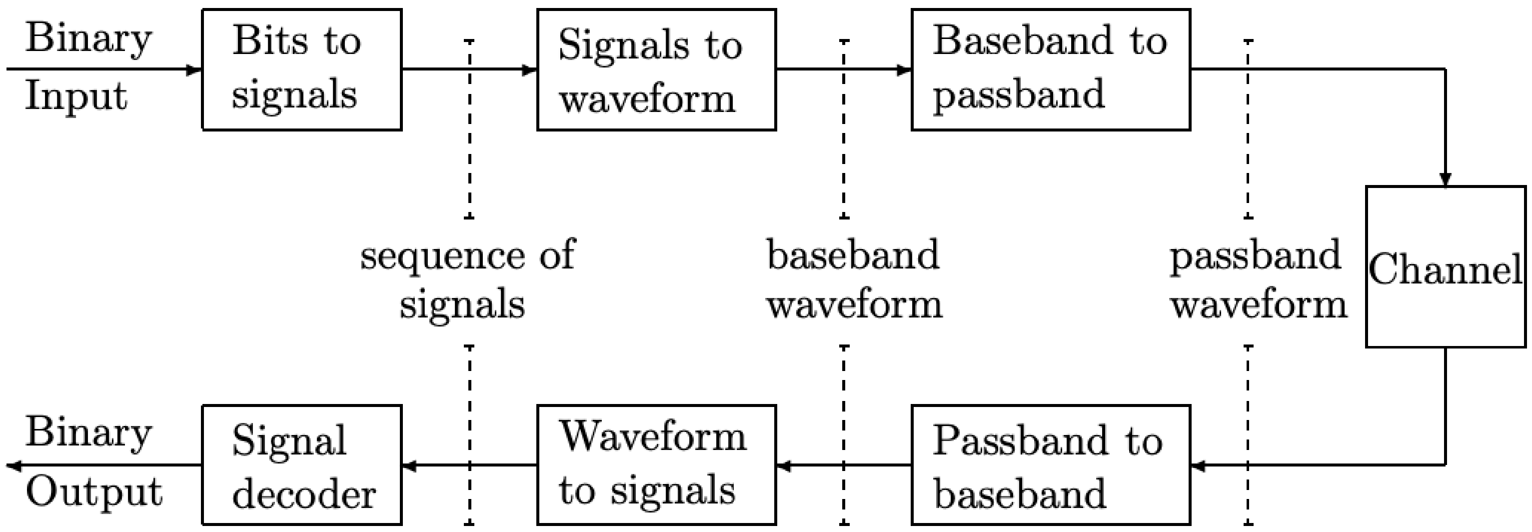
THE FIRST RADIO WEEK (VDSI)

Fondamenti di Telecomunicazioni

MODULATION BLOCKS



1. mapping from bits to numerical signals
2. the conversion of signals to a waveform

(3. mapping of the baseband waveform into a passband waveform)

