RF System Design

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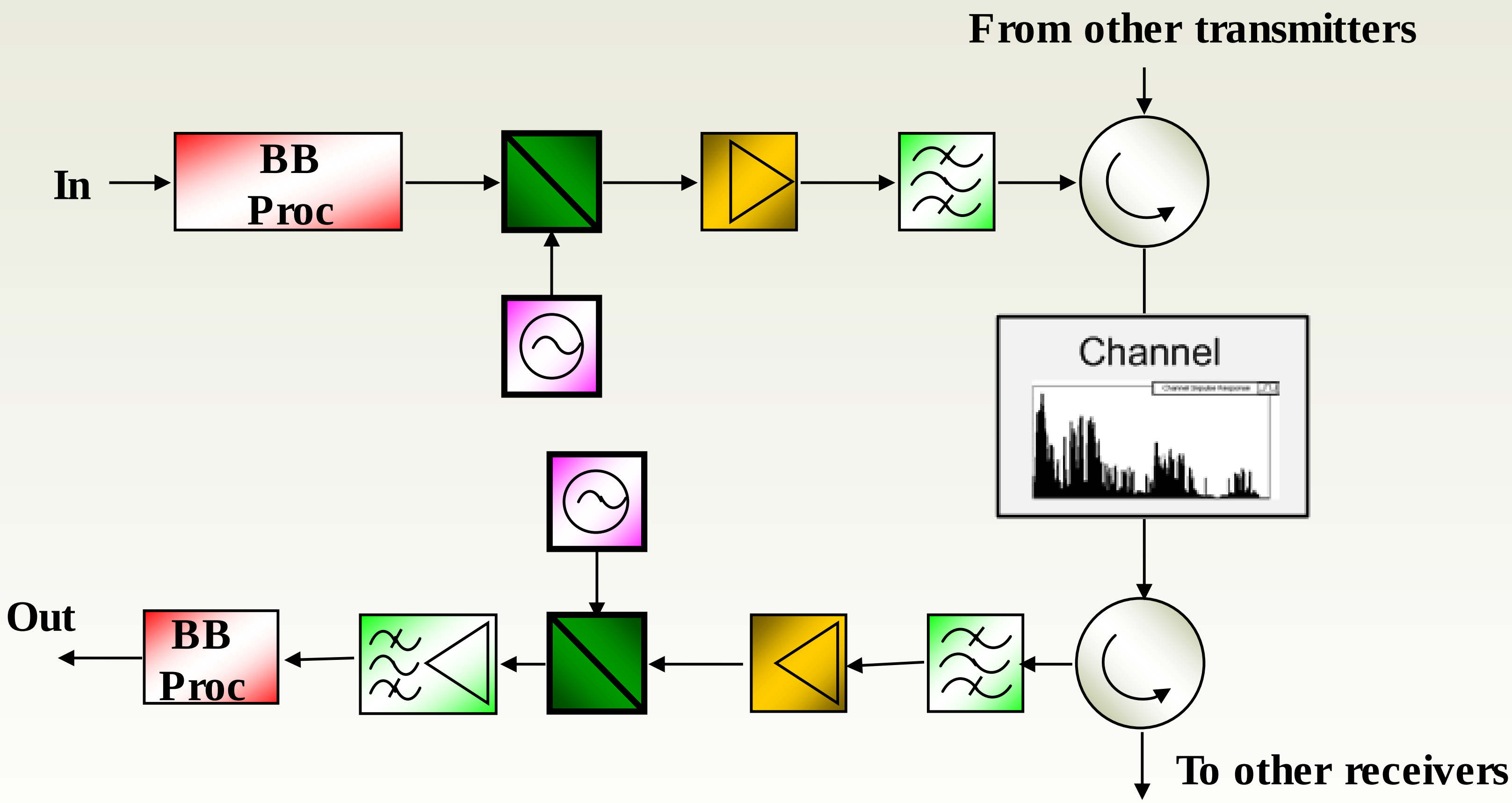
Outline

- RF Equipment considerations
- BaseBand (BB) processing
- Spectrum efficiency
- Probability of Error
- Modulation tradeoffs
- MIMO systems
- Satellite Communications
- Link budget example problem

This Video : RF Transceivers

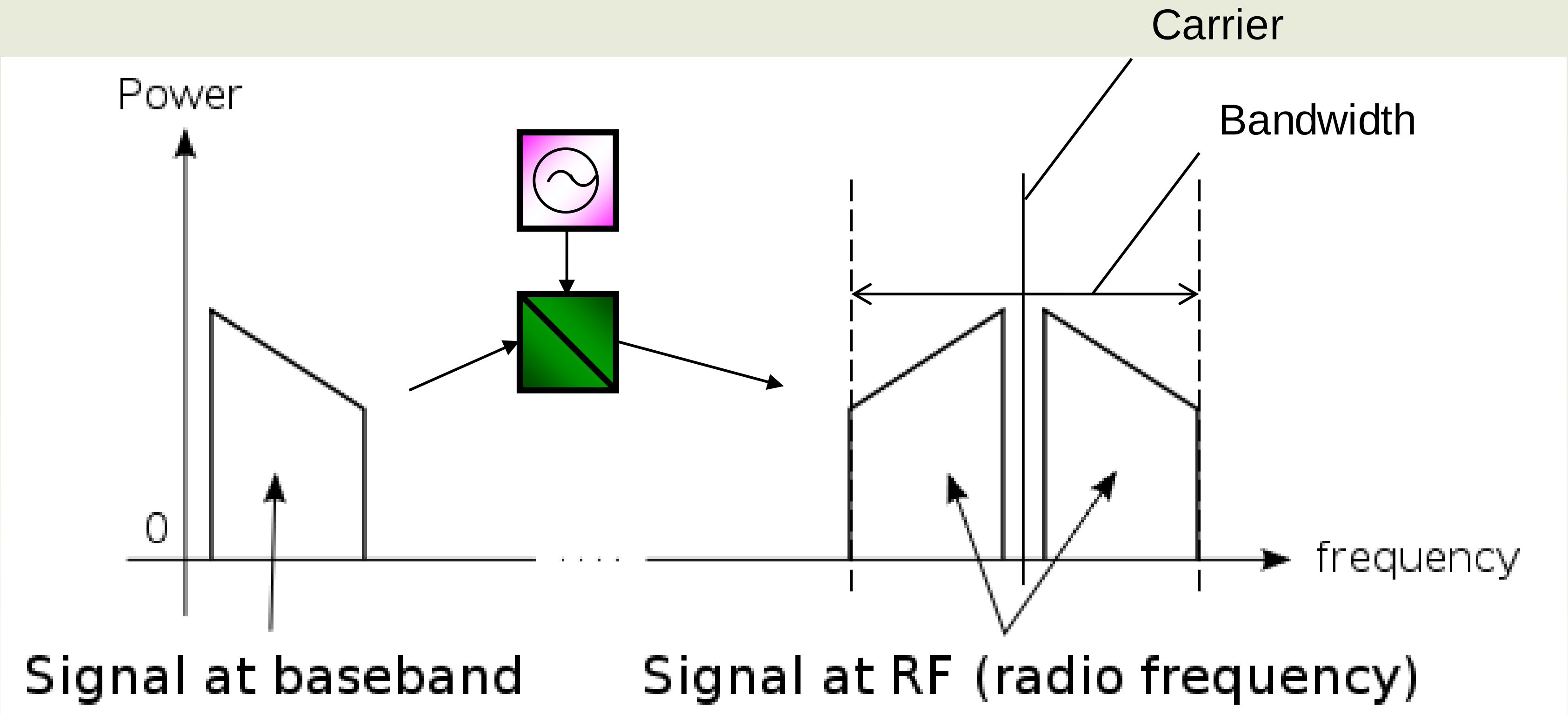
- RF components
- BaseBand processing

Equipment considerations



- Tx and Rx block diagram at terminal station

Up conversion

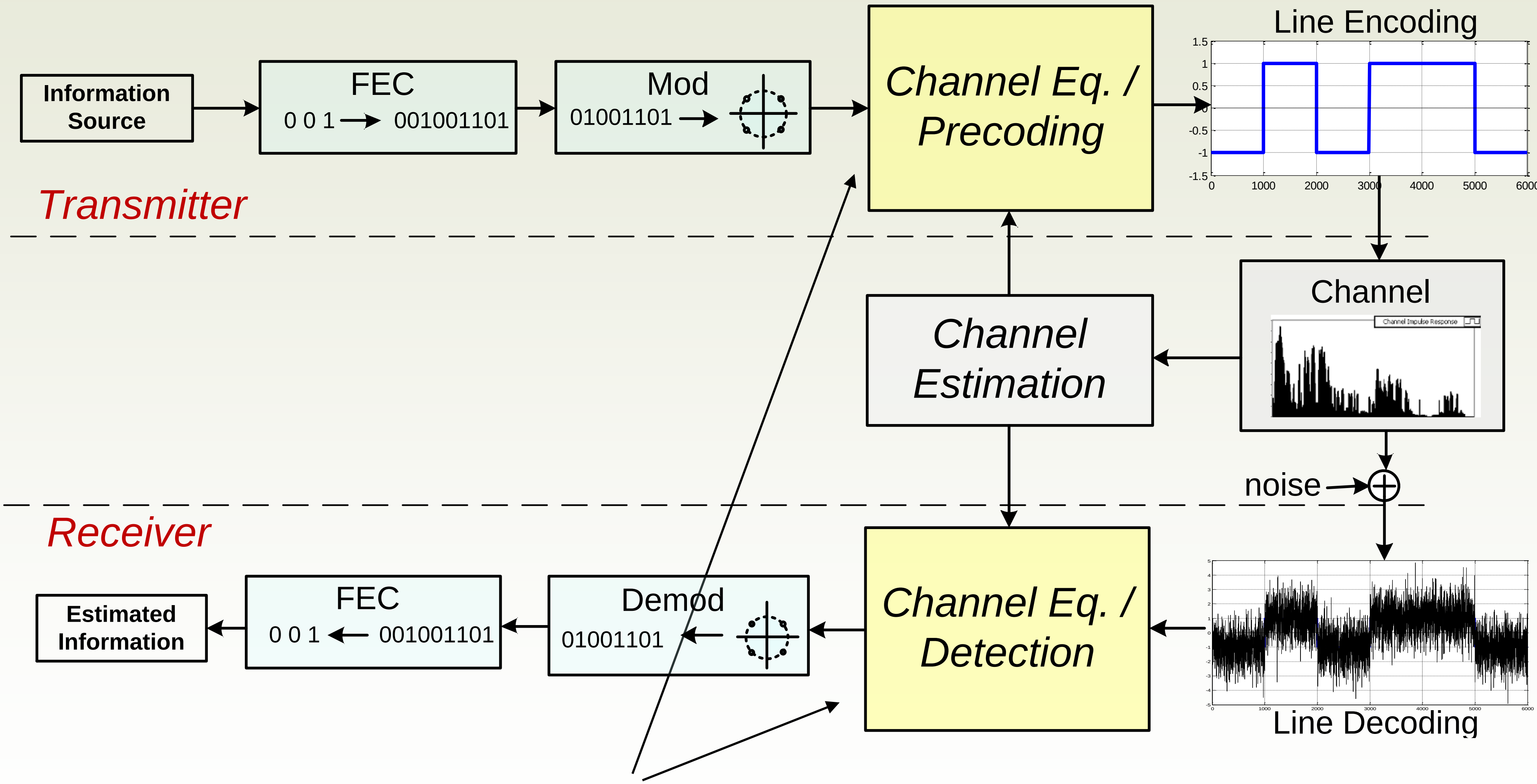


Baseband: $m(t) = M \cdot \cos(\omega_m t + \phi)$

Carrier: $c(t) = A \cdot \sin(\omega_c t + \phi_c)$

Passband: $y(t) = \frac{AM}{2}\left[\sin((\omega_c + \omega_m)t + \phi) + \sin((\omega_c - \omega_m)t - \phi)\right]$

