TTN

Vehicular Communications – Part II
Transmission Techniques for Noise Limited Systems

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Slides are provided as supporting tool, they are not a textbook!

Outline

1. **Fundamentals of Digital Communications**
2. **System Model**
3. **Signal Based Power Control**
4. **Link Adaptation**
5. **FEC, ARQ, HARQ**
6. **Exercises**

The scope of this lecture block is to introduce the fundamentals of digital transmission techniques for noise limited links.

1. Fundamentals of Digital Comms

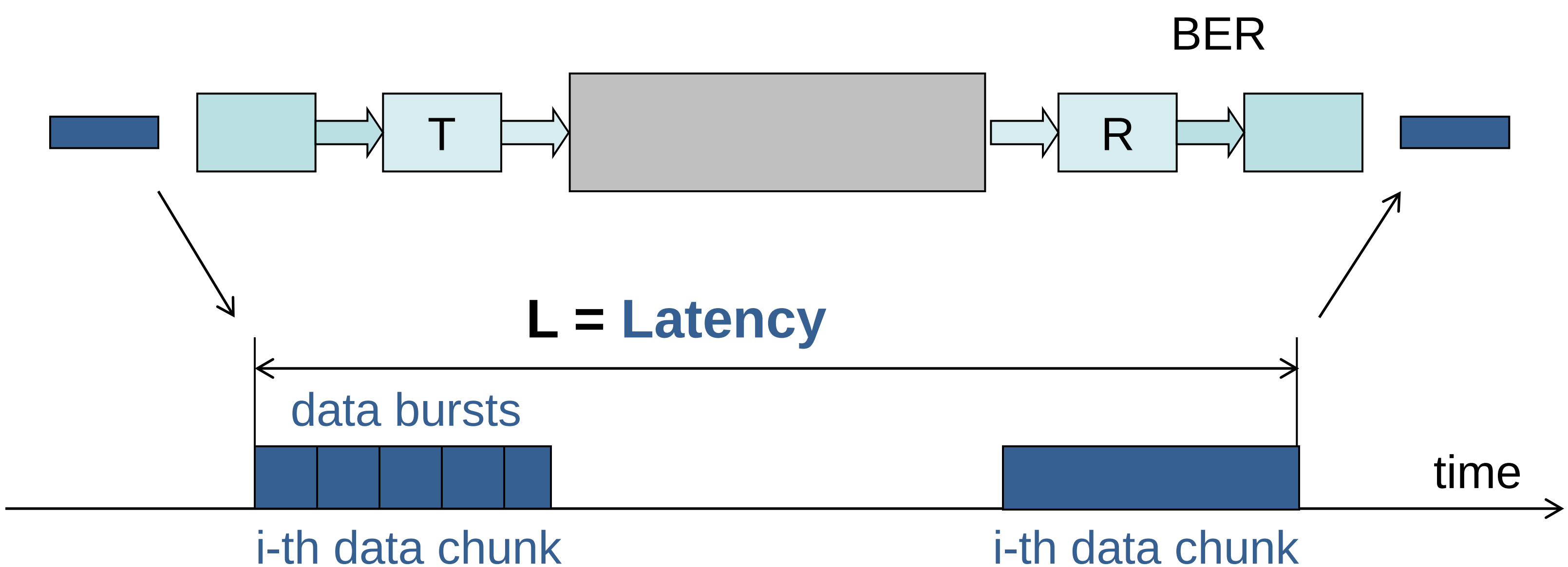
Fundamentals of Digital Communications

Digital Communications → Application Requirements

Fundamentals of Digital Communications

Digital Communications → Application Requirements

User Plane



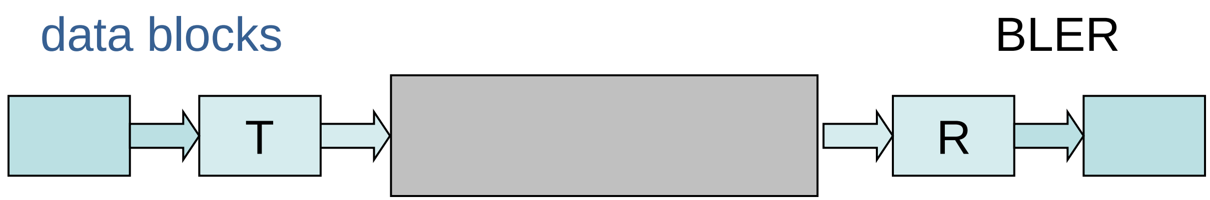
U = User Throughput = Number of information bits per second received

BER = Bit Error Rate = Percentage of erroneous bits

Fundamentals of Digital Communications

Digital Communications → Application Requirements

User Plane



BLER = BLock Error Rate = Percentage of erroneous data blocks

Fundamentals of Digital Communications

Digital Communications → Application Requirements

Some examples

	Interactive audio	Interactive video	web browsing	control
user throughput	10 Kbit/s	100 Kbit/s	n. a.	n. a.
latency	300 ms	500 ms	n. a.	1-10 ms
BLER	0.01	0.001	zero	zero

Fundamentals of Digital Communications

Digital Communications → Application Requirements

Both Planes

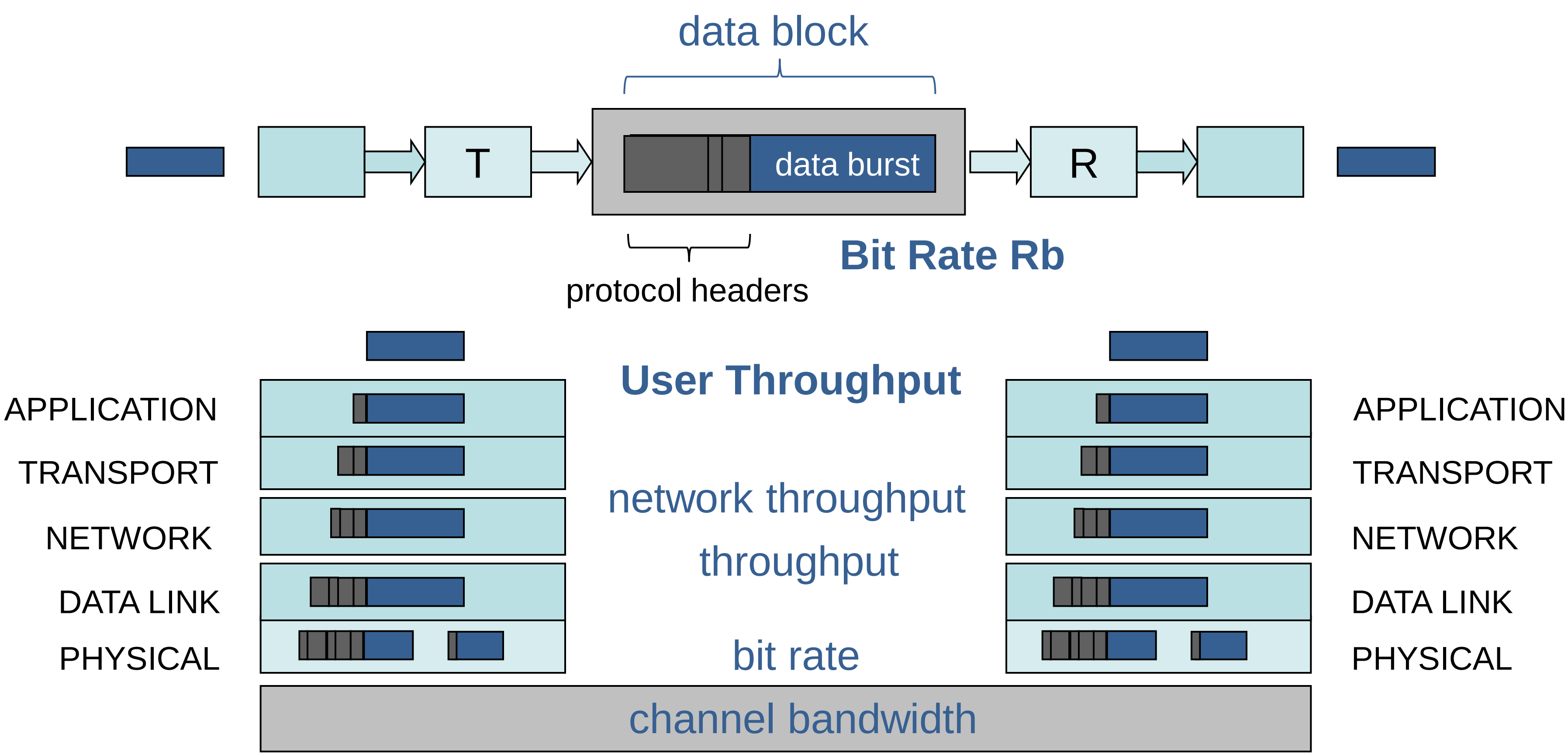
Y = Energy Efficiency = Number of information bits per joule received

