DDS for 5G/6G Cellular Network Calibration and Ranging

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Agenda

- Intro: **Abdelrahman Khaled Fouad Abdelrahim**
- DDS: **Ahmed Hossam Rafik Elgamal**
- OFDM 1sT part: **Moustafa Saad Dawood**
- OFDM 2nd part: **Mohamed Adel Abdelrahem**
- Chirp and TDM: **Ahmed Haitham Othman Othman**
- FDM and overlapping BW: **Youssef Mohamed Mamdouh**
- FFT, IFFT & conclusion: **Mohamed Ahmed Mohamed Hussein**

Intro:
Abdelrahman Khaled Fouad

Main idea of the project

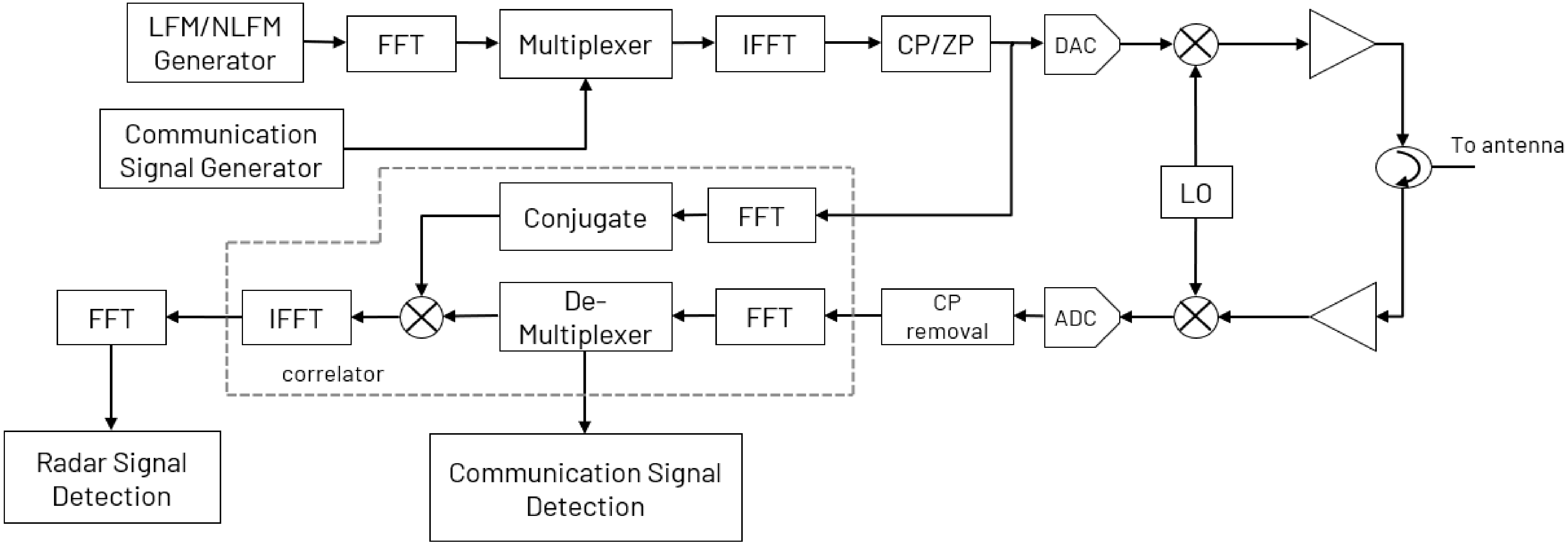
- **What is DDS ?**
  - Direct Digital Synthesis (DDS) is a digital technique used to generate precise analog waveforms—most commonly sine waves—using digital circuitry.
- **Key points:**
  - Uses a fixed reference clock and digital processing to generate output signals Provides fine frequency, phase, and amplitude control.
  - Enables fast frequency switching with high resolution.
  - Commonly implemented using: Phase accumulator and Lookup table (LUT).
- **Digital-to-Analog Converter (DAC) Applications:**
  - Signal generators.
  - Communication systems.
  - Radar and instrumentation.