Baseband Processing

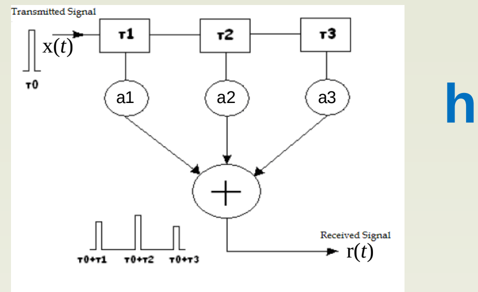


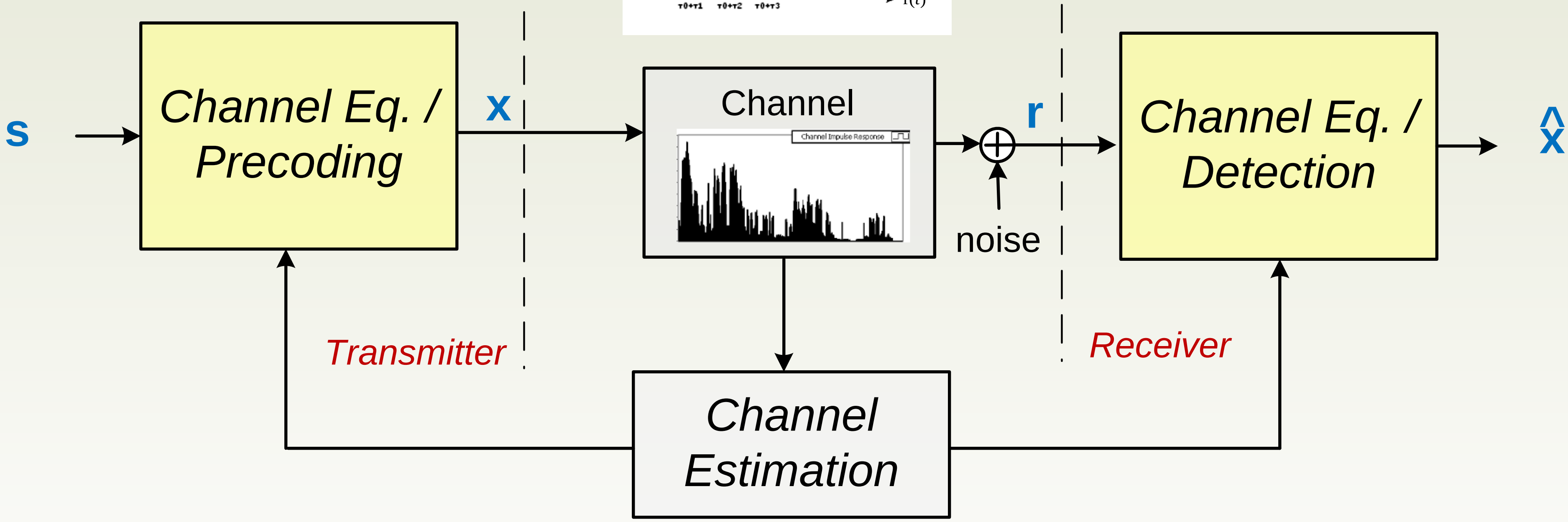
These take care of small scale fading

This Video : RF Transceivers

- Channel estimation

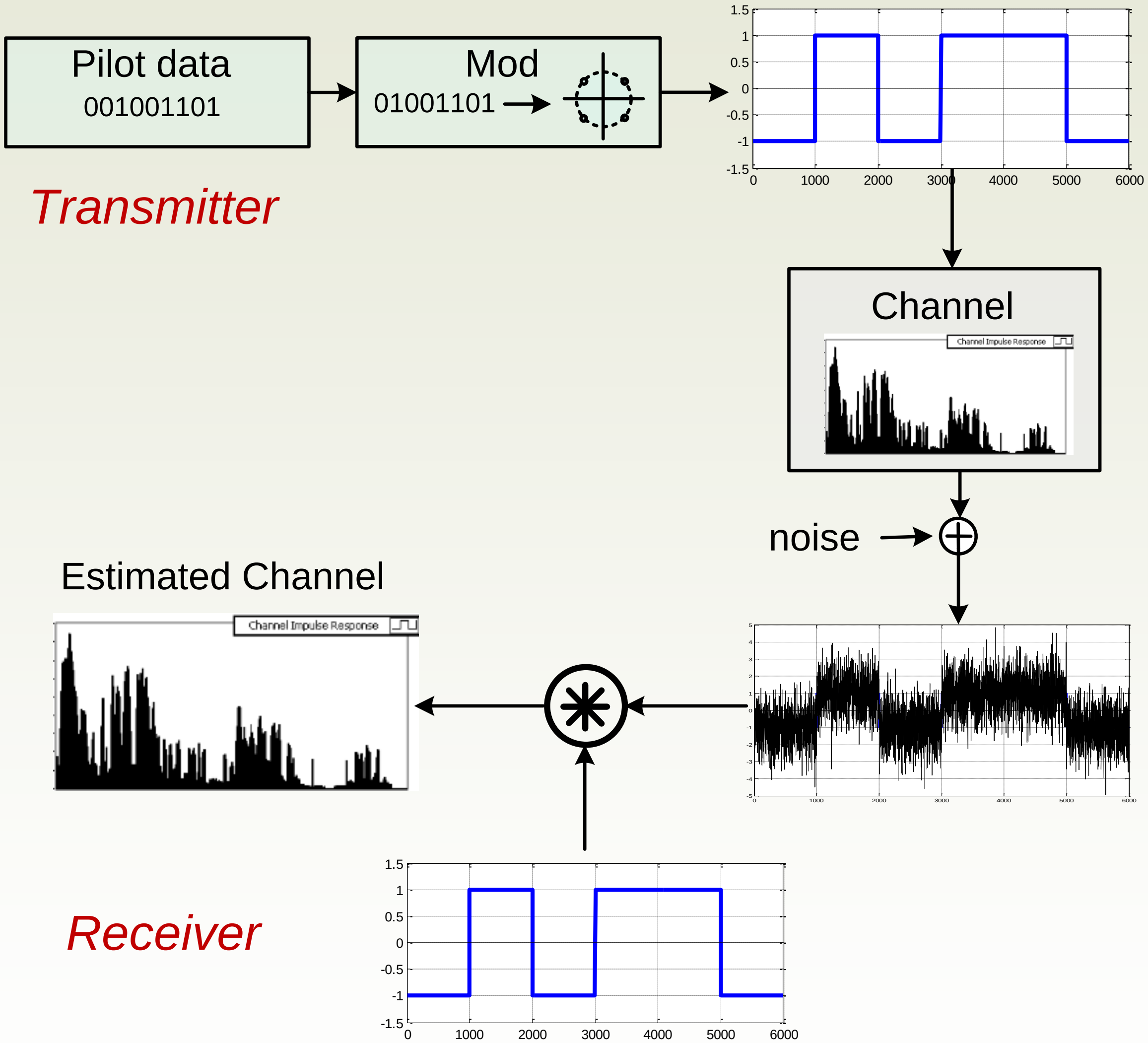
Baseband Processing





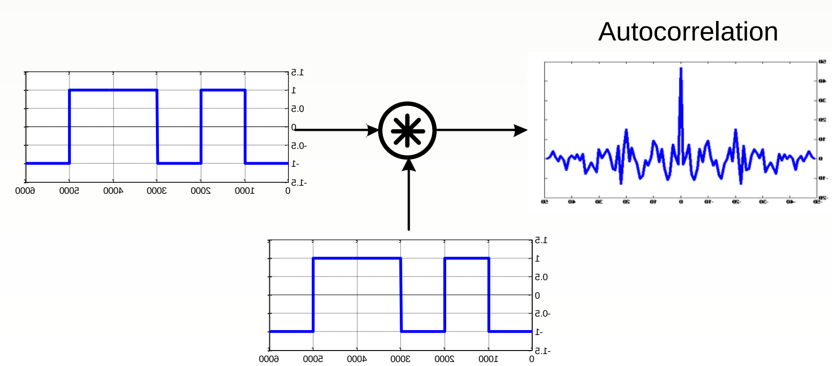
- What is the relation between the received *r* and transmit *x* signals?
- How do I estimate the channel?
- What waveform do I ideally transmit?

Channel Estimation



$$r = x \otimes h$$

Carefully selected Pilot symbols with good autocorrelation

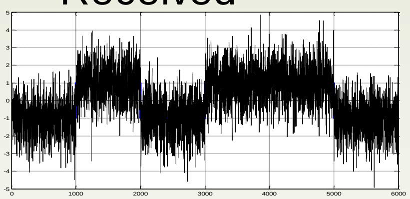


$\circledast$: Correlation

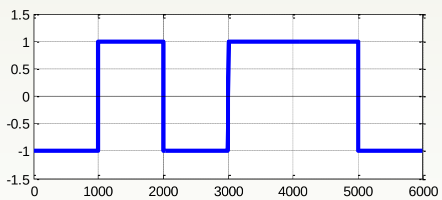
Channel Estimation – How it works

Correlation of Tx and Rx signals = Convolution of channel with pilot autocorrelation function