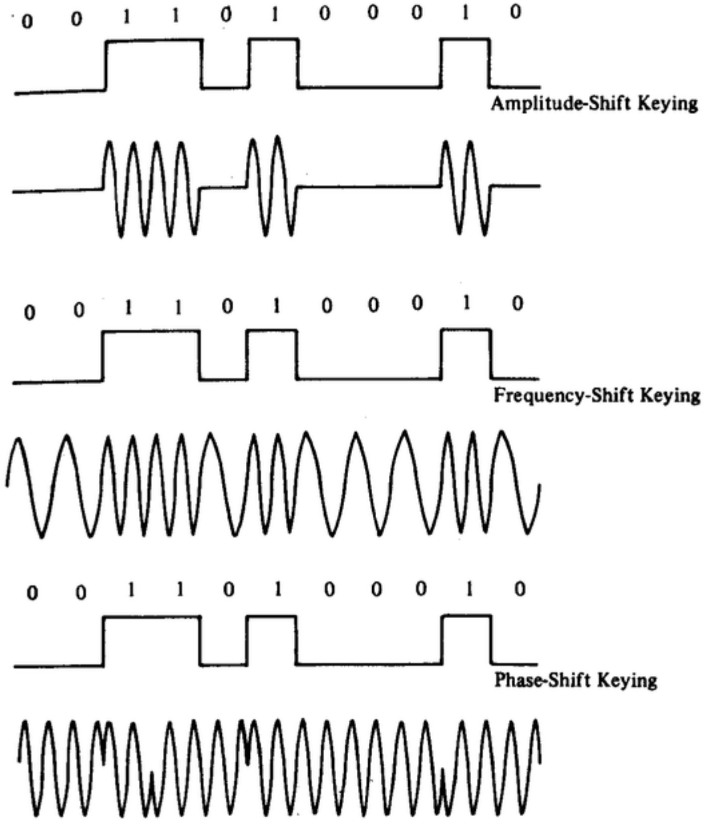
SINGLE CARRIER MODULATION

0 0 1 1 0 1 0 0 0 1 0

$$A(t)\cos(2\pi f_c t + \phi(t))$$

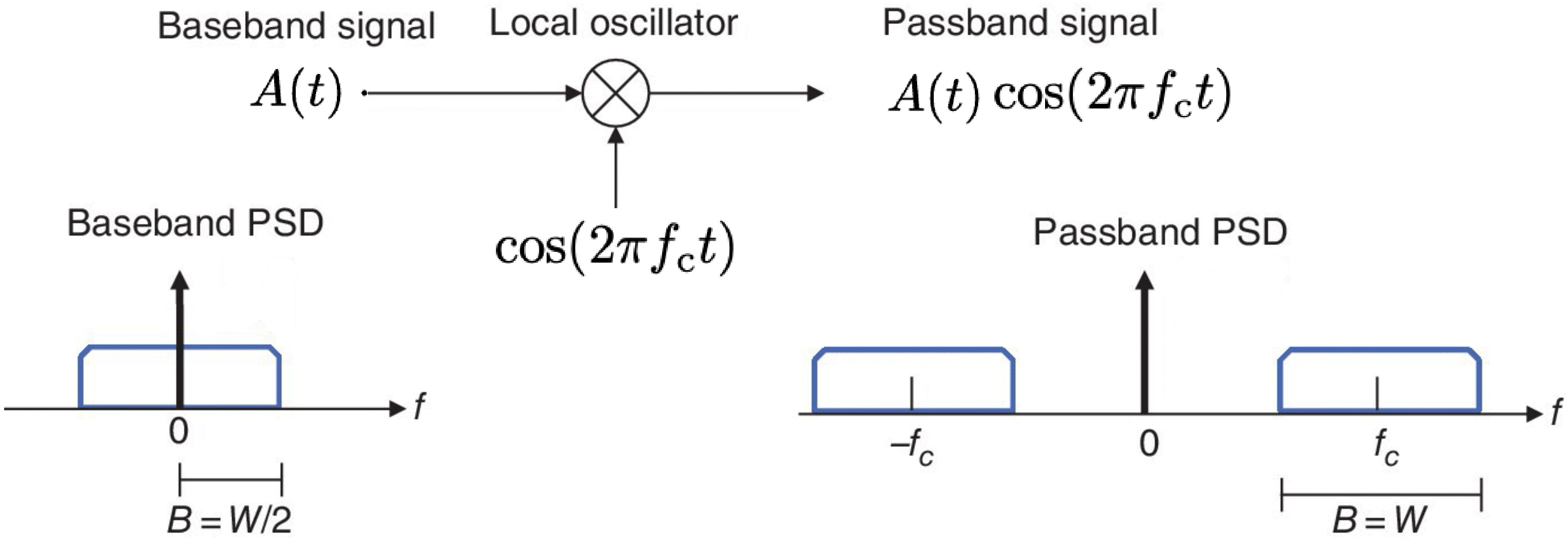
SINGLE CARRIER MODULATION

0 0 1 1 0 1 0 0 0 1 0

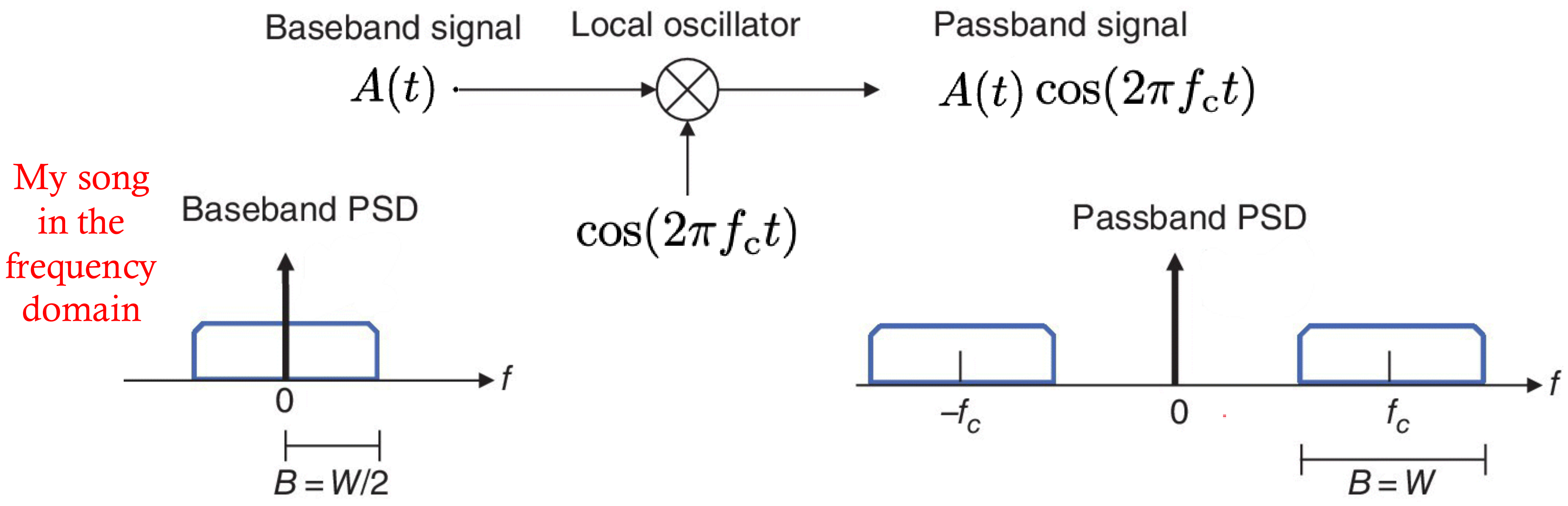


$$A(t) \cdot \cos[2\pi f t + \varphi(t)]$$

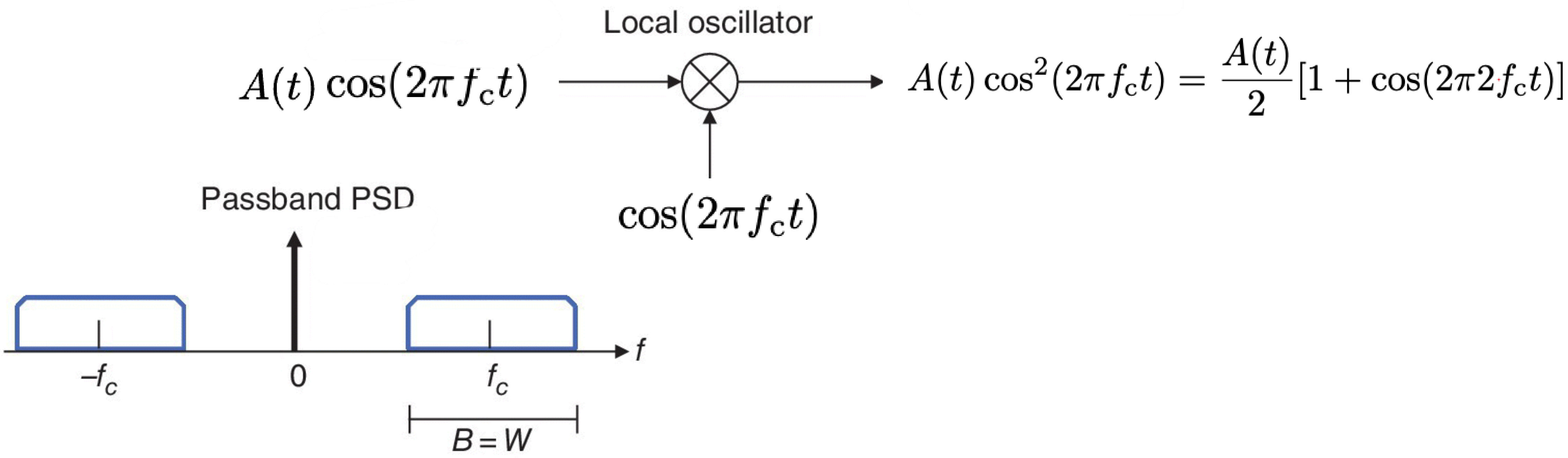
SINGLE CARRIER MODULATION



SINGLE CARRIER MODULATION



SINGLE CARRIER DEMODULATION



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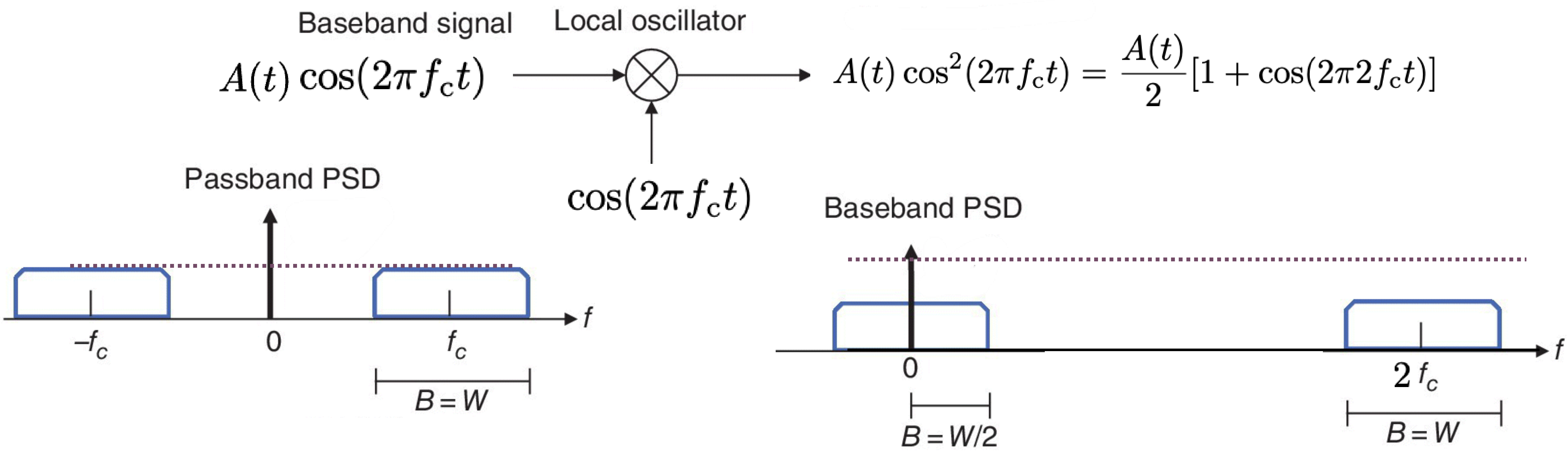

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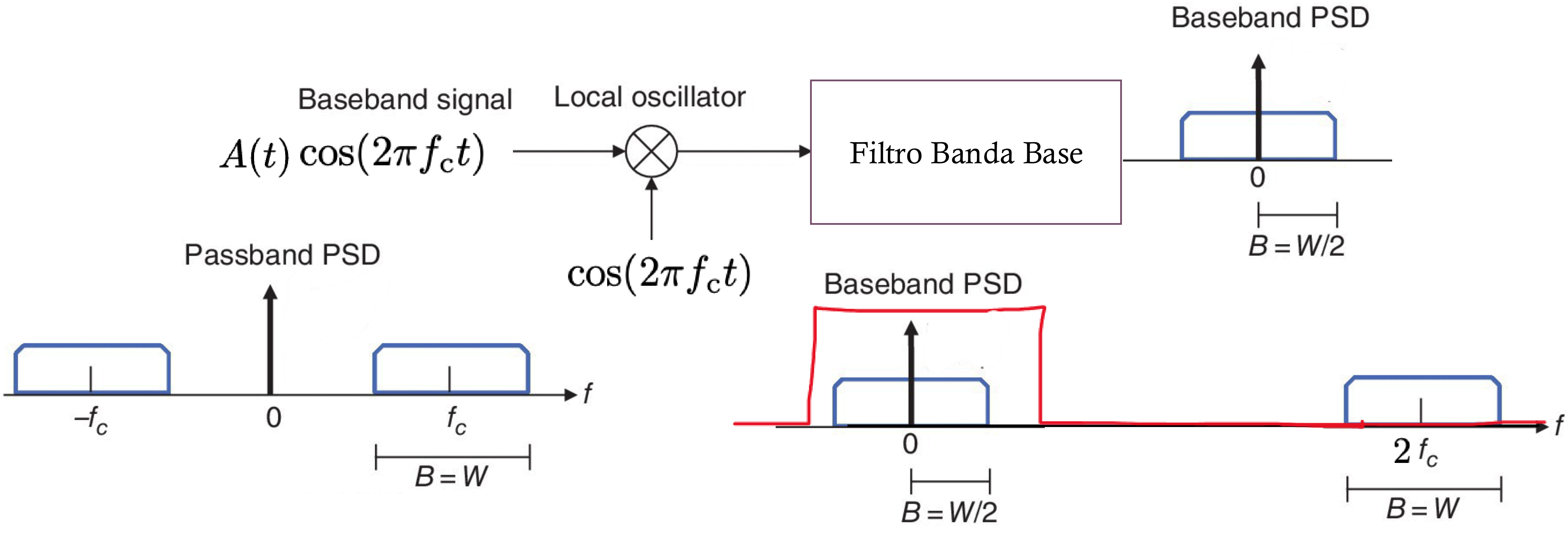

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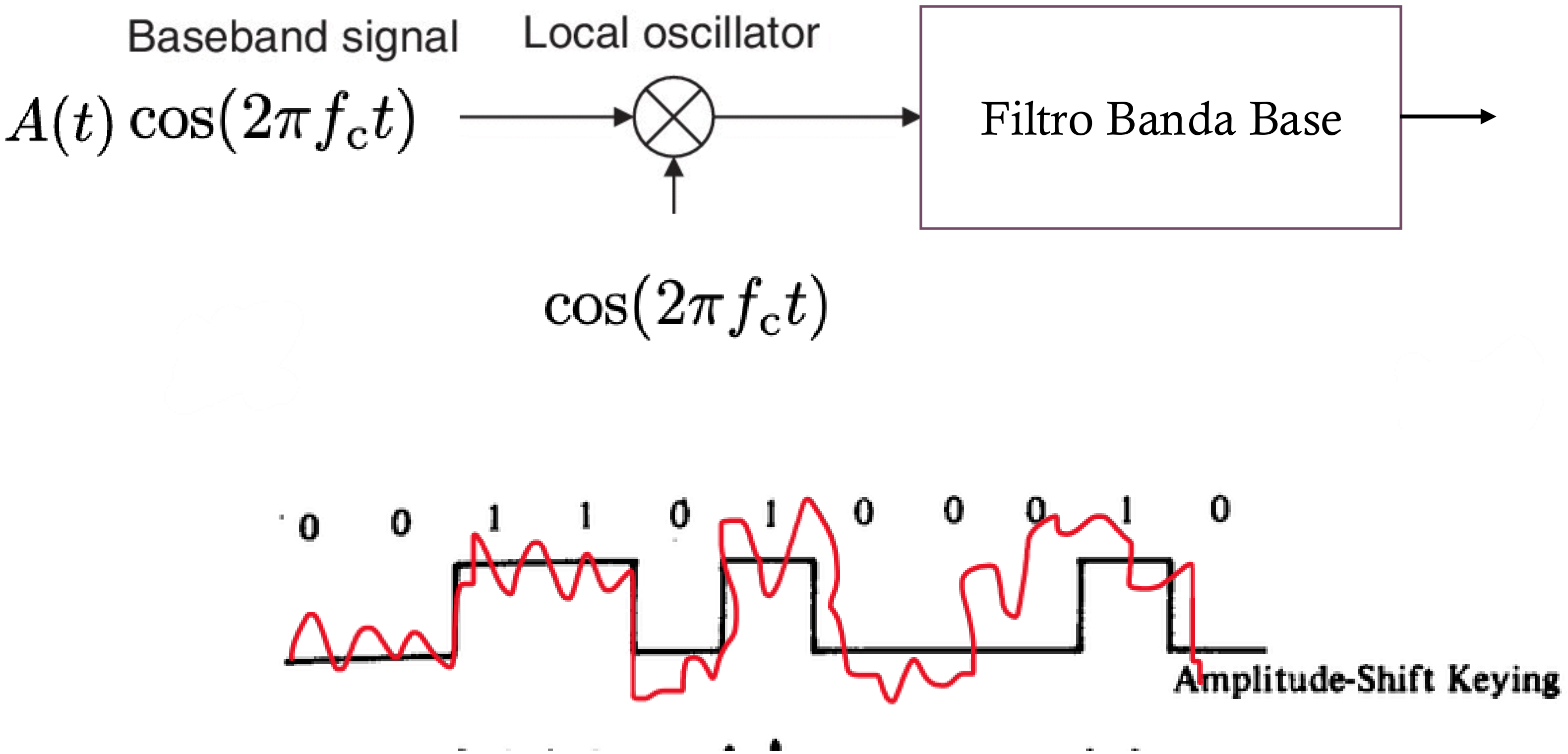