Fundamentals of Digital Communications

Digital Communications → Protocol Overhead

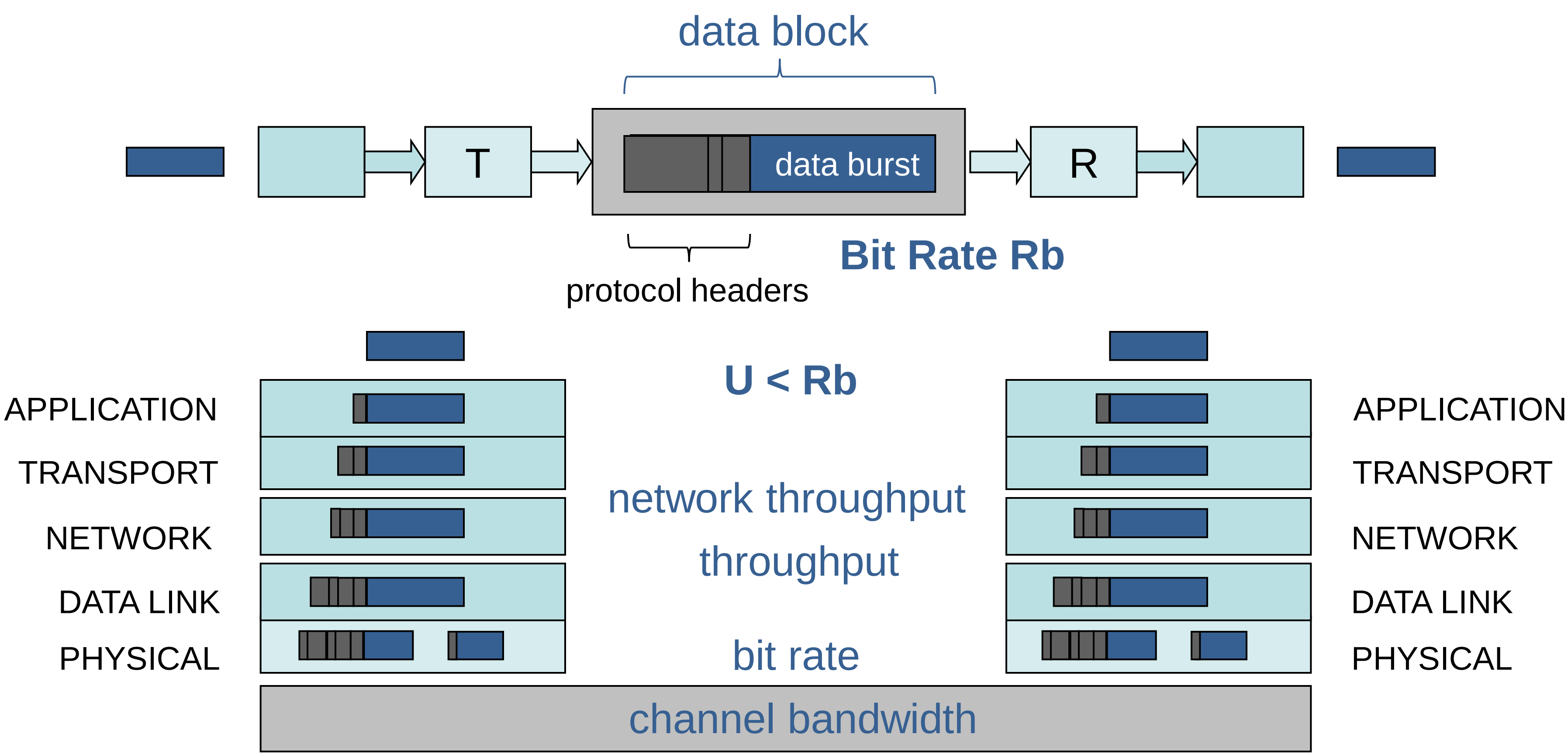
Fundamentals of Digital Communications

Digital Communications → Protocol Overhead



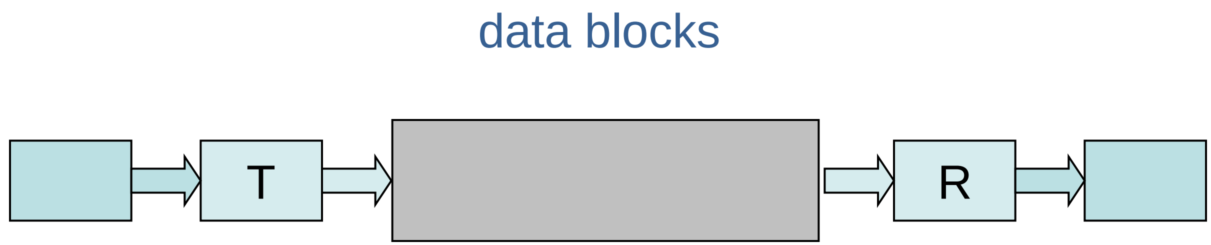
Fundamentals of Digital Communications

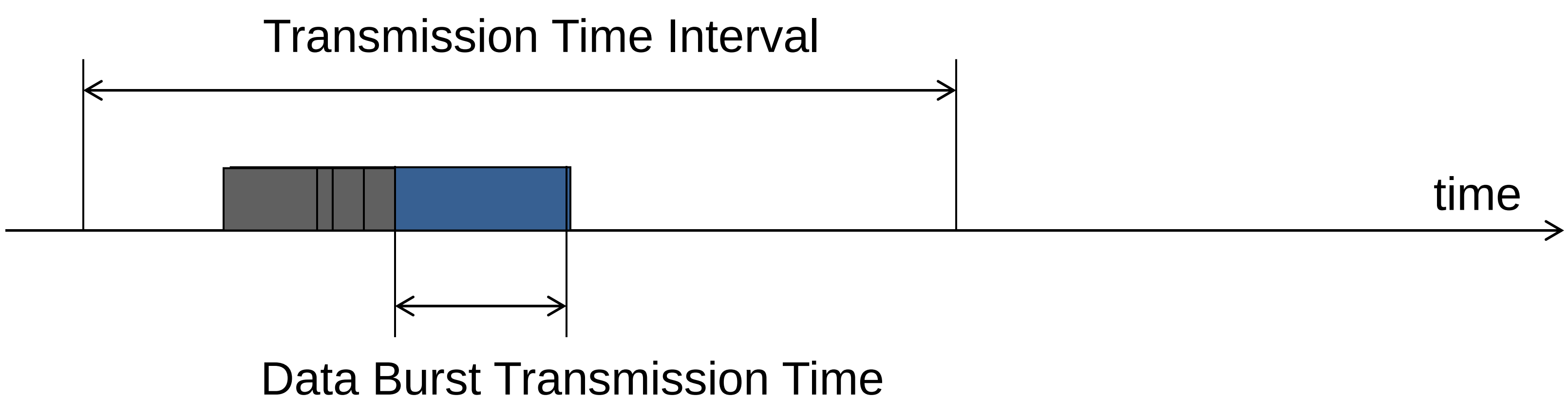
Digital Communications → Protocol Overhead



Fundamentals of Digital Communications

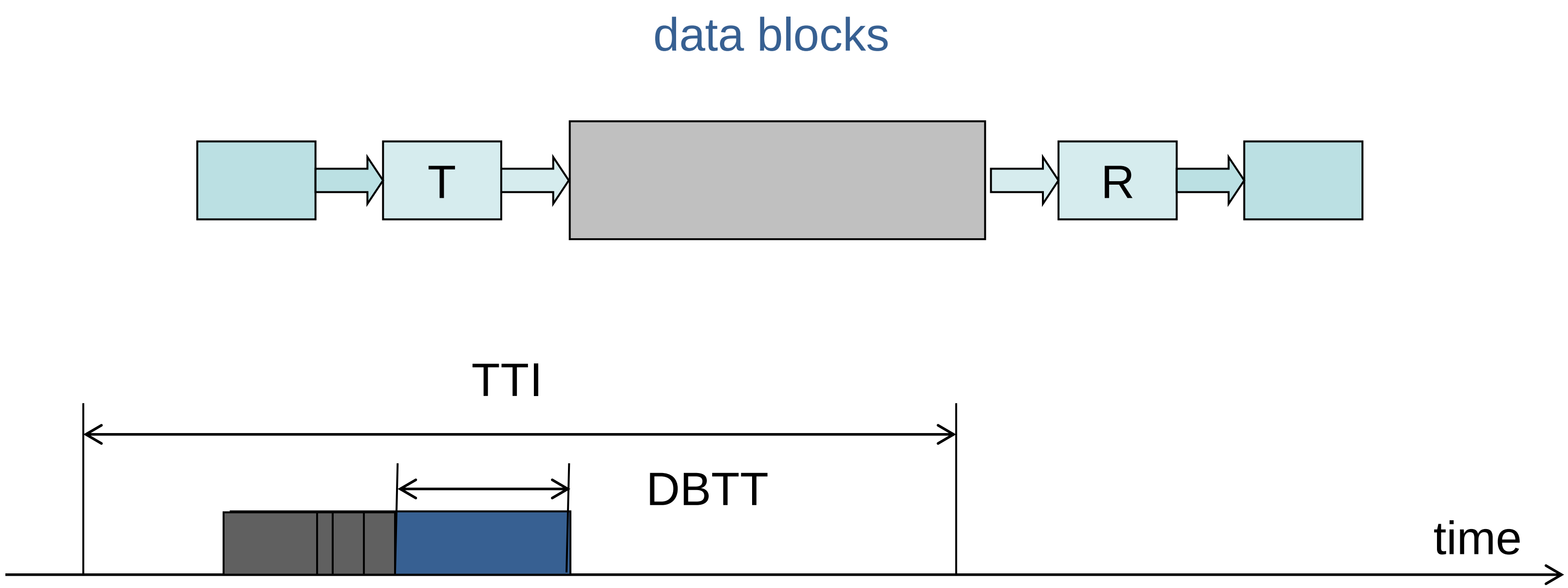
Digital Communications → Protocol Overhead





Fundamentals of Digital Communications

Digital Communications → Protocol Overhead



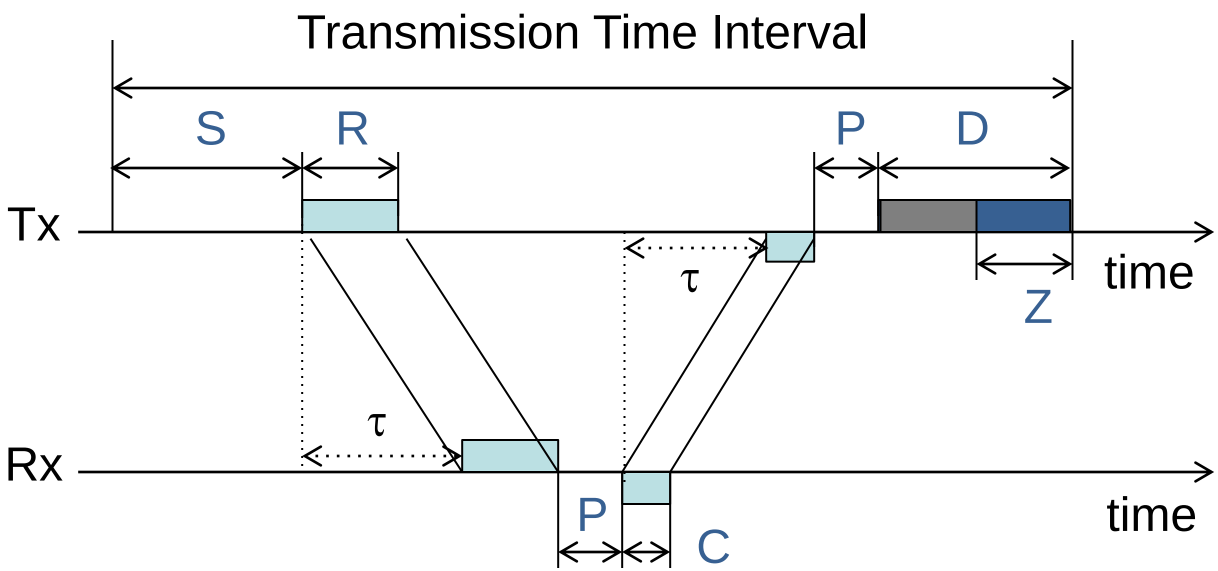
Protocol Efficiency = η_p = DBTT / TTI < 1

User Throughput = bit rate * η_p < bit rate (ideal channel conditions)

Fundamentals of Digital Communications

Digital Communications → Protocol Overhead

CSMA

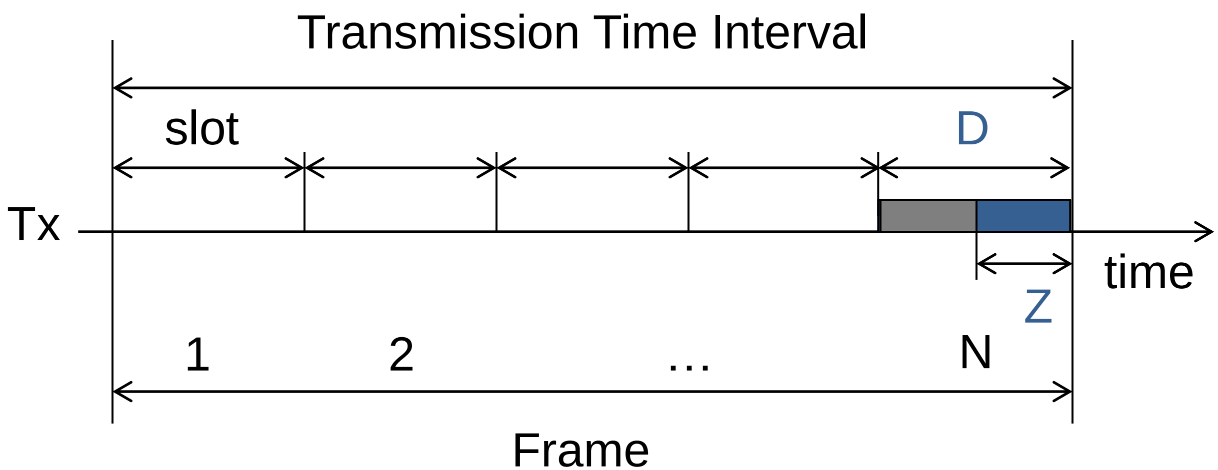


Protocol Efficiency = η_p = Z / [Z + (S+R+C+(D-Z)+2P+2τ)]
E.g. in WiFi $\eta_p \cong 1 / [\, 1 + (S+2\tau)/Z\,] \cong 0.5$ with large data bursts (1 KB)