Received



Pilot



$$\circledast \; =$$

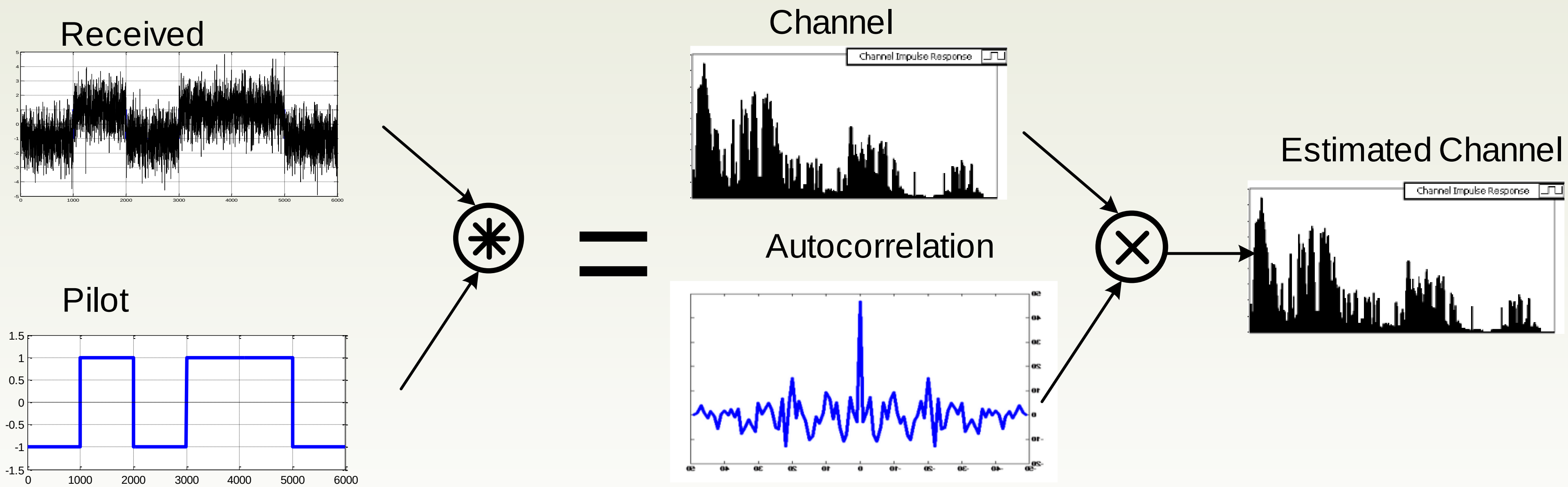
$$
\begin{aligned}
y(t) &= r(t) \circledast x(t) \\
&= [x(t) \otimes h(t)] \circledast x(t) \\
&= [x(t) \circledast x(t)] \otimes h(t)
\end{aligned}
$$

$\circledast$: Correlation

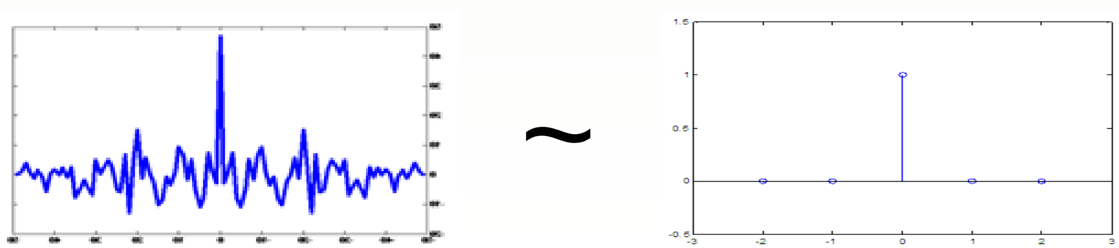
$\otimes$: Convolution

Channel Estimation – How it works

Correlation of Tx and Rx signals = Convolution of channel with pilot autocorrelation function



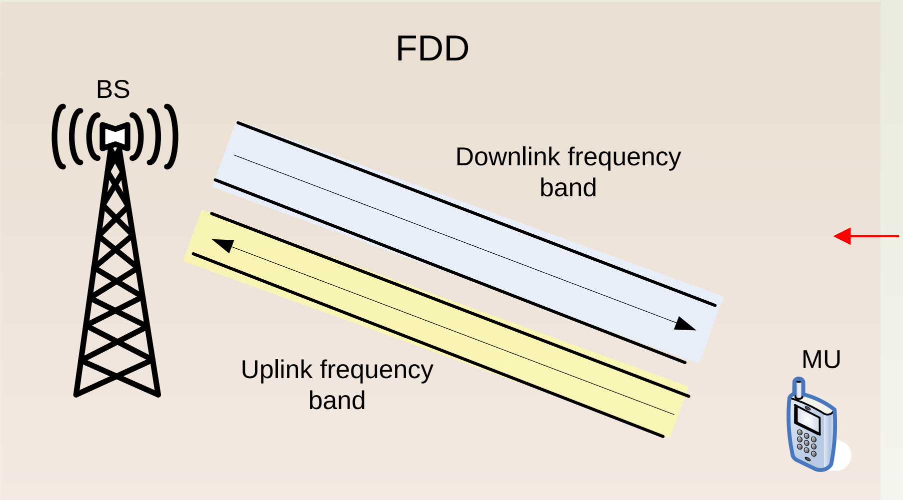
Need pilots with good autocorrelation function (close to impulse)



$\circledast$: Correlation

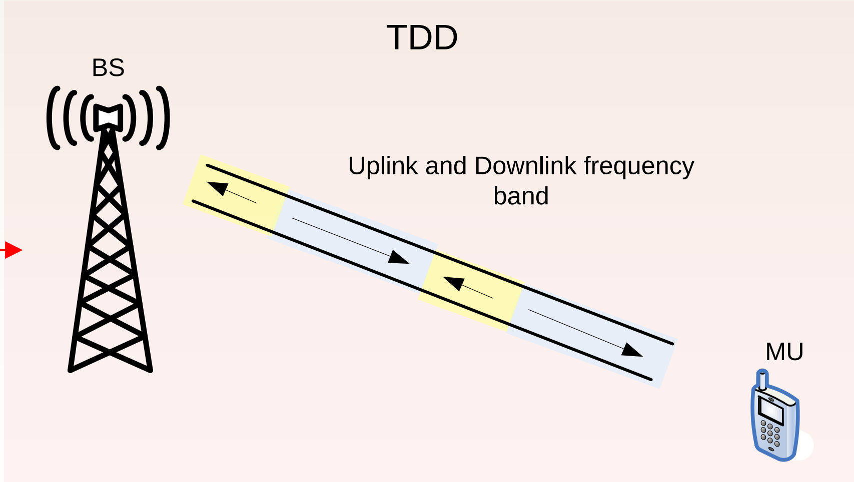
$\otimes$: Convolution

Frequency- and Time- Division Duplex (FDD, TDD) Transmission Modes



- BS and MU transmit on different frequencies
- Uplink and downlink channels are highly ***uncorrelated***
- MU needs to estimate downlink channel and feed back to BS

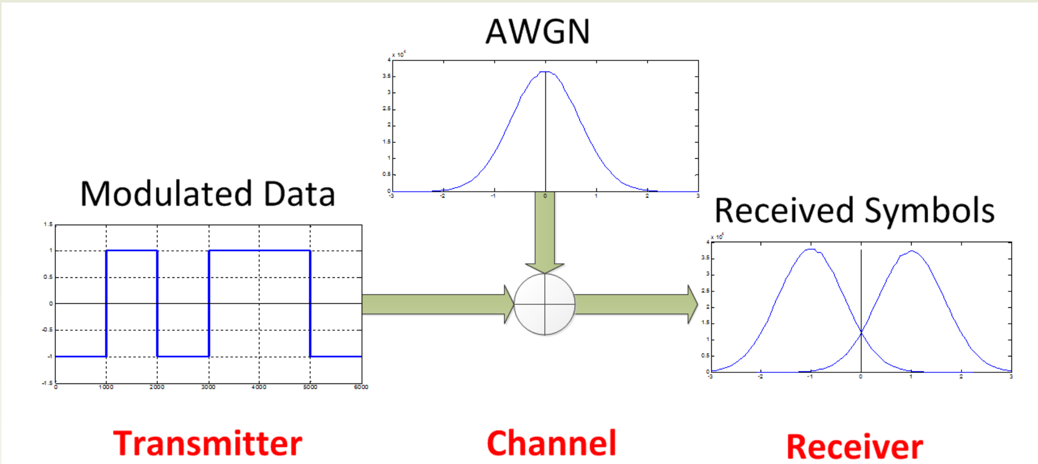
- BS and MU transmit on the same frequency
- Uplink and downlink channels are highly ***correlated***
- BS can accurately estimate the downlink channel during uplink reception



This Video : RF Transmission

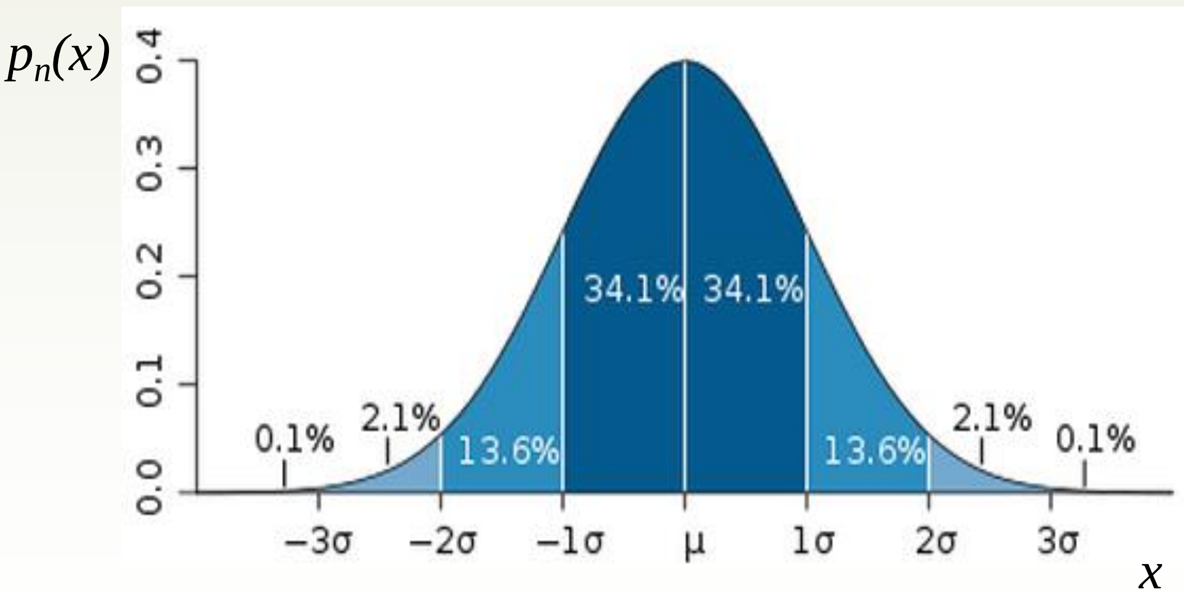
- Additive White Gaussian Noise
- Bit Error Rate

Additive White Gaussian Noise (AWGN)



$$r = s + n$$

$$n \sim \mathcal{N}(\mu, \sigma^2)$$



Characterised by:

