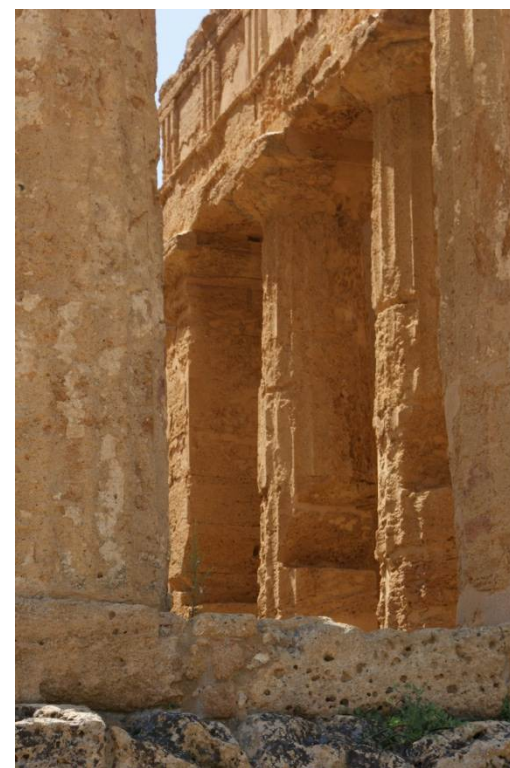


**DTN**

# Radio Networks

## Digital Transmission in Noise Limited Systems

**Roberto Verdone**  
[www.robertoverdone.org](http://www.robertoverdone.org)



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

# Outline

1. **System Model**
2. **Signal Based Power Control**
3. **Link Performance of M-QASK in AWGN**
4. **Link Adaptation**
5. **Equalisation**
6. **FEC, ARQ, HARQ**
7. **Link Performance and Capacity**
8. **Radio Resources**
9. **Assignment of Radio Resources**
10. **Exercises**

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

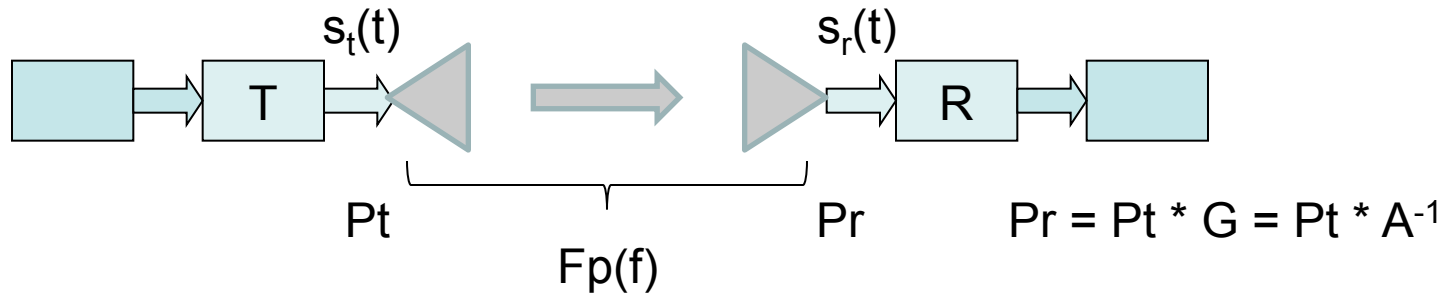
**The final target is to characterise the BLER as a function of SNR for a generic digital communication link.**

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# 1. System Model

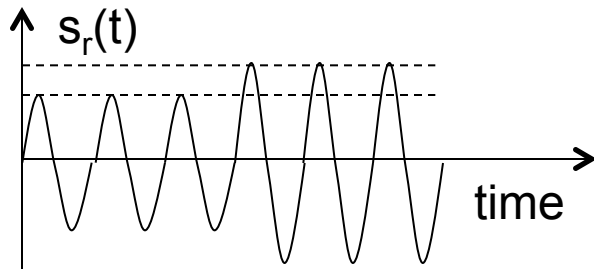
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# System Model



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

Channel Gain



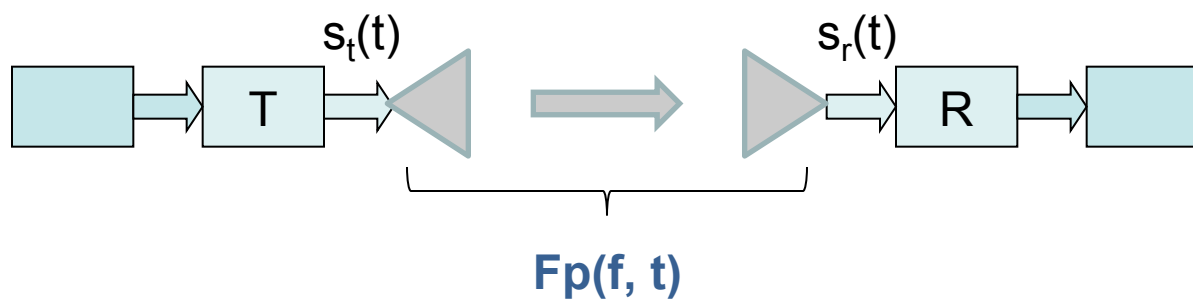
$P_t$                       peak transmit power

$P_r$                       peak receive power

The **Channel** can be

**Flat**                      if  $|F_p(f)|$  is constant over the entire band of the signal, of bandwidth  $B_c$   
**Distorting**              otherwise

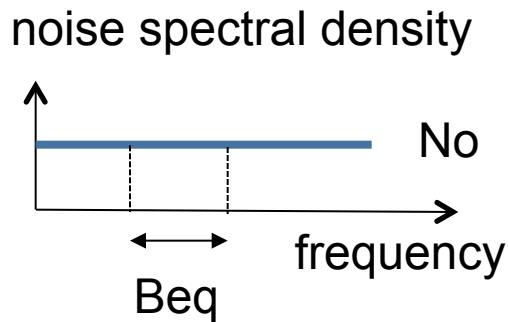
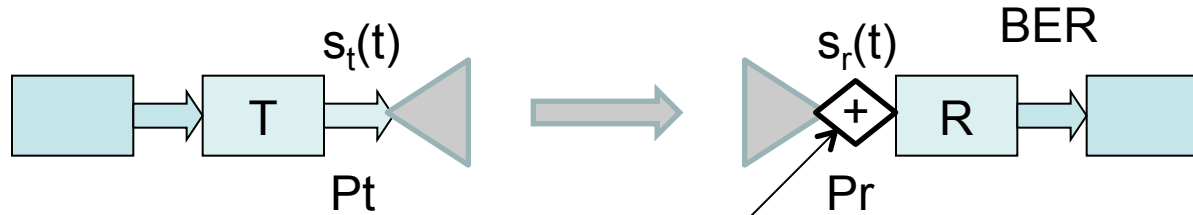
# System Model



$$F_p(f, t) \xleftrightarrow{\mathcal{F}} h(t, \tau)$$

**Linear Time Variant (LTV) Channel**

# System Model: AWGN



$v(t)$

$P_n = No B_{eq}$

$SNR_m = P_{rm} / P_n$

**Conventional SNR:**

$SNR_c = \gamma = P_r / No R_b = F * E_b / No$

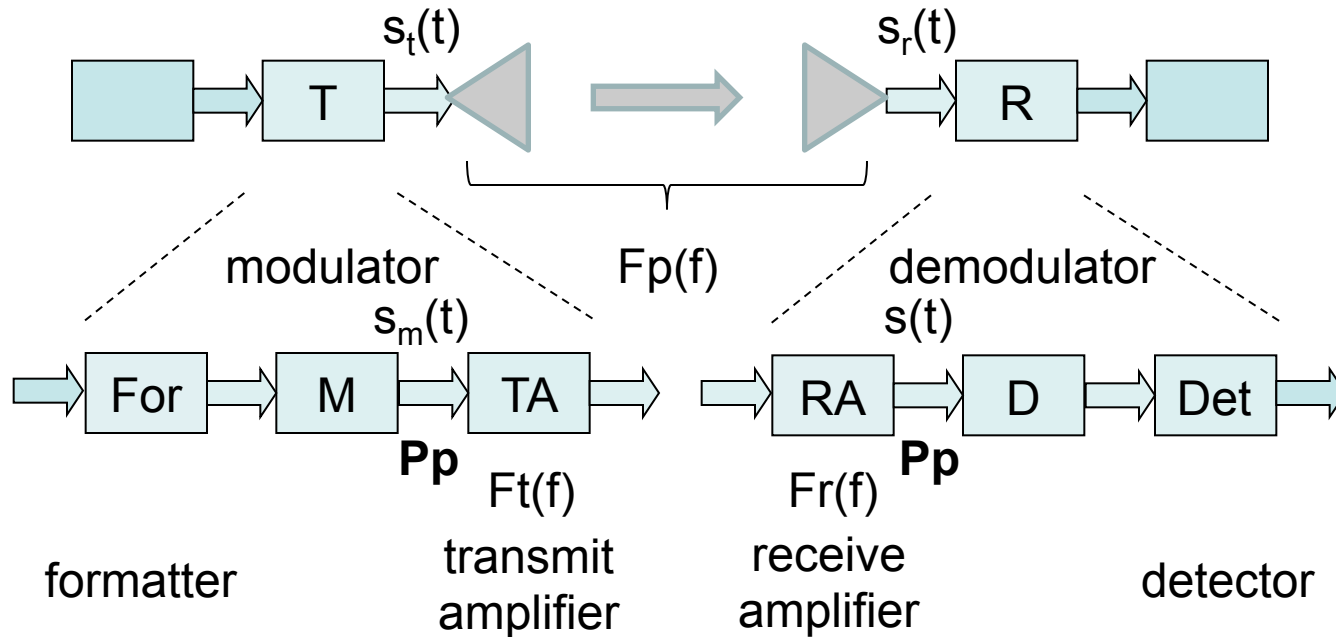
**In this course we will assume  $P_n$  is a value deterministically known:**