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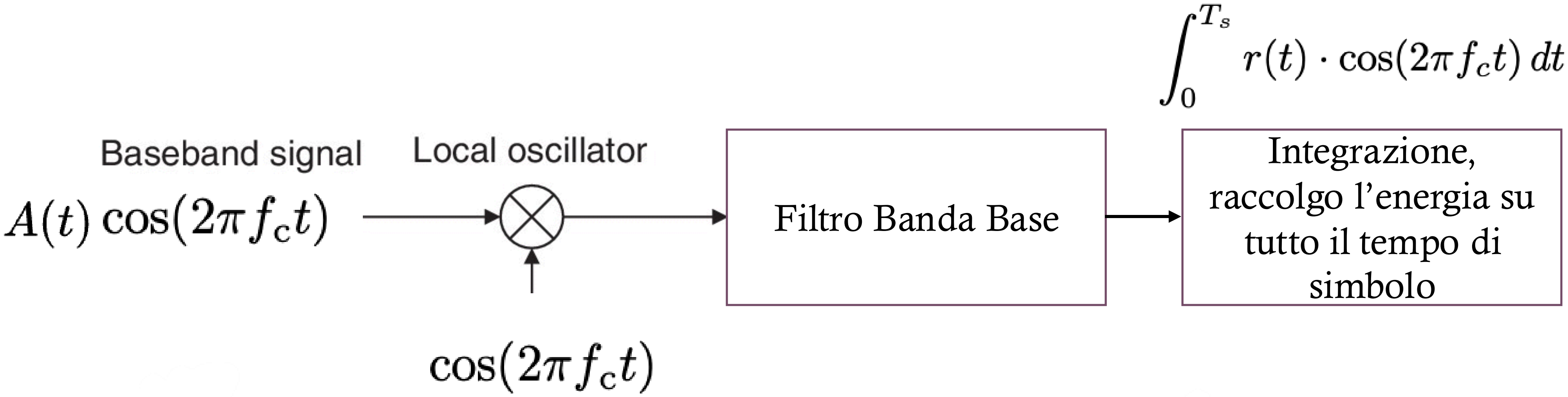
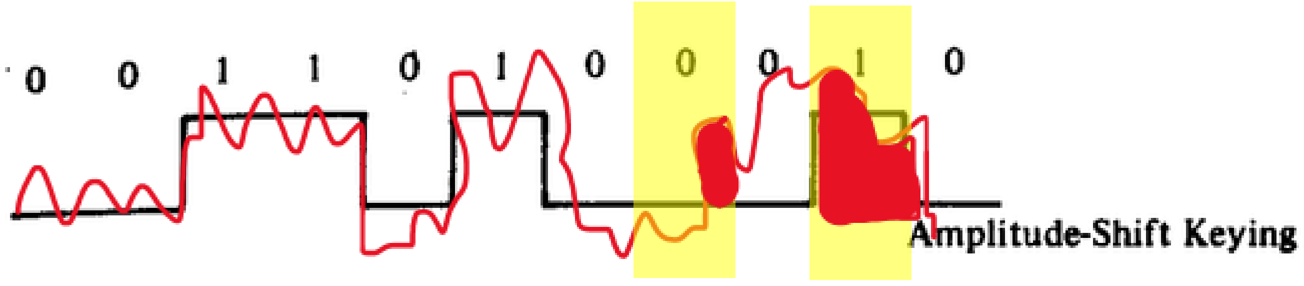
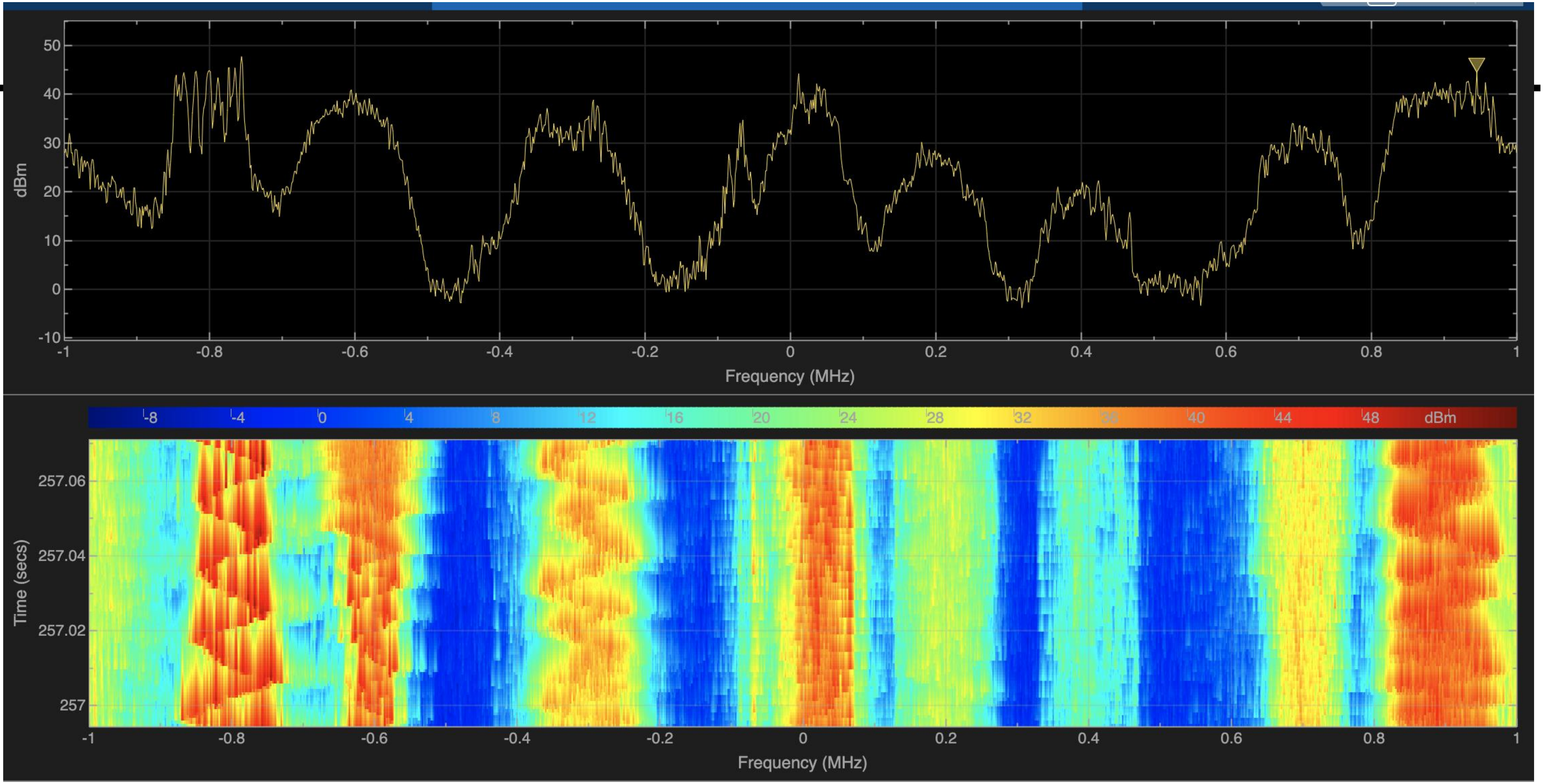






Harmonic Distortion

RTL-SDR Re...	THD	SNR	SINAD	SFDR	H1	H2	H3	H4	H5	H6
Frequency (kHz)					945.3125					
Power (dBm)					44.4816					
Rel. Power (dBc)	-Infinity	-15.0608	-15.0608	0.3020	0.0000					
%	0.0000									

POWER UNITS – DB AND DBM

- Decibel (dB): log unit of intensity; indicates *power* lost or gained between two signals
- Named after Alexander Graham Bell

P_{A} = 1 Watt
P_{B} = 50 milliWatt :
→ P_{A} = 13 dB greater than P_{B}

$$10\,log_{10}\left({}^{P_{\mathrm{A}}}/{}_{P_{\mathrm{B}}}\right)$$

- dBm: absolute value (reference = 1 mW)
  - Versus dB = relative value = ratio
  - Power in dBm = 10 log(power/1mW)

DECIBELS - DBM

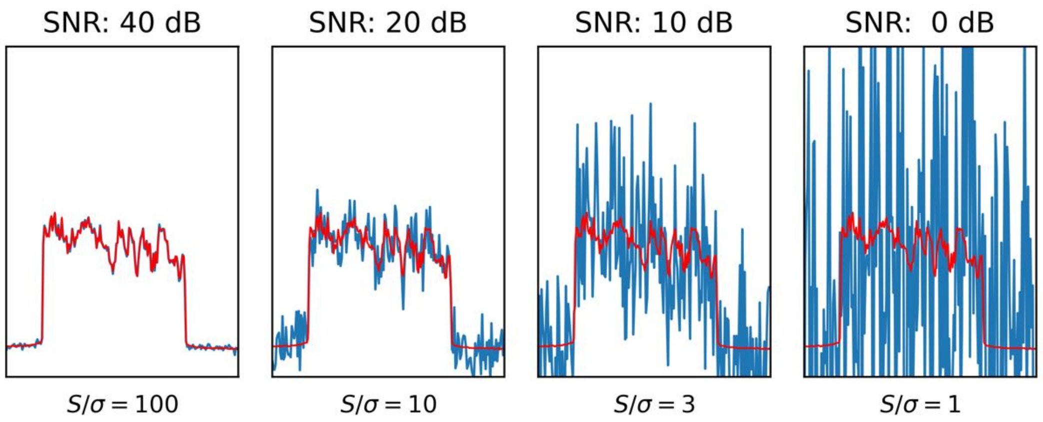
- Examples
  - 10 mW = 10 $\log_{10}(0.01/0.001)$ = 10 dBm
  - 10 μW = 10 $\log_{10}(0.00001/0.001)$ = -20 dBm
  - 26 dBm = ___ 2W= ___ dBm?
  - S/N ratio = -3dB → S = ___ X N?
- Transmit power
  - Measured in dBm
    - Es. 23 dBm
- Receive Power
  - Measured in dBm
    - Es. –50 dBm
- Path Loss
  - Receive power / transmit power
  - Measured in dB
  - Loss (dB) = transmit (dBm) – receive (dBm)
    - Es. 43 dB = attenuation by factor 20.000