μ : mean

σ : standard deviation

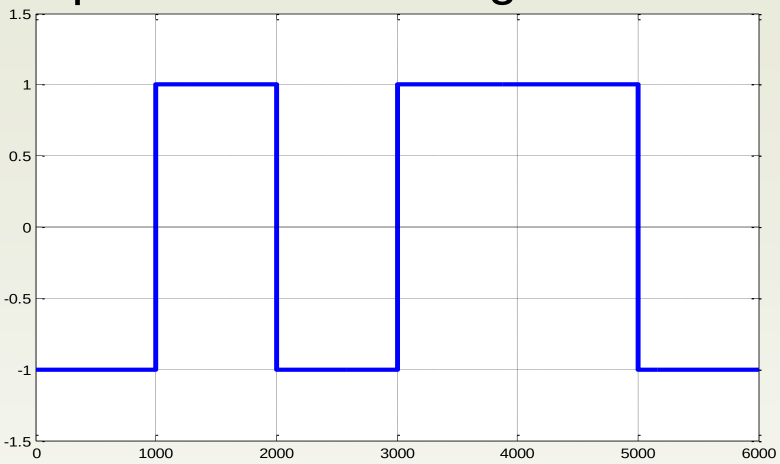
σ^2 : variance

$N_0 = 2\sigma^2$: Noise spectral density

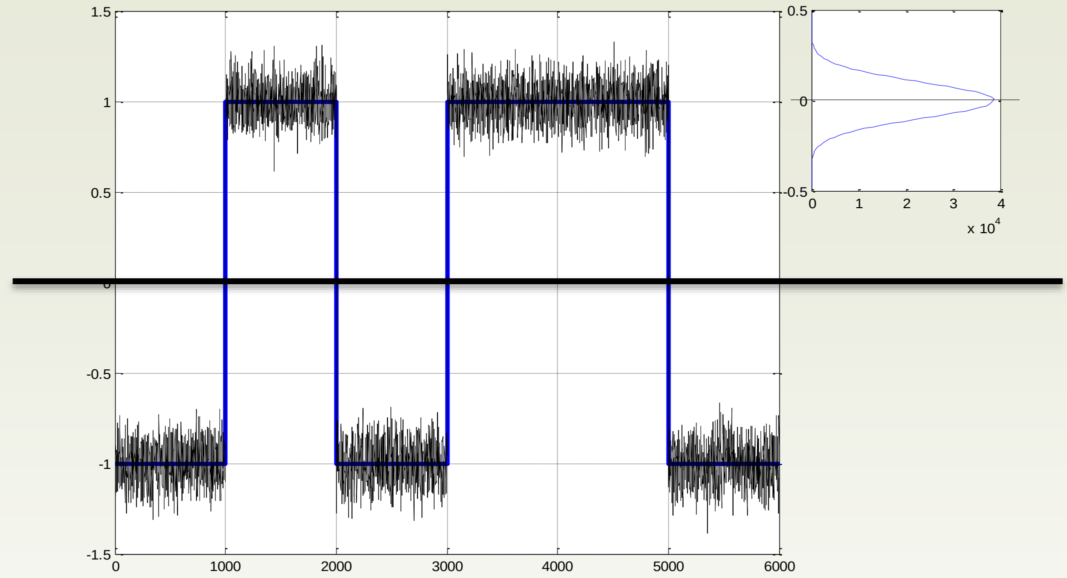
$$p_n(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

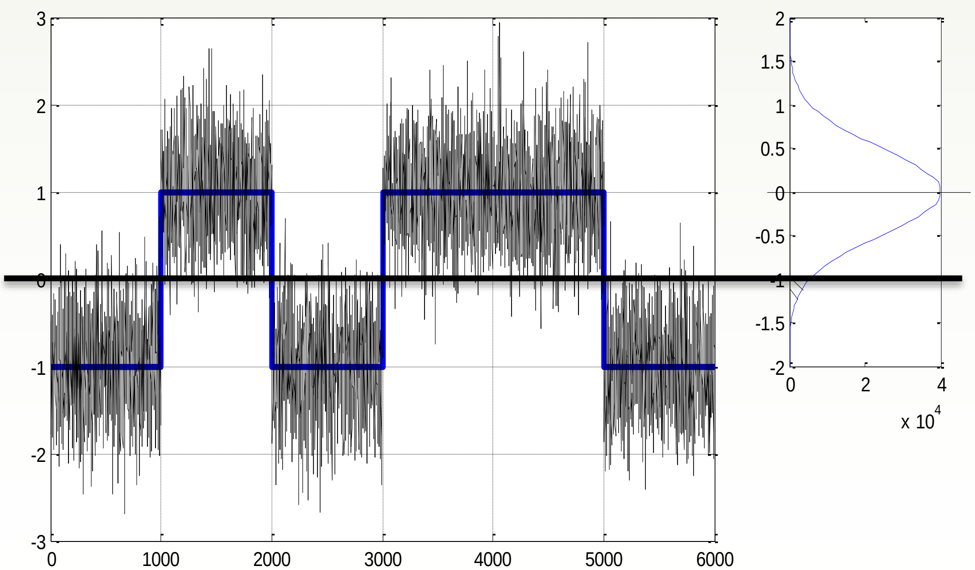
Probability of Error

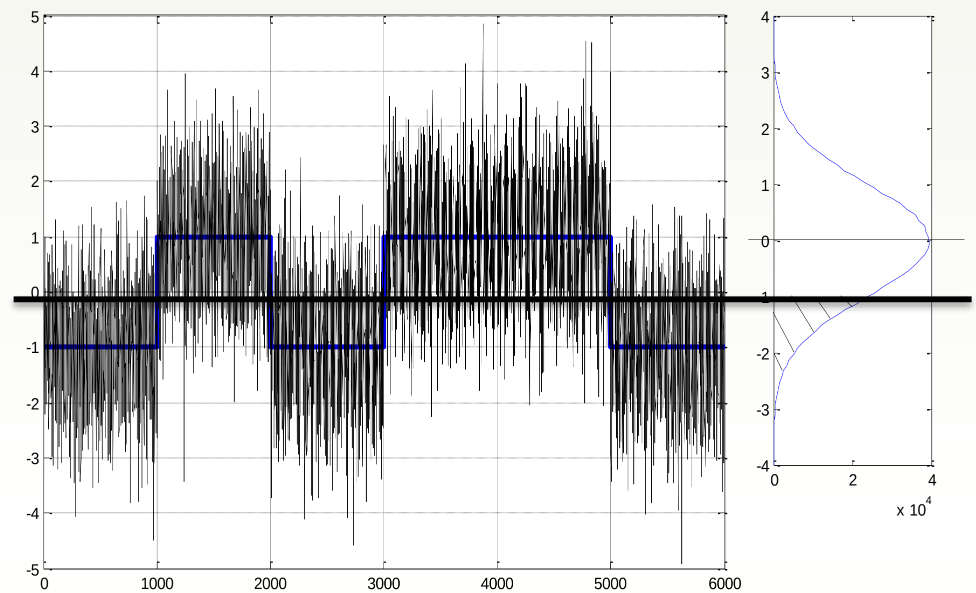
Bipolar baseband signal :



signal + noise :

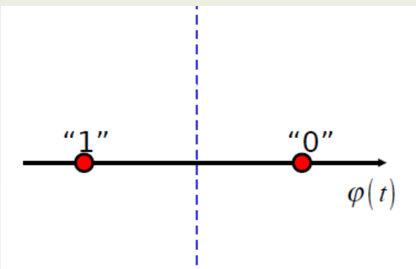


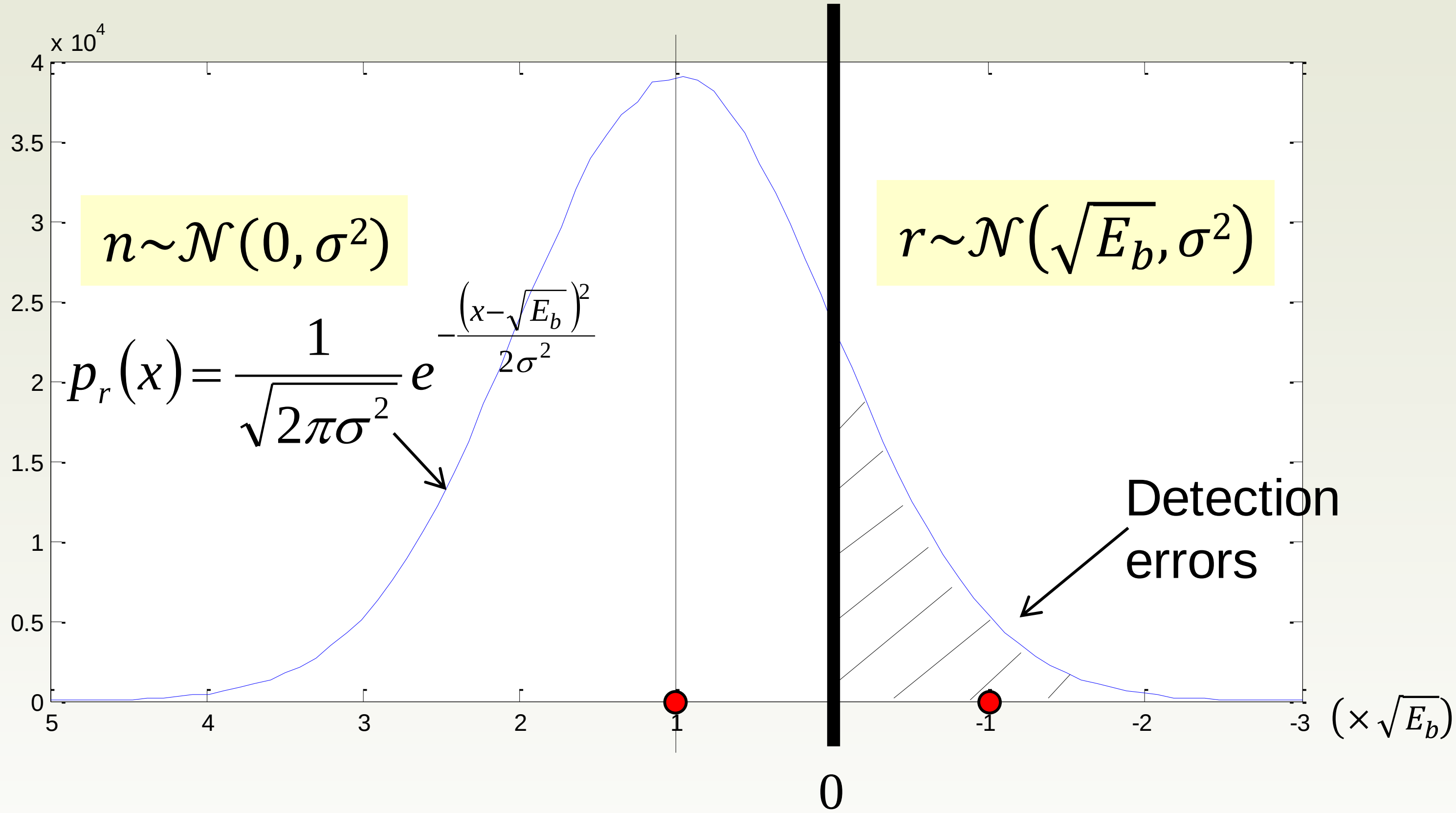




Probability of Error – Binary antipodal example

$$r = s + n$$





$$p_e = p(r < 0 | s = \sqrt{E_b}) = \int_{-\infty}^{0} p_r(x)dx = \int_{-\infty}^{0} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\sqrt{E_b})^2}{2\sigma^2}} dx$$

$$p_e = Q\left(\sqrt{\frac{2E_b}{N_0}}\right) \quad (N_0 = 2\sigma^2) \qquad Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} \exp\left(-\frac{u^2}{2}\right) du$$