$P_{rm} \rightarrow SNR_m$

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

**The two definitions of SNR differ by a factor  $F * B_{eq} / R_b$  assumed to be known as well**

# System Model



$$R_b = 1 / T_b$$

$$R_s = 1 / T = R_b / D * \log_2(L)$$

$$\{a_n\} \text{ in } \{ \pm (L-1); \dots ; \pm 3; \pm 1 \}$$

$$L = 2, 4, 8, 16, \dots$$

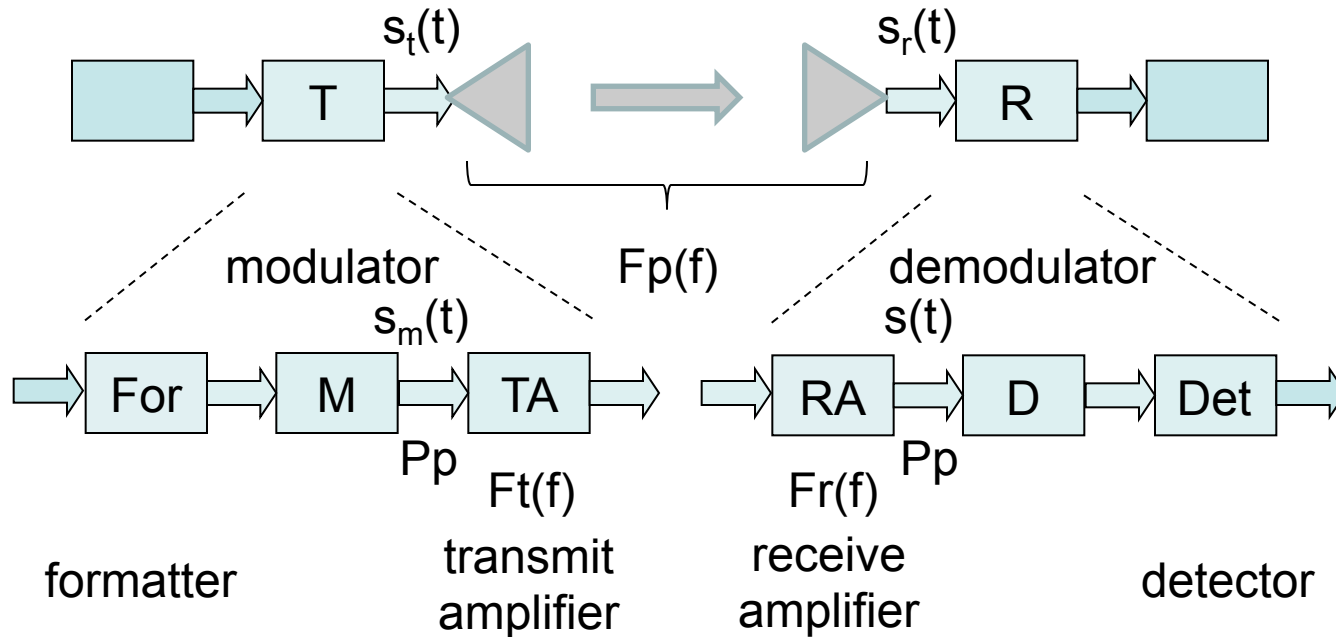
**Modulation** can be

**Linear** (e.g. BPSK, M-QASK, MSK, OFDM)

**Non Linear** (e.g. GMSK)

**$P_p$ : peak power**

# System Model: BPSK



$$D = 1 \quad L = 2$$

$$R_s = R_b$$

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

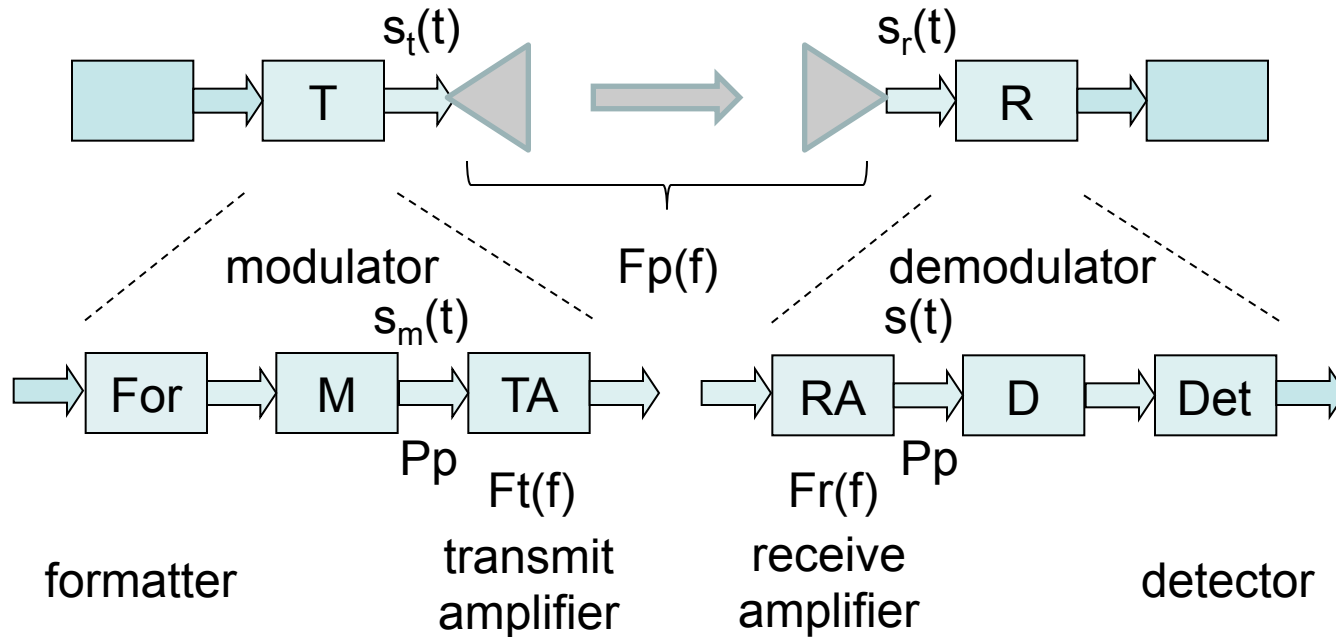
$$s_m(t) = V * v_p(t) * \cos(2\pi f_c t)$$

$$F = 1$$

$$v_p(t) = \sum a_n g(t - nT)$$



# System Model: M-QASK



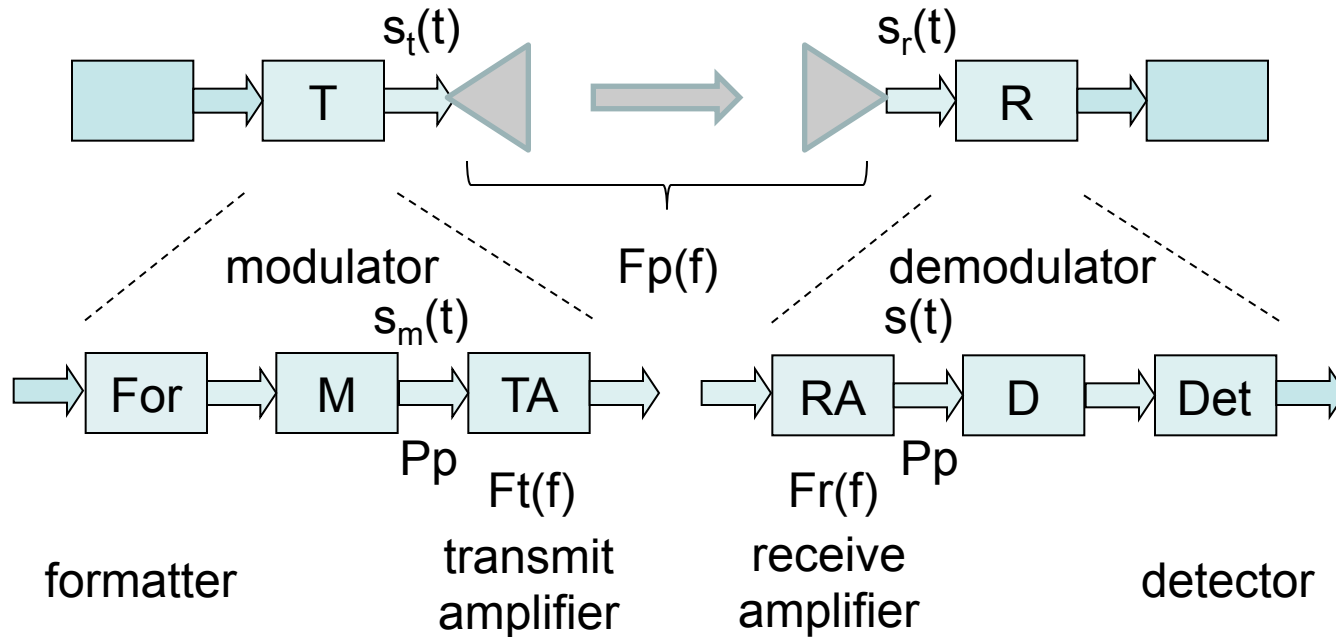
$$D = 2 \quad L = 2, 4, 8, \dots \quad M = L^2 = 4, 16, 64, \dots$$

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

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

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

# System Model

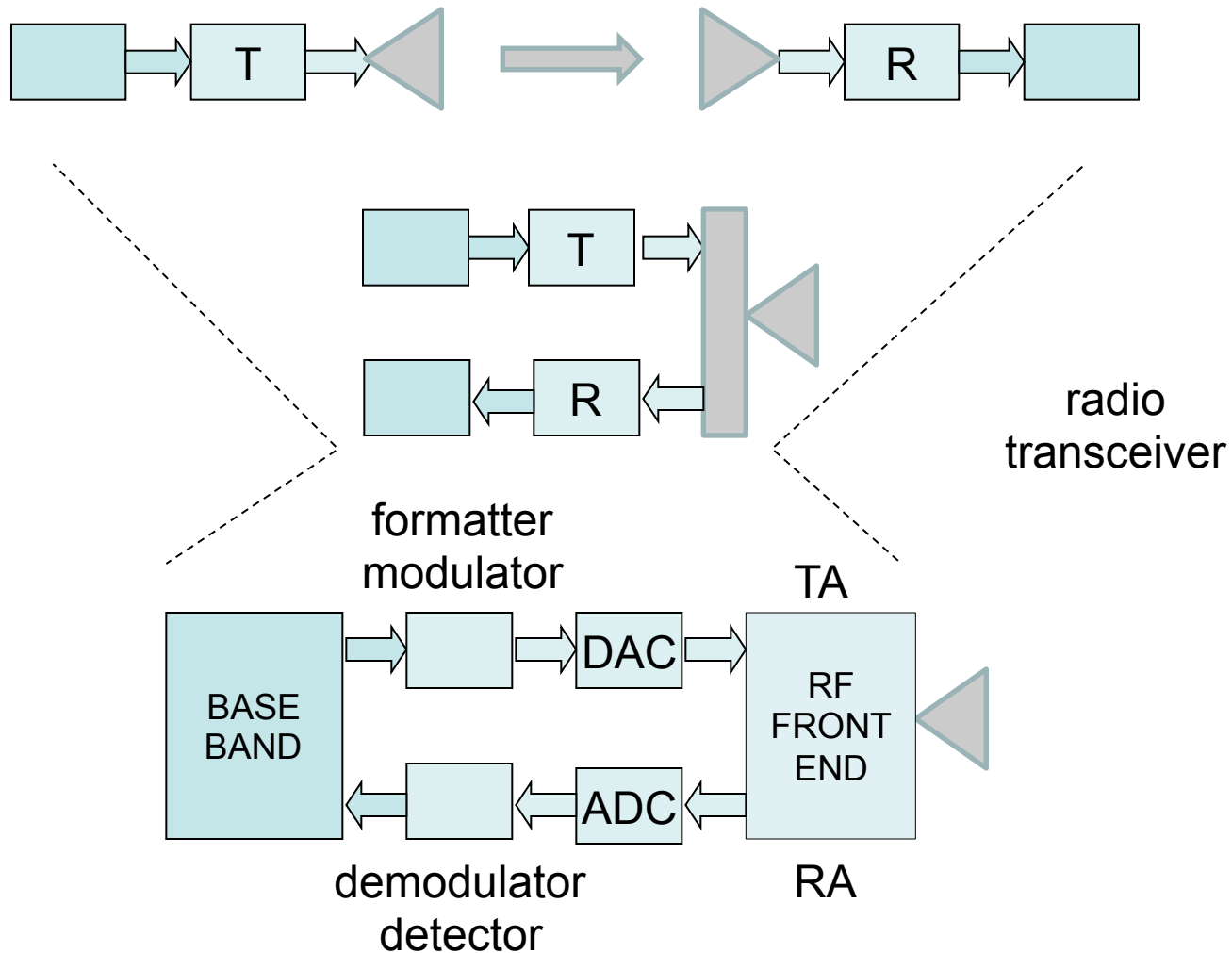


**Demodulation can be**

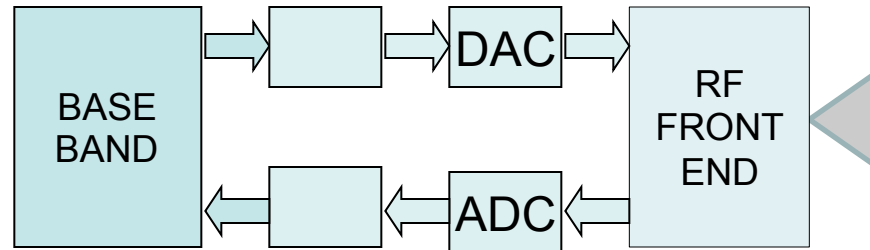
**Linear** (normally used for linear modulated signals like BPSK, M-QASK, MSK)

**Non Linear** (normally used for phase or frequency modulated signals like GMSK)

# 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

## 2. Signal Based Power Control

---

## Signal Based Power Control (PC)

The transmit power  $P_t$  is set by the transmitter to a value in the range  $[P_{tmin}, P_{tmax}]$  adapted to the level of received power  $P_r$ . The larger is  $P_r$ , the lower is the next value of transmitted power  $P_t$ . 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  $P_r$
  - 2) decision on the next value of  $P_t$
  - 3) setting of the level of  $P_t$
-

## Signal Based Power Control (PC)

**Open loop PC:** estimation of  $P_r$  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  $P_r$  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  $P_t$  are made at a rate in the order of 10-1000 Hz.

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

---

## Signal Based Power Control (PC)

### Full Compensation PC:

**P<sub>t</sub>** is set in order to fully control variations of the channel gain.

→ The received power **P<sub>r</sub>** is set to a specified target level, **P<sub>ro</sub>**, above or equal to receiver sensitivity

$$P_r = P_t * G = P_{ro} \quad \rightarrow \quad P_t = P_{ro} / G = P_{ro} * A$$

### Partial Compensation PC:

**P<sub>t</sub>** is set in order to partially compensate the channel gain.

→ The received power **P<sub>r</sub>** is not kept to a specified level

$$P_t = P_{rc} * A^\delta \quad \rightarrow \quad P_r = P_{rc} * A^{\delta-1}$$

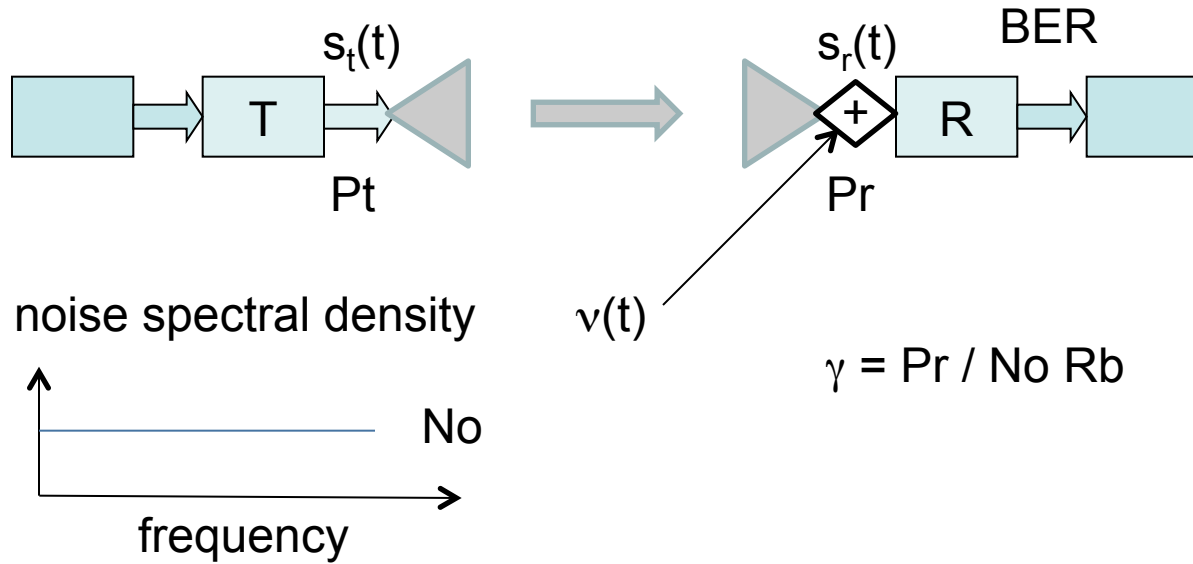
where  $\delta < 1$  (e.g.  $\delta = 0.5$ , Half Compensation PC),