Fundamentals of Digital Communications

Digital Communications → Protocol Overhead

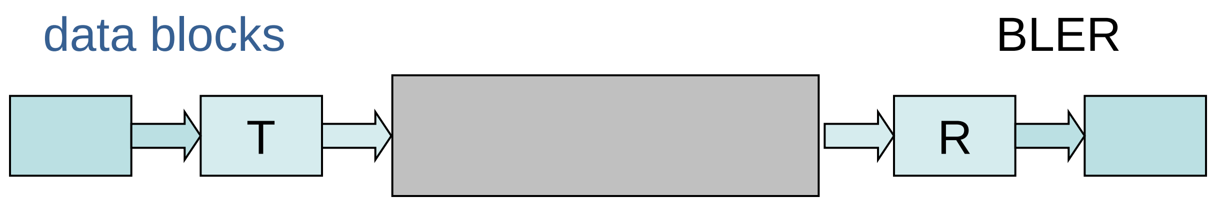
TDMA



Protocol Efficiency = η_p = Z / [N (Z + (D-Z))]
E.g. in 2G $\eta_p \cong 0.05$ when using only one slot

Fundamentals of Digital Communications

Digital Communications → Protocol Overhead



$$U = Rb * \eta_p * (1 - BLER)$$

Higher user throughputs require:

- Larger bit rates
- More efficient protocols
- Reliable channels

Fundamentals of Digital Communications

Digital Communications → Channel Constraints

Fundamentals of Digital Communications

Digital Communications → Channel Constraints

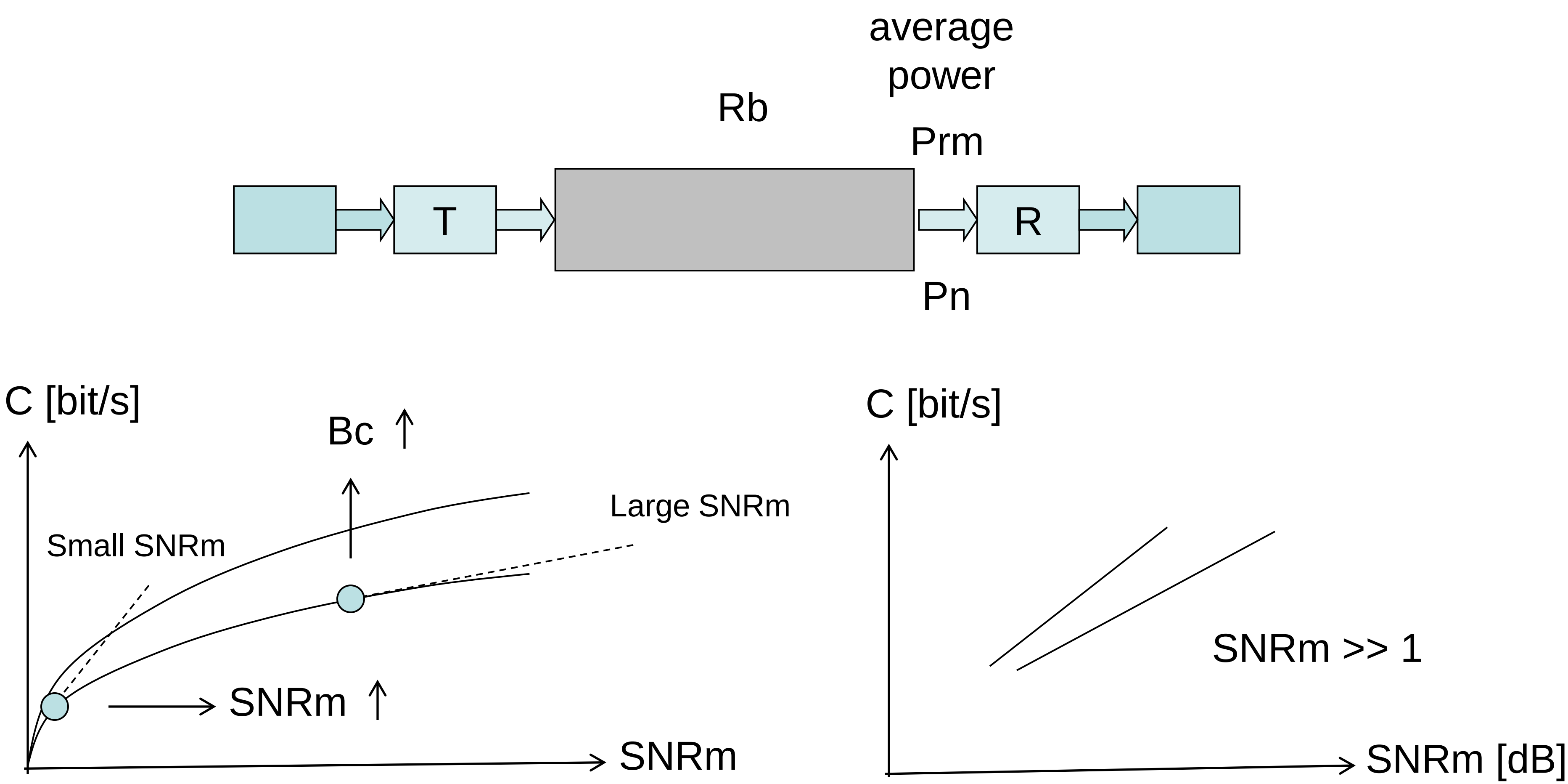
Channel Capacity:
Maximum bit rate that can be transmitted
over the AWGN channel with Bit Error Rate (BER) zero.

$C = Bc * \log_2 [1 + SNRm]$ **[Shannon, 1949]**

SNRm = mean signal power / noise power = Prm / Pn **Pn = No * Beq**

Fundamentals of Digital Communications

Digital Communications → Channel Constraints



Fundamentals of Digital Communications

Digital Communications → Channel Constraints

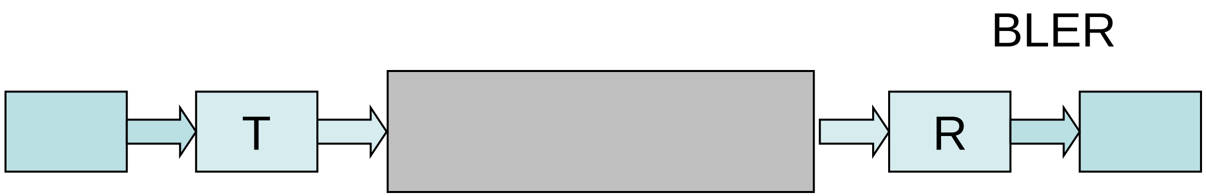
$$C = Bc * \log_2 [1 + SNRm]$$

Larger bit rates require:

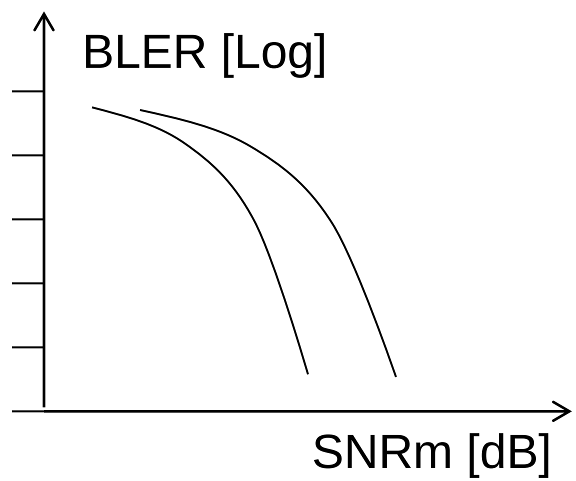
- Larger bandwidth
- Higher received powers

Fundamentals of Digital Communications

Digital Communications → Channel Constraints



BLER = f (SNRm)



Reliability requires:

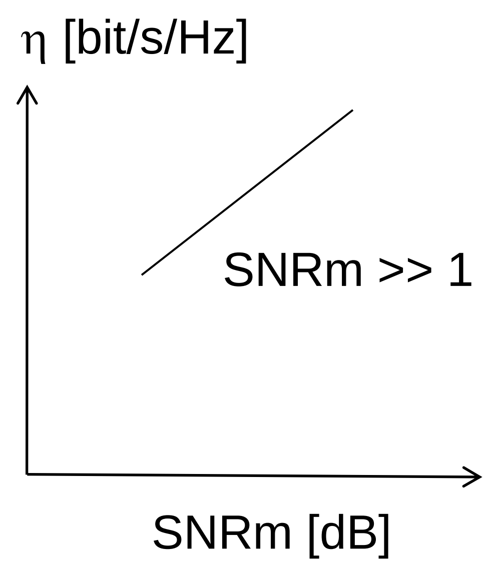
- **Efficient Transmission Techniques**
- **Higher received powers**

Fundamentals of Digital Communications

Digital Communications → Transmission Techniques

Fundamentals of Digital Communications

Digital Communications → Transmission Techniques



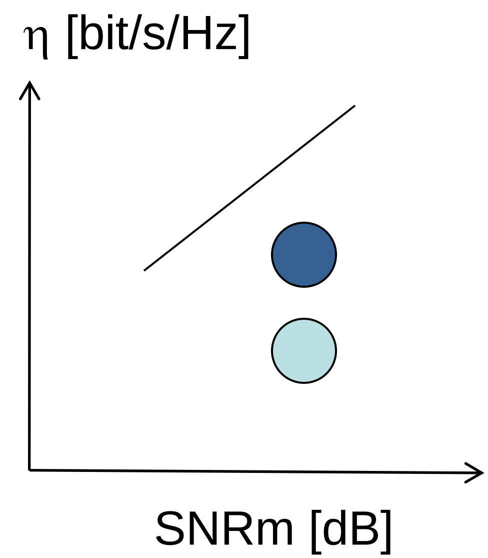
Link Spectrum Efficiency:
Bit rate transmitted per spectrum unit

$\eta = Rb / Bc$ [bit/s/Hz]

$\eta < C / Bc = k \; 10 \log_{10} [1 + SNRm]$

Fundamentals of Digital Communications

Digital Communications → Transmission Techniques

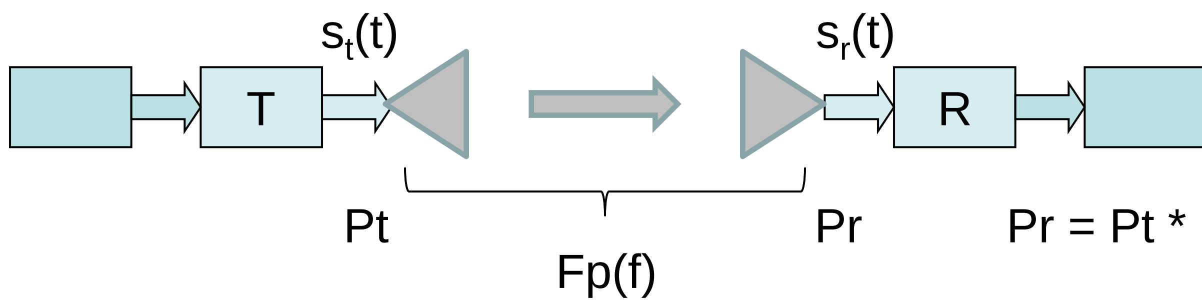


Larger bit rates require:

- **Larger link spectrum efficiency**

2. System Model

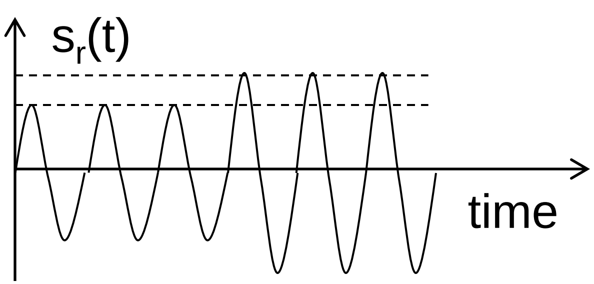
System Model



$Pr = Pt * G = Pt * A^{-1}$

$G = 1 / A = |Fp(f)|^2$

Channel Gain



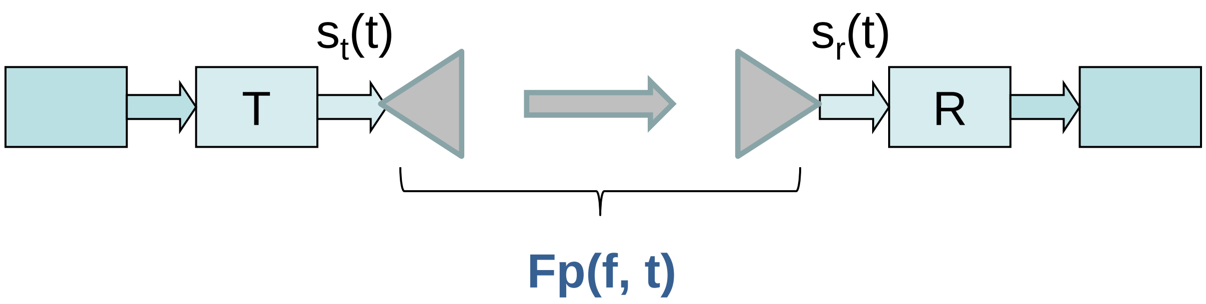
Pt	peak transmit power
Pr	peak receive power

The **Channel** can be

Flat if $|Fp(f)|$ is constant over the entire band of the signal, of bandwidth Bc

Distorting otherwise

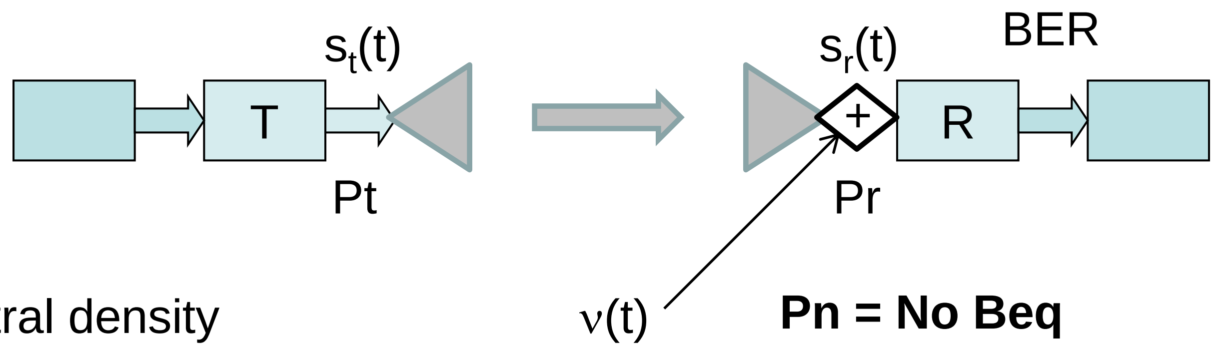
System Model



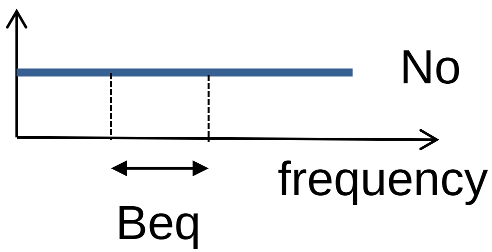
$$Fp(f, t) \overset{F}{\longleftrightarrow} h(t, \tau)$$

Linear Time Variant (LTV) Channel

System Model: AWGN



noise spectral density



Pn = No Beq

No = k (Ts + Tr)

k = 1.38 10^{-23} J/K

SNRm = Prm / Pn

In this course we will assume Pn is a value deterministically known:

Prm → SNRm

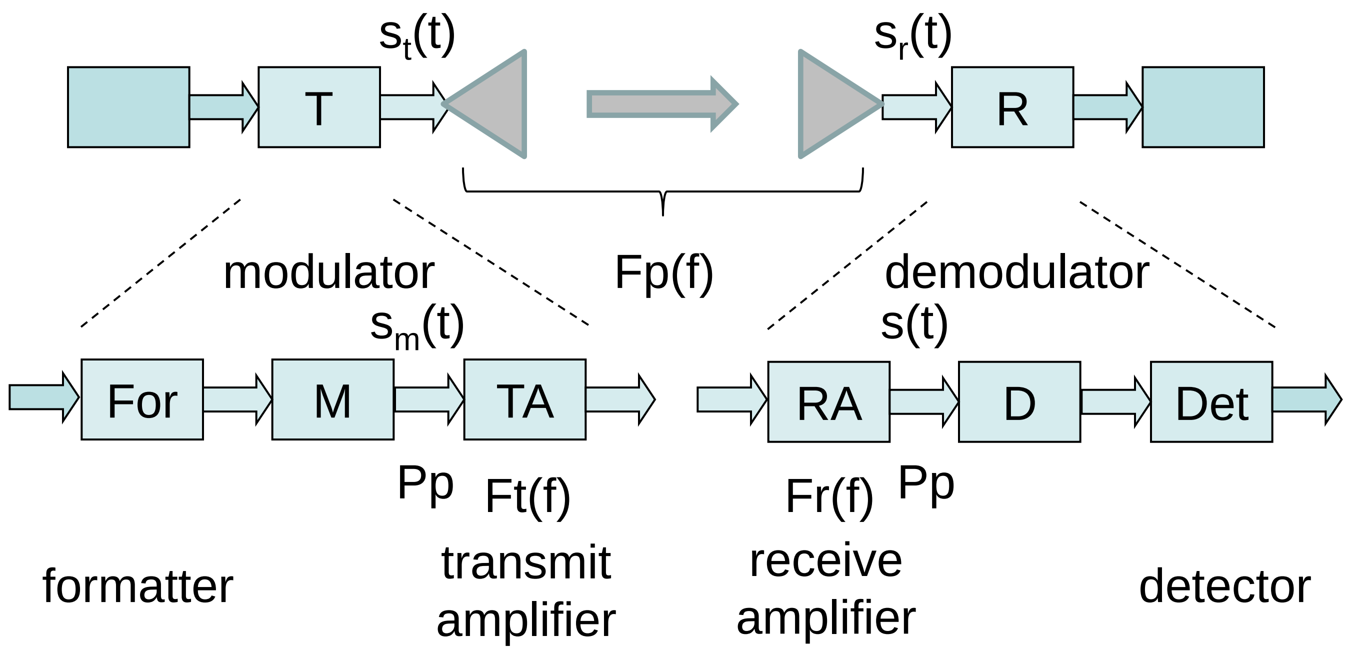
Conventional SNR:

SNRc = γ = Pr / No Rb = F * Eb /No

Eb av. received energy per bit
F Peak-Average Power Ratio

The two definitions of SNR differ by a factor F * Beq / Rb assumed to be known as well