$p_e = f(SNR)$

This Video : RF Transmission

- Modulation Tradeoffs

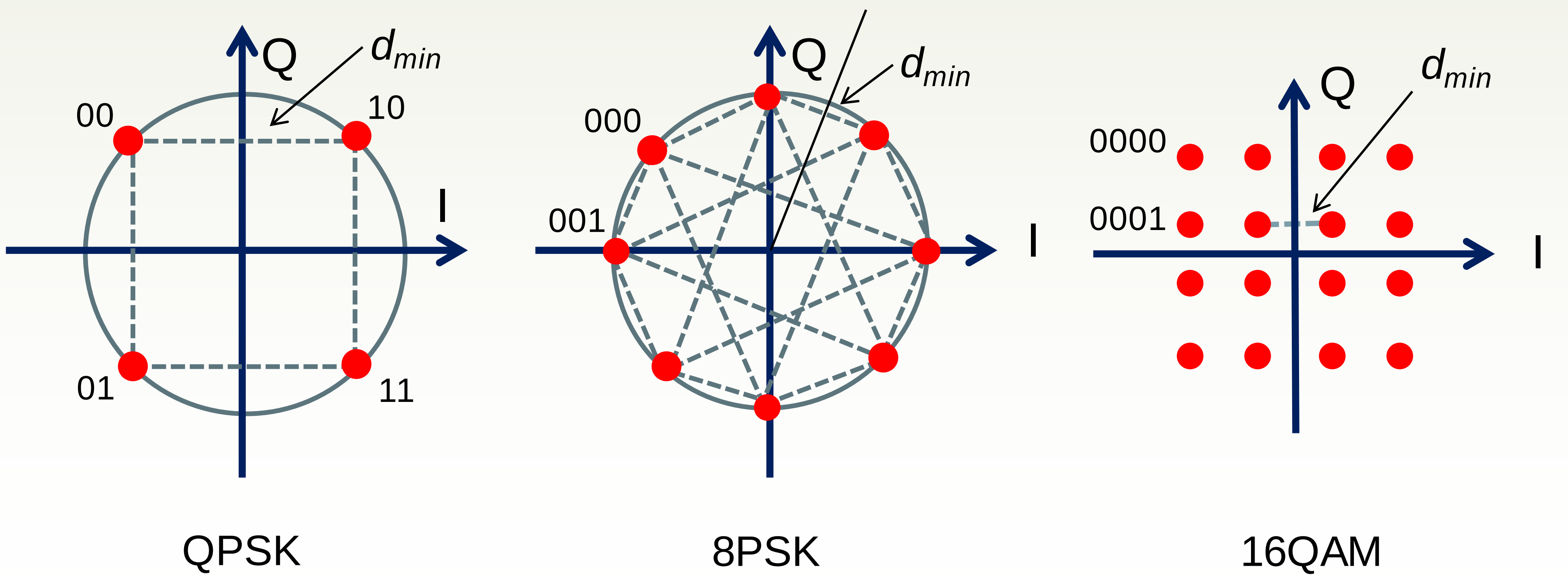
Tradeoffs of modulation

⇧ Modulation : ⇧ Spectral Efficiency (⇧ number of constellation points)

$$SE = log_2 M \quad (bits\,/\,symbol)$$

⇧ Error rate (⇩ minimum constellation distance)

equivalently: ⇧ Transmit power required for given BER



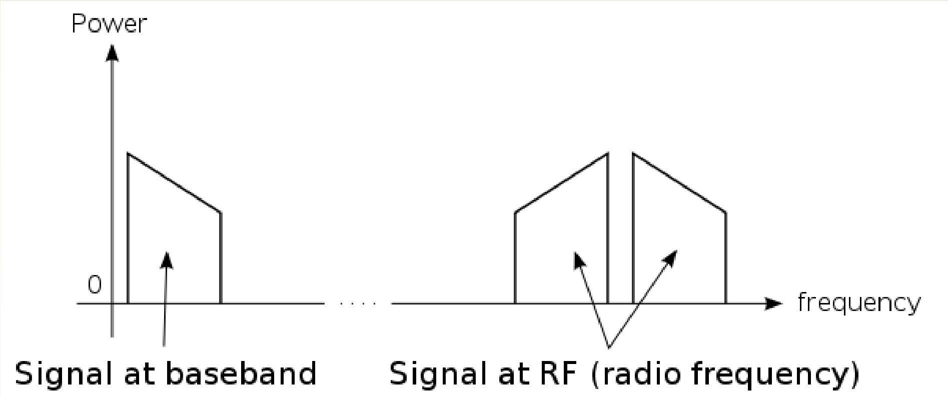
Spectral efficiency → Bandwidth requirements

SE: bps / Hz: Rate / Bandwidth

Baseband!

Gross pass band bandwidth required (double-sideband modulation):

BW = 2 × (Rate / SE)



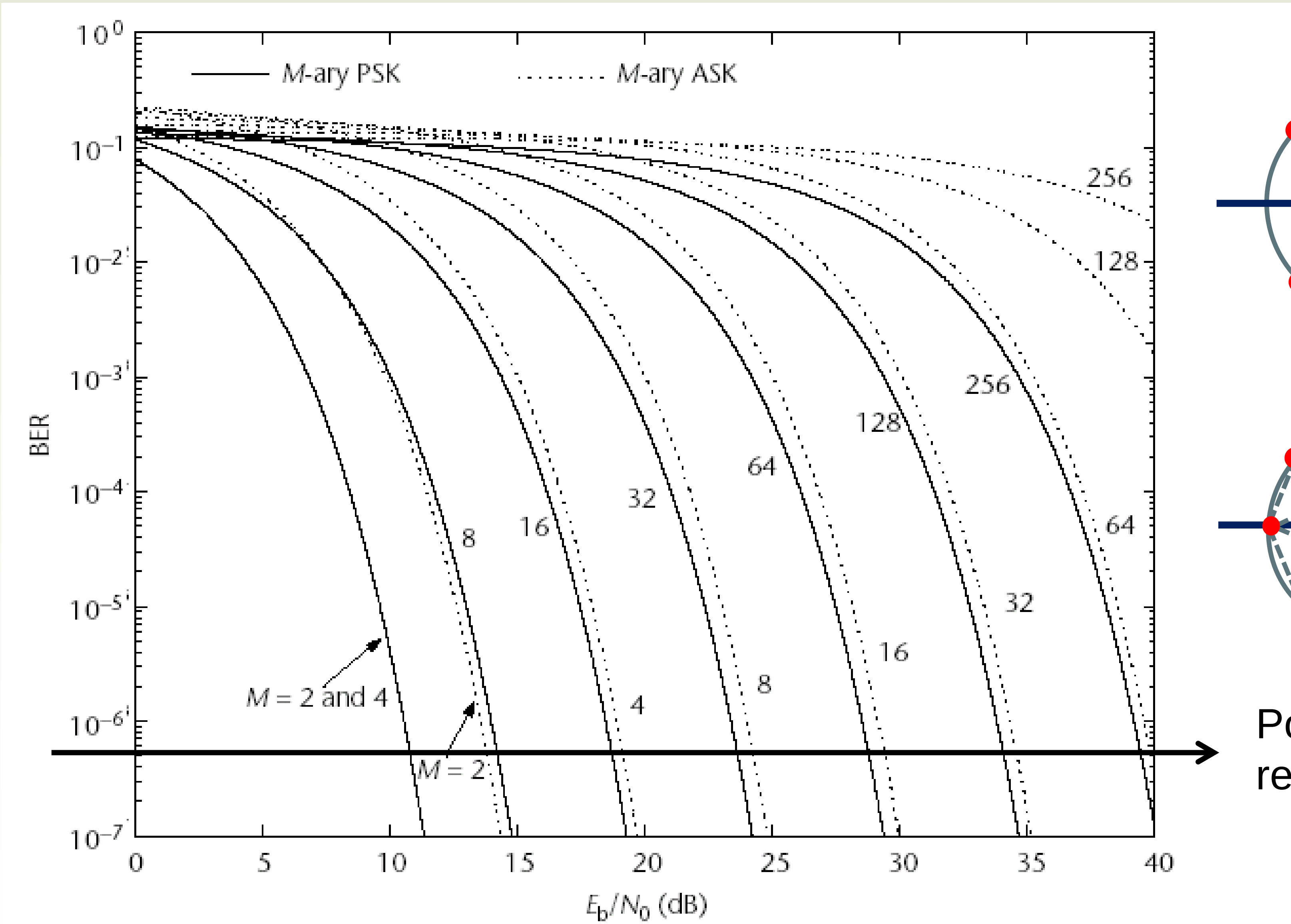
Example:

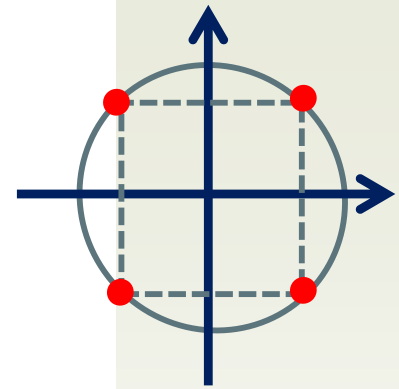
For a 1.5 Gbit/sec data rate:

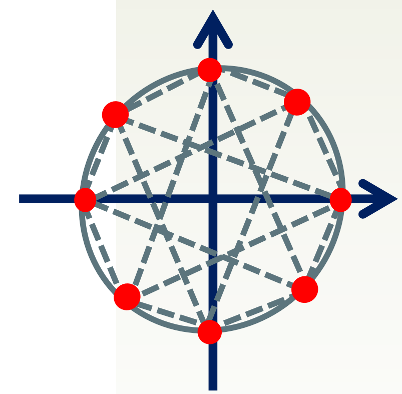
- BPSK requires 3GHz (SE=1b/s/Hz)
- QPSK: 1.5 GHz (SE=2b/s/Hz)
- 16QAM: 750 MHz (SE=4b/s/Hz)
- 64QAM: 500 MHz (SE=6b/s/Hz)

⇧ Modulation : ⇧ Spectral Efficiency ~ ⇩ Bandwidth required

Error performance for different modulation techniques in an AWGN channel (no fading)