**P<sub>rc</sub>** is a reference value sufficiently above receiver sensitivity

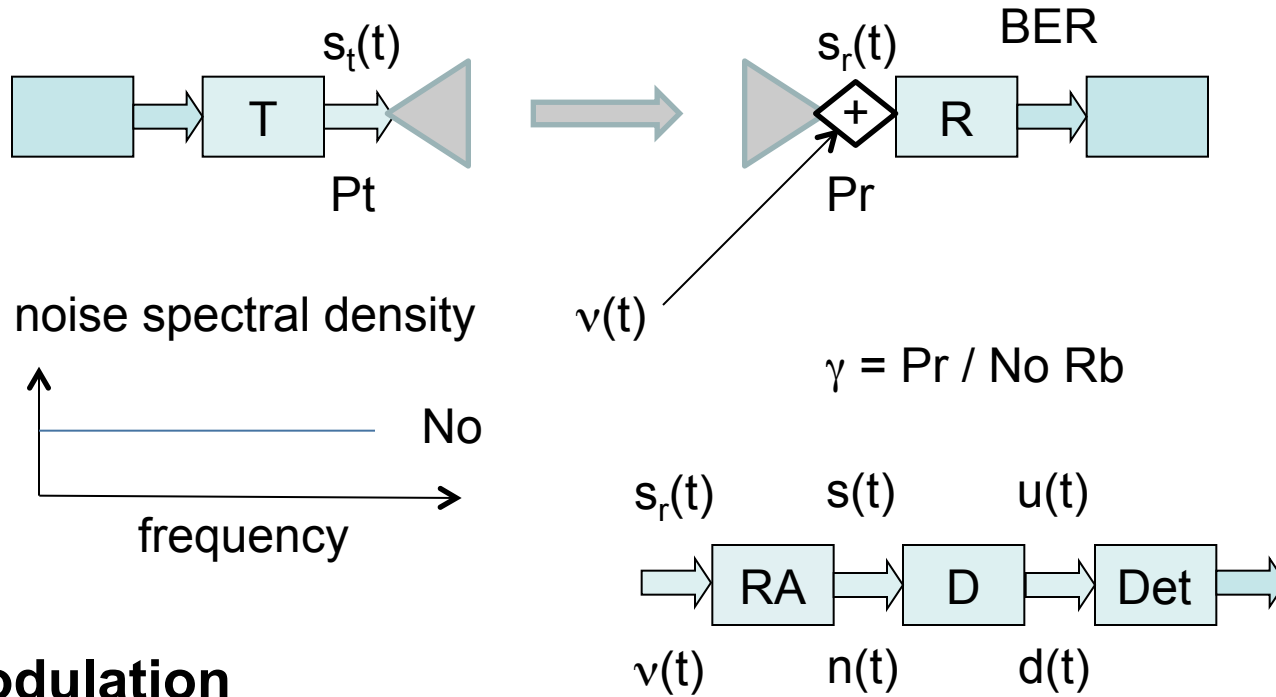


# 3. Link Performance: M-QASK in AWGN

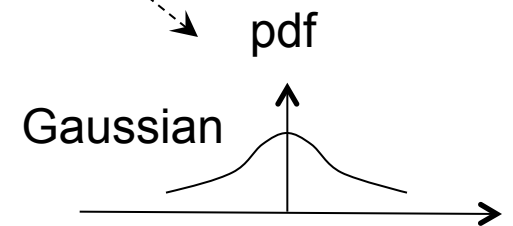
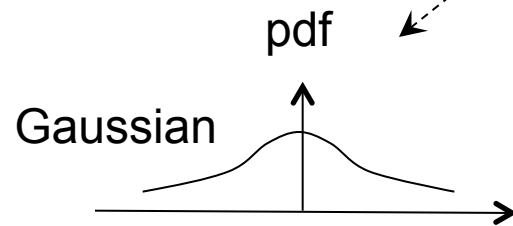
# Link Performance in AWGN



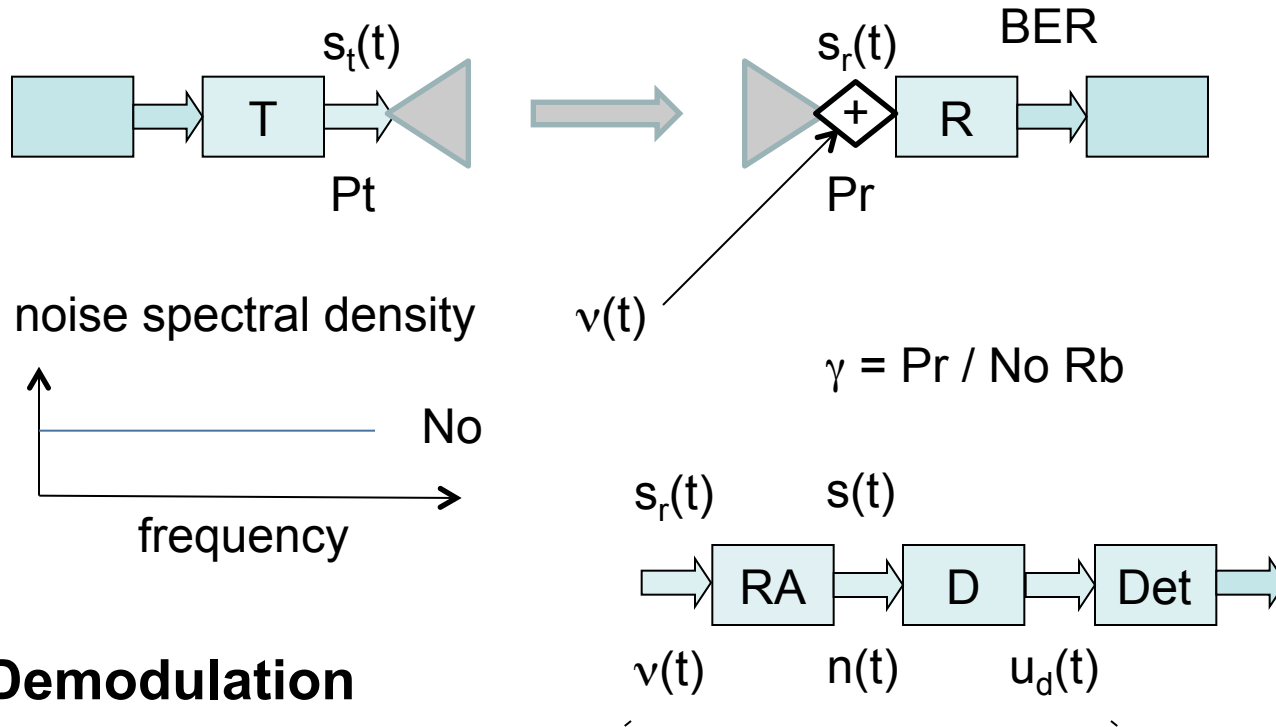
# Link Performance in AWGN



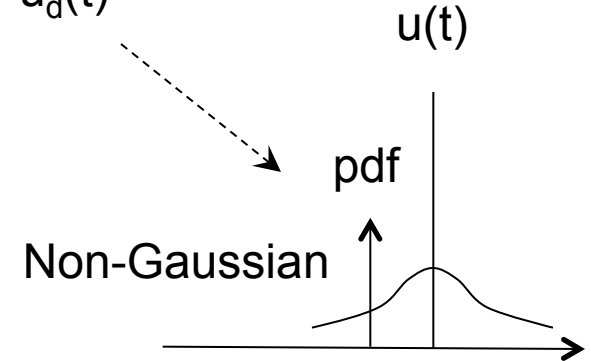
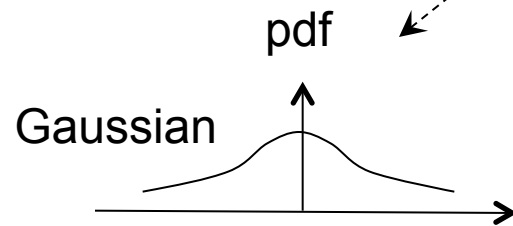
## Linear Demodulation



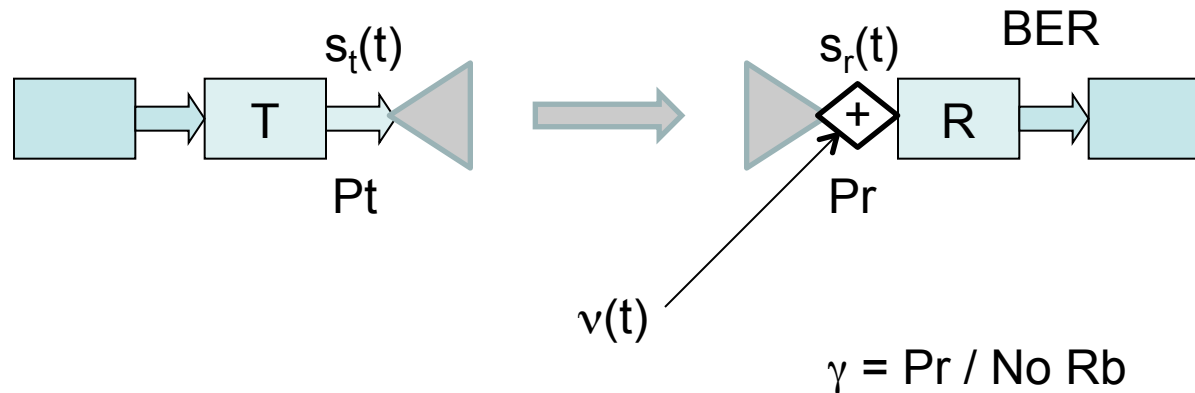
# Link Performance in AWGN



## Non Linear Demodulation



# Link Performance of M-QASK in AWGN

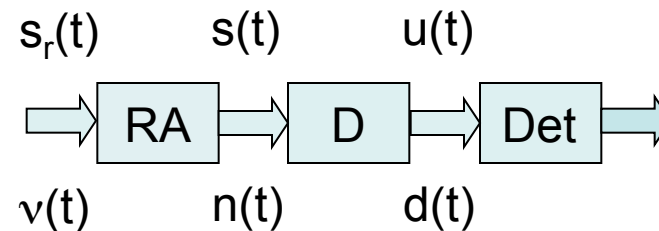


$$s_m(t) = V * v_p(t) * \cos(2\pi f_c t) - V * v_q(t) * \sin(2\pi f_c t) \quad F = 3(L-1) / (L+1)$$

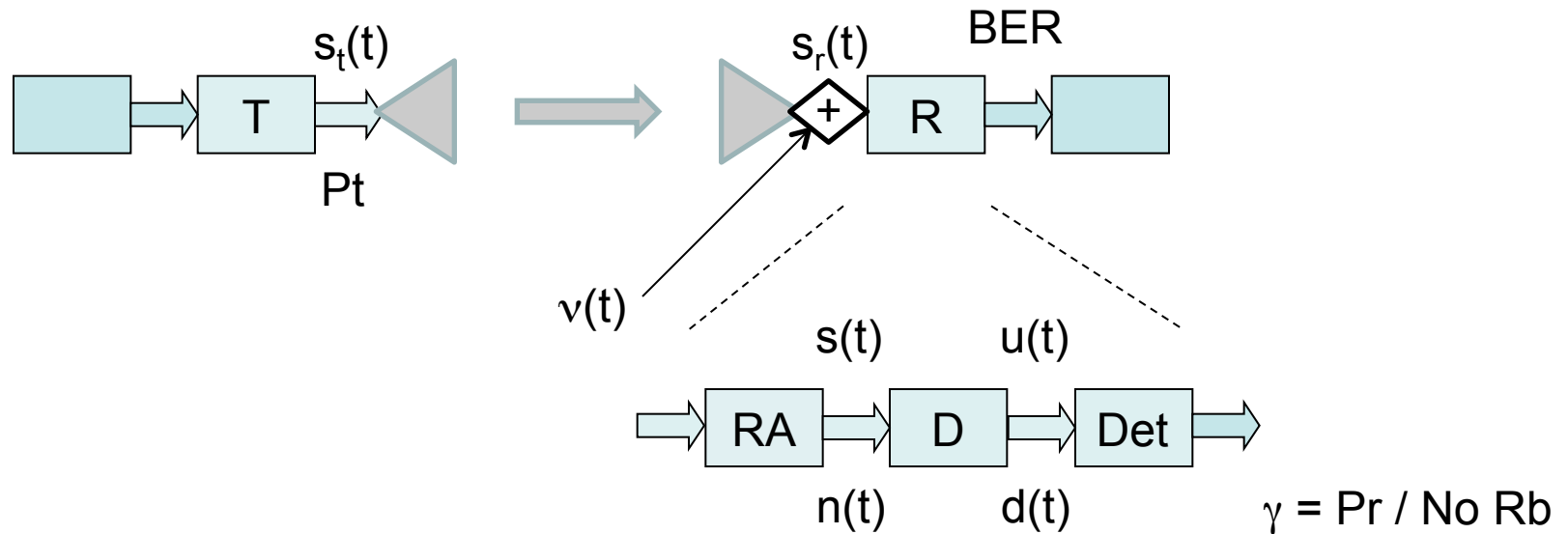
$$v_p(t) = \sum a_{pn} g(t - nT) \quad v_q(t) = \sum a_{qn} g(t - nT)$$