UNINTENTIONAL NOISE & INTERFERENCE

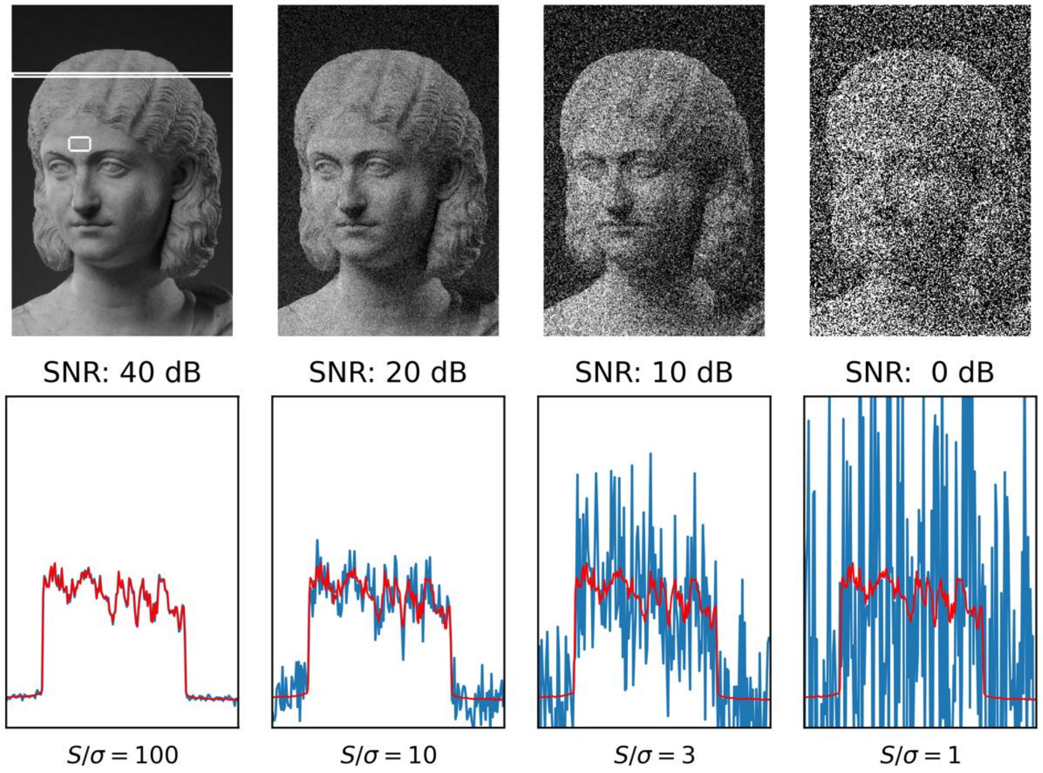
- **Thermal Noise**
  - All electronic devices naturally generate random electrical fluctuations.
  - This is due to the **motion of electrons** inside circuits and antennas.
  - It’s always present — known as **Johnson-Nyquist noise**

- **Intermodulation Noise**
  - Occurs when multiple signals mix in a nonlinear device.
  - Creates **unwanted frequencies** (sum & difference of originals).
  - Common in **RF amplifiers and mixers**.

NOISE AND SNR

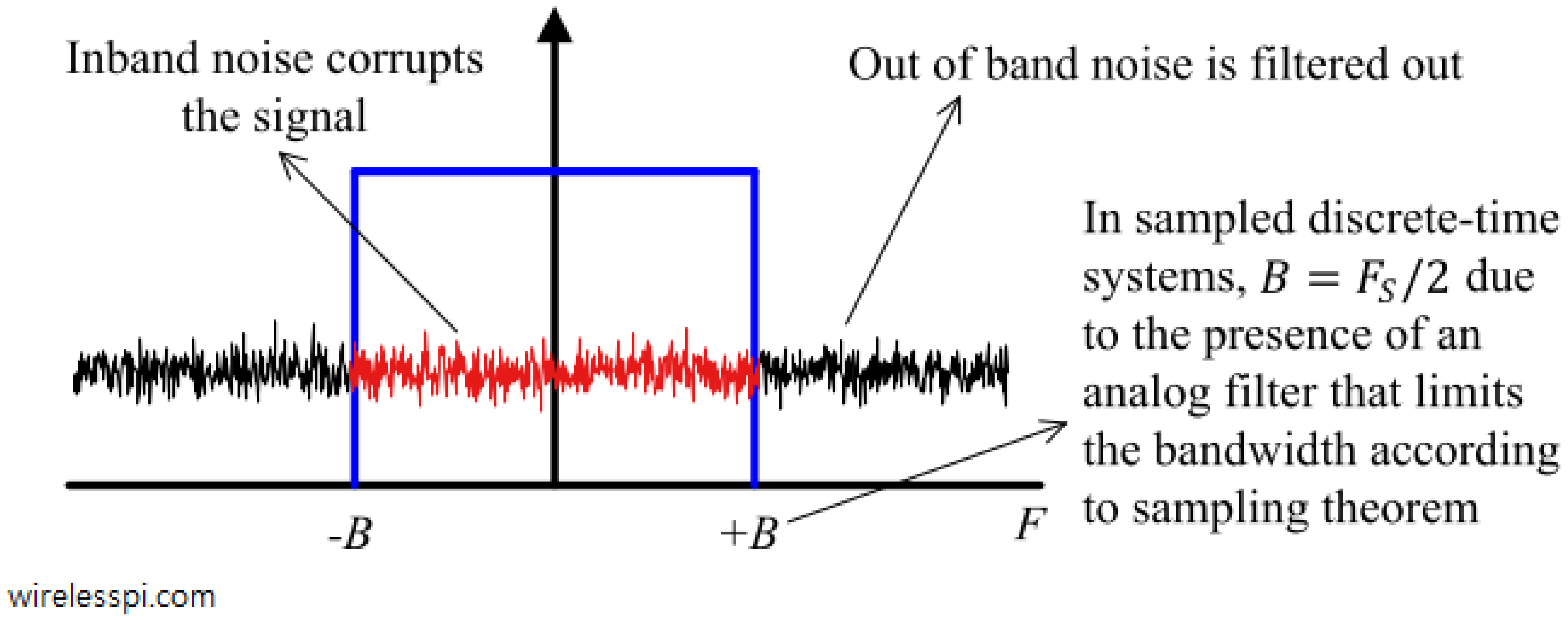


NOISE AND SNR

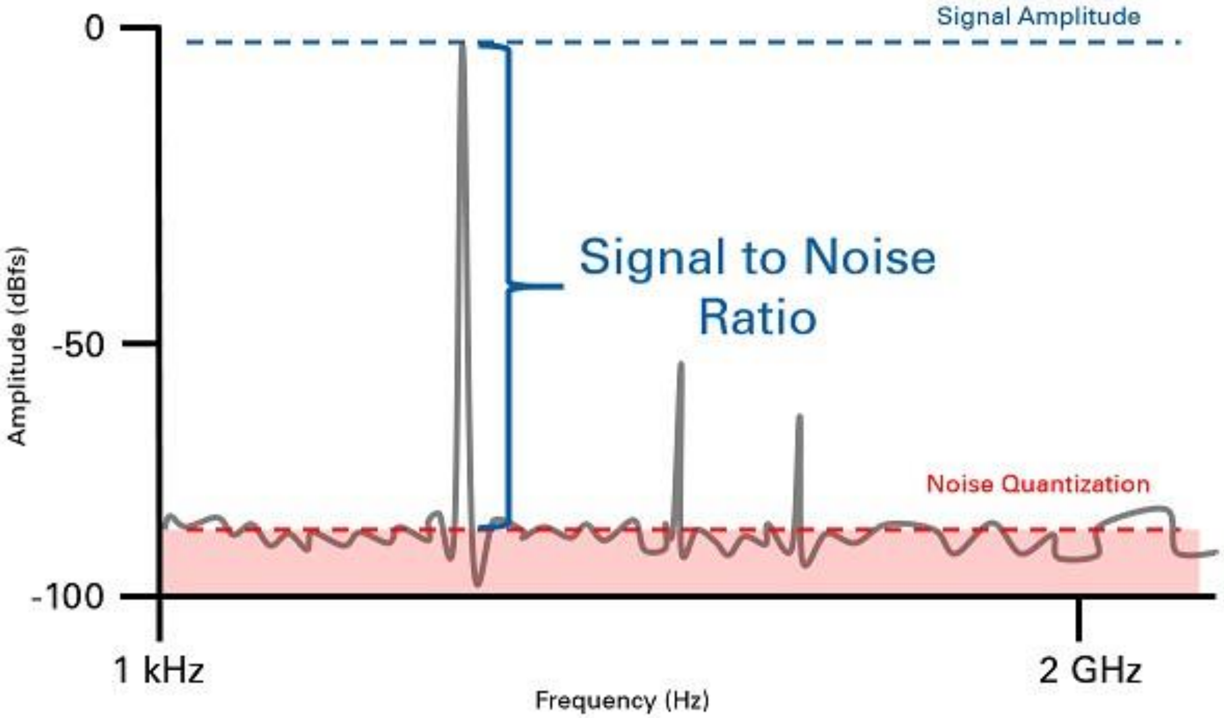


WHITE NOISE

White noise is a type of noise that has **equal power across all frequencies** within a given bandwidth.



SNR MEASUREMENT



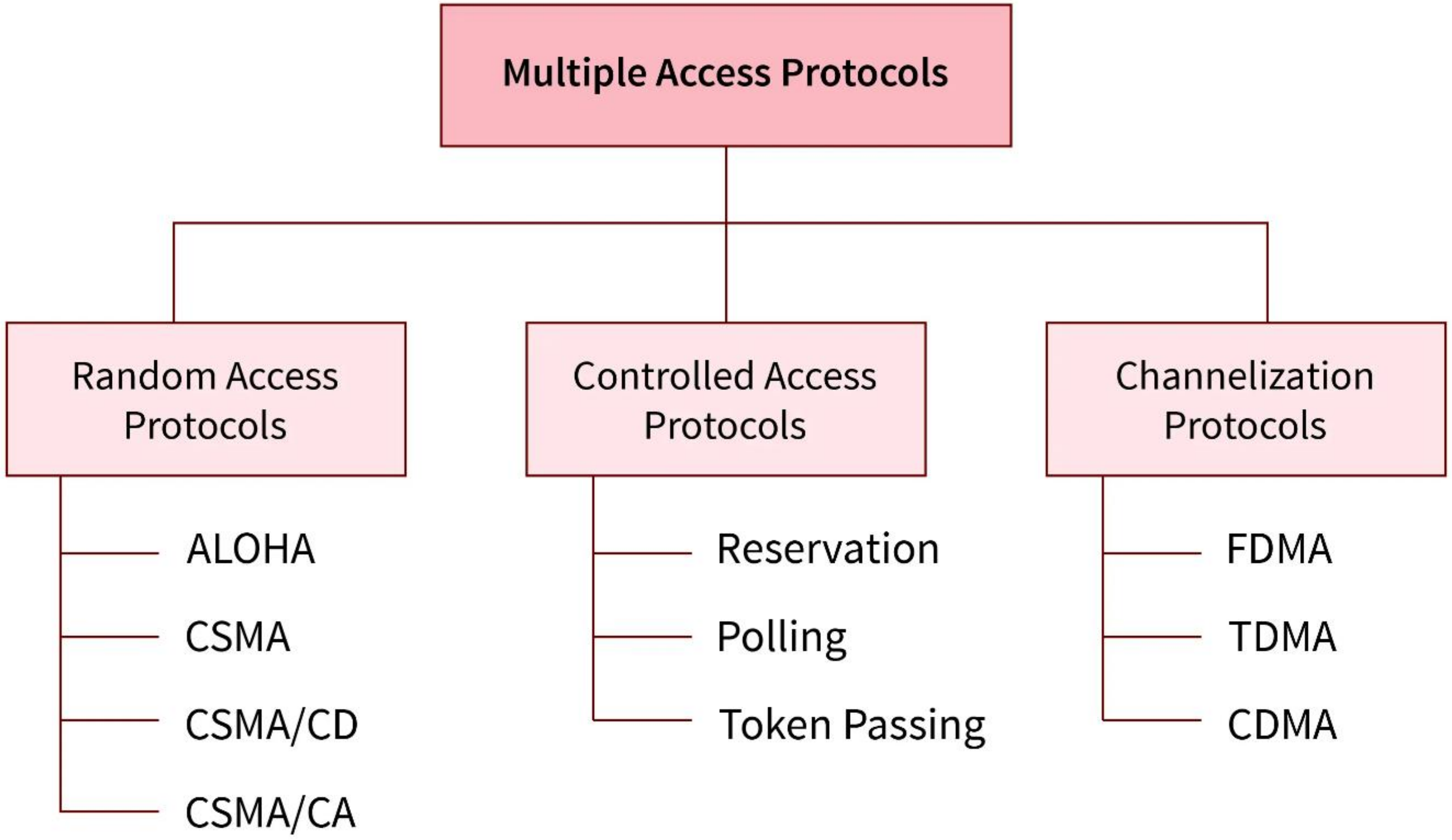
UNINTENTIONAL NOISE & INTERFERENCE

- **Atmospheric Noise**
  - Comes from **natural sources** (e.g., lightning, solar flares).
  - Affects lower frequency bands (especially **AM radio**).
- **Man-Made Noise**
  - Caused by **electrical devices**: motors, computers, fluorescent lights.
  - Usually **broadband** and varies with human activity.

