Summary of Performance of Analog Modulation with Noise

The figure of merit is the processing gain, G_p

The processing gain is included in the link budget to account for the modulation.

There is a threshold effect in AM and FM.

In FM the $(S/N)_{\text{post}}$ can be increased by using more RF bandwidth.

Modulation	G_p	B_{RF}	Comments
DSB – SC	1	$2\ B_{bb}$	Coherent Detection
SSB	1	B_{bb}	Coherent Detection
DSB – LC (Envelope Detection)	$\frac{\mu^2}{2+\mu^2}$	$2\ B_{bb}$	Large $(S/N)_{\text{pre}}$ (above threshold)
FM	$\frac{3}{2}\beta^2$	$2\ B_{bb}\ (1+\beta)$	Large $(S/N)_{\text{pre}}$ (above threshold)

The quadratic nature of the detector output noise spectrum is leveraged using preemphasis/deemphasis to obtain additional processing gain.

Preemphasis/deemphasis is an example of modifying the the transmitted signal and then post processing the received signal to achieve improved system performance.

Summary of Performance of Digital Modulation with Noise

Performance metric is BER

BER depends upon the energy/bit and the variance of the decision variable.

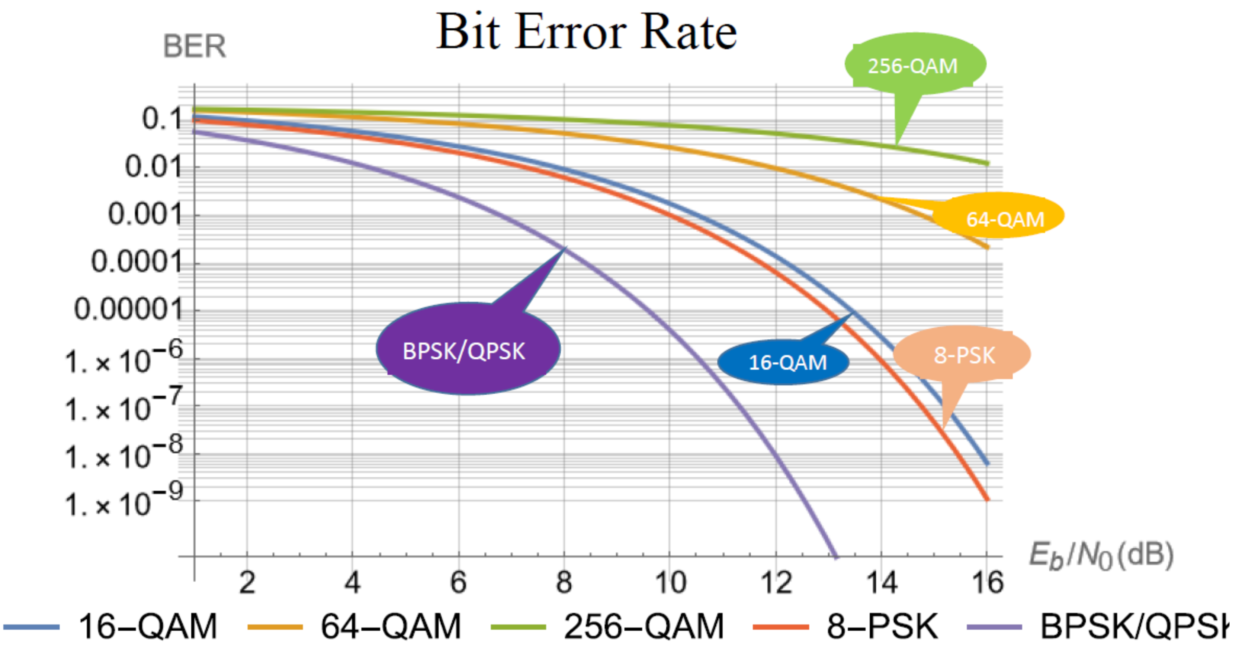
Commonly the BER is a function of $\frac{E_b}{N_0}$ and the relationships often involves the Q(x) function.

BER can be reduced by increasing the signal power = $\frac{E_b}{T}$

BER can be reduced by increasing the symbol time, allowing more averaging of the noise.

For M-ary digital transmission there is a tradeoff between BER and B_{RF}, BER can be sacrificed to reduce B_{RF}.