The L-level symbols are split on two parallel flows, each of rate  $R_s / 2$   
 $M = L^2$

**Demodulation is linear**



# Link Performance of M-QASK in AWGN



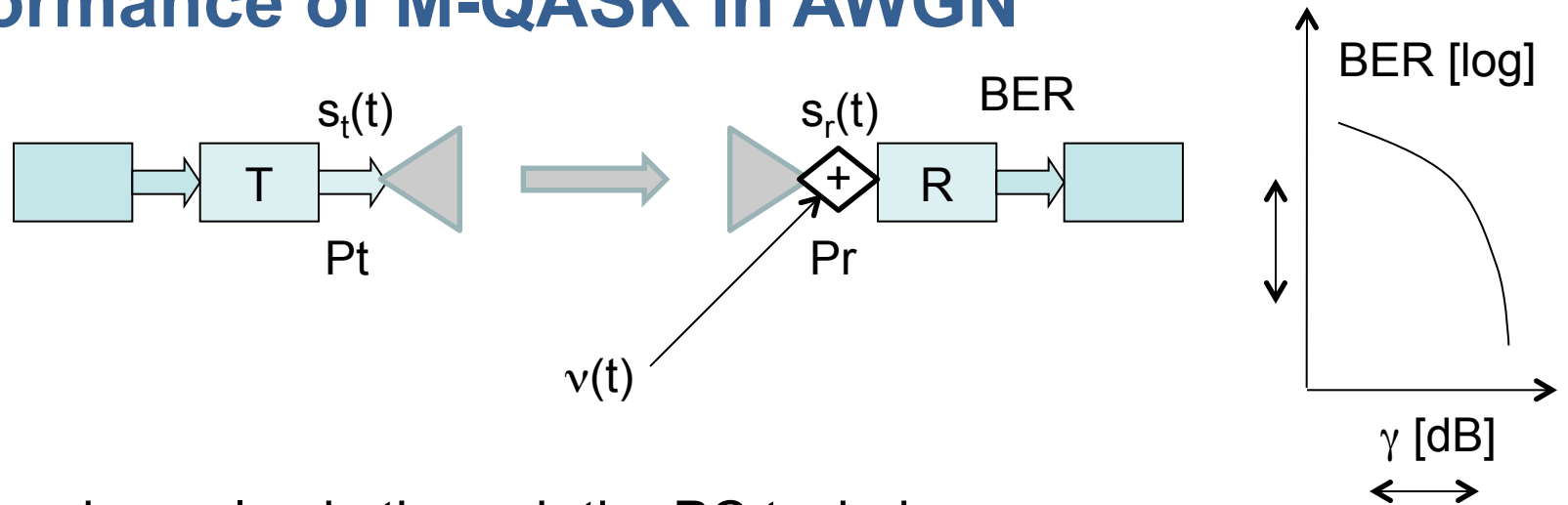
Assumptions: perfect frequency synchronisation (coherent detection)  
 perfect time synchronisation  
 no inter-symbol interference  
 matched filter at the receiver  
 Gray encoding

Math. derivation

$$\rightarrow \text{BER} = \left[ \frac{L-1}{L \log_2(L)} \right] \text{erfc} \left( \sqrt{\gamma \log_2(L) / (L-1)^2} \right)$$

$$L = \sqrt{M}$$

# Link Performance of M-QASK in AWGN



$P_r$  depends on channel gain through the PC technique:

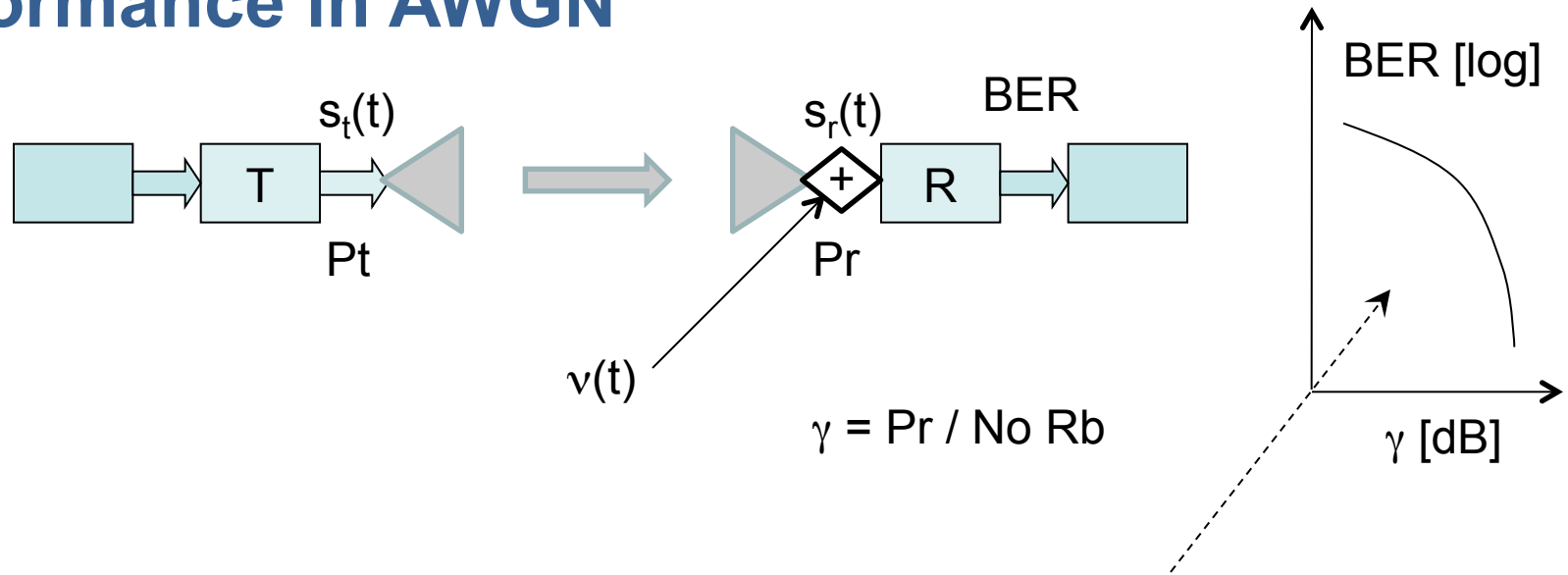
FC-PC:	$\gamma = P_{ro} / N_0 R_b$	constant
PC-PC:	$\gamma = P_{rc} / N_0 R_b A^{1-\delta}$	variable
No PC:	$\gamma = P_t / N_0 R_b A$	variable

$$\gamma = P_r / N_0 R_b$$

The expression of BER does not depend on PC. The SNR does.

Coherent M-QASK	$BER = [(L-1)/(L \log_2(L))] \operatorname{erfc}(\sqrt{[\gamma \log_2(L) / (L-1)^2]})$	$L = \sqrt{M}$
-----------------	--	----------------

# Link Performance in AWGN



**We will assume it is known**

Reference Systems:

Coherent BPSK

$$\text{BER} = 0.5 \operatorname{erfc}(\sqrt{\gamma})$$

Coherent QPSK

$$\text{BER} = 0.5 \operatorname{erfc}(\sqrt{\gamma})$$

Coherent M-QASK

$$\text{BER} = \left[ \frac{L-1}{L \log_2(L)} \right] \operatorname{erfc}(\sqrt{[\gamma \log_2(L) / (L-1)^2]})$$

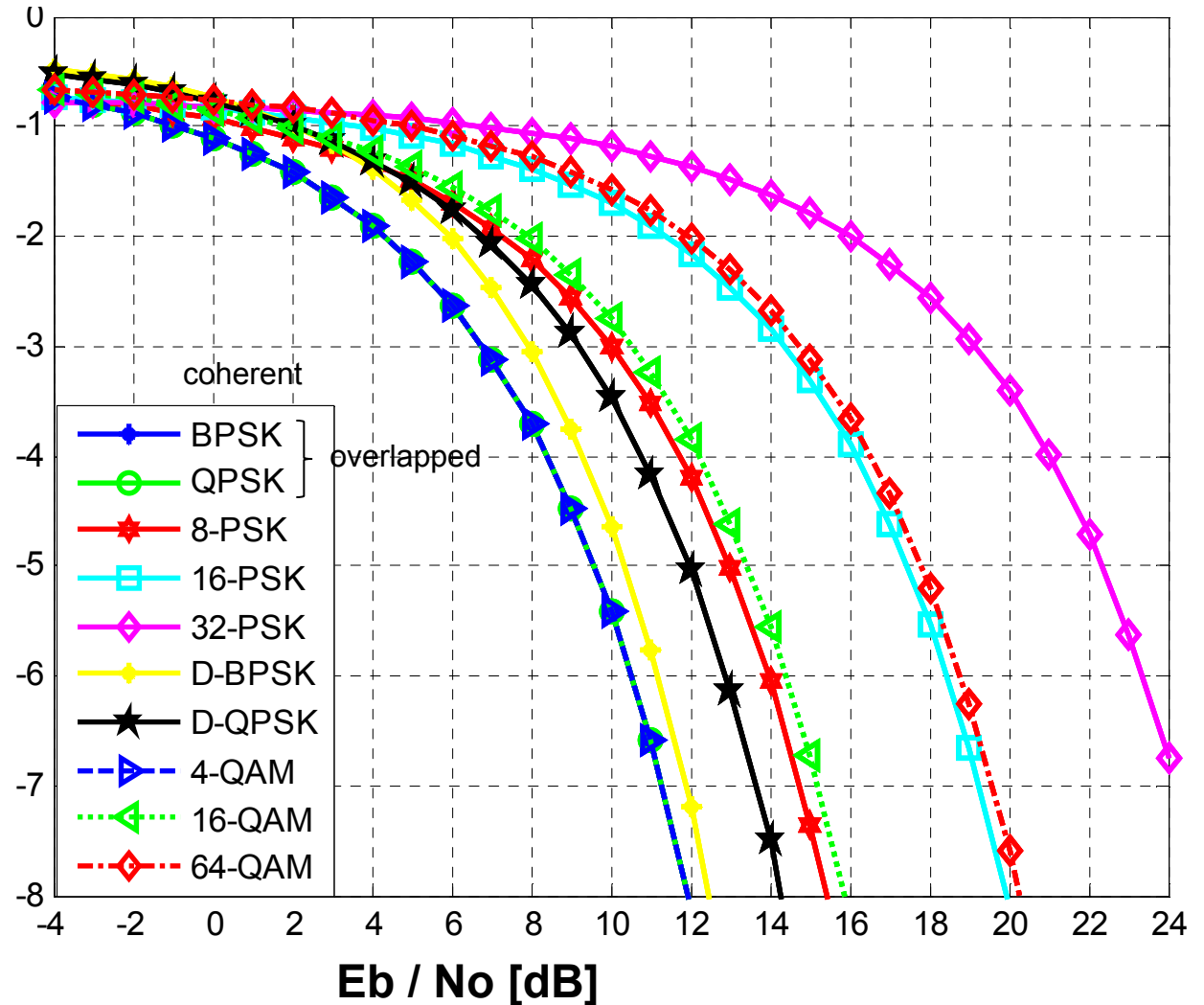
$$L = \sqrt{M}$$



# Link Performance in AWGN

## Mathematical derivation

BER [Log]



# 4. Link Adaptation

---

## 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  $P_r \rightarrow \text{SNR}$
  - 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.**

---



# 5. Equalisation

---

# Equalisation

The receive amplifier filters the received signal by adapting its transfer function  $F_r(f)$  to the Channel Impulse Response,  $h(\tau)$ , which represents the Channel State Information (CSI) needed to avoid signal distortion.

## Scope of Equalisation:

- correction of distorting effects introduced by the channel

The CSI is extracted by the receiver using a training sequence of known symbols (e.g. transmitted within the data block).