System Model: BPSK



$D = 1 \quad L = 2$

$Bc = Rs\,(1 + \alpha)$

$Rs = Rb$

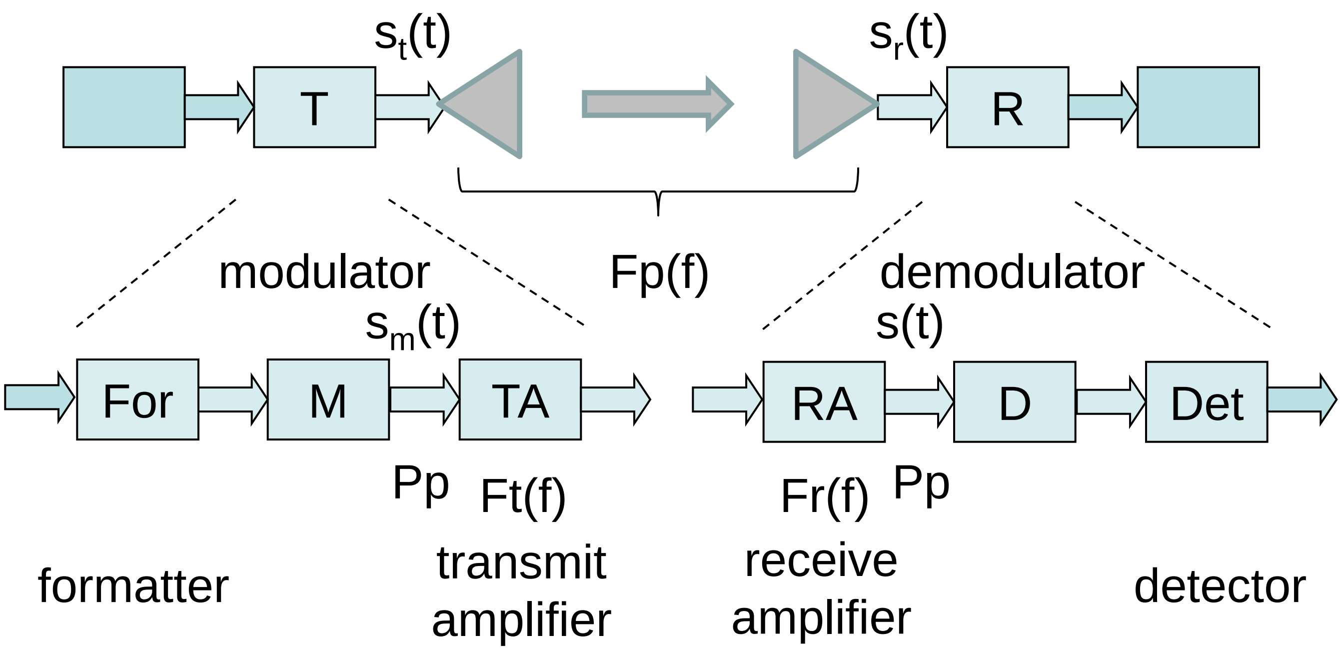
$\{a_n\}$ in $\{\pm 1\}$

$s_m(t) = V * v_p(t) * \cos(2\pi f_c t)$

$F = 1$

$v_p(t) = \Sigma\, a_n\, g(t - nT)$

System Model: M-QASK



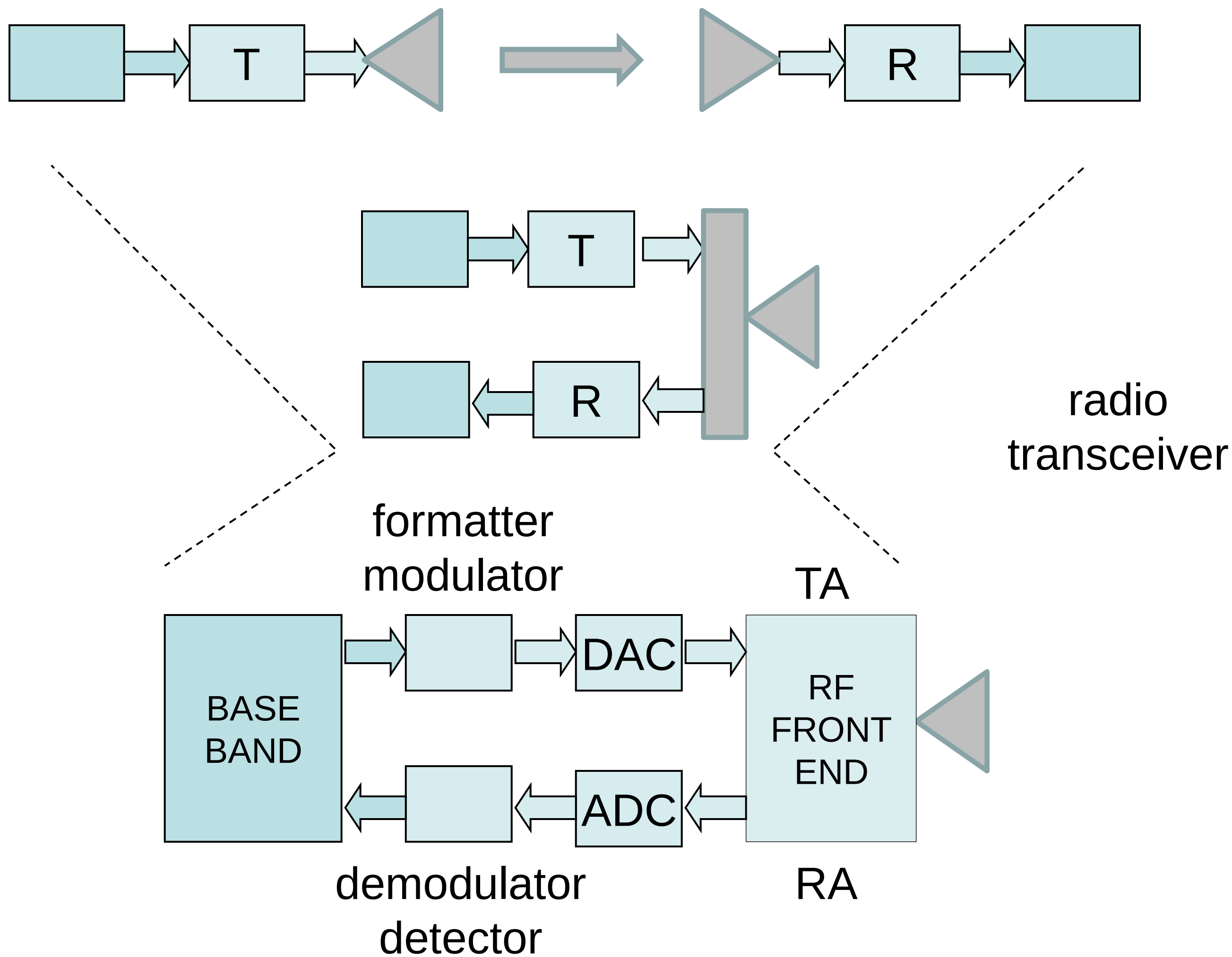
$D = 2 \quad L = 2, 4, 8, \ldots \quad M = L^2 = 4, 16, 64, \ldots \quad Bc = Rs\,(1 + \alpha)$

$Rs = Rb / 2 * \log_2(L) \quad \{a_{pn}\}, \{a_{qn}\} \text{ in } \{\pm\,(L-1); \ldots ; \pm\,3; \pm\,1\}$

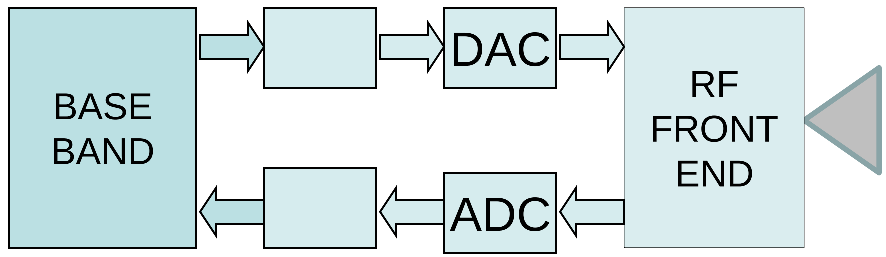
$s_m(t) = V * v_p(t) * \cos(2\pi f_c t) - V * v_q(t) * \sin(2\pi f_c t) \quad F = 3\,(L-1) / (L+1)$

$v_p(t) = \sum a_{pn}\, g(t - nT) \quad v_q(t) = \sum a_{qn}\, g(t - nT)$

System Model



System Model



The transceiver can be

Half Duplex	if transmitter and receiver can NOT work simultaneously
Full Duplex	if transmitter and receiver can work simultaneously

3. Signal Based Power Control

Signal Based Power Control (PC)

The transmit power Pt is set by the transmitter to a value in the range [Ptmin, Ptmax] adapted to the level of received power Pr. The larger is Pr, the lower is the next value of transmitted power Pt. PC is effective for flat channels.

Scope of PC:

- **reduction of energy consumed at transmitter**
- **reduction of e.m. radiation and impact on environment / humans**
- **reduction of interference towards other systems**

The control loop of PC includes:

1) measurement or estimation of Pr
2) decision on the next value of Pt
3) setting of the level of Pt

Signal Based Power Control (PC)

Open loop PC: estimation of Pr happens on the transmitter side, e.g. by measuring the received power on the reverse link and assuming link reciprocity. Loop delay is minimised.

Closed loop PC: estimation of Pr happens on the receiver side, through measurements, and PC commands are sent to the transmitter.
Loop delay depends on the transmission rate of PC commands.

Fast PC: changes in the level of Pt are made at a rate in the order of 10-1000 Hz.

Slow PC: changes in the level of Pt are made at a rate in the order of 0.1-1 Hz.

Signal Based Power Control (PC)

Full Compensation PC:

Pt is set in order to fully control variations of the channel gain.

→ The received power Pr is set to a specified target level, Pro, above or equal to receiver sensitivity

$$Pr = Pt * G = Pro \quad \rightarrow \quad Pt = Pro / G = Pro * A$$

Partial Compensation PC:

Pt is set in order to partially compensate the channel gain.

→ The received power Pr is not kept to a specified level

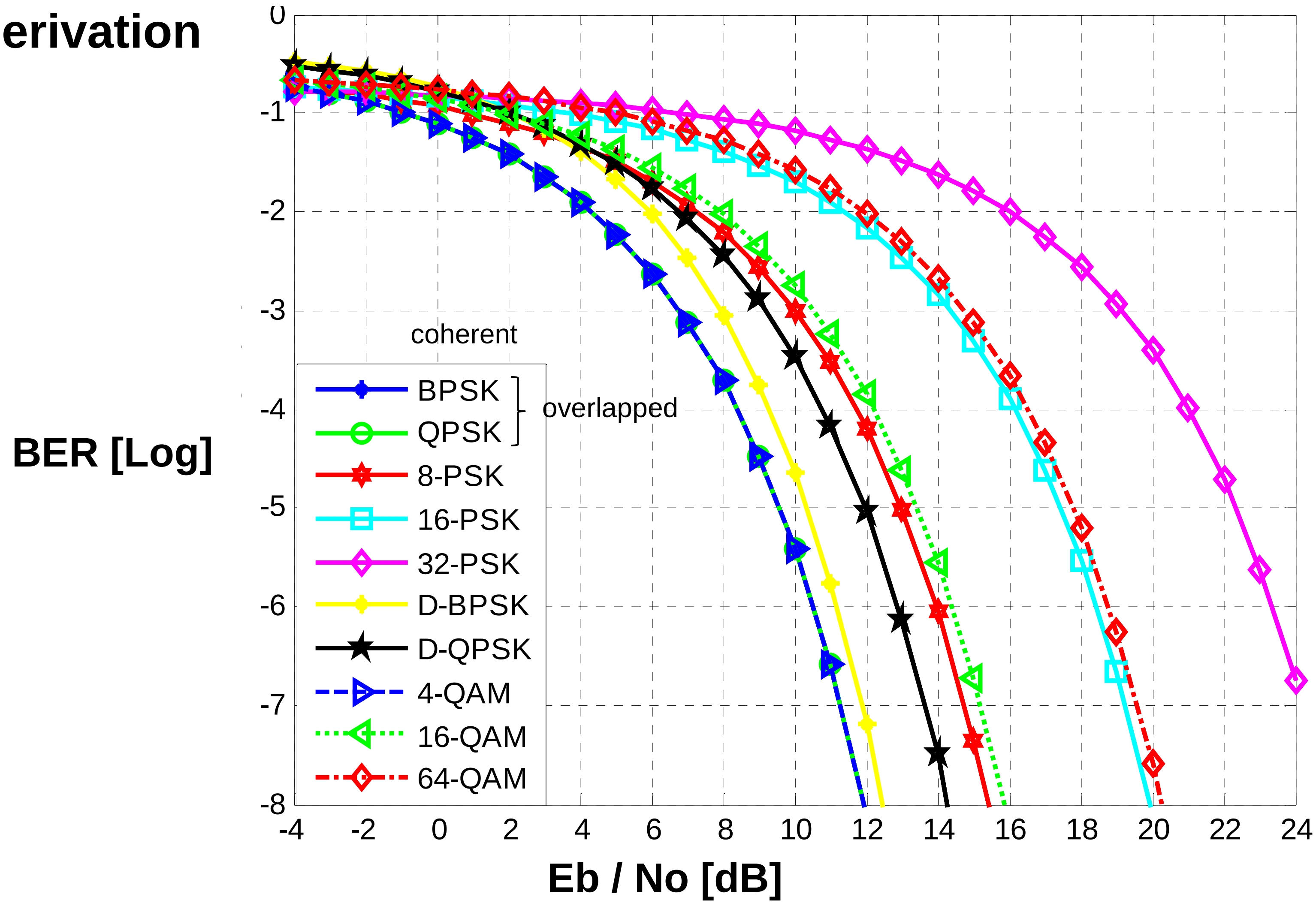
$$Pt = Prc * A^{\delta} \quad \rightarrow \quad Pr = Prc * A^{\delta - 1}$$

where $\delta < 1$ (e.g. $\delta = 0.5$, Half Compensation PC),
Prc is a reference value sufficiently above receiver sensitivity

4. Link Adaptation

Link Performance in AWGN

Mathematical derivation



Link Adaptation (LA)

The modulation format is adapted to the link quality. In noise limited systems, link quality is measured through the SNR. The higher the SNR is, the higher the modulation level implemented. If the error correction code is also adapted, the technique is known as Adaptive Modulation and Coding (AMC). The choice of a Modulation and Coding Scheme is denoted as MCS. LA is effective for flat channels.

Scope of LA:

- **achievement of maximum instantaneous throughput possible**

The control loop of LA includes:

1) measurement or estimation of Pr → SNR
2) decision on the next value of modulation / coding level
3) setting of the modulation / coding level

Link Adaptation (LA)

The user perception is that the user throughput varies with time (depending on variations of SNR).