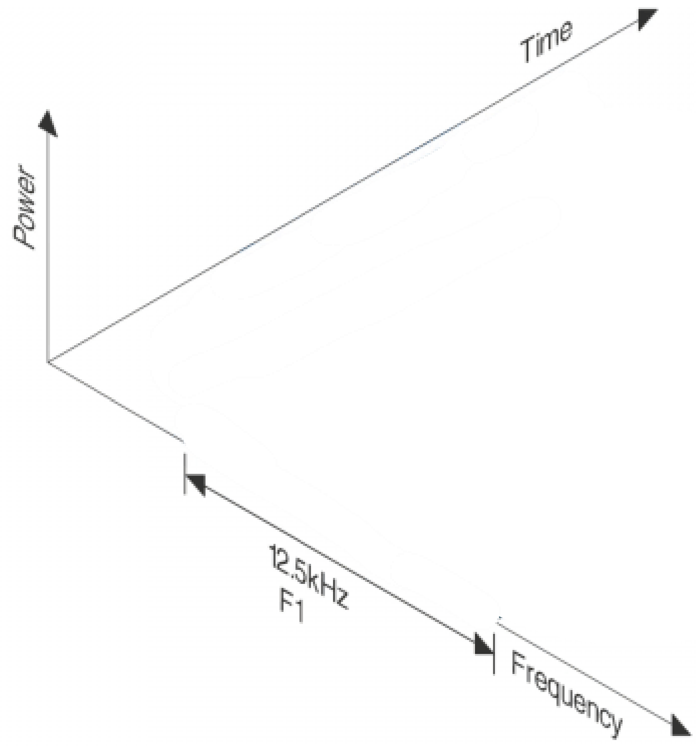
UNINTENTIONAL NOISE & INTERFERENCE

- **Multipath Fading**
  - Signal reflects off surfaces (buildings, terrain), causing **multiple paths**.
  - Signals can **cancel each other out** or reinforce.
  - Leads to **fading and distortion**.
- **Interference from Other Wireless Systems**
  - Caused by **co-channel** or **adjacent-channel** users.
  - Common in crowded bands like **2.4 GHz ISM**.

MULTIPLE ACCESS PROTOCOLS

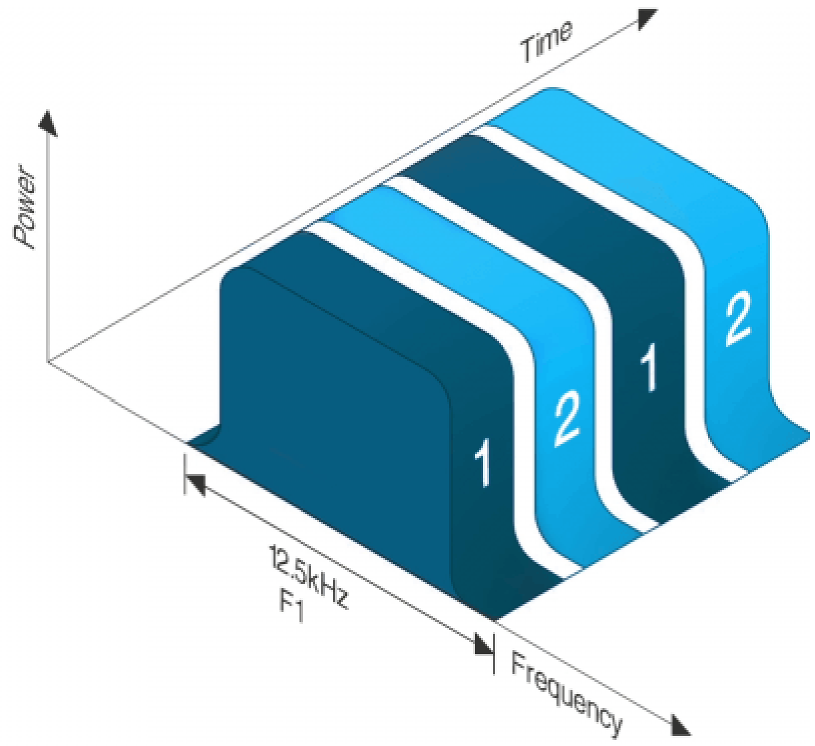


CHANNELIZATION PROTOCOLS



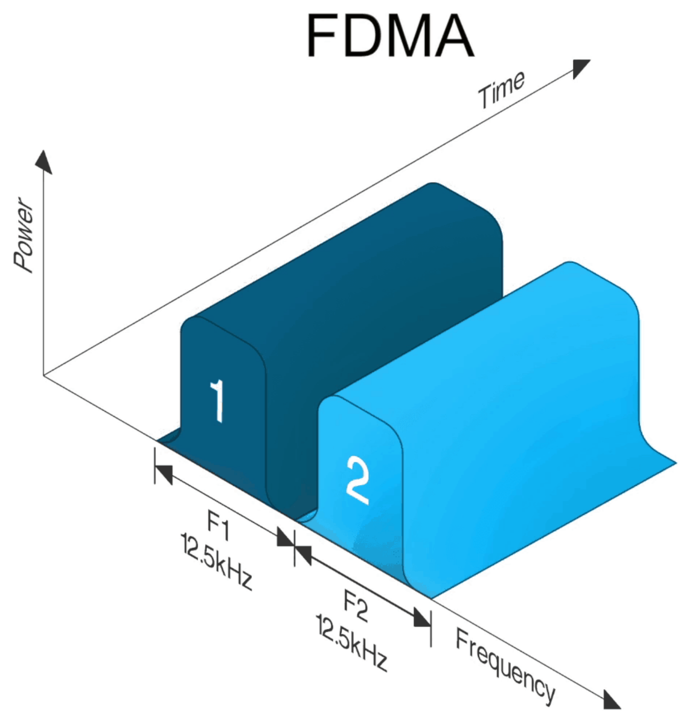
- TDMA
- FDMA
- CDMA
- SDMA
- OFDMA
- NOMA

TIME DIVISION MULTIPLE ACCESS



- Each user is allowed to transmit only within specified time intervals
- Different users transmit in differents time slots
- When users transmit, they occupy the whole frequency bandwidth

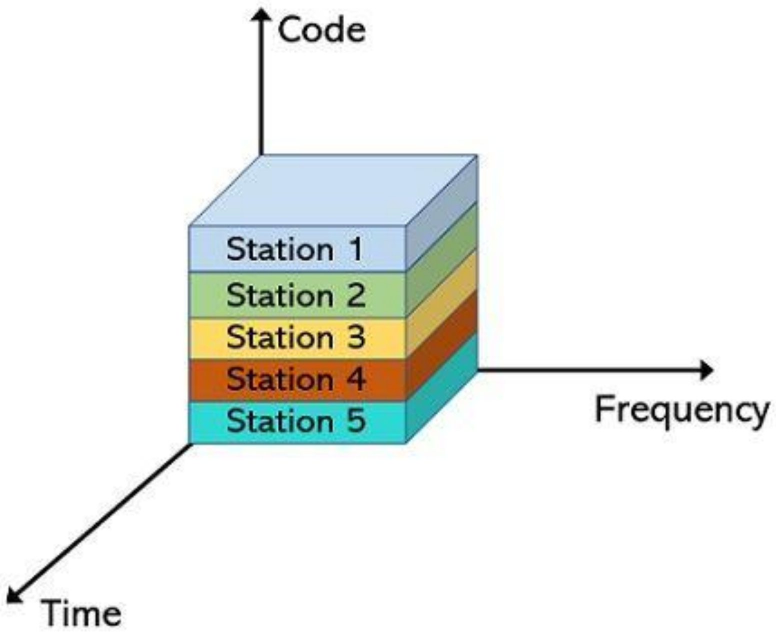
FREQUENCY DIVISION MULTIPLE ACCESS



- Each user transmits with no limitations in time, but using only a portion of the whole available frequency bandwidth.
- Different users are separated in the frequency domain.

CDMA

- **All users transmit simultaneously** — there is no time-slot division.
- CDMA stands for **Code Division Multiple Access**.
- Each user is assigned a **unique code**, which is used to encode and decode their signal.



CODE DIVISION

- Assume we have **4 stations** connected on the **same channel**
- The data to be sent are d_1, d_2, d_3, d_4 and the assigned codes are c_1, c_2, c_3, c_4
- Each station **multiplies its data by its unique code** before transmission
- All stations transmit their **coded signals at the same time** over the shared channel

$$d = d_1 \cdot c_1 + d_2 \cdot c_2 + d_3 \cdot 3 + d_4 \cdot c_4$$

ORTHOGONAL CODES

- If we **multiply each code with a different code**, the result is **0** (they are **orthogonal**).
- If we **multiply a code by itself**, the result is the **number of stations** (e.g., 4).
- When a station wants to receive data from another station:
  - It **multiplies the received signal** by the **sender's code**.
  - Then it **divides the result by the number of stations** to extract the original data.
- **Example**: Station 2 wants to receive data from Station 1
  - It uses **Code 1 (c_1)** to decode the received signal and retrieve **Data 1 (d_1)**.

$$
\begin{aligned}
&[(d_1 \cdot c_1 + d_2 \cdot c_2 + d_3 \cdot c_3 + d_4 \cdot c_4) \cdot c_1] / 4 \\
&= [d_1 \cdot c_1 \cdot c_1 + d_2 \cdot c_2 \cdot c_1 + d_3 \cdot c_3 \cdot c_1 + d_4 \cdot c_4 \cdot c_1] / 4 = (4 \times d_1) / 4 = d_1
\end{aligned}
$$

ORTHOGONAL CODES

- **CDMA** is based on **coding theory**, where signals are transmitted using unique codes.
- Each station is assigned a **code**, which is a **sequence of numbers**, called **chips**.
- **Orthogonal sequences** are used to ensure that different stations' signals do not interfere with each other.