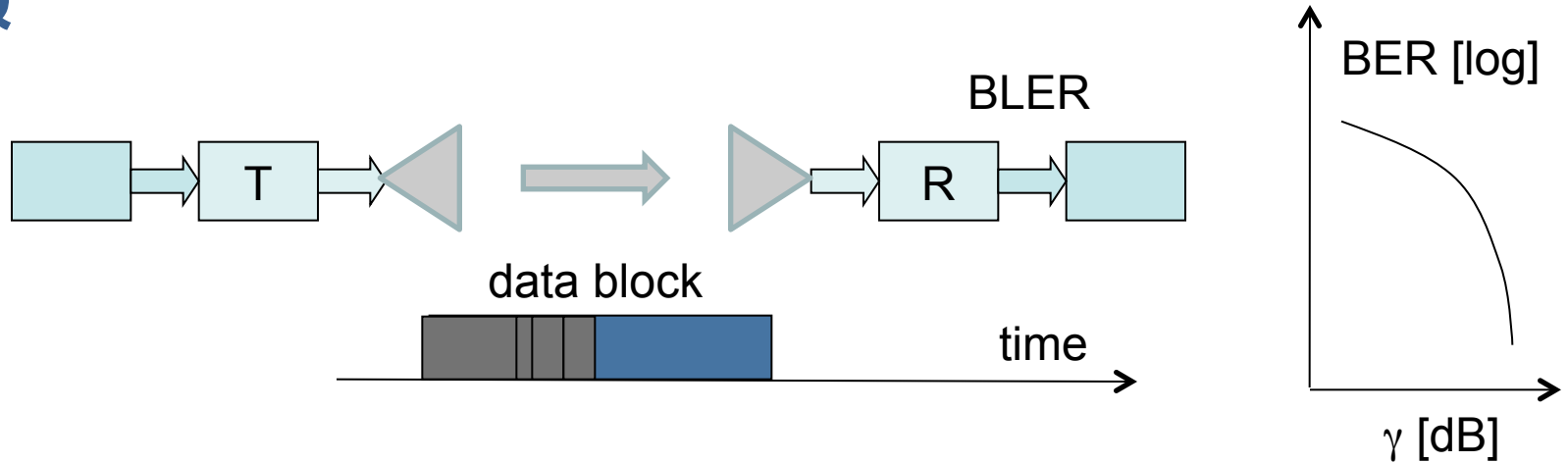


$$s_r(t) = s_t(t) \star h(t) = \int_{-\infty}^{\infty} s_t(t - \tau) h(\tau) d\tau$$

