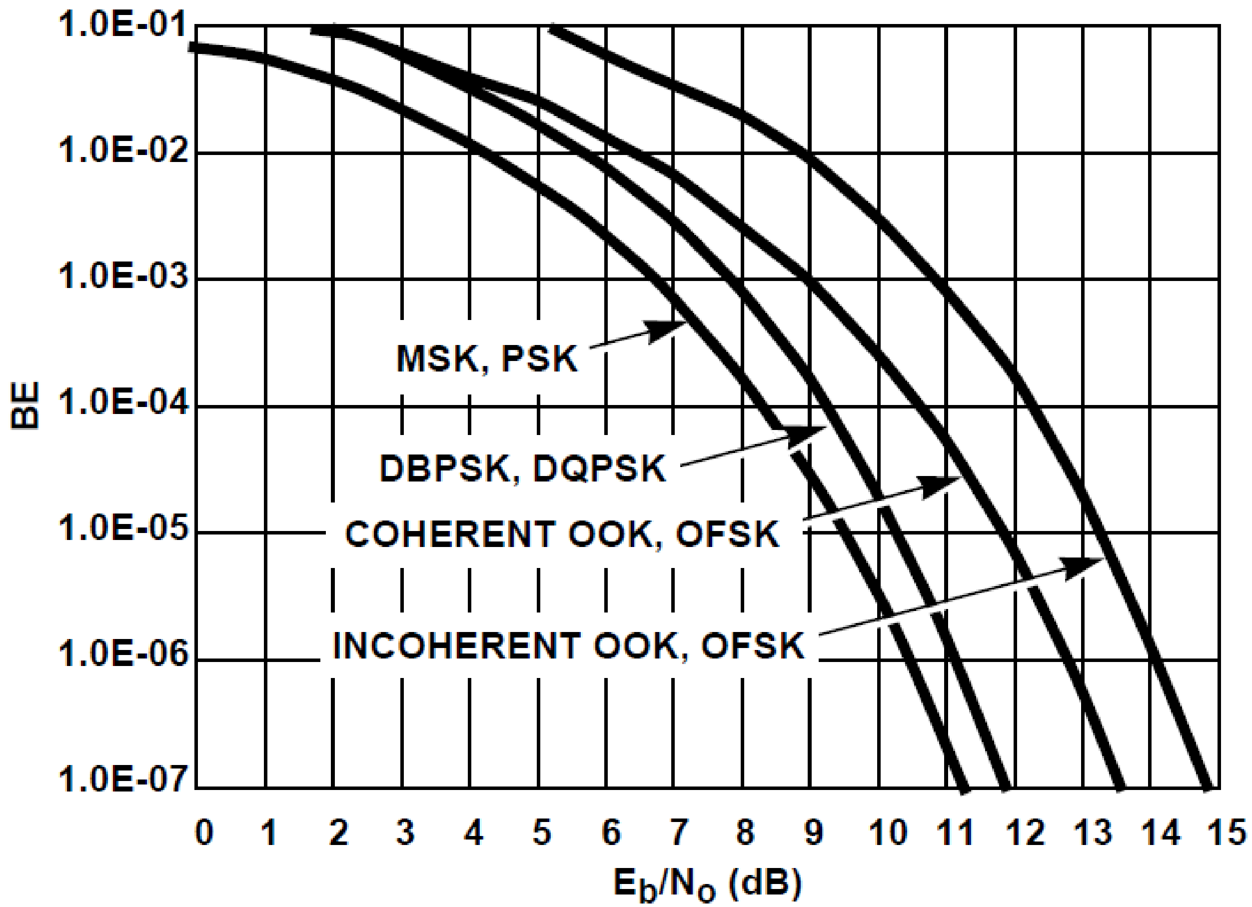


FIGURE 4. PROBABILITY OF BIT ERROR FOR COMMON MODULATION METHODS

Source: Intersil, Tutorial Link budget Analysis 1998

Link-Budget Calculator

- Excel Sheet

OFDM System Parameter Choice

Channel Parameters (T_{RMS}, Mobility, …)

- Strong multipath propagation and high bit rate
  - OFDM (otherwise single carrier scheme sufficient)
- Delay spread of channel T_{RMS} determines :
  - guard time (cyclic prefix): T_{CP} ~ 2… 4 x T_{RMS}
  - T_{OFDM} ~ > 5 x T_{CP} -> ($T_{sym} = T_{CP} + T_{FFT}$)
  - T_{FFT} ~ > 4 x T_{CP}
- Number of subcarriers:
  - $N_{sub} = B * T_{FFT}$
  - N_{sub} = target bitrate / (bitrate/subcarrier) (-> modulation scheme)
- Channel Coherence Time T_C determines:
  - Pliot scheme (time axis)
- Channel Coherence Bandwidth B_C
  - Pilot scheme (frequency axis)

OFDM System Parameter Choice II

Example scenario for OFDM-parameter choice (@ board)

Channel properties / target parameters:

- Application scenario:
  Large office; metal coated windows
- Delay spread of channel: T_{RMS} = 200 ns
- Available bandwidth: B = 20 MHz
- Target data rate: R = 50 Mb/s
- Coherence time of channel: $T_C = 5\ \mu s$
- Coherence bandwidth of channel: B_C = 5 MHz