C_1: [+1 +1 +1 +1]

C_2: [+1 −1 +1 −1]

C_3: [+1 +1 −1 −1]

C_4: [+1 −1 −1 +1]

ORTHOGONAL CODES

- **Each sequence consists of N elements** (where N = number of stations), and **N must be a power of 2** (e.g., 2, 4, 8, 16…).
- If we **multiply a sequence by a number**, each element of the sequence is multiplied by that number.

$$2 \times [+1, +1, -1, -1] = [+2, +2, -2, -2]$$

- If we **multiply two identical sequences** and sum the results, we get **N**, the number of elements in the sequence.

$$[+1, +1, -1, -1] \times [+1, +1, -1, -1] = 1 + 1 + 1 + 1 = 4$$

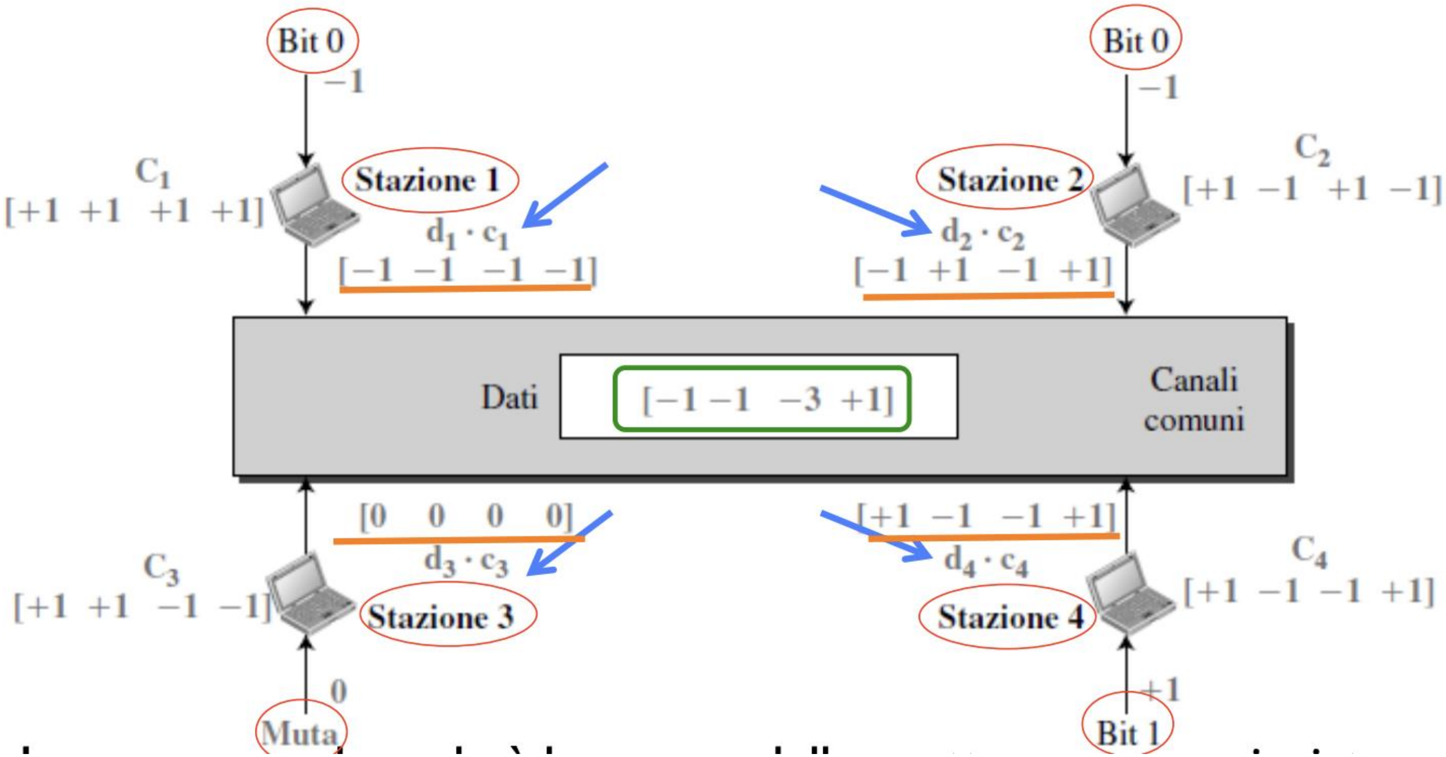
- If we **multiply two different sequences** and sum the results, we get **0**. This is known as the **inner product** of two different sequences.

$$[+1, +1, -1, -1] \times [+1, +1, +1, +1] = 1 + 1 - 1 - 1 = 0$$

- **Summing two sequences** means adding their corresponding elements together

$$[+1, +1, -1, -1] + [+1, +1, +1, +1] = [+2, +2, 0, 0]$$

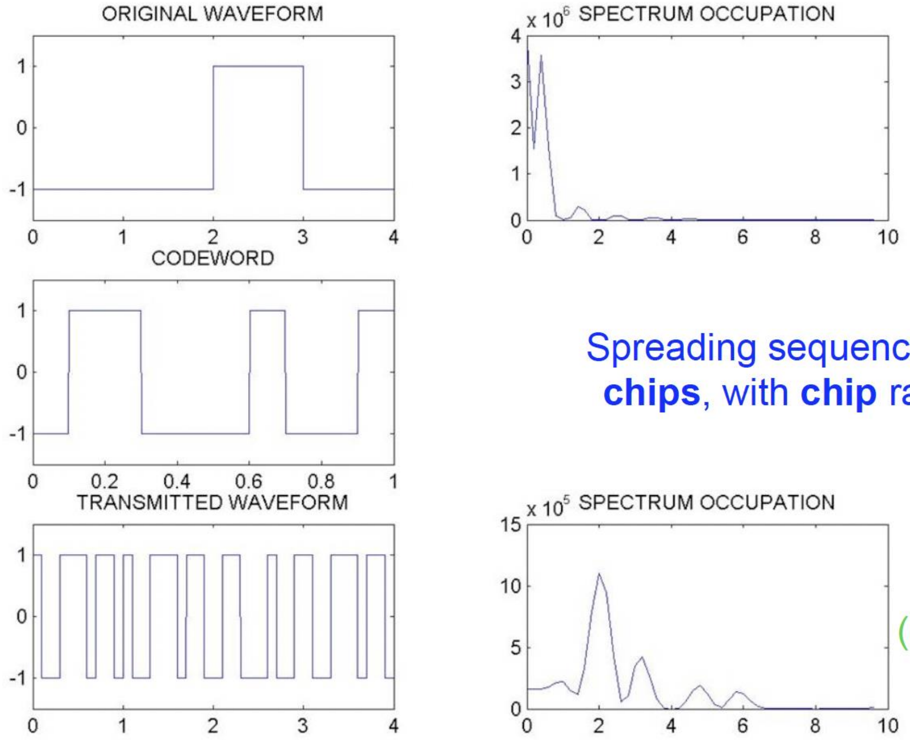
EXAMPLE



La sequenza sul canale è la somma delle quattro sequenze inviate dalle stazioni v La stazione 3 ascolta la 2

$$[-1\ -1\ -3\ +1] \cdot$$
$$[+1\ -1\ +1\ -1]$$
$$= -4\ /\ 4\ = -1 \rightarrow \text{bit } 0$$

SPREAD SPECTRUM



Original signal
(band related to the **bit** rate)

Spreading sequence composed by
chips, with **chip** rate >> **bit** rate

Coded signal
(band related to the **chip** rate)

SPREAD SPECTRUM MODULATION

- CDMA is based on spread-spectrum modulation.
- If multiple users transmit a spread-spectrum signal at the same time, the receiver will still be able to distinguish between users, provided that each user has a unique code that has a sufficiently low crosscorrelation with the other codes.

CDMA SCHEMES

- **Direct Sequence CDMA (DS-CDMA)**
- The original data signal is multiplied directly by the high chip rate spreading code.
- **Frequency Hopping CDMA (FH-CDMA)**
- The carrier frequency at which the original data signal is transmitted is rapidly changed according to the spreading code.
- **Time Hopping CDMA (TH-CDMA)**
- The original data signal is not transmitted continuously. Instead, the signal is transmitted in short bursts where the times of the bursts are decided by the spreading code.

JAMMING: INTENTIONAL NOISE & INTERFERENCE

- **Deliberate transmission** of radio signals to disrupt communication.
- Goal: **Degrade or deny** service by overpowering or interfering with legitimate signals.

- It happens when the jammer injects a signal which, when combined with the legitimate transmission, prevents the receiver from extracting the information contained in the legitimate transmission.

- Jamming can be surgical and affect only the message preamble thus preventing decoding, or can be comprehensive and aim to affect every symbol in the transmission

NOISE JAMMERS

- Flood the channel with random noise to drown out the real signal.
- **Broadband (Barrage) Jammer**
  - Jams **a wide frequency range** all at once.
  - Think of it as yelling across the whole room.
- **Narrowband Jammer**
  - Targets **a specific frequency** (e.g., Wi-Fi at 2.412 GHz).
  - More power-efficient and stealthy.
- **Spot Jammer**
  - Like narrowband but dynamically **tracks and jams specific channels**.

COUNTERMEASURES – ANTI-JAMMING TECHNIQUES

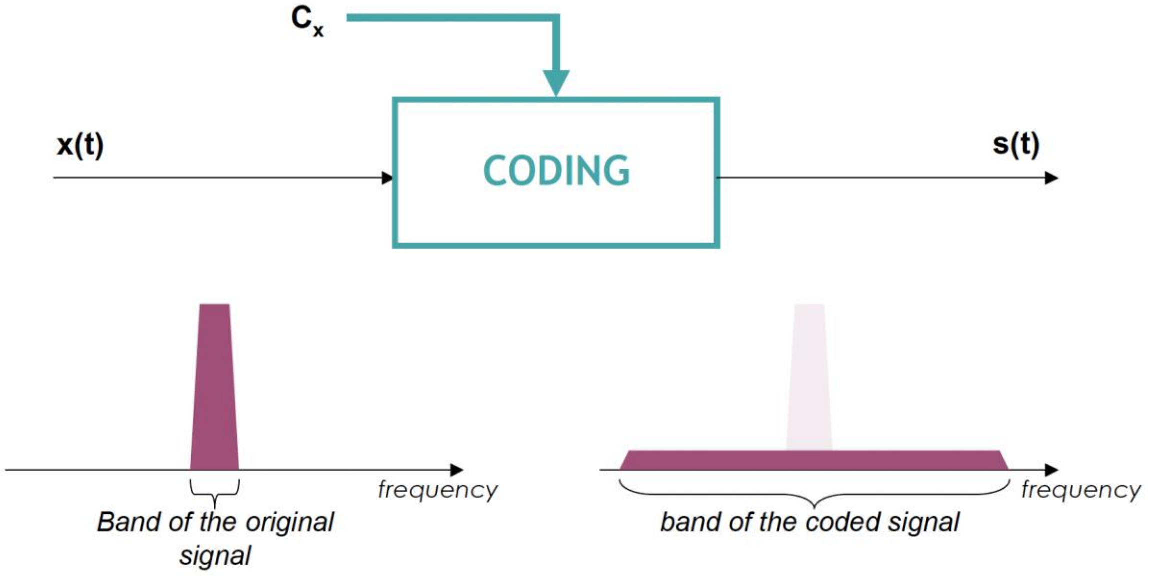
- Spread Spectrum (e.g., FHSS, DSSS)
- Error correction coding
- Directional antennas / beamforming
- Frequency hopping
- Signal detection and avoidance

SPREADING = HIDING THE SIGNAL

- Spread Spectrum **spreads a signal over a much wider bandwidth** than needed.
- Makes the signal look like **background noise** to anyone not synchronized.
- A jammer would need to **jam the entire wideband**, which is **power-hungry and inefficient**.
- Spread spectrum often uses **redundant encoding** (like error correction).