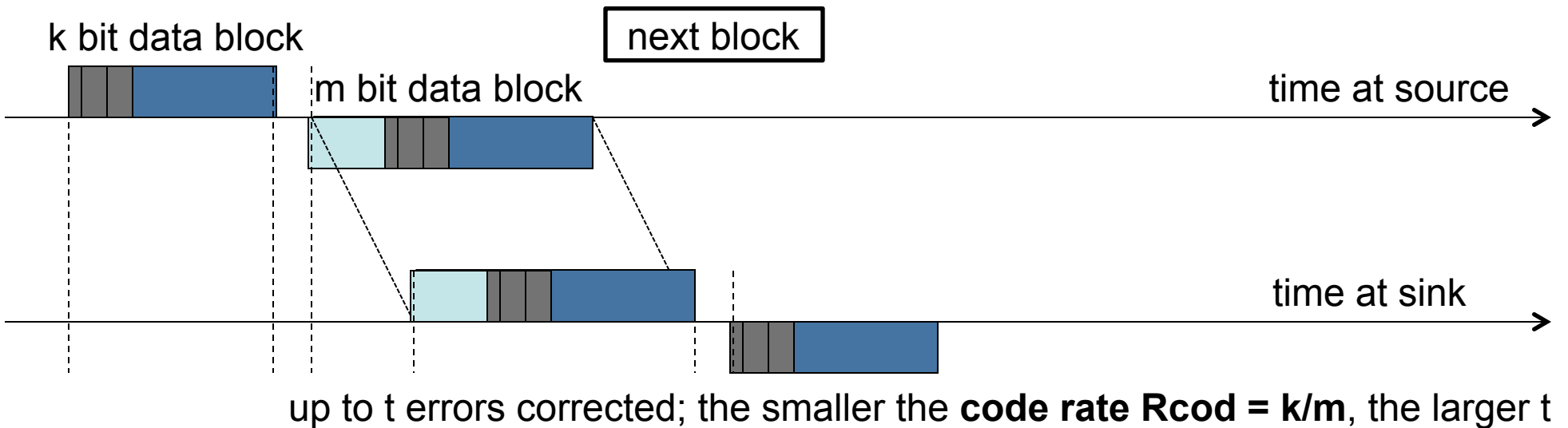
## 6. FEC, ARQ, HARQ



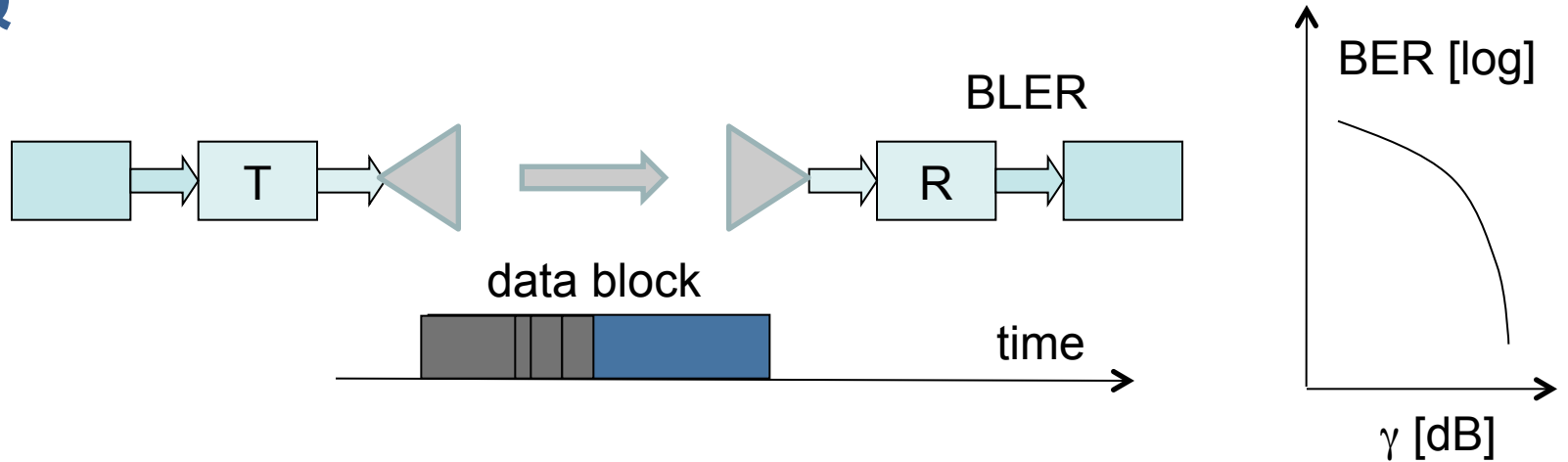
# FEC, ARQ



## FEC: Forward Error Correction

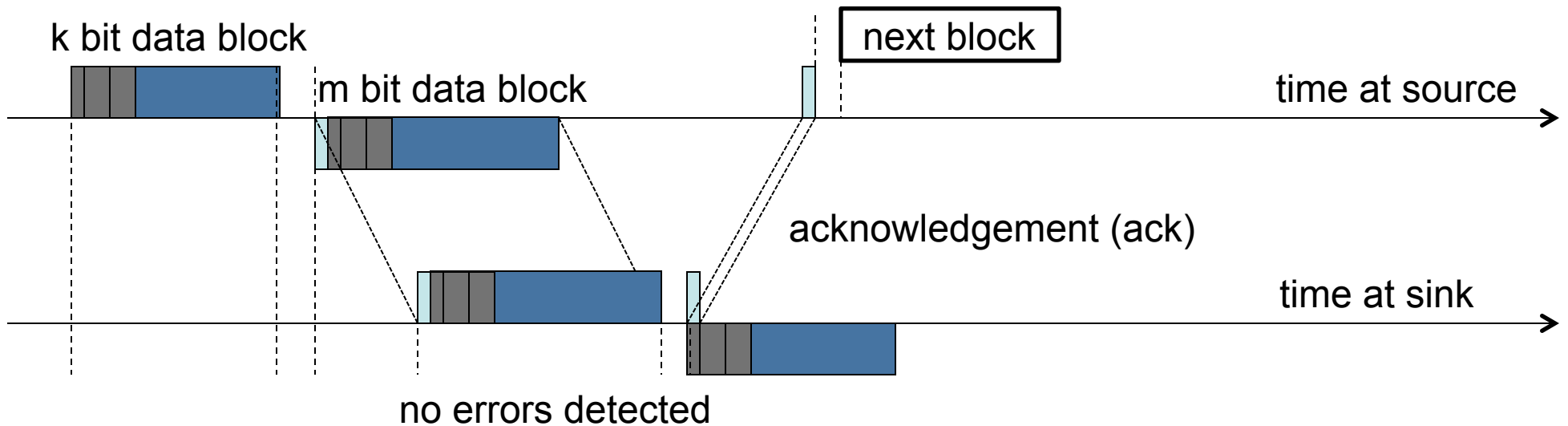


# FEC, ARQ

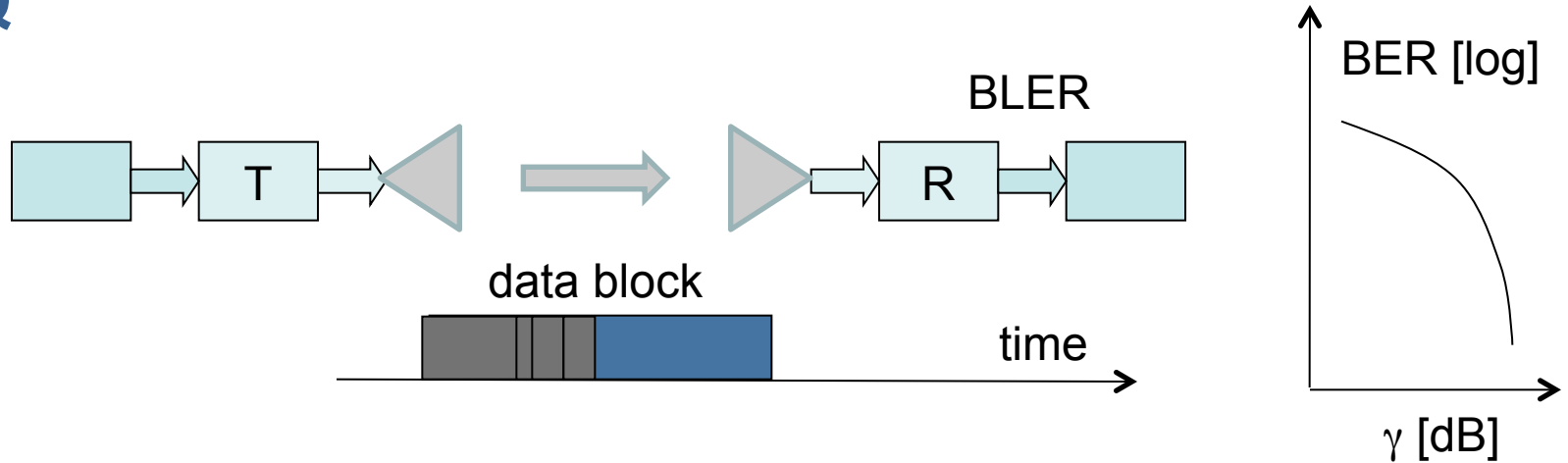


## ARQ: Automatic Repeat Request

## Stop and Wait

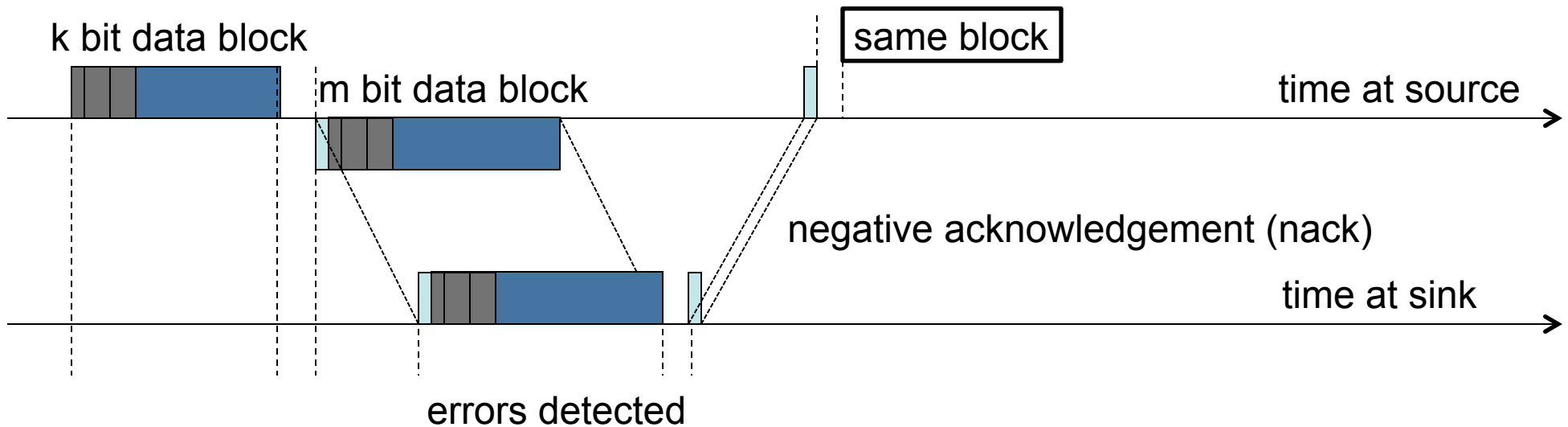


# FEC, ARQ

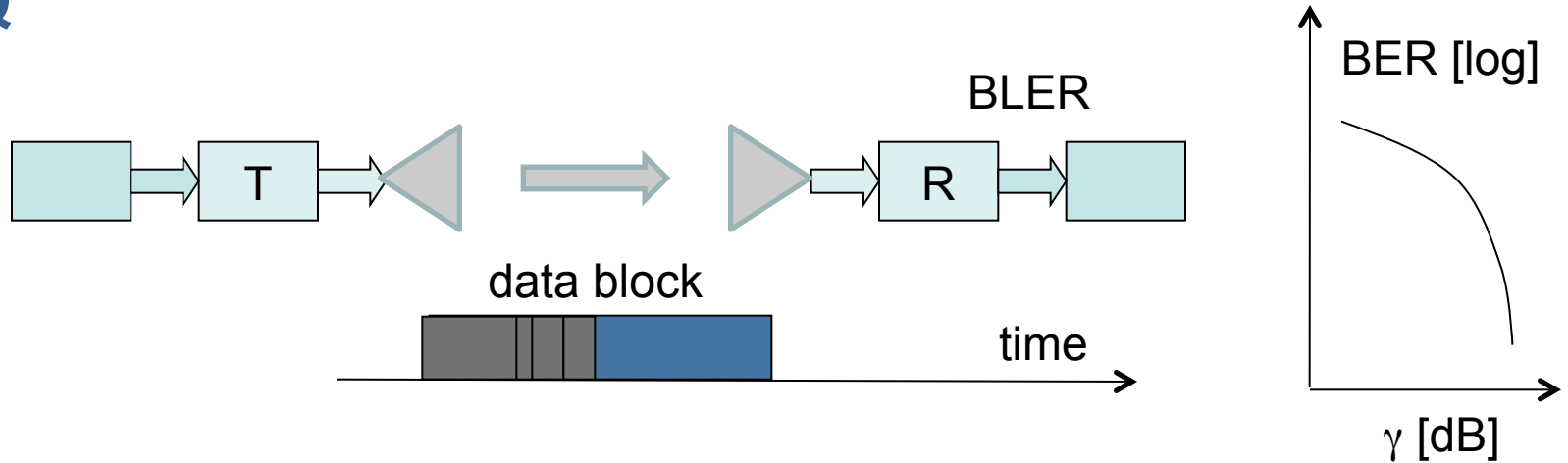


## ARQ: Automatic Repeat Request

## Stop and Wait

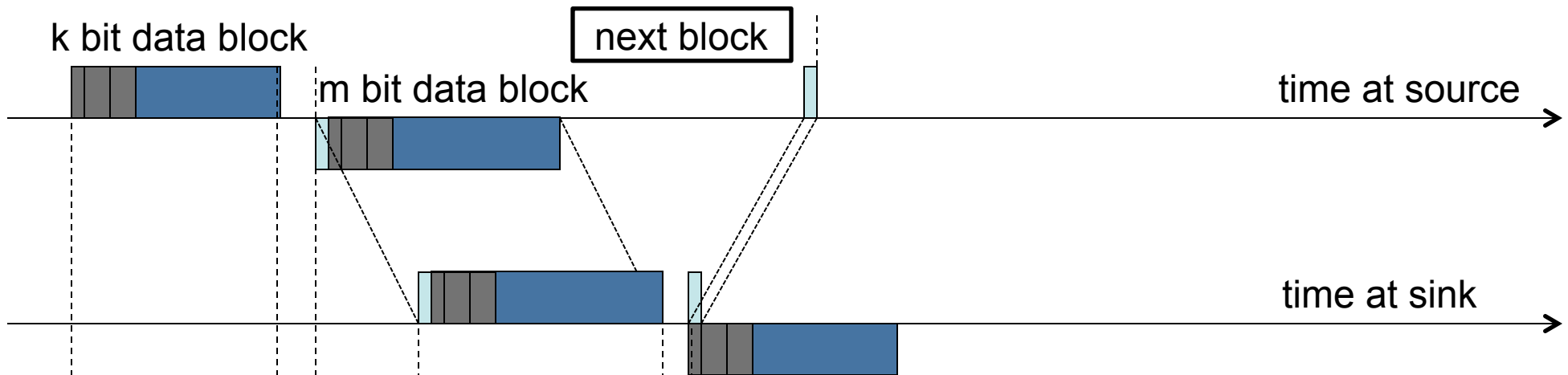


# FEC, ARQ

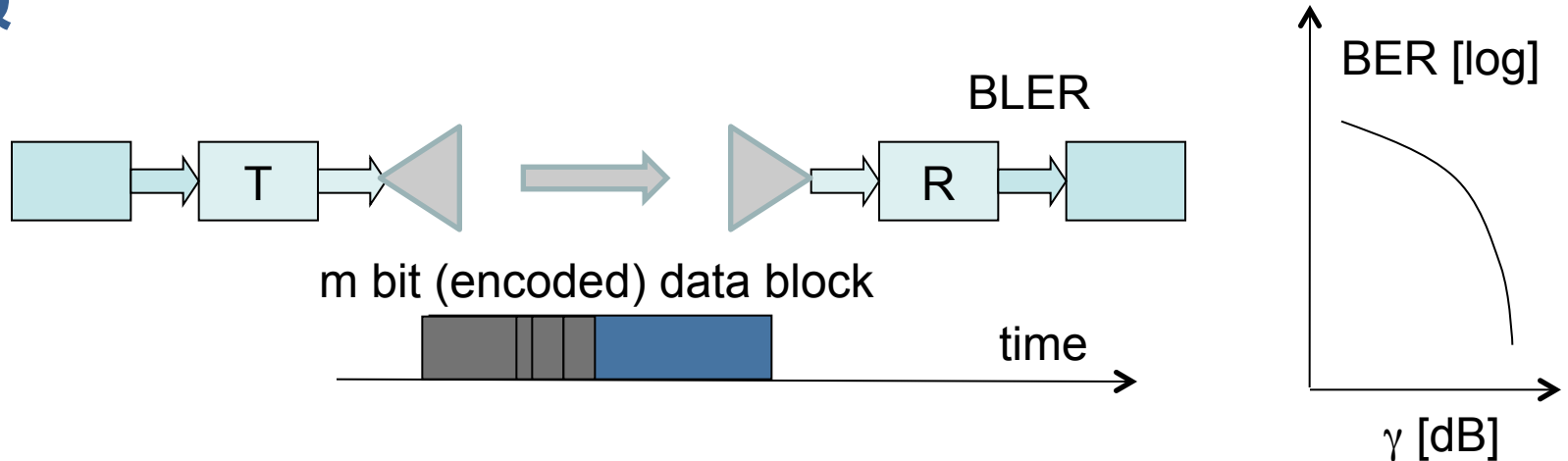


## ARQ: Automatic Repeat Request

## Go Back N



# FEC, ARQ



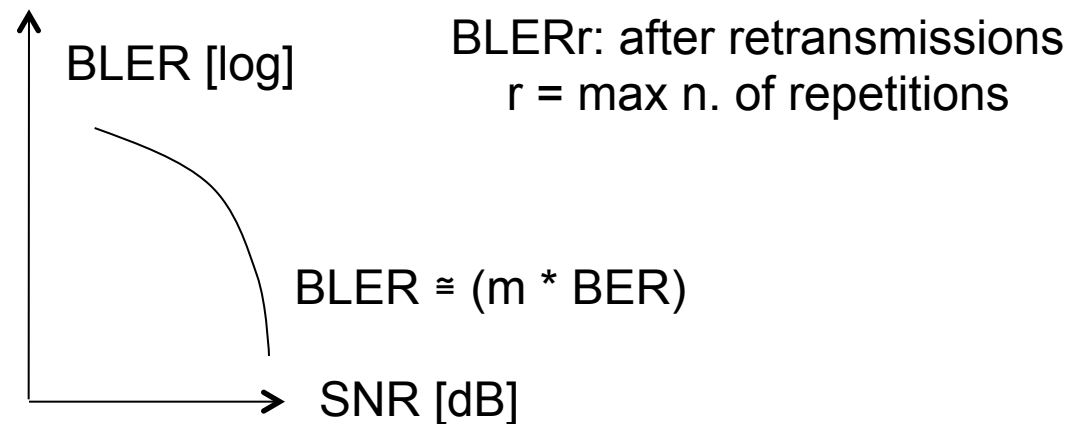
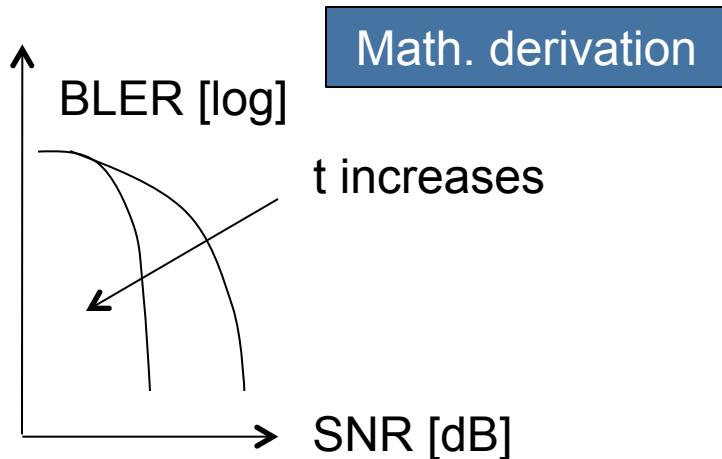
## FEC: Forward Error Correction

## ARQ: Automatic Repeat Request

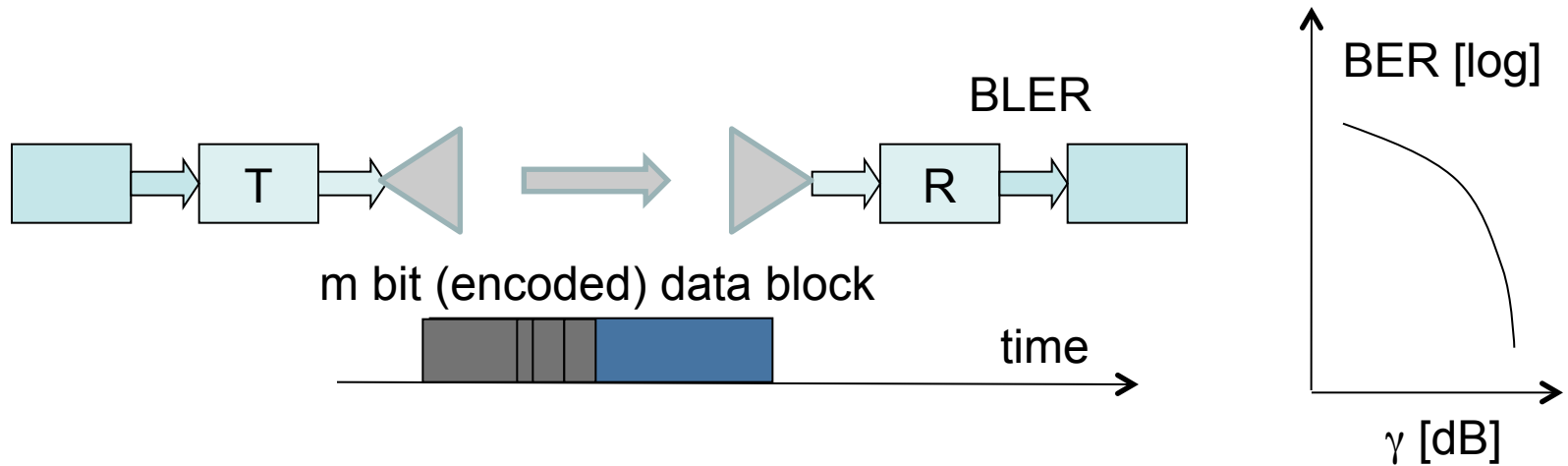
$BLER = f(BER, m, t)$

$BLER = 1 - (1 - BER)^m$

$BLER_r = BLER^{(r+1)}$



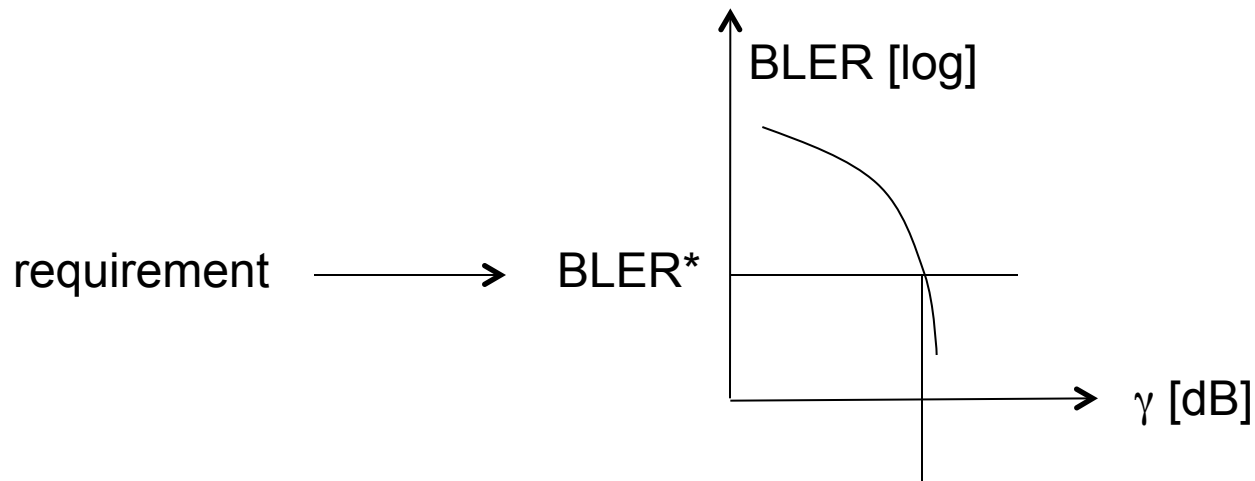
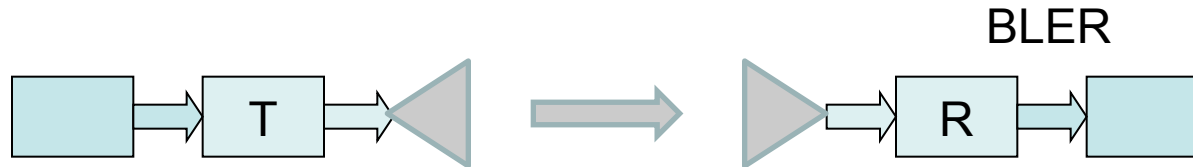
# HARQ