Main idea of the project

- **DDS in ISAC** Systems Integrated Sensing and Communication (ISAC) combines wireless communication and sensing (e.g., radar) using shared hardware and signals.
- **Role of DDS in ISAC:**
  - Generates highly stable and agile waveforms for both sensing and communication
  - Supports frequency hopping and phase-coherent signals, essential for radar sensing
  - Enables flexible waveform design, allowing one system to serve dual purposes
  - Improves spectral efficiency and reduces hardware complexity
- **Why DDS is important for ISAC**:
  - Precise control → accurate sensing
  - Fast reconfigurability → adaptive communication
  - Digital implementation → easy integration with modern DSP systems

ISAC block diagram

Integrated sensing and communication



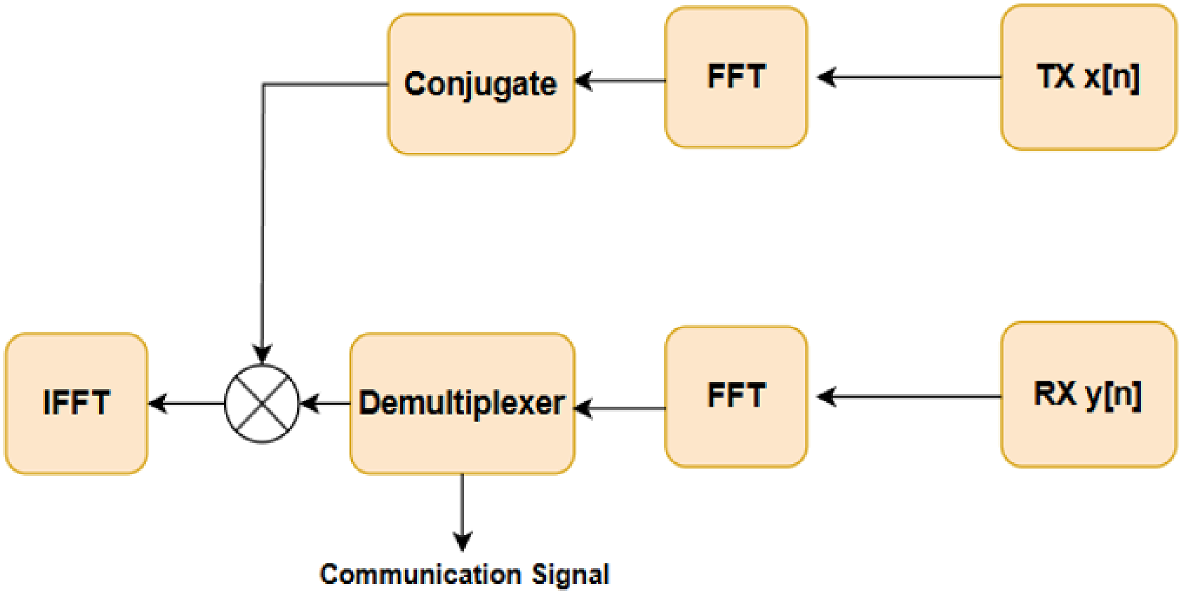
What are we going to implement

- FFT
- IFFT
- DDS “direct digital synthesis’ or “LFM generator”
- Correlator
- we have studied the main concepts in communication and sensing, learned about the DDS and intend to do its modeling, RTL design, verification and ASIC implementation if there is enough time.

Correlator

Implementation follows a specific digital signal processing sequence:

- **Reference Branch:** Takes the digital signal post-IFFT, applies an **FFT and** then performs a **Conjugate** operation.
- **Signal Branch:** Receives the echo signal and applies an **FFT**.
- **Mixing:** The two signals are multiplied in the frequency domain.
- **Time-Domain Conversion:** An **IFFT** is applied to the product to generate the correlation peak In the time domain for detection.



$$R_{xy}[m] = \sum_{n=0}^{N-1} x^*[n]y[n+m] \iff R_{xy}[n] = \mathrm{IFFT}\left\{\mathrm{FFT}(x[n])^* \cdot \mathrm{FFT}(y[n])\right\}$$

DDS:
Ahmed Hossam Rafik

DDS simple block diagram

- DDS is a digital method to create any desired frequency based on single stable master clock.