SPREAD SPECTRUM

- The bandwidth of the coded data signal is chosen to be much larger than the bandwidth of the original data signal, that is, the encoding process enlarges (spreads) the spectrum of the data signal.



COORDINATED SPREAD SPECTRUM

- Coordinated Spread Spectrum techniques *rely on pre-shared secret keys*
- They are used not only to increase resilience to jamming, but also to cope with interference from neighboring devices.
- Spreading is used in practically all wireless communication technologies, in e.g.,802.11, cellular, Bluetooth, global satellite positioning systems

UNCOORDINATED SPREAD SPECTRUM

- Jamming resilience in scenarios in which keys cannot be pre-shared (e.g., broadcast)
- Each device randomly selects frequency (or hopping sequence) and transmits data using its own spread method.
- Collisions are possible but **rare due to spreading** and random timing.
- Intelligent guessing (trial and error) and robust modulation schemes like **chirps**.

LAB R01 - FM RECEIVER LAB: SIGNAL, DEMODULATION & JAMMING

- **Receive FM Broadcast Signal**
  - Use SDR (Software Defined Radio) to capture real FM radio signals from the air.
- **Demodulate the Signal**
  - Convert the frequency-modulated signal into audio you can listen to.
  - Understand how the FM signal carries information (music, voice, etc.).
- **Observe the Spectrum**
  - Visualize the signal in the frequency domain using a spectrum analyzer.
  - Identify the FM carrier and its sidebands.
- **Introduce a Jammer**
  - The instructor introduced a jamming signal near or at the same frequency.
- **What Changes in the Spectrum?**
  - **Signal becomes distorted or disappears**
  - **Noise or spikes appear in the spectrum**
  - **Audio quality degrades or is lost**
  - Explore how interference impacts communication systems.

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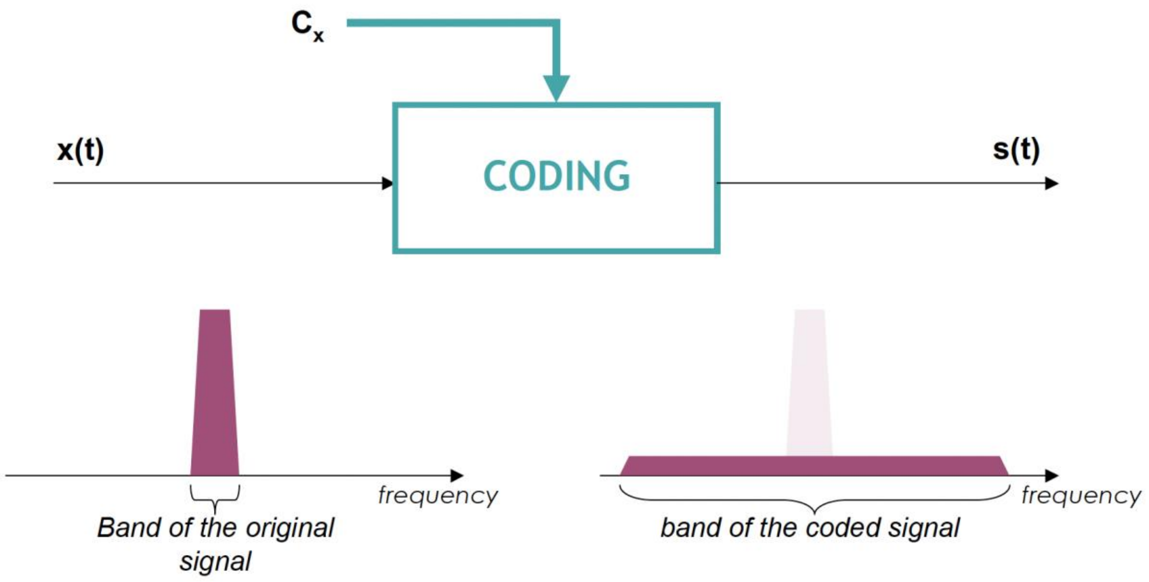
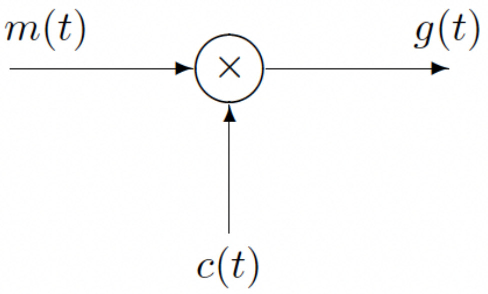


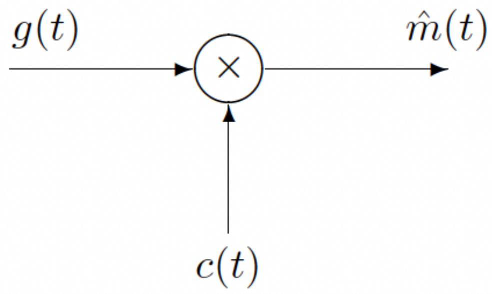
LAB R02 – SPREAD SPECTRUM

- Explain how spreading codes are used in direct sequence spread spectrum communication systems.
- Explain the importance of code synchronization in a spread spectrum communication system.
- Simulate a direct sequence spread spectrum communication system.
- Simulate a multi-user communication system that uses code-division multiplexing.

This laboratory concerns direct sequence spread spectrum (DSSS) communication systems. We will consider the baseband modulator (transmitter) given by the following block diagram



where $m(t)$ is the message signal and $c(t)$ is the spreading signal. The baseband demodulator (receiver) is given by the following block diagram

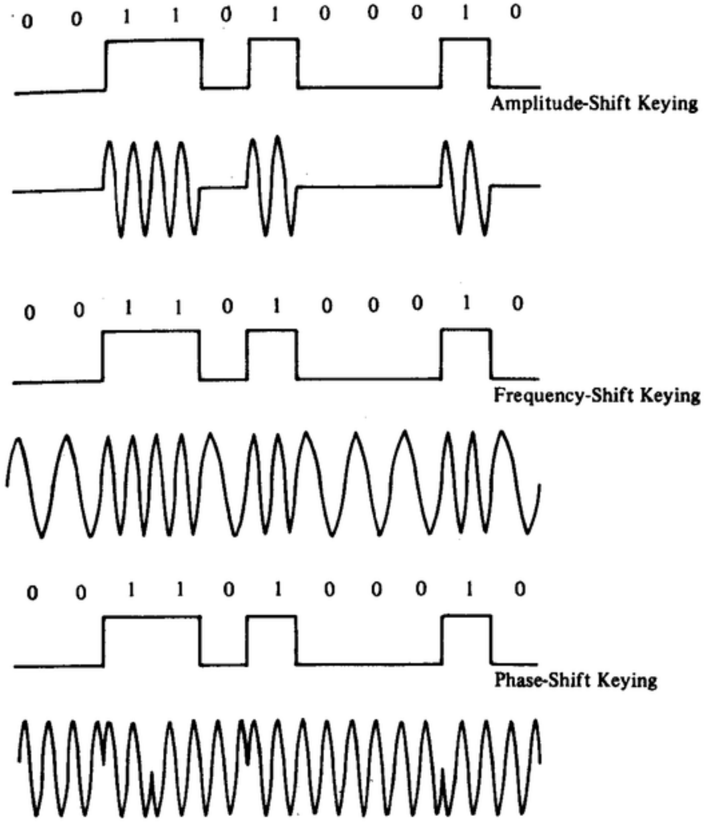


We will consider DSSS systems described as follows:

- The message signal $m(t)$ represents binary digital information and encodes the message bits as having values ± 1 over the bit interval, T_b. Therefore, $m(t)$ is the complex envelope of a BPSK communication signal.

SINGLE CARRIER MODULATION

0 0 1 1 0 1 0 0 0 1 0



$$A(t) \cdot \cos[2\pi f t + \varphi(t)]$$

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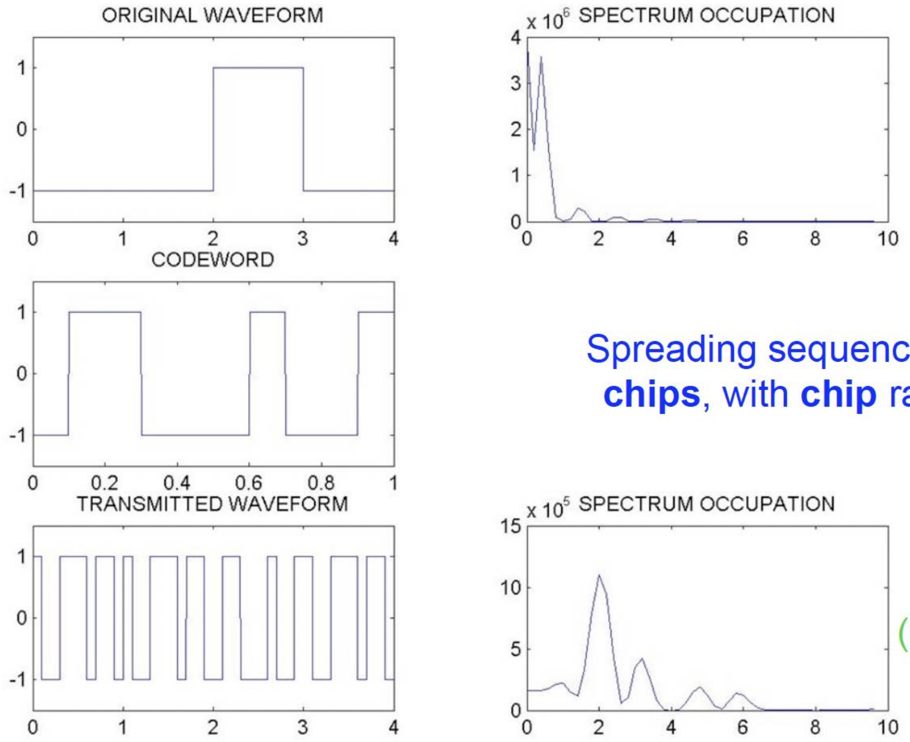
- The spreading waveform $c(t)$ has values ± 1 over the chip interval, T_c. The sequence of values in $c(t)$ is given by a pseudo-noise (PN) code of length M. We define $c(t)$ to be a periodic repetition of the PN sequence, and therefore $c(t)$ has period MT_c.