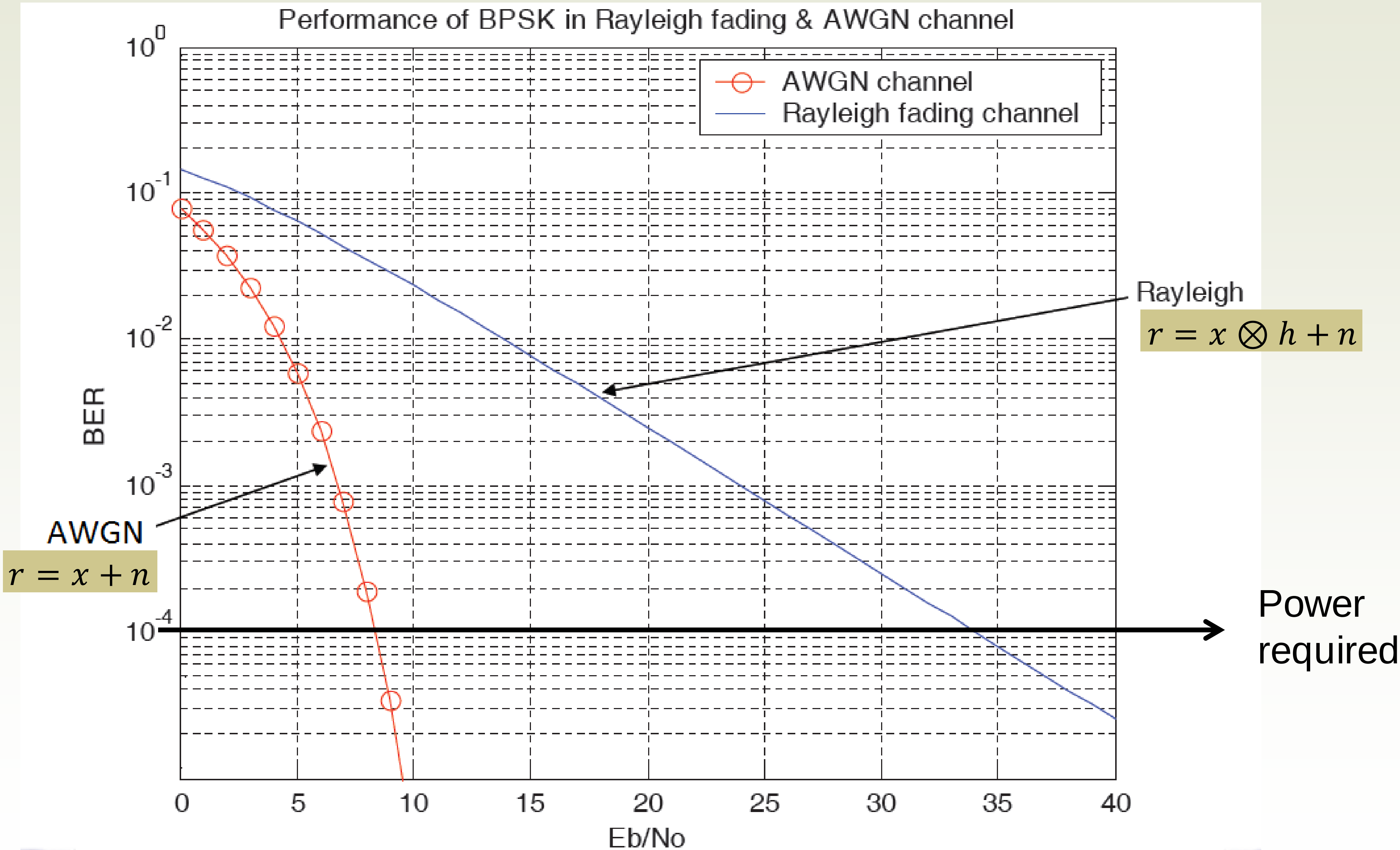




Power required

⇧ Modulation : ⇧ Error rate ~ ⇧ Tx power required for same BER

Effect of multipath fading on error performance



Comparison of Modulation Schemes

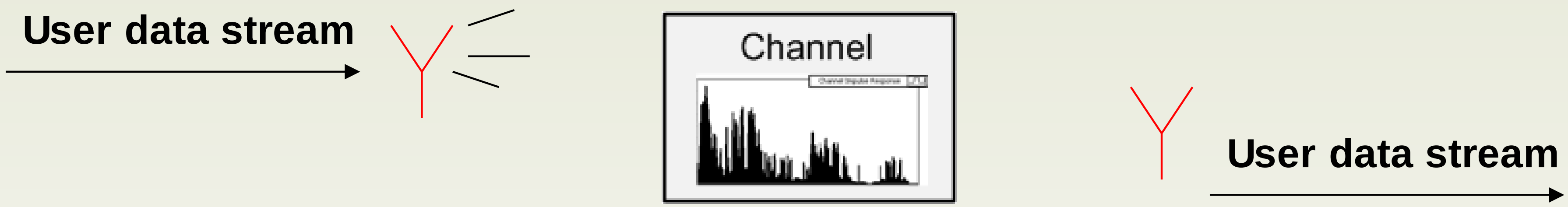
Modulation Scheme	Bandwidth efficiency C/B (bits/symbol)	Log2(C/B)	Error-free (BER ~10^{-6}) E_b/N_o in AWGN
128 QAM	7	2.8	24dB
16 QAM	4	2	15dB
8 PSK	3	1.6	14.5dB
4 PSK	2	1	10dB
4 QAM	2	1	10dB
BFSK	1	0	13dB
BPSK	1	0	10.5dB

Design guide: - **high** order modulation ~ minimize BW / maximise Rate
- **low** order modulation ~ minimize BER / minimize tx power

This Video : MIMO Systems

Antenna Configurations

- Single-Input-Single-Output (SISO) antenna system

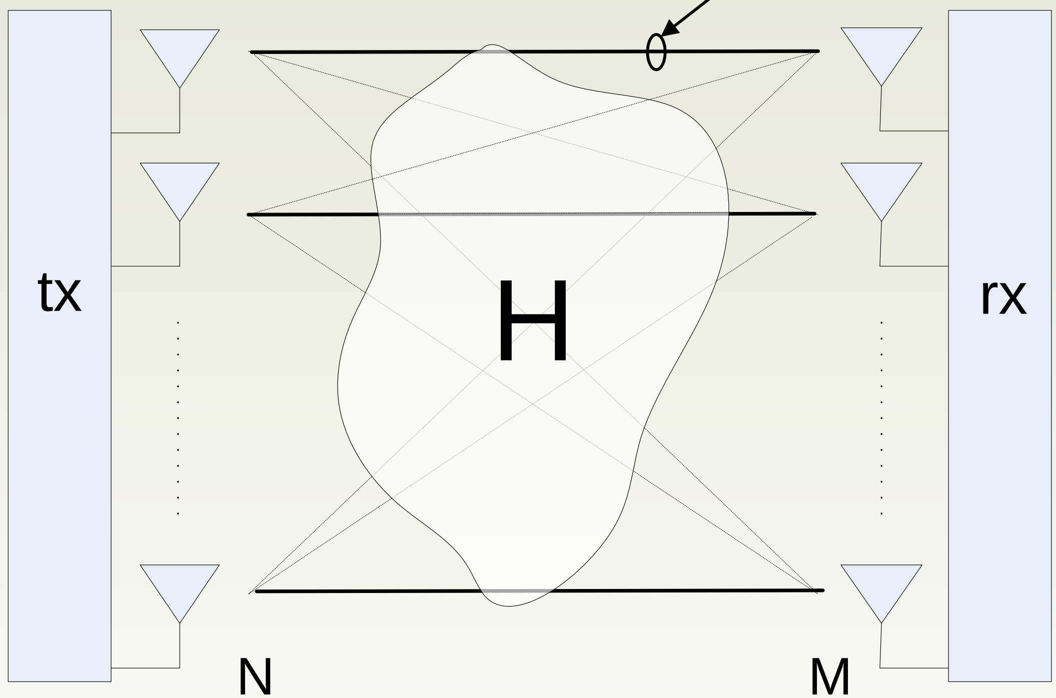


Channel capacity: $$C = BW \times \log_2\left(1 + \frac{P}{N_0}\right)$$ (in b/s)

- Theoretically, the 1Gbps rate can be achieved using this configuration if you are allowed to use much power and as much BW as you so please!
- Extensive research has been done on SISO under power and BW constraints. A combination of smart *modulation, coding and multiplexing techniques* have yielded good results but far from the 1Gbps barrier

Multiple Antenna Links

$$C = BW \times \log_2\left(1 + \frac{P}{N_0}\right)$$

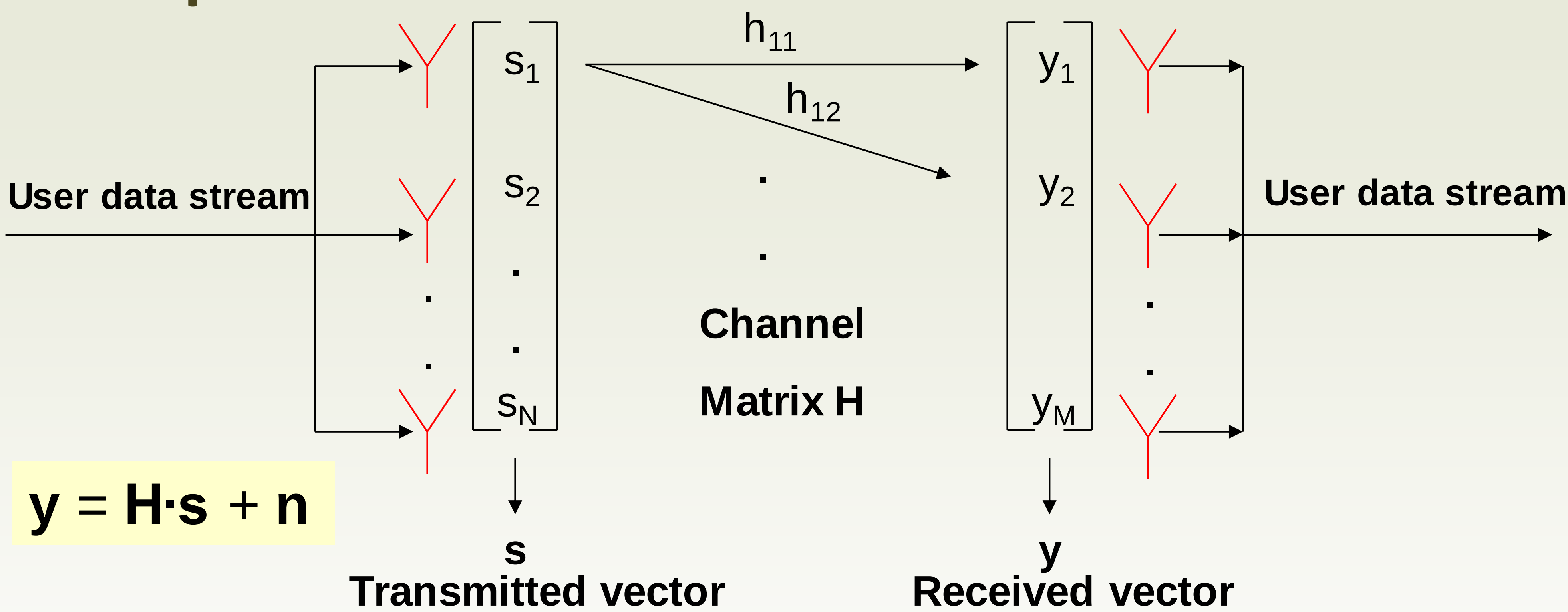


Channel capacity:

$$C \leq BW \times \min(M, N) \times \log_2\left(1 + \frac{P}{N_0}\right)$$

Up to a $\min(M, N)$ factor increase!!