Modulation Type	BER	Spectral Efficency
ASK coherent detection	$Q\left(\sqrt{\frac{E_b}{N_0}}\right)$	1
ASK and FSK envelope detection	$\frac{1}{2}\, e^{-\frac{E_b}{2 N_0}}$	1
DPSK	$\frac{1}{2}\, e^{-\frac{E_b}{N_0}}$	1
BPSK	$Q\left(\sqrt{\frac{2 E_b}{N_0}}\right)$	1
QPSK	$Q\left(\sqrt{\frac{2 E_b}{N_0}}\right)$	2
M – ary PSK	$\frac{2\, Q\left(\sqrt{\frac{2 \log_2(M)\, E_b}{N_0} \sin^2\left(\frac{\pi}{M}\right)}\right)}{\log_2(M)}$	$\log_2(M)$
QAM	$\frac{4\left(\sqrt{M}-1\right)}{\sqrt{M}\, \log_2(M)}\, Q\left(\sqrt{\frac{3 E_b \log_2(M)}{N_0 (M-1)}}\right)$	$\log_2(M)$



BER Equations

BPSK/QPSK $Q\left(\sqrt{\frac{2 E_b}{N_0}}\right)$ Coherent ASK $Q\left(\sqrt{\frac{E_b}{N_0}}\right)$ Noncoherent ASK $\frac{1}{2} e^{-\frac{E_b}{2 N_0}}$

M-PSK $\frac{2 Q\left(\sqrt{\frac{2 \log_2(M) E_b}{N_0} \sin^2\left(\frac{\pi}{M}\right)}\right)}{\log_2(M)}$; QAM (Square Grid) $\frac{4\left(\sqrt{M}-1\right)}{\sqrt{M} \log_2(M)} Q\left(\sqrt{\frac{3 E_b \log_2(M}{N_0(M-1)}}\right.$

Summary of Multimegabit/sec Terrestrial Wireless Communications: Impairments and Implementation

Wireless channels, in general, are frequency selective
OFDM provides a spectral efficient mechanism to take data from a high speed link and process it with a serial-to-parallel converter and send each parallel data stream over an orthogonal low bandwidth channel, where the low bandwidth channel experiences flat fading.
OFDM implementations use IFFT/FFTs
A CP is used to remove remaining channel effects
Adaptive modulation and coding techniques are used to match the transmissions to multiple users with their channel individual conditions.
WiFi, HDFM, LTE (4G) and 5G systems use OFDM

Test 2 Review

Summary of Frequency Division Multiplexing (FDM) and Orthogonal Frequency Division Multiplexing (OFDM)

FDM enables sharing of spectrum

Guard bands are placed between the channels to prevent adjacent channel interference.

FDM can support independent transmitters and receivers, i.e., the broadcast case.

Composite baseband signals can be constructed using FDM then modulated to RF.

Bandwidth of FDM signals.

FDMA

Combined TDMA and FDMA

OFDM

- No explicit sidebands
- $\frac{1}{T_s}=\Delta f$ (subcarriers are orthogonal)
- N=Number of subcarriers
- $B_{\mathrm{RF}}=(N+1)\Delta f$ (Not a function of the QAM modulation on each subcarrier)
- $r_b=N*\Delta f*\gamma$ (γ=#bits/symbol, assumes same QAM on all subcarrier)
- Transmitter/receiver use IDFT/DFT

OFDM combined with TDMA

- T_f=frame time = Number of slots * (Number of OFDM symbols/time slot) * T_s
- $r_b=\frac{\text{Number of bits in } a\ T_f}{T_f}$

Summary of DSB - LC

$B_{\mathrm{RF}}=2\,B_{\mathrm{bb}}$.

Not power efficient, power efficiency = $\frac{\mu^2}{1+\mu^2}$ with maximum = 33%.

Poor low frequency response.

Very simple receiver, envelope detector. No carrier recovery required.

ASK is a form of DSB-LC, an envelope detector followed by an integrate and dump can be used as an ASK receiver.

Summary of SSB

$B_{\mathrm{RF}}=B_{\mathrm{bb}}$

Transmitter- Sideband Filtering, requires sharp frequency cut-off on the BPF

Transmitter-Phasing, requires wideband constant amplitude phase shifting filter.

Needs a coherent receiver, carrier synchronization is required.

SSB-LC is feasible, wastes power in transmitting the carrier, enables the use of an envelope detector with poor LF response.

Introduced a signal space diagram for analog modulated signals.