**Type I, Type II, Type III**

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

# Receiver Sensitivity



$$\gamma^* = P_{rmin} / N_0 R_b \rightarrow P_{rmin} = \gamma^* N_0 R_b$$

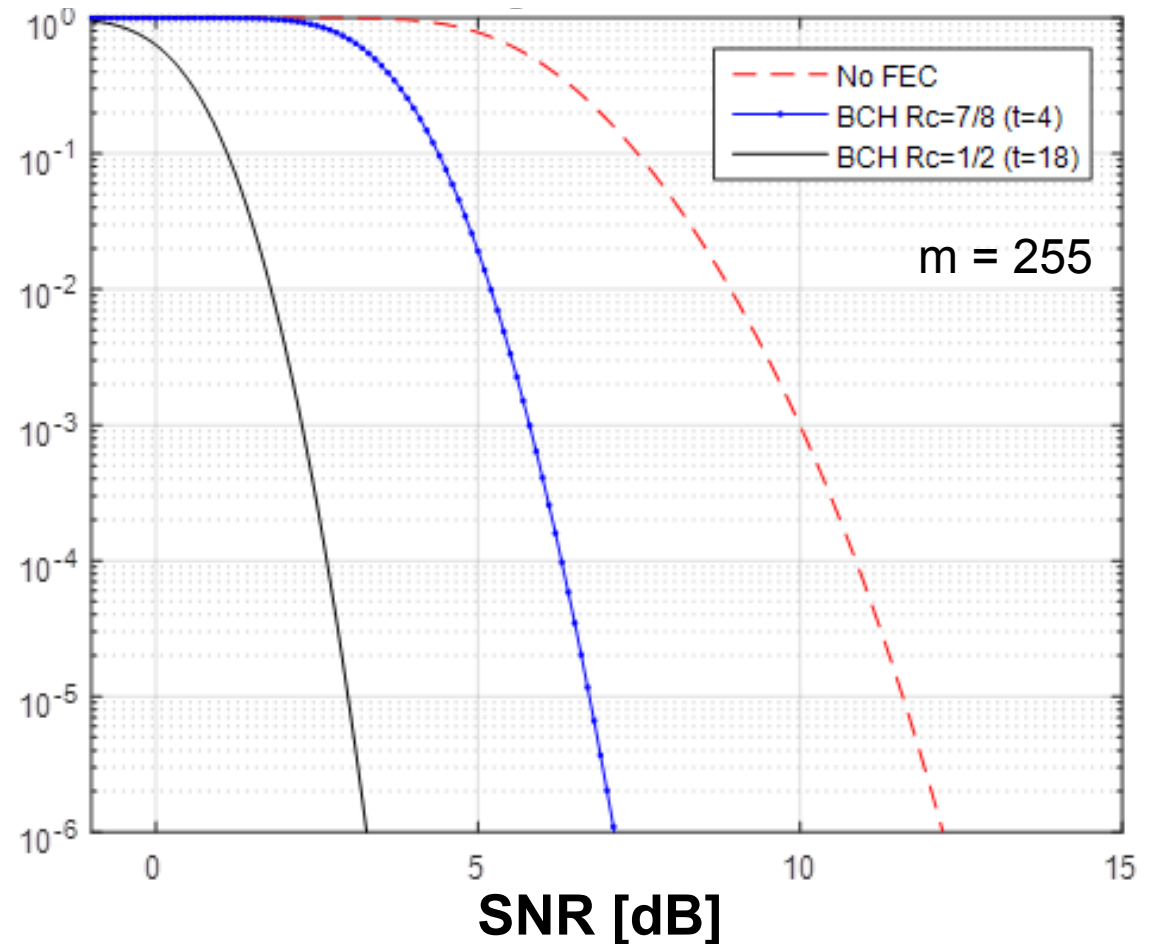
$P_{rmin}$  is denoted as **receiver sensitivity**

# FEC, ARQ

Example: BCH FEC over QPSK

Mathematical derivation

**BLER**

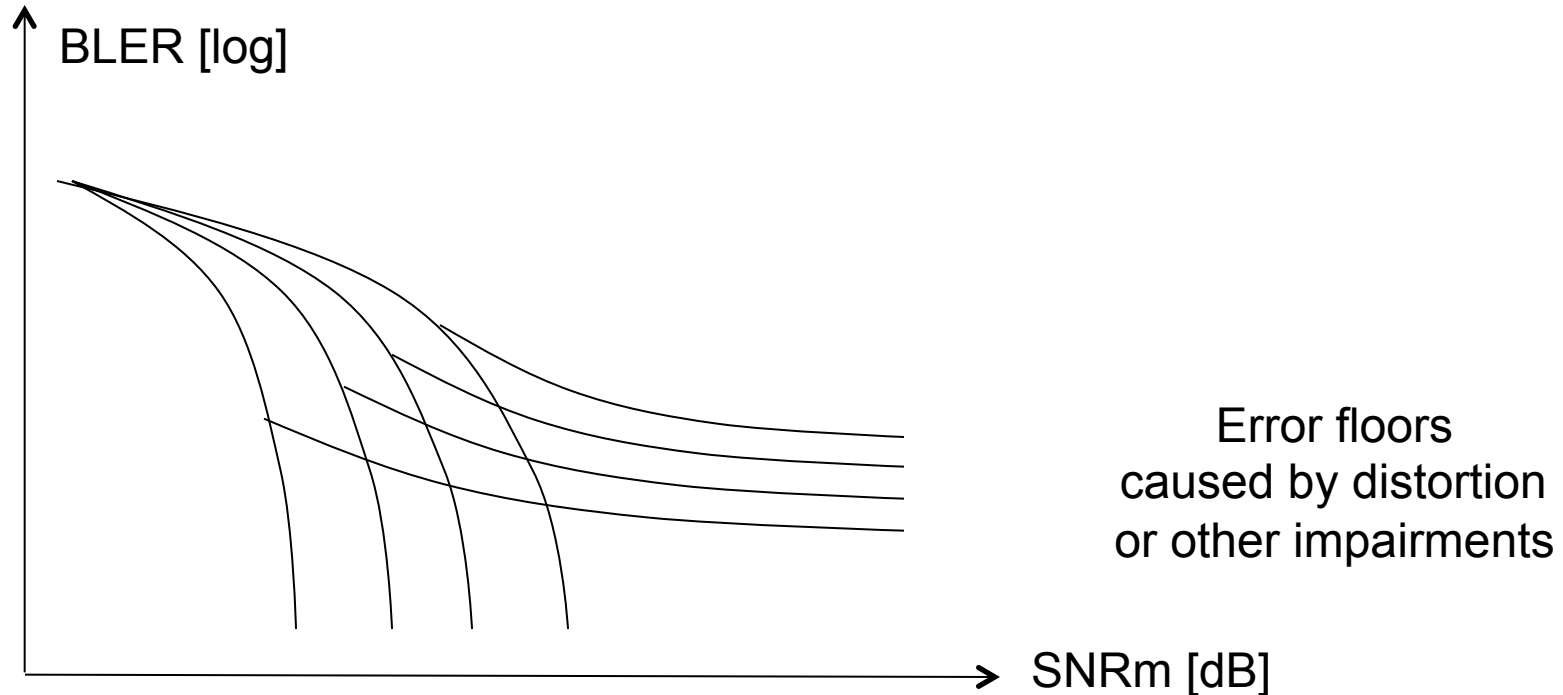




# 7. Link Performance and Capacity

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# Link Performance and Capacity



$$U = R_b * \eta_p * (1 - \text{BLER}(\text{SNR}_m))$$

$$R_b < C = B_c \log_2 (1 + \text{SNR}_m)$$

## 8. Radio Resources

---

# Radio Resources

## Medium Access Control (MAC) and Radio Resource Control (RRC)

Both MAC and RRC address the problem of assigning radio resource units to data blocks in a shared radio environment, at a different pace

## Radio Resource (RR)

*A radio waveform* allowing the transmission of a given data block (m bits)

## Radio Resource Payload

Amount of information bits (as seen by data link layer) carried by the radio resource

## Radio Resource Unit (RU)

A RR carrying the minimum value of Radio Resource Payload that can be assigned

**The scope of RR Assignment is to maximise the exploitation of the available RUs while fulfilling Quality of Service (QoS) requirements:**

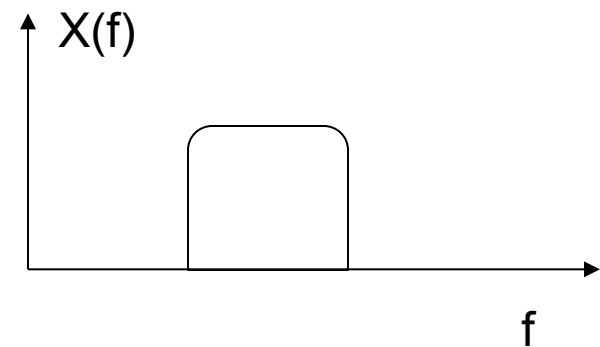
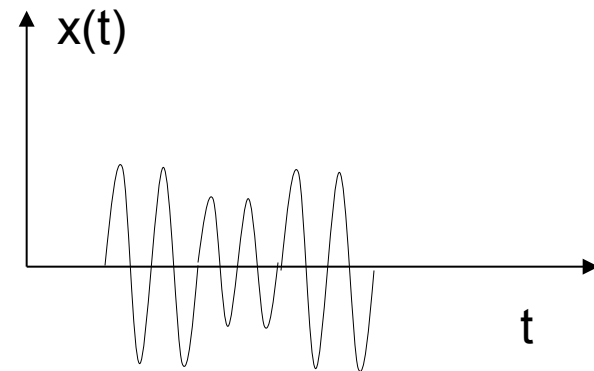
**tradeoff between network spectrum efficiency and QoS**

---

# Radio Resources

The RU assignment implies the definition of all characteristics of the radio waveform.

From the signal viewpoint:



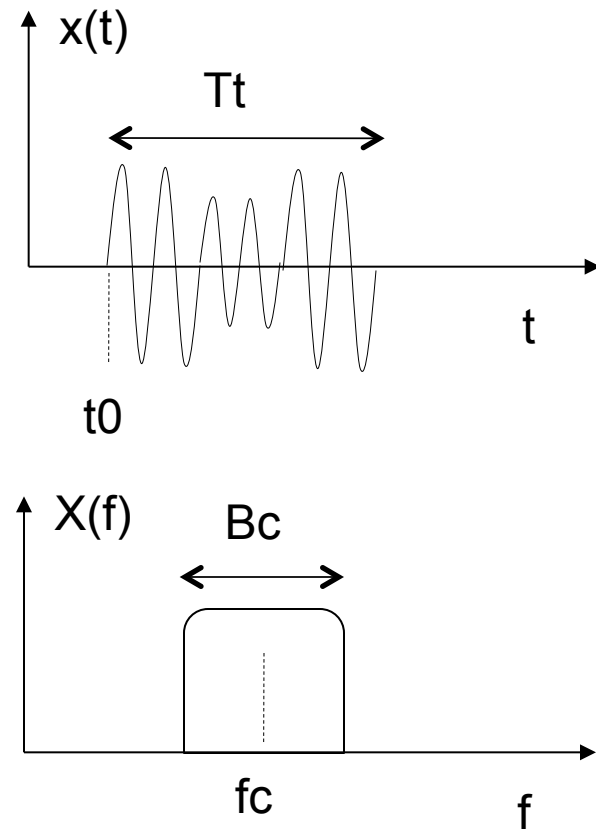
$$\text{RU} = [ ? ]$$

# Radio Resources

The RU assignment implies the definition of all characteristics of the radio waveform.

From the signal viewpoint:

- energy level (E),
- modulation and coding scheme (MCS),
- carrier frequency ( $f_c$ ),
- start time ( $t_0$ ),
- duration ( $T_t$ ),
- bandwidth ( $B_c$ ).



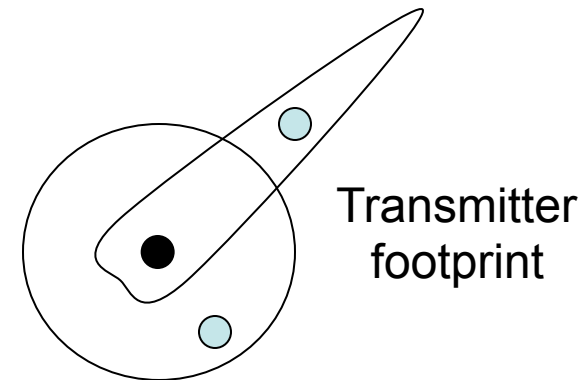
$$\text{RU} = [ E, \text{MCS}, f_c, t_0, T_t, B_c ]$$

# Radio Resources

The RU assignment implies the definition of all characteristics of the radio waveform.