Multiple Antenna Links



$$\mathbf{y} = \mathbf{H} \cdot \mathbf{s} + \mathbf{n}$$

$$\text{Where } \mathbf{H} = \begin{array}{c} \xleftarrow{\quad M_T \quad} \\ \begin{bmatrix} h_{11} & h_{21} & \ldots\ldots\ldots & h_{N1} \\ h_{12} & h_{22} & \ldots\ldots\ldots & h_{N2} \\ . & . & \ldots\ldots\ldots & . \\ h_{1M} & h_{2M} & \ldots\ldots\ldots & h_{NM} \end{bmatrix} \end{array} \updownarrow M_R$$

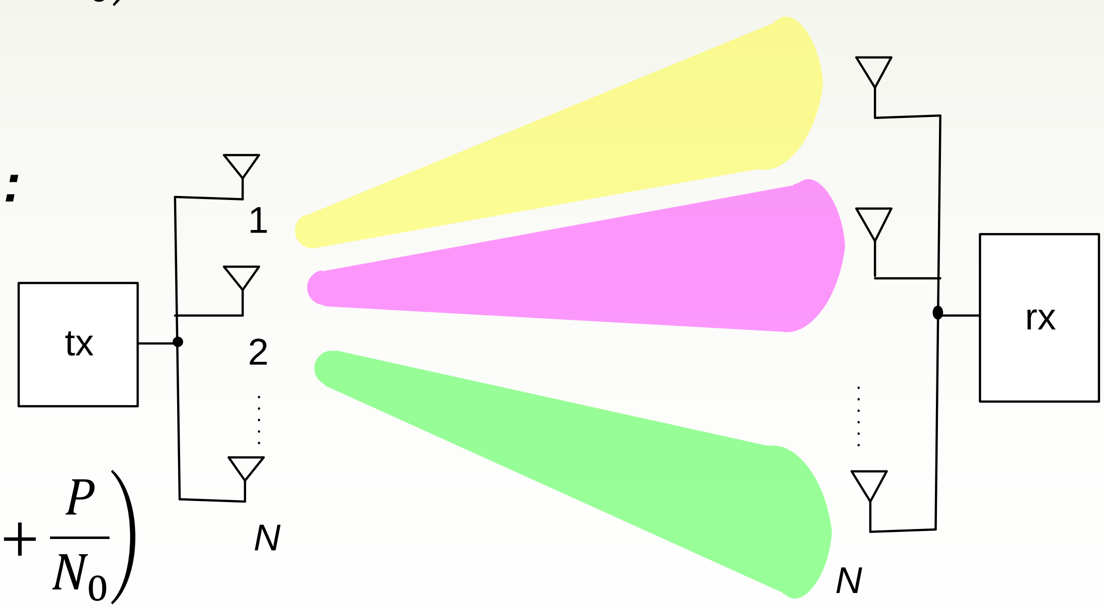
h_{ij} : Complex Gaussian random variable that models fading gain between the i-th transmit and j-th receive antenna

Gains - Multiple Antenna Links

- ***Diversity gain :*** transmit the same signal from all antennas to compensate for 'bad' channels

$$C \leq BW \times \min(M,N) \times \log_2\left(1+\frac{P}{N_0}\right)$$

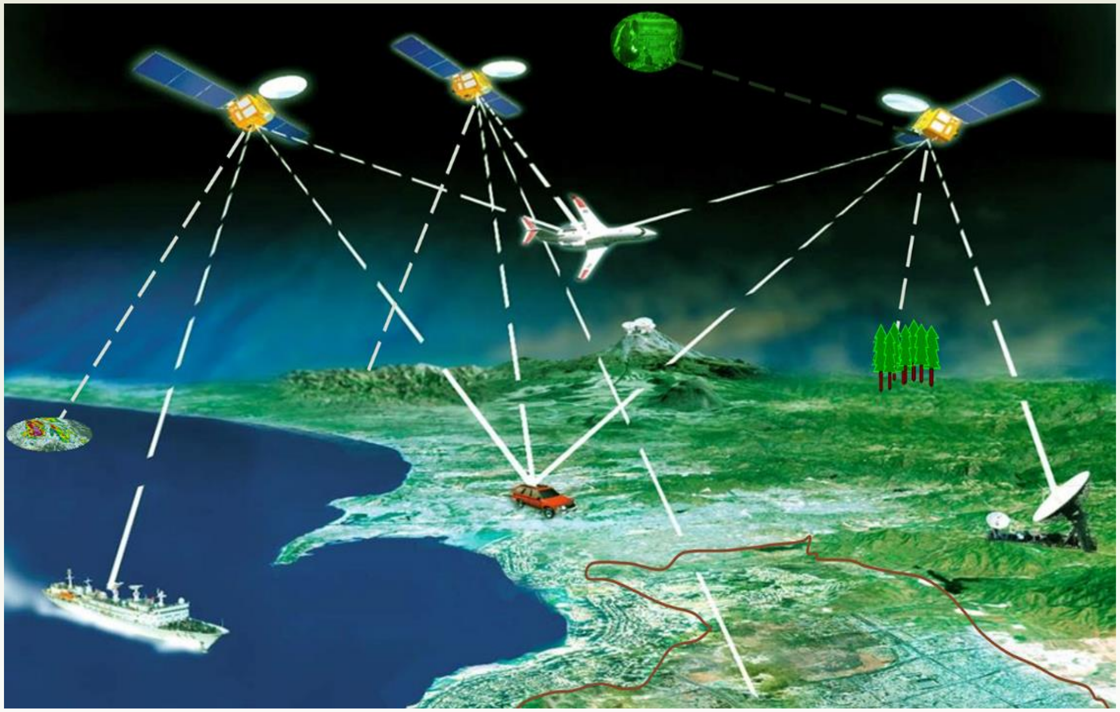
- ***Spatial multiplexing gain :*** transmit independent signals from different antennas → higher data rate.



$$C \leq BW \times \min(M,N) \times \log_2\left(1+\frac{P}{N_0}\right)$$

This Video : Satellite Communications

SatComs vital for IoT - Coverage



Connecting remote assets - remote facility monitoring real-time asset management unmanned sites and offshore platforms.

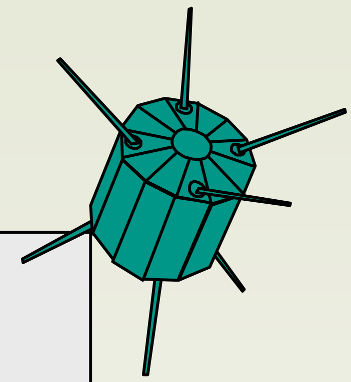
Remote sensor networks - satellite-based sensor networks to support offshore exploration.

Transportation infrastructure - Broadband connectivity on trains, cargo vehicles and maritime vessels.

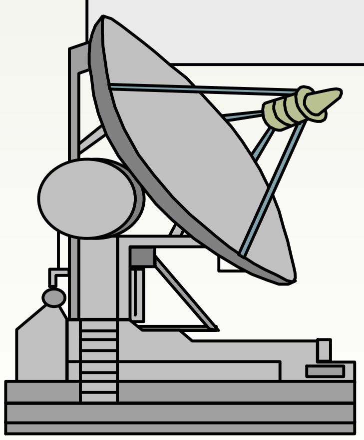
Developing sustainable cities - smart grids in remote regions reliable backup network for critical services such as safety and security.

Connected Cars - safety (emergency calling and airbag deployment notifications) everywhere.

ITU satellite service definitions:



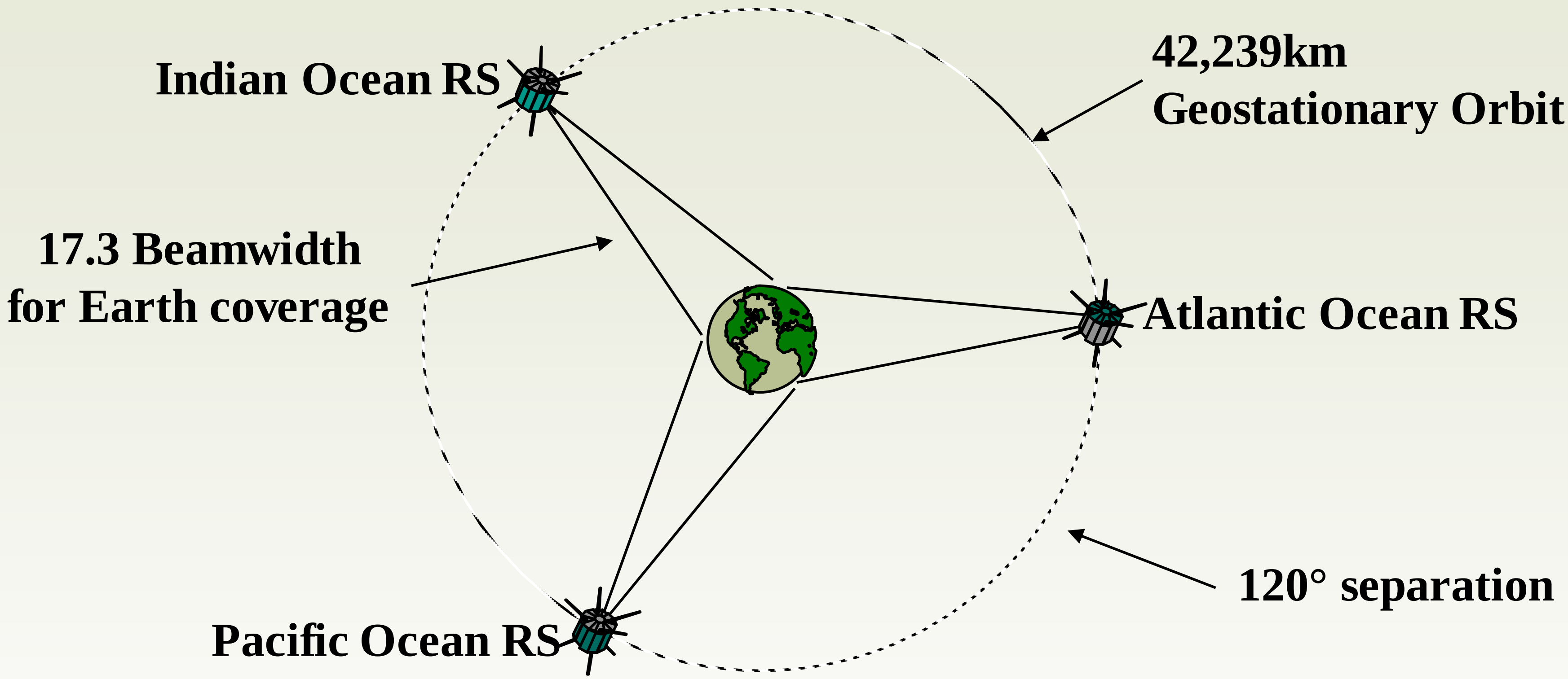
- Fixed satellite services (FSS)
- Broadcast satellite services (BSS)
- Mobile satellite services (MSS)



Only FSS considered here

Service Type	Freq Band GHz (up/down link)	Band Designation	Allocated Bandwidth GHz
FSS	6/4 14/12 (or 11) 30/20	C band Ku band K band	1.0 1.1 3.5
BSS	14/12 18/12	DBS band DBS band	0.8 0.8
MSS	1.6/1.5	L band	34/29 MHz