Original signal
(band related to the **bit** rate)

Spreading sequence composed by
chips, with **chip** rate >> **bit** rate

Coded signal
(band related to the **chip** rate)

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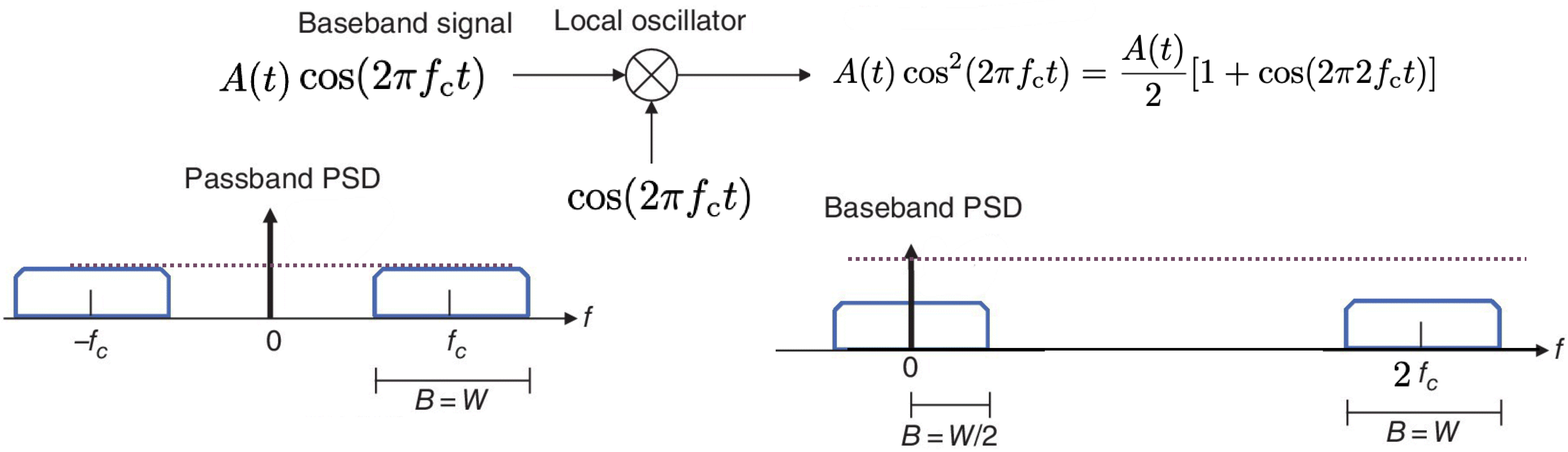
- The spreading waveform $c(t)$ has values ± 1 over the chip interval, T_c. The sequence of values in $c(t)$ is given by a pseudo-noise (PN) code of length M. We define $c(t)$ to be a periodic repetition of the PN sequence, and therefore $c(t)$ has period MT_c.
- We will assume $T_c << T_b$. That is, the chip rate $R_c = 1/T_c$ is much higher than the bit rate $R_b = 1/T_b$. The multiplication by $c(t)$ in the modulator causes a *spreading* of the message signal spectrum. We define the spreading factor, L, to be

$$L = \frac{R_c}{R_b} \tag{1}$$

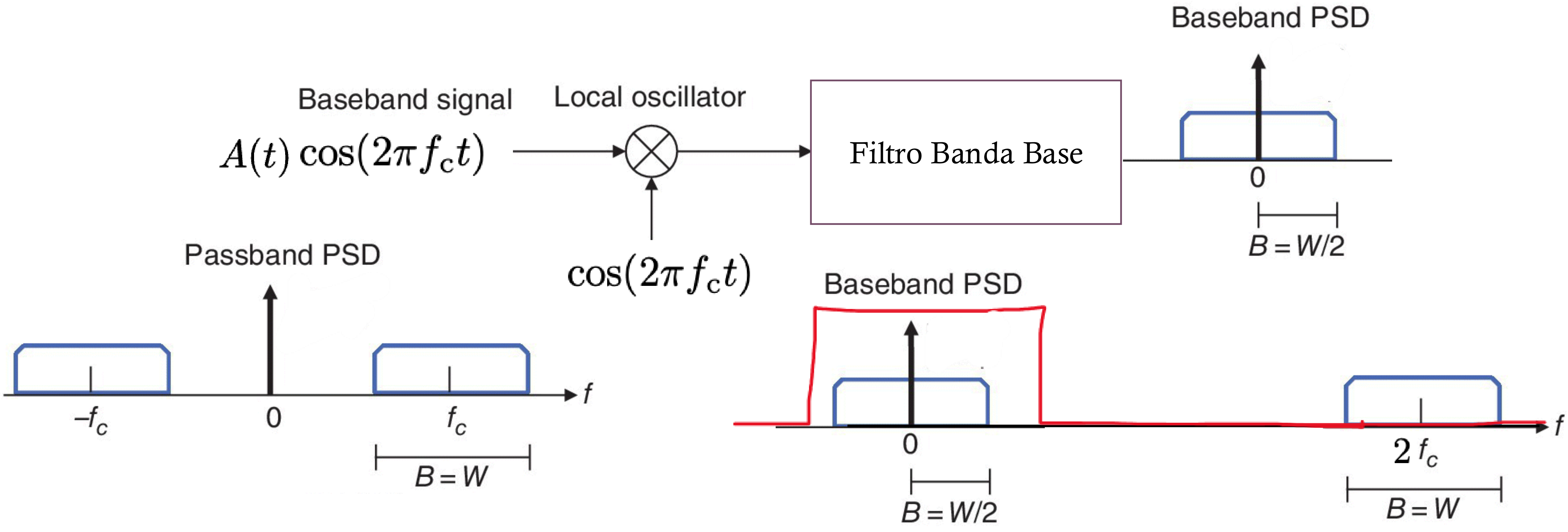
- Because both $m(t)$ and $c(t)$ have values ± 1, $g(t)$ also has values ± 1. Therefore, we can consider $g(t)$ to be the complex envelope of a BSPK communication signal. The passband communication signal can then be expressed as

$$
\begin{aligned}
s(t) &= \Re\{g(t)e^{j2\pi f_c t}\} \\
&= m(t)c(t)\cos(2\pi f_c t)
\end{aligned}
$$

SINGLE CARRIER DEMODULATION



SINGLE CARRIER DEMODULATION



- Because both $m(t)$ and $c(t)$ have values ± 1, $g(t)$ also has values ± 1. Therefore, we can consider $g(t)$ to be the complex envelope of a BSPK communication signal. The passband communication signal can then be expressed as

$$\begin{aligned} s(t) &= \Re\{g(t)e^{j2\pi f_c t}\} \\ &= m(t)c(t)\cos(2\pi f_c t) \end{aligned}$$

- Note that the output of the multiplier in the receiver is

$$\begin{aligned} \hat{m}(t) &= g(t)c(t) \\ &= m(t)c^2(t) \\ &= m(t) \end{aligned}$$

since the spreading waveform $c(t)$ takes on values ± 1. The multiplication in the receiver is often referred to as a *despreading* operation.

Question 2.1: Based on the parameters specified in Step 1 above, what is the spreading factor of the DSSS system?

Question 2.2: Use MATLAB to compute the autocorrelation function for the sequence given in Step 2 above. Comment on the properties of the autocorrelation function. Does the sequence exhibit desirable properties for use in a DSSS communication system? Submit your MATLAB code and plot of the autocorrelation function.

Question 2.3: In the `DSSS BPSK Transmitter`, connect a **Spectrum Analyzer** block to the BPSK message waveform $m(t)$ and the spread waveform $m(t)c(t)$. Submit a screen capture. Measure the bandwidth of each signal. Do these bandwidth measurements agree with the spreading factor of the DSSS system? *Hint:* Measure the bandwidth as the frequency of the first spectral null.

Question 2.4: In the `DSSS BPSK Receiver`, connect a **Time Scope** and **Spectrum Analyzer** block to the recovered message waveform (output of the **Product** block). Carefully examine these plots as you adjust the `Delay length` parameter of the **Delay** block. You should observe that the receiver properly recovers the message signal when the `Delay length` parameter is 0. Describe what happens to the recovered message when the `Delay length` parameter is 1. Describe what happens when the `Delay length` parameter is 16. Explain the results.

DSSS FOR CDMA

- Spread spectrum techniques can be used to transmit multiple message signals simultaneously in the same frequency band.
- Such techniques, referred to as code-division multiplexing (CDM), are often used in mobile phone communications. This form of multiplexing is made possible by assigning each user a unique spreading code from a set of codes.
- Then, multiple spread-spectrum signals can be transmitted in the same frequency band, and the messages can be decoded at each receiver using the unique (and properly synchronized) spreading code.
- In this way, the larger bandwidth used by spread-spectrum systems is o set by allowing multiple users to simultaneously access the frequency band.

DSSS FOR CDMA

- One of the best-known sets of spreading codes used in CDM systems are the Walsh-Hadamard codes.
- These particular codes have the desirable property that they are mutually orthogonal. That is, when properly synchronized, the correlation between any one code and any other code is exactly zero.

$$H_8 \quad = \quad \begin{bmatrix} +1 & +1 & +1 & +1 & +1 & +1 & +1 & +1 \\ +1 & -1 & +1 & -1 & +1 & -1 & +1 & -1 \\ +1 & +1 & -1 & -1 & +1 & +1 & -1 & -1 \\ +1 & -1 & -1 & +1 & +1 & -1 & -1 & +1 \\ +1 & +1 & +1 & +1 & -1 & -1 & -1 & -1 \\ +1 & -1 & +1 & -1 & -1 & +1 & -1 & +1 \\ +1 & +1 & -1 & -1 & -1 & -1 & +1 & +1 \\ +1 & -1 & -1 & +1 & -1 & +1 & +1 & -1 \end{bmatrix}$$

LAB QUESTIONS FOR CDMA

- Question 3.1: In the Transmitter, use Time Scope and Spectrum Analyzer blocks to observe the inputs to and the output of the Add block. That is, observe the User 1 and User 2 DSSS signals, and their sum. Include screen captures and comment on what you observe. In particular, comment on the signal bandwidths.

- Question 3.2: Use a Time Scope block to display the User 1 and User 2 messages in the transmitter, and the User 1 and User 2 messages recovered in the receiver. Submit screen captures for simulations where the AWGN noise variance is 0, 1, and 10. Comment on the results.

- Question 3.3: Repeat the previous problem, however now change the User 2 Receiver sequence to [1 -1 1 -1 -1 1 -1 1]