Summary of VSB

$B_{bb} < B_{RF} < 2\,B_{bb}$

Requires a transmit BPF with specific characteristics, $H_v(f + f_c) + H_v(f - f_c) =$ constant

VSB without a large carrier requires carrier synchronization.

VSB-LC can be received with an envelope detector.

Moduation	B_{RF}	Transmitter Complexity	Receiver Complexity	Power Efficency
DSB – SC	$2\,B_{bb}$	Simple	Complex Requires Carrier Recovery	Adequate
DSB – LC	$2\,B_{bb}$	Simple	Simple Envelope Detector	Poor
SSB	B_{bb}	Complex	Complex Requires Carrier Recovery	Adequate
VSB – SC	$B_{bb} < B_{RF} < 2\,B_{bb}$	Complex	Complex Requires Carrier Recovery	Adequate
VSB – LC	$B_{bb} < B_{RF} < 2\,B_{bb}$	Complex	Simple Envelope Detector	Poor

Summary of FM and PM

Instantaneous phase $\theta_i(t)$ and frequency $f_i(t) = \frac{1}{2\pi}\,\frac{\theta_i(t)}{dt}$ (Hz)

In FM $f_i(t) \propto x_{bb}(t)$.

In PM $\theta_i(t) \propto x_{bb}(t)$

The spectrum of $X_{FM}(f)$ is not a translation of $X_{bb}(f)$.

FM (PM) is a non-linear modulation

Considered the special case of $x_{bb}(t) = A_m \cos(2\,\pi f_m t)$

For $x_{bb}(t) = A_m \cos(2\,\pi f_c t)$ defined the frequency deviation Δf and the FM modulation index $\beta = \frac{\Delta f}{f_m}$

For $x_{bb}(t) = A_m \cos(2\,\pi f_c t)$ the FM signal is $x_{FM}(t) = A_c \sum_{n=-\infty}^{\infty} J_n(\beta) \cos(2\,\pi(f_c + n f_m)t)$

The characteristics of $X_{FM}(f)$ are driven by the properties of the Bessel function $J_n(\beta)$

The approximate RF bandwidth for FM is $2\,B_x(1+\beta)$

The average power in $x_{FM}(t) = P_{FM} = \frac{A_c^2}{2}$, same as the power in an unmodulated carrier.

FM transmitters;

Indirect FM

VCO

FM demodulators;

Differentiator/envelope detector

Balanced discriminator

PLL

Digital FM techniques;

FSK

M-ary FSK

DPSK

For coherent FSK systems orthogonal carriers can be used with $\Delta f = \frac{1}{T_s}$

For non-coherent FSK systems $\Delta f \geq \frac{2}{T_s}$

The approximate RF bandwidth for FSK $= 2\Delta f + (1+\alpha)\, r_s$

Summary of Superheterodyne Receiver

Down converts RF signal to a fixed IF frequency.

RF section provides sensitivity

IF section provides selectivity

Variable carrier frequency changed at same time as variable local oscillator frequency

$f_{\mathrm{IF}} = f_{\mathrm{LO}} - f_c$

Image frequency

Summary of Communications Channels, Noise and Link Budgets

Path loss, function of the carrier frequency and the environment.

Antenna gain, function of the carrier frequency and the antennal size, i.e., the size of the antenna relative to the wavelength.

Signal-to-noise ratio (S/N), output S/N is the $\frac{\text{Power in } x_o(t)}{\text{Power in } n_o(t)}$.

Flat noise, $S_n(\mathrm{f}) = \frac{N_o}{2}\ \forall\ \mathrm{f}$.

Thermal noise, kTB noise.

External noise input to the receiver is modeled as an T_a= antenna temperature.

Specification of component noise using equivalent temperature of the device, T_e.

Specification of component noise using noise figure of the device, F.

Relationship between equivalent temperature and noise figure $T_e = T_0(\mathrm{F}-1)$.

Noise figure of resistive attenuator, $\mathrm{F} = 1 + (L-1)\,\frac{T_P}{T_o}$ if $T_P = T_o$ the F=L.

For multistage systems $T_e = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1\,G_2} + \frac{T_4}{G_1\,G_2\,G_3}$ ....

For multistage systems $\mathrm{F} = F_1 + \frac{F_2-1}{G_1} + \frac{F_3-1}{G_1\,G_2} + \frac{F_4-1}{G_1\,G_2\,G_3}$ .....

Link budgets are used to evaluate system tradeoffs.