Geostationary Global Coverage

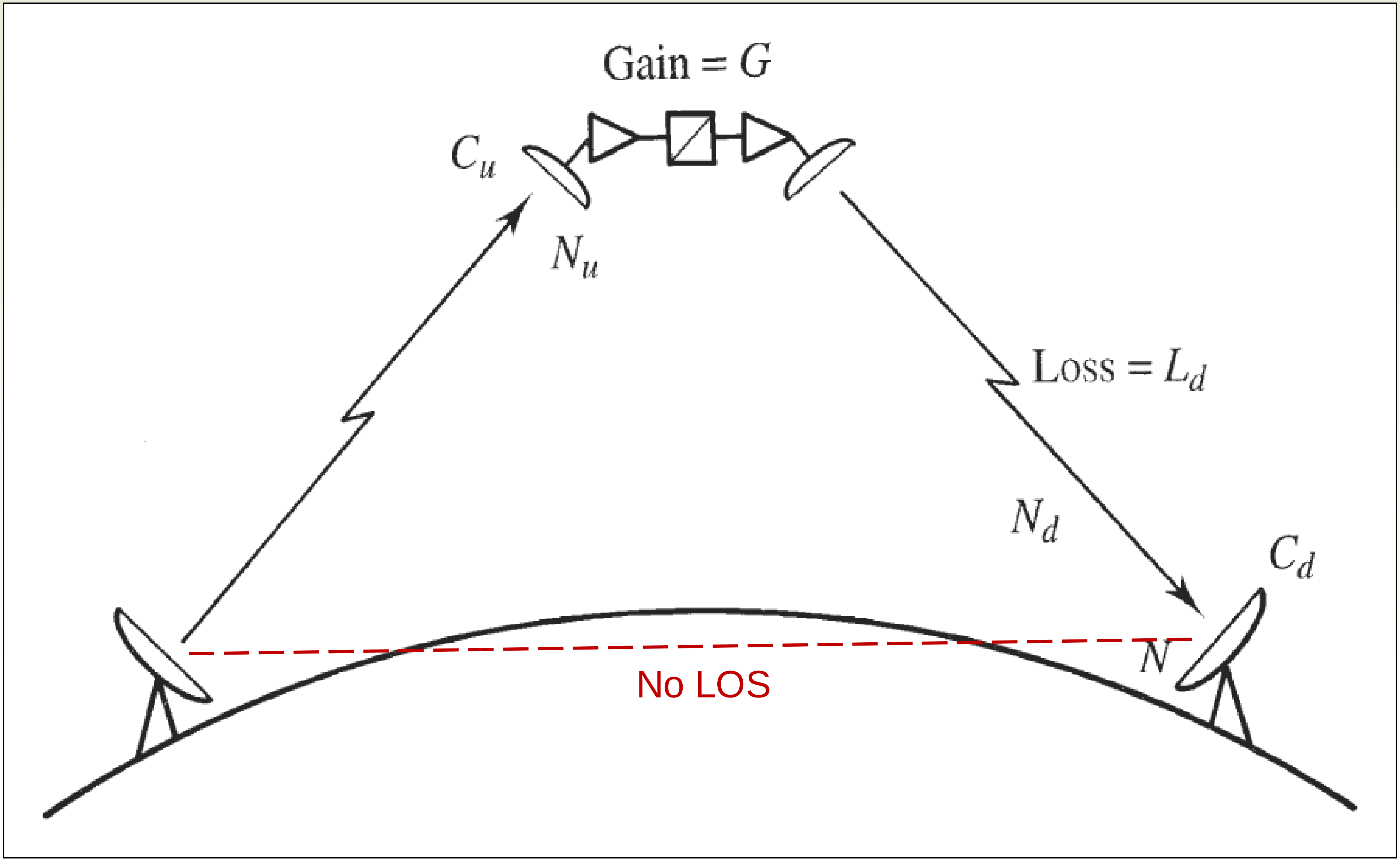


- First proposed by Arthur C Clarke in an article in Wireless World
- Three satellites in geostationary orbit provide global coverage
- Used for long distance links
- Ideal for global Broadcasting

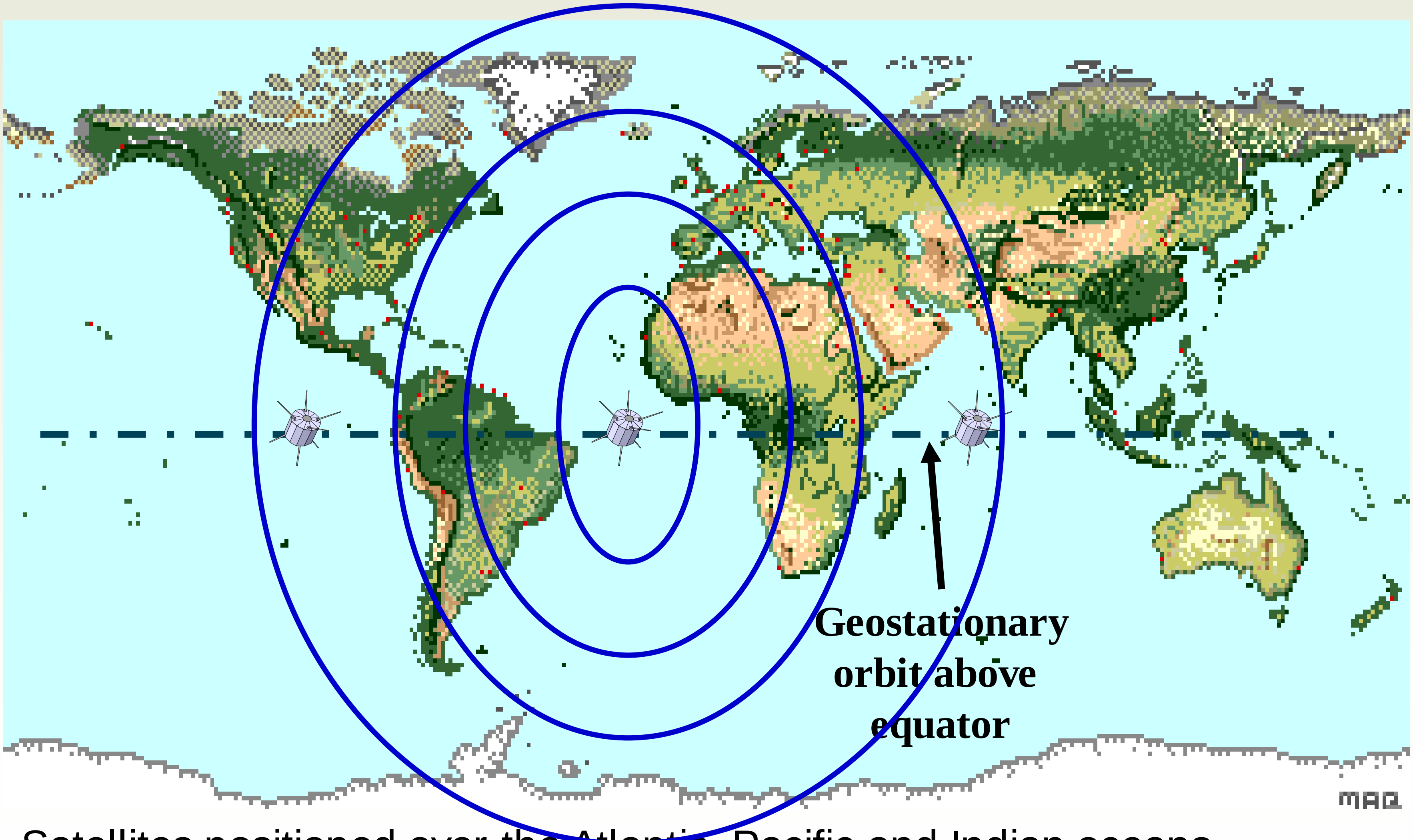
\+ Easy link establishment – just point the antenna to a satellite, no Doppler shift

\- High Path loss, long delays

Long distance relaying



Satellite Positions



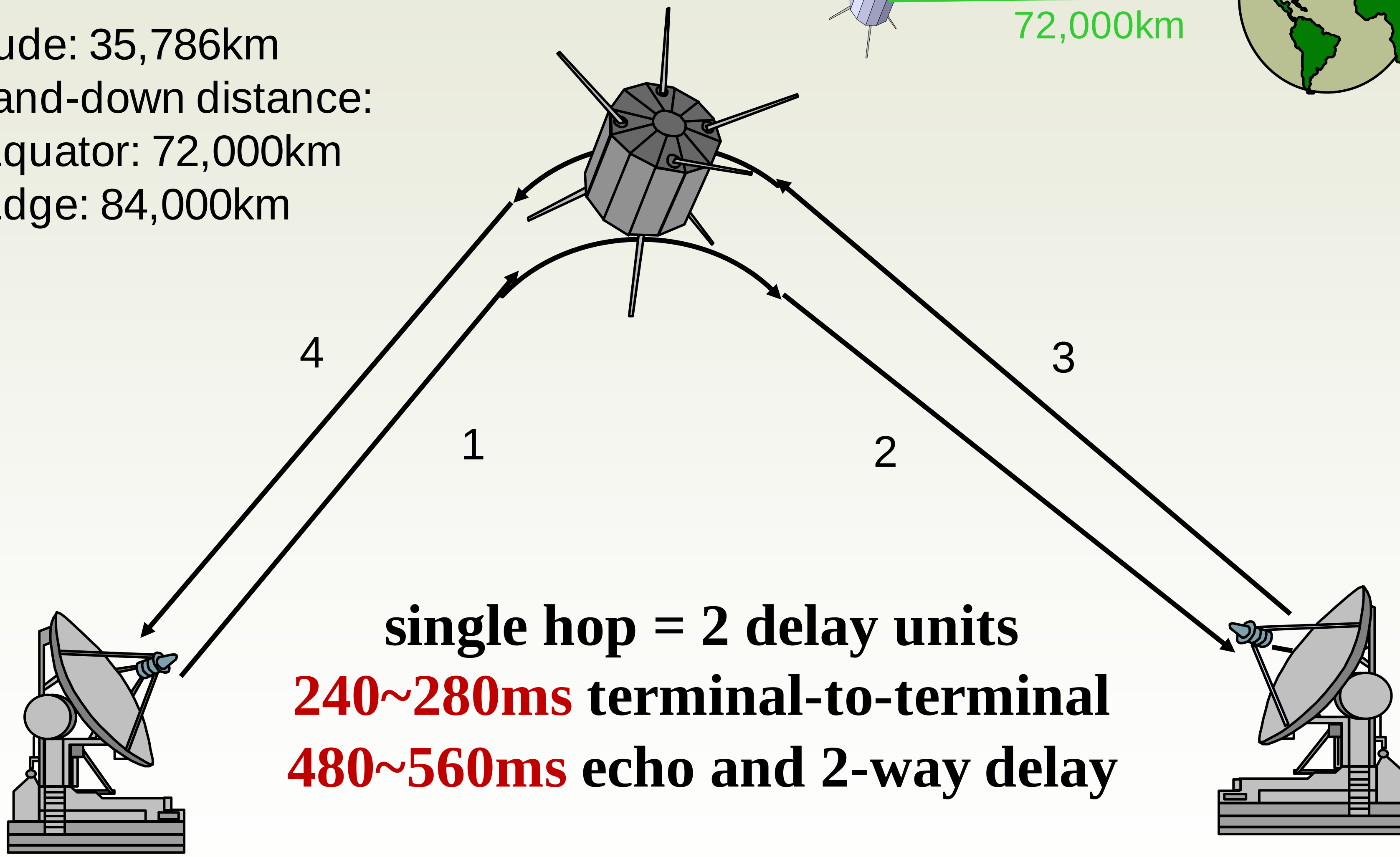
Satellites positioned over the Atlantic, Pacific and Indian oceans

Delay and Echo

Altitude: 35,786km

Up-and-down distance:

- Equator: 72,000km
- Edge: 84,000km



single hop = 2 delay units

240~280ms terminal-to-terminal

480~560ms echo and 2-way delay

Summary

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- RF Equipment considerations
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