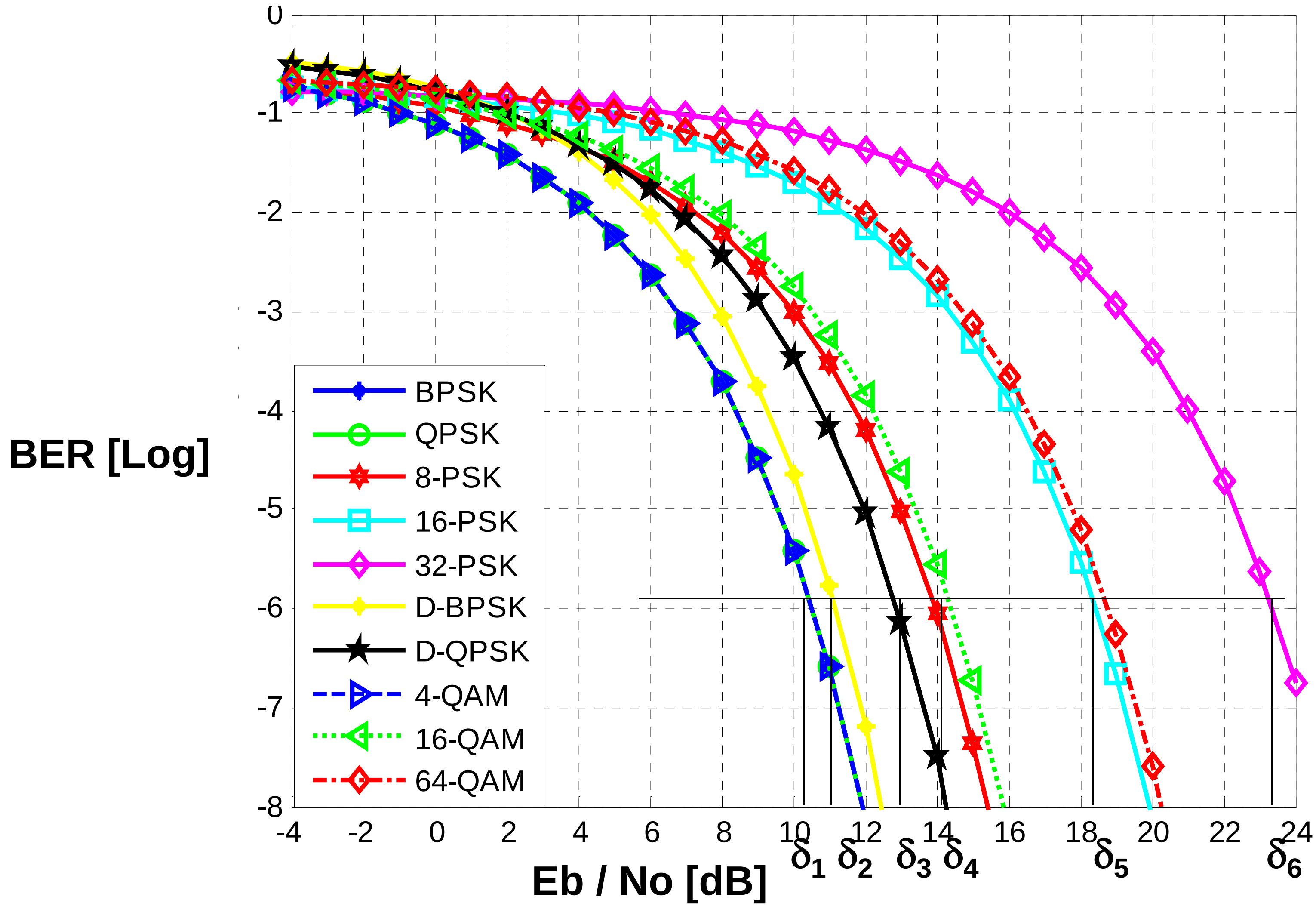
A programmable HW platform is needed at baseband.

LA is normally based on a closed loop, and adaptation is performed independently for each data block.

LA can be combined to PC.

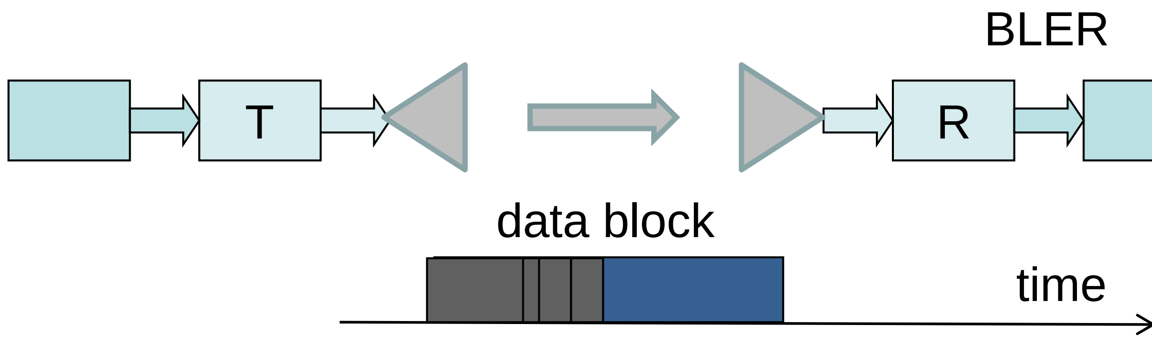
Link Adaptation (LA)