From the *radio* signal viewpoint:

- energy level (E),
- modulation and coding scheme (MCS),
- carrier frequency (fc),
- start time (t0),
- duration (Tt),
- bandwidth (Bc),
- antenna pattern (Ga)



$$\mathbf{RU} = [ \mathbf{E}, \mathbf{MCS}, \mathbf{f_c}, \mathbf{t_0}, \mathbf{T_t}, \mathbf{B_c}, \mathbf{G_a} ]$$

# Radio Resources: Bi-directionality

## FDD (Frequency Division Duplexing)

The two links use different frequency bands  
(e.g. GPRS)

$$RU = [ E, MCS, f_c, t_0, T_t, B_c, G_a ]$$



## TDD (Time Division Duplexing)

The time axis is divided in two, and fast alternate transmissions occur  
(e.g. WiFi)

$$RU = [ E, MCS, f_c, t_0, T_t, B_c, G_a ]$$





# Radio Resources: Bi-directionality

<b>Duplexing Technique</b>	<b>Advantages</b>	<b>Disadvantages</b>
<b>FDD</b>	<b>simple</b>	<b>duplexer needed to avoid transmitter-to-receiver interference</b>
<b>TDD</b>	<b>cheaper</b>	<b>synchronisation at link level receiver sensitivity (larger overall bit rate) synchronisation at network level</b>

---

# 9. Assignment of Radio Resources

---

# Radio Resource Assignment

## Radio Resource Set

It is the set of RUs available to the users in a given area.

## Radio Resource Set Capacity

It is the number of RUs that can be assigned to the users in a given area under some QoS constraints.

**Hard Capacity:** in some cases the maximum number of RUs available is known

**Soft Capacity:** in some other cases this number has no fixed maximum value

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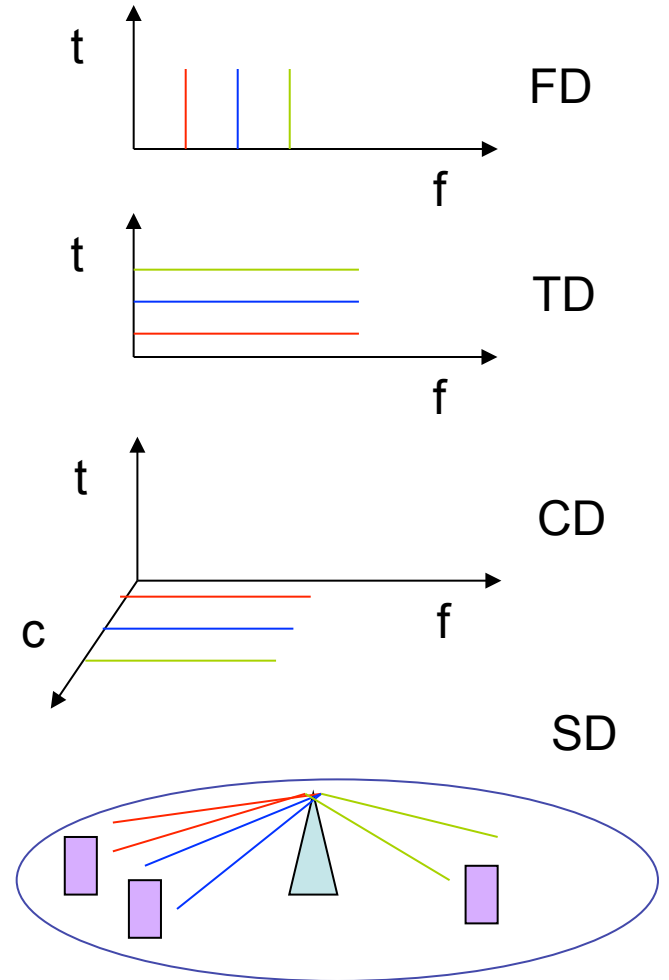
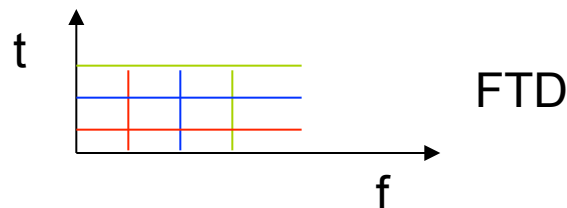
# Radio Resource Assignment

Radio Resources can be assigned to users *orthogonally* within a given area:

$$\text{Int} [ x(t) y(t) ] = 0$$

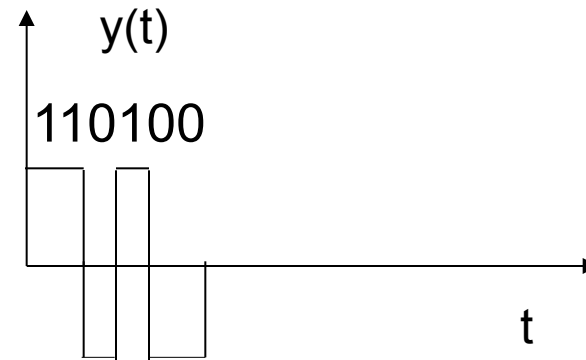
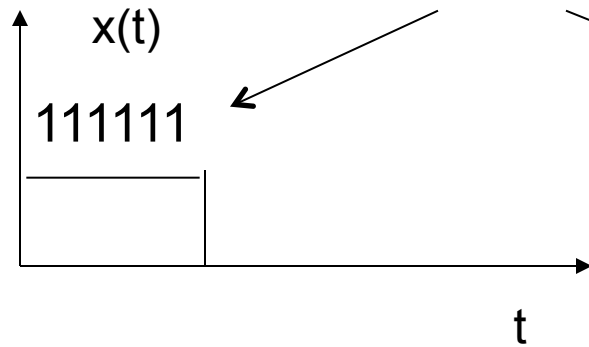
If they are orthogonal, users will not interfere. Otherwise, *collision resolution* or *interference rejection* techniques must be used.

Orthogonality can be reached via Frequency (FD), Time (TD), Code (CD), Space Division (SD) or a mixture of them (e.g. FTD)

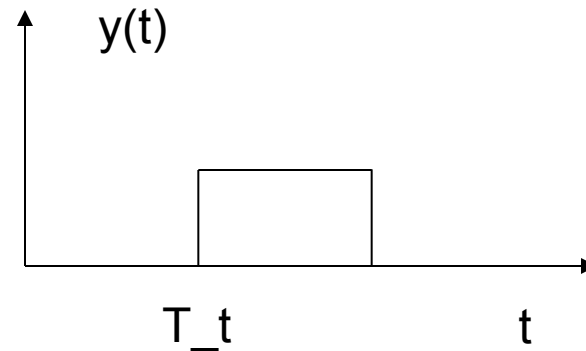
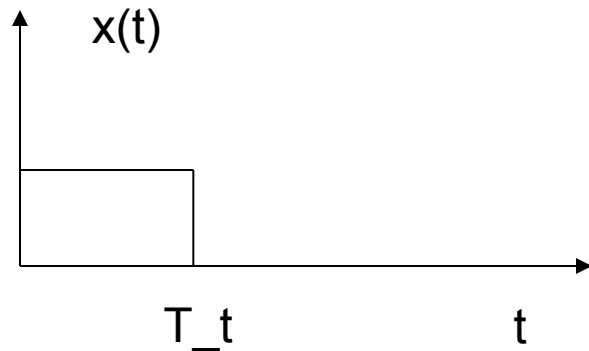


# Radio Resource Assignment

sequence of chips



CDMA



TDMA

$$x(t) = X \cos(2 \pi f_1 t) \text{rect}(t/T)$$

$$y(t) = Y \cos(2 \pi f_2 t) \text{rect}(t/T)$$

$$f_1 \neq f_2$$

FDMA  
(approx)

# Radio Resource Assignment

**RU = [ E, MCS,  $f_c$ ,  $t_0$ , Tt, Bc, Ga ]**



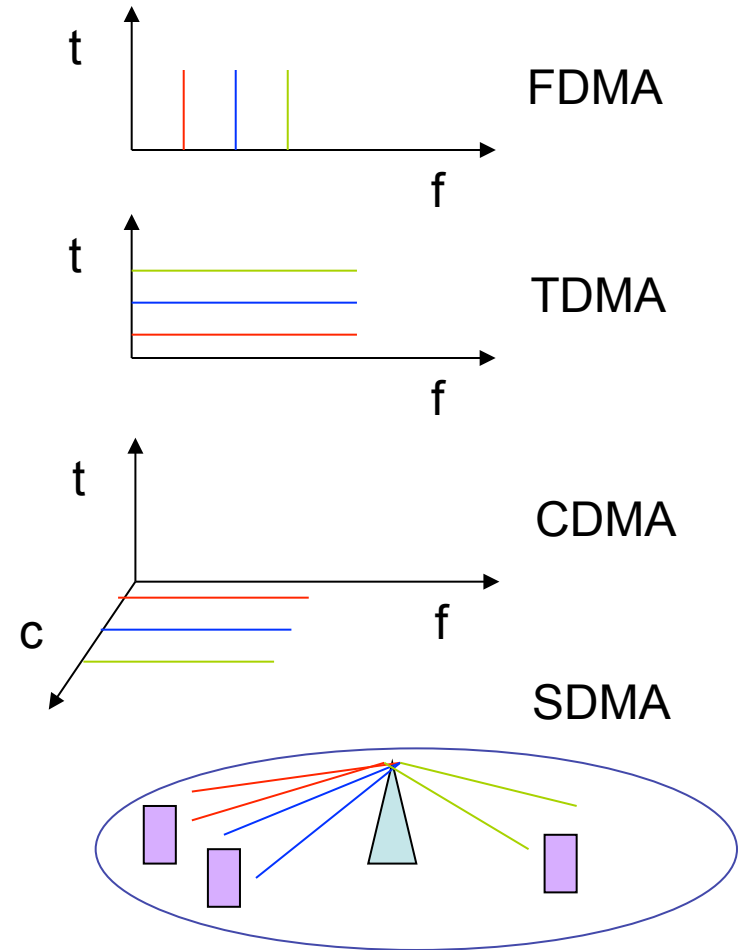
**RU = [ E, MCS,  $f_c$ ,  $t_0$ , Tt, Bc, Ga ]**



**RU = [ E, MCS,  $f_c$ ,  $t_0$ , Tt, Bc, Ga ]**

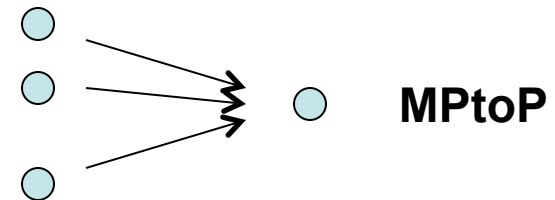
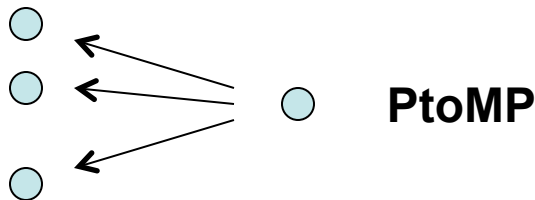


**RU = [ E, MCS,  $f_c$ ,  $t_0$ , Tt, Bc, Ga ]**



# Radio Resource Assignment

MA Technique	Advantages	Disadvantages
FDMA	simple	# of receivers in MPtoP non linear effects in PtoMP
TDMA	cheaper in MPtoP slots for measurements	synchronisation receiver sensitivity
CDMA	inherent encryption time resolution	code orthogonality larger bandwidth
SDMA	protection against interference space is not limited resource	technological complexity



# Radio Resource Assignment

## **(Centralised) Fixed RR Assignment**

A centralised network entity assigns RUs to nodes based on pre-defined schemes

## **(Centralised) Dynamic RR Assignment**

A centralised network entity assigns RUs to nodes based on dynamic schemes

[scheduling]

## **(Distributed) Controlled RR Assignment**

Nodes self-assign RUs based on concerted policies

## **(Distributed) Random RR Assignment**

Nodes self-assign RUs without concerted policies

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# 10. Exercises

## Exercise DTN#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 DTN#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.**

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## Exercise DTN#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 [20 dBm; 0 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).**

**Repeat the exercise with partial compensation PC ( $\delta = 0.5$ ). Choose the value of reference receive power providing equivalent outage interval.**

**Repeat the exercise with no PC, setting the transmit power at 20 dBm.**

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## Exercise DTN#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  $L = 2, 4, 8$  or 16 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.**

**What is the maximum transmission range of the base station?**

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## Exercise DTN#5

**A network uses power control with 64 levels of transmit power, an F-TDMA scheme with 56 sub-bands and 8 slots per frame, 4 different MCSs obtained by varying the channel encoding scheme. The duration of all data blocks is fixed, antenna patterns are fixed, the signal bandwidth is fixed.**

**How many RUs are available?**

**How many of them are orthogonal?**

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# Self-Assessment: Exemplary Exam Questions

- **How does signal based power control works? How many types?**
  - **How does link adaptation works? Can you show a performance diagram summarising its impact?**
  - **What are the pros and cons of the different medium access techniques?**
  - **How can you achieve radio resource orthogonality?**
  - **Determine the BER of M-QASK as a function of SNR.**
  - **How can you compute the BLER of a system, if the level of BER is known?**
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# Radio Networks

## Digital Transmission in Noise Limited Systems

The End

**There is no good house  
without good foundations...**





# Radio Networks

## Digital Transmission in Noise Limited Systems

The End