$(S/N)_{\mathrm{pre}} = \frac{P_T\,G_T\,G_R}{L_M\,L_p\,k(T_a+T_0(F-1))\,B_e}$

Test 1 Review

Summary of Baseband Transmission

- Line Coding
  - On-Off
  - NRZ
  - RZ
  - Manchester
- M-ary baseband signals
  - $r_b = \frac{1}{T_b}$
  - γ bits/symbol (binary case $\gamma = 1$)
  - $T_s = \gamma * T_b$
  - $r_s = \frac{1}{T_s}$ = symbol rate
  - $B_0 = \frac{r_s}{2}$ = minimum baseband bandwidth
- Symbol detection
  - Minimum distance decision algorithm
  - Integrate & dump is the same as filter & sample
  - Decision based on the output of the Integrate & dump (or filter & sample)
  - One symbol error can cause multiple bit errors
- ISI
  - Pulse shaping
  - Criteria for no ISI, $p(0) = 1$ (constant) and $\sum_{\substack{k=-\infty \\ k \neq 0}}^{\infty} p(t - \mathrm{k}T_s) = 0$
  - Raised cosine pulse shaping,
  - $B_T = B_0(1+\alpha)$
  - Eye-diagram
- Analog-to-Digital (A/D) conversion
  - PAM
  - PCM
  - $(S/N)_Q \approx 6\gamma$ (dB)

Summary of Time Division Multiplexing

- Time frame
- Time slot & number of time slots/frame
- Number of bits/time slot
- Bit rate = $\frac{\#\text{ bits/frame}}{\text{Frame Time}}$
- TDMA

TDD

Uplink and downlink

Frame synchronization

TDM/PAM

Minimum baseband bandwidth= $\frac{r_s}{2}$

TDM/PCM

Minimum baseband bandwidth= $\frac{r_b}{2}$

Summary of DSB-SC

$x_{\text{DSB-SC}}(\text{t}) = A_c\, x_{\text{bb}}(t) \cos(2\,\pi \text{f}_c \text{t})$

$B_{\text{RF}} = 2\,B_{\text{bb}}$

In general requires a synchronous (coherent) receiver, carrier recovery is needed

DSB-SC is a linear modulation

ASK is a digital modulation using DSB-SC with a specific digital baseband signal, $x_{\text{ON-Off}}(\text{t})$

$B_{\text{RF}} = r_b$

Spectral efficiency = (1b/s)/Hz

BPSK is a digital modulation using DSB-SC with a specific digital baseband signal, $x_{\text{NRZ}}(\text{t})$

$B_{\text{RF}} = r_b$

Spectral efficiency = (1b/s)/Hz

Power in the DSB-SC signal, $A_c\text{x}(\text{t})\cos(2\,\pi\text{f}_c\text{t})$, is $P_{\text{DSB-SC}} = \frac{A_c^2\,P_x}{2}$

Summary of Quadrature Modulation and Multiplexing

Quadrature Multiplexing allows two signals to use (share) the same RF spectrum, one signal on the I-channel and one on the Q-channel

Carrier recovery is required to demodulate quadrature modulated signals

Quadrature modulation is used to transmit digital signals

One baseband digital signal (NRZ or M-ary) transmitted on the I-channel and one on the Q-channel

Constellation (signal-space) diagrams

Minimum distance detection of transmitted symbols-in two dimensions

Transmitter block diagram

Receiver block diagram

Relationships:

γ bits/symbol

Symbol time $T_s = \gamma \text{T}_b$

QPSK 2 bits/symbols, γ=2

M-QAM; M= 2^{γ}

M-ary PSK; M= 2^{γ}

Maximum spectral efficiency = γ (b/s)/Hz

Modulation Type	Maximum Spectral Efficency (b / s) / Hz
ASK	1
BPSK	1
QPSK	2
8 – ary PSK	3
16 – QAM	4
64 – QAM	6
256 – QAM	8
1024 – QAM	10

Representations of RF Signals

$y_l(t) = y_c(t) + \mathrm{j} y_s(t)$

$\mathrm{Re}(y_l(t) e^{\mathrm{j}2\pi \mathrm{f}_c t})$

$V(t) \cos(2\pi \mathrm{f}_c t + \Theta(\mathrm{t}))$

$y_c(t) \cos(\mathrm{j}2\pi \mathrm{f}_c t) - y_s(t) \sin(\mathrm{j}2\pi \mathrm{f}_c t)$