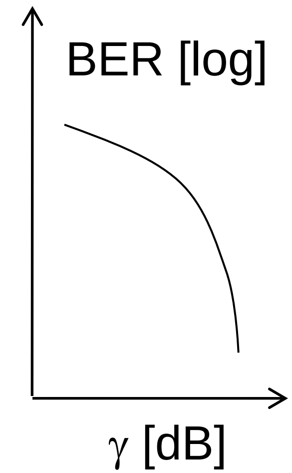
Example



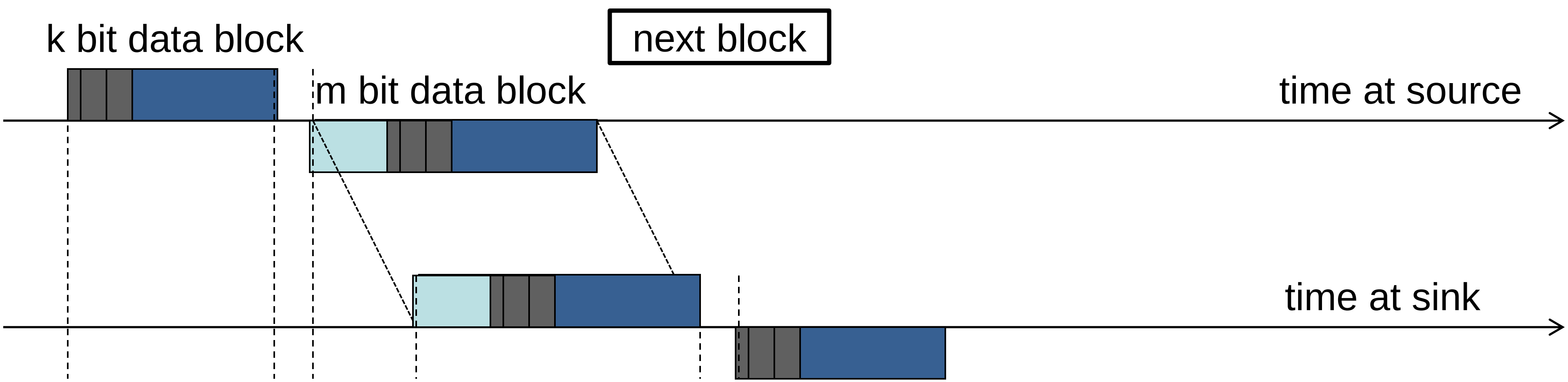
5. FEC, ARQ, HARQ

FEC, ARQ



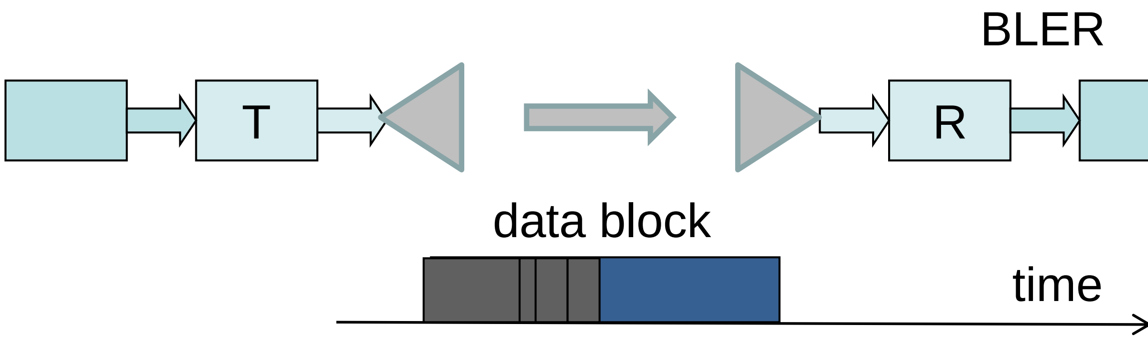


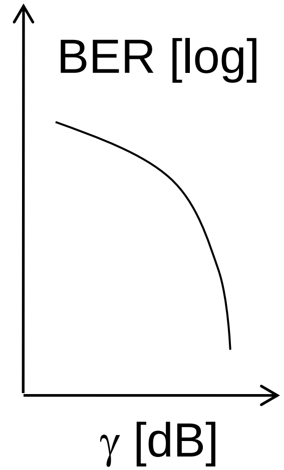
FEC: Forward Error Correction



up to t errors corrected; the smaller the **code rate Rcod = k/m**, the larger t

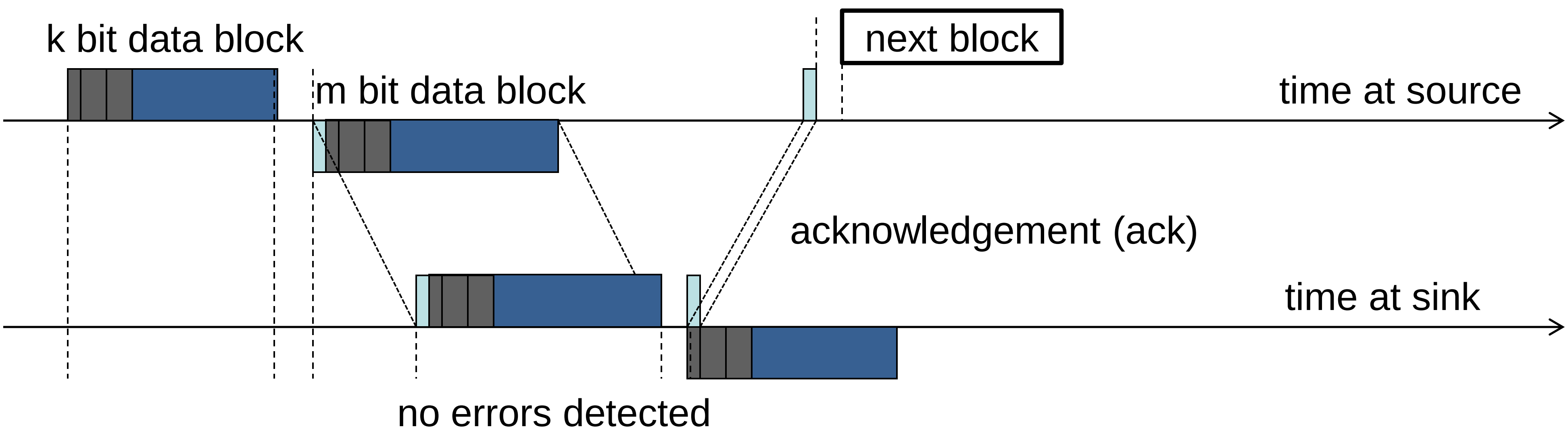
FEC, ARQ



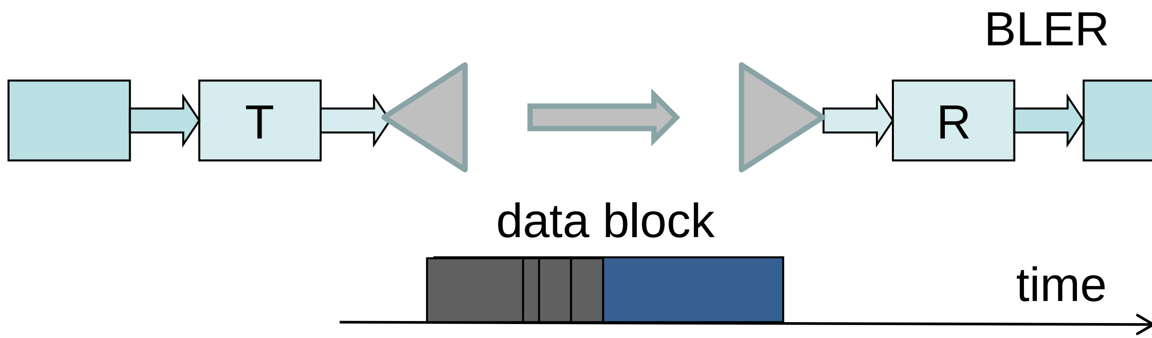


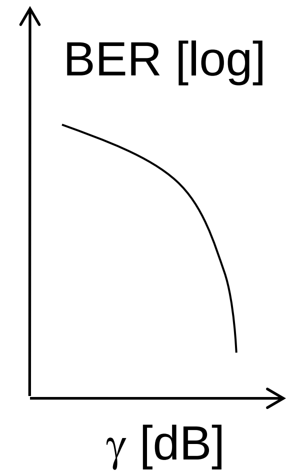
ARQ: Automatic Repeat Request

Stop and Wait



FEC, ARQ





ARQ: Automatic Repeat Request

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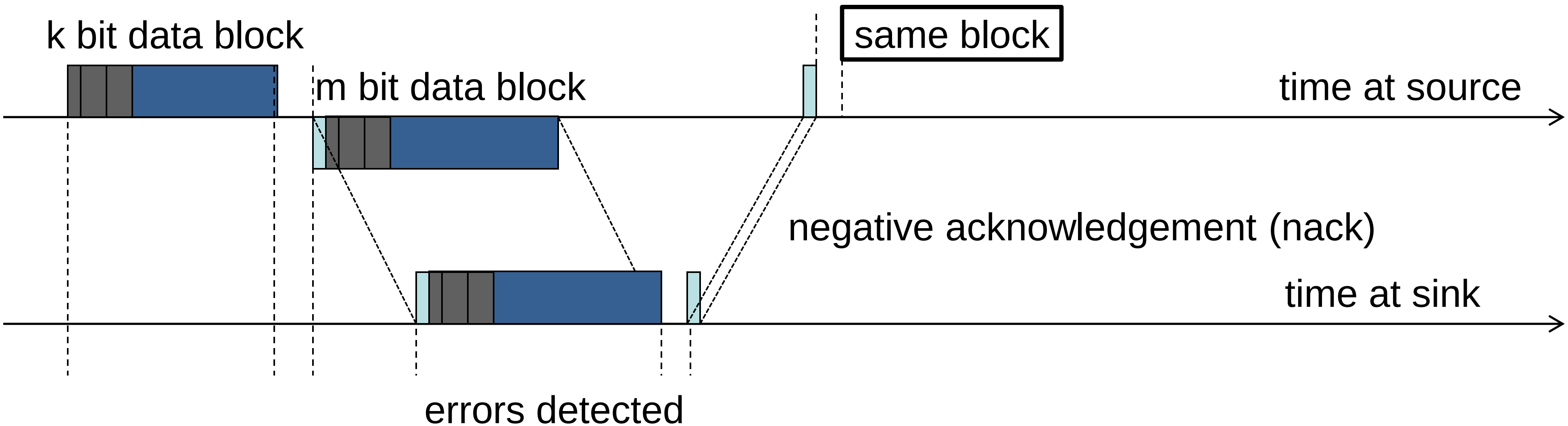
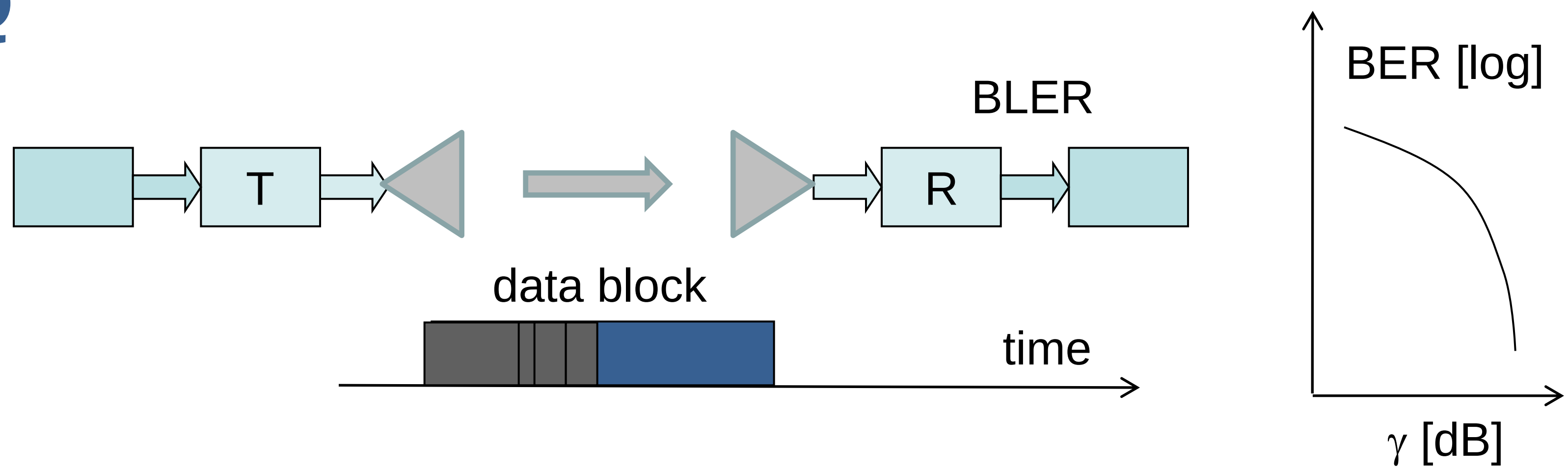
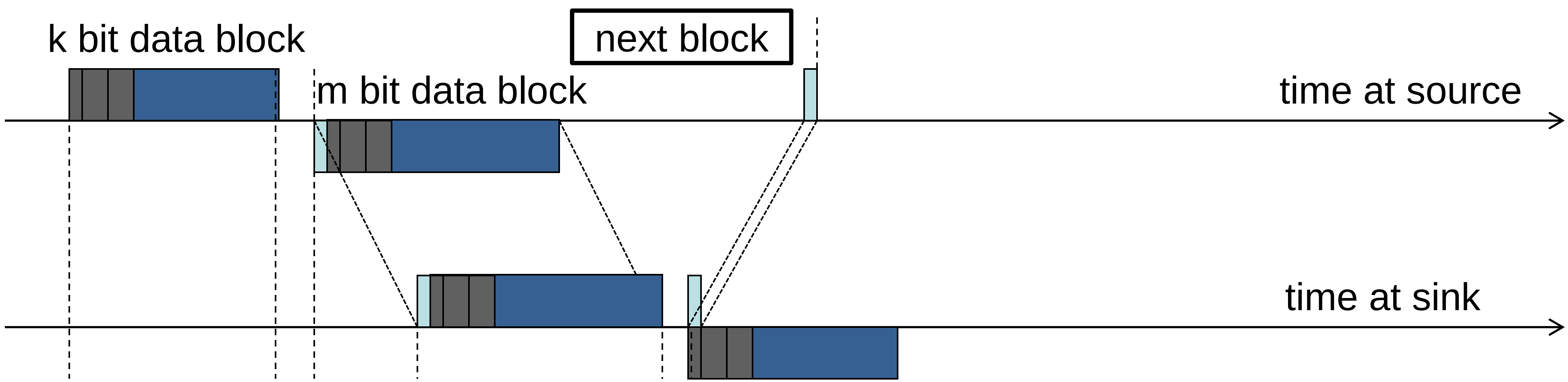


FEC, ARQ

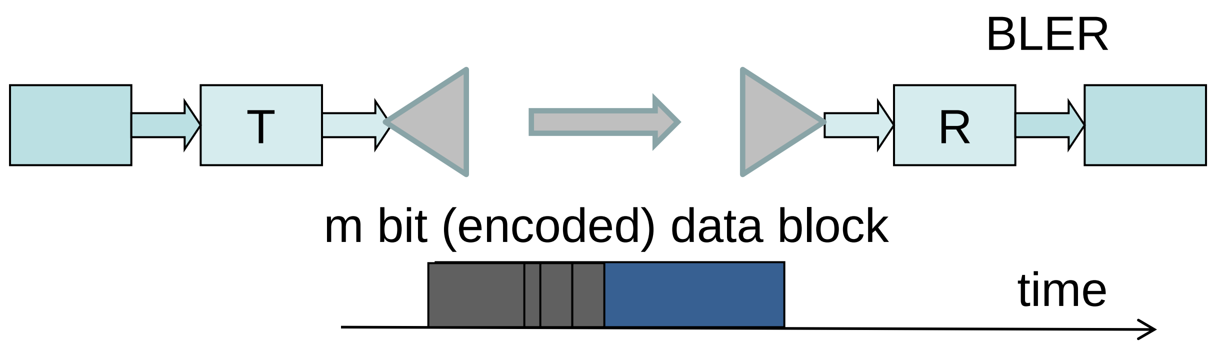


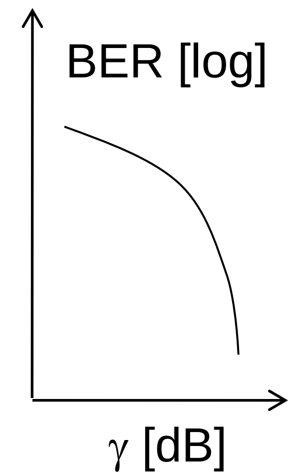
ARQ: Automatic Repeat Request

Go Back N



FEC, ARQ

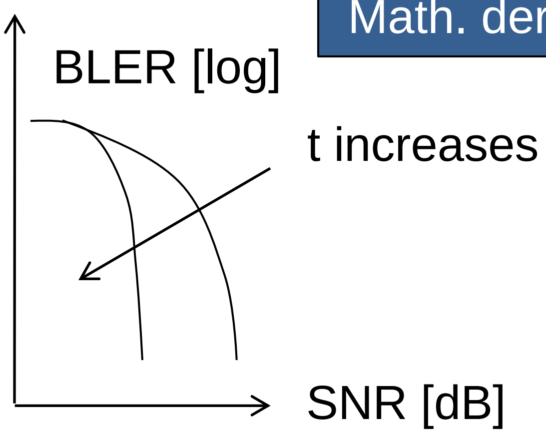




FEC: Forward Error Correction

BLER = f (BER, m, t)

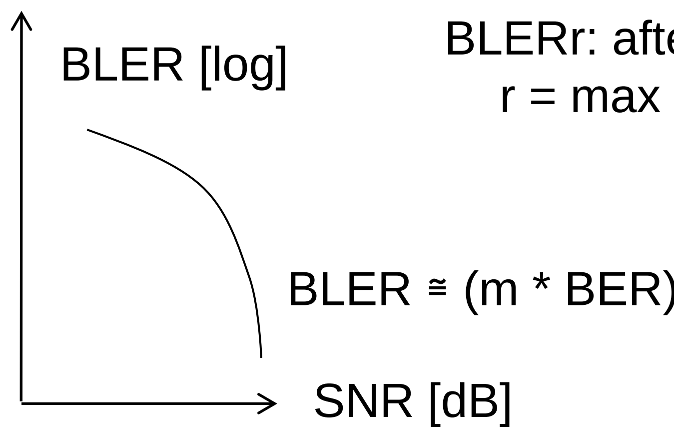
Math. derivation



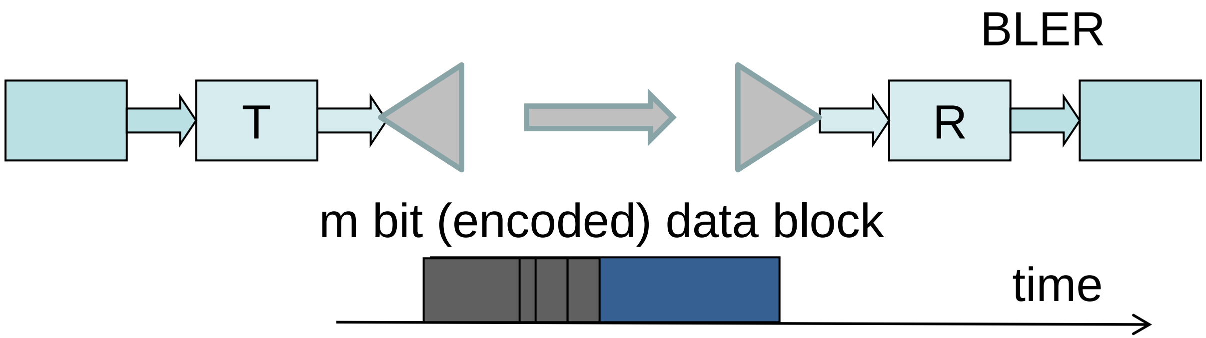
ARQ: Automatic Repeat Request

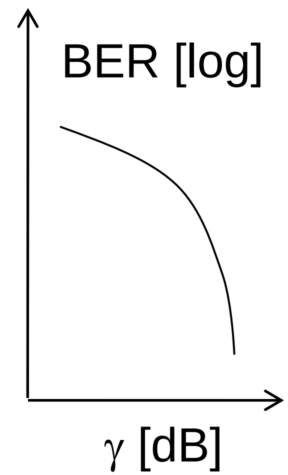
BLER = 1 – (1 – BER)^{m} **BLERr = BLER$^{(r+1)}$**

BLERr: after retransmissions
r = max n. of repetitions



HARQ

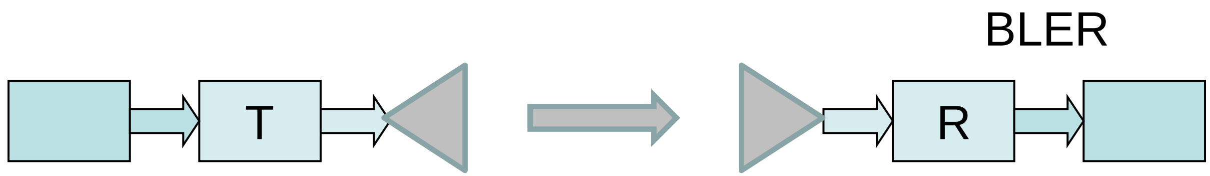


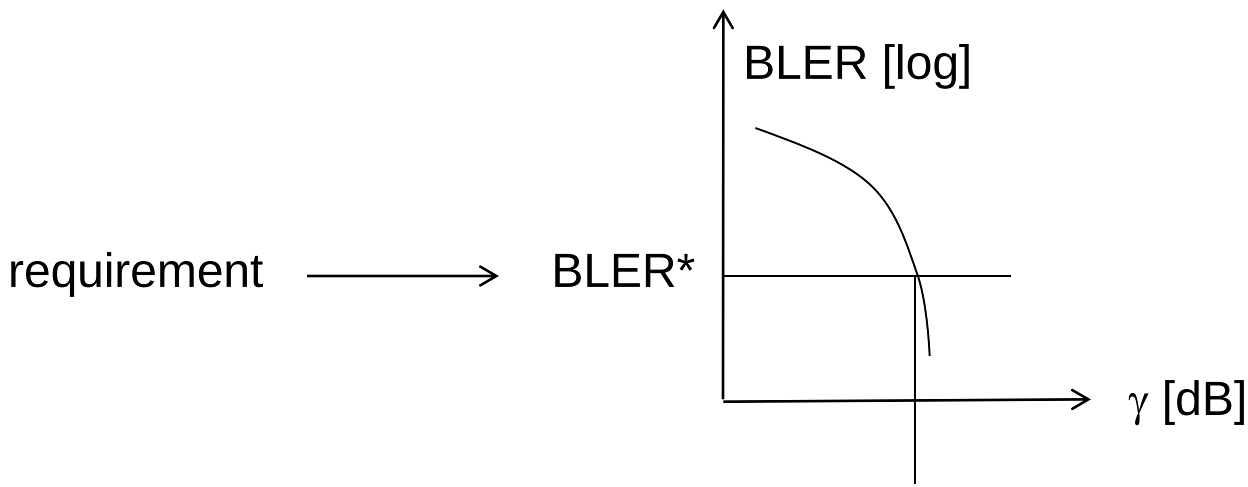


Type I, Type II, Type III

In case of retransmission, part of the information is kept from first transmission

Receiver Sensitivity



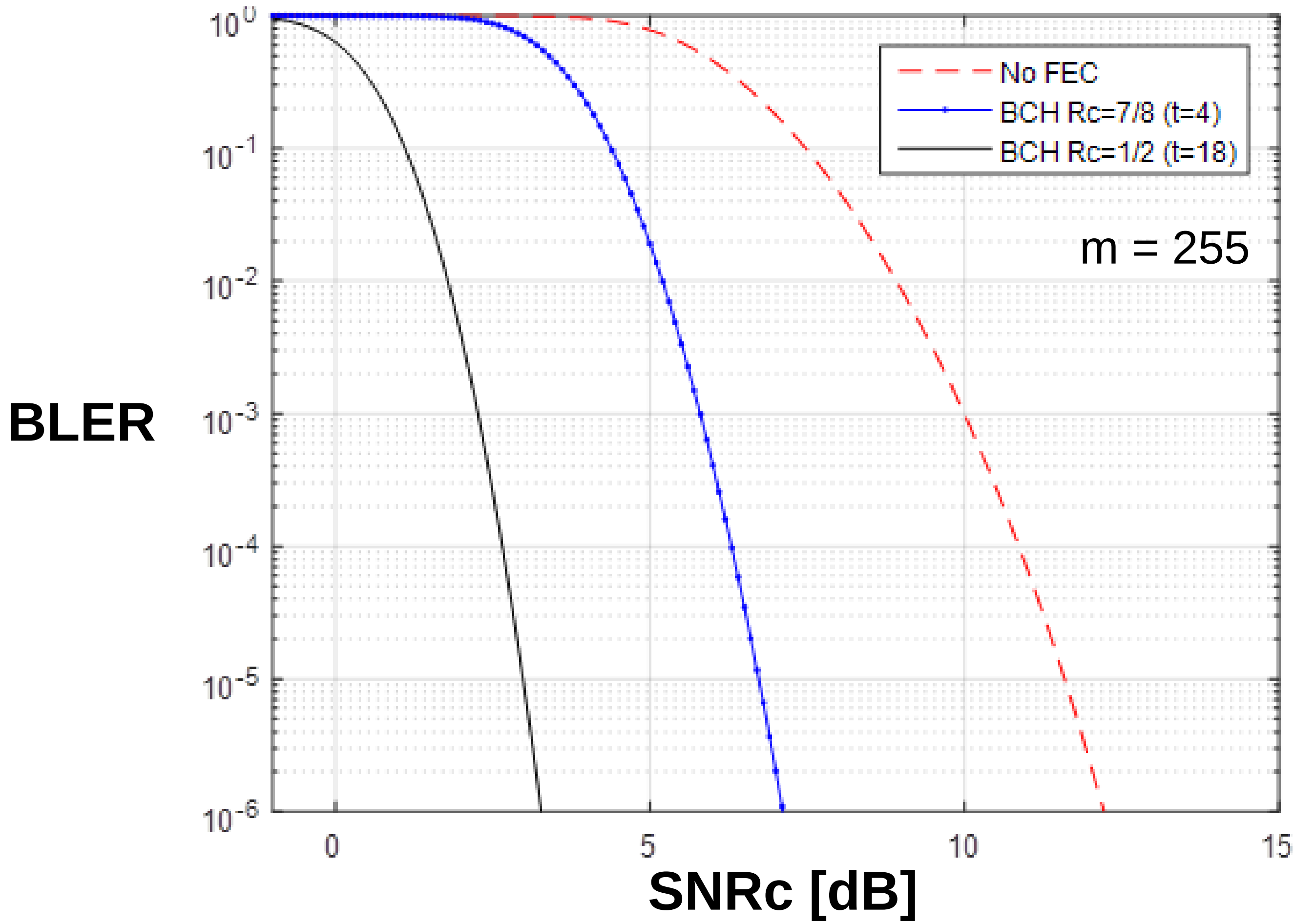


$\gamma^* = Prmin / No\ Rb \rightarrow Prmin = \gamma^*\ No\ Rb$

Prmin is denoted as **receiver sensitivity**

FEC, ARQ

Example: BCH FEC over QPSK Mathematical derivation



6. Exercises

Exercise TTN#1

A radio system uses QPSK over an AWGN channel with ARQ with up to three retransmissions. Data blocks have size of 255 bits. The bit rate is 54 Mbit/s. The channel bandwidth is 22 MHz, centred at carrier frequency 2.45 GHz. The (monolateral) noise density power is 10^{-20} W/Hz. Determine the receiver sensitivity [dBm] defined as the minimum received power ensuring BLER = 0.01.
Does it depend on the data block size?

The same system uses BCH FEC (with m = 255 and coderate 7/8) instead of ARQ. Determine the receiver sensitivity [dBm] defined as the minimum received power ensuring BLER = 0.01.
Does it depend on the data block size?

Exercise TTN#2

An access point covers a service area using 16-QASK over an AWGN channel with ARQ with up to two retransmissions. Data blocks have size of 10^4 bits. The bit rate is 11 Mbit/s. The channel bandwidth is 22 MHz, centred at carrier frequency 2.45 GHz. The (monolateral) noise density power is 10^{-20} W/Hz. The requested BLER is 0.001. Determine the maximum transmission range of the access point assuming free space conditions, omnidirectional antennas and transmit power 100 mW.

Exercise TTN#3

A node moves on a route of length 100 m from A to B while receiving data blocks from a transmitter. When in A, the channel gain is -60 dB. When in B, it is -100 dB. Moving from A to B, the channel gain decreases linearly. The transmitter uses full compensation PC; the allowed range of transmit power is [0 dBm; 20 dBm]. The target level of received power is -70 dBm, with the receiver sensitivity set at -75 dBm. Draw the level of transmit power as a function of the node location, from A to B. Draw the level of receive power as a function of the node location, from A to B. Determine the length of the route affected by receive power lower than receiver sensitivity (outage interval).

Exercise TTN#4

A base station covers an area transmitting a signal with transmit power equal to 33 dBm, and an omnidirectional antenna with gain 10 dB. The system uses LA; M-QASK is used, with symbols of L = 2, 4, or 8 levels. ARQ (up to two retransmissions) is used, and data blocks have size of 10000 bits. The required level of BLER is 0.001. The signal uses a channel bandwidth of 5 MHz. The roll-off factor of the raised cosine filters is 0.25. The noise spectral density is -170 dBW/Hz. Assume a node equipped with omnidirectional antenna with gain 0 dB moves radially from the base station towards an infinite distance. Draw a graph showing throughput as a function of distance. Assume free space loss.