Pros	Cons
Extremely fine controllability	Spurious Emissions
Instant frequency change	Power Consumption at High Speeds
Phase continuity	Bandwidth Limitation

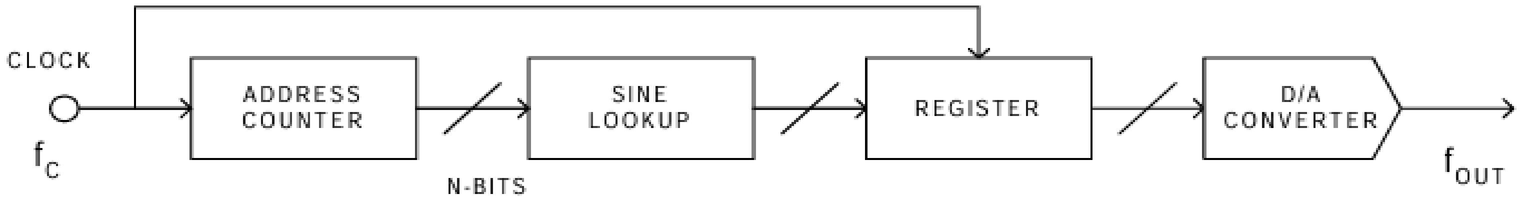
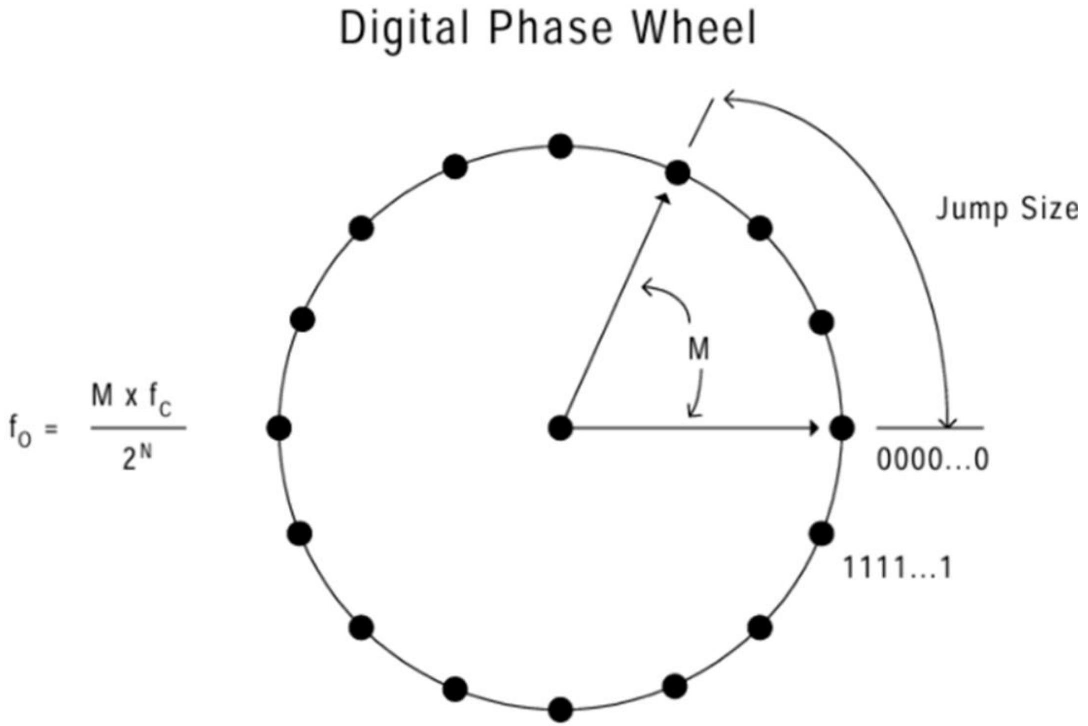


Figure 1-1. Simple Direct Digital Synthesizer

DDS simple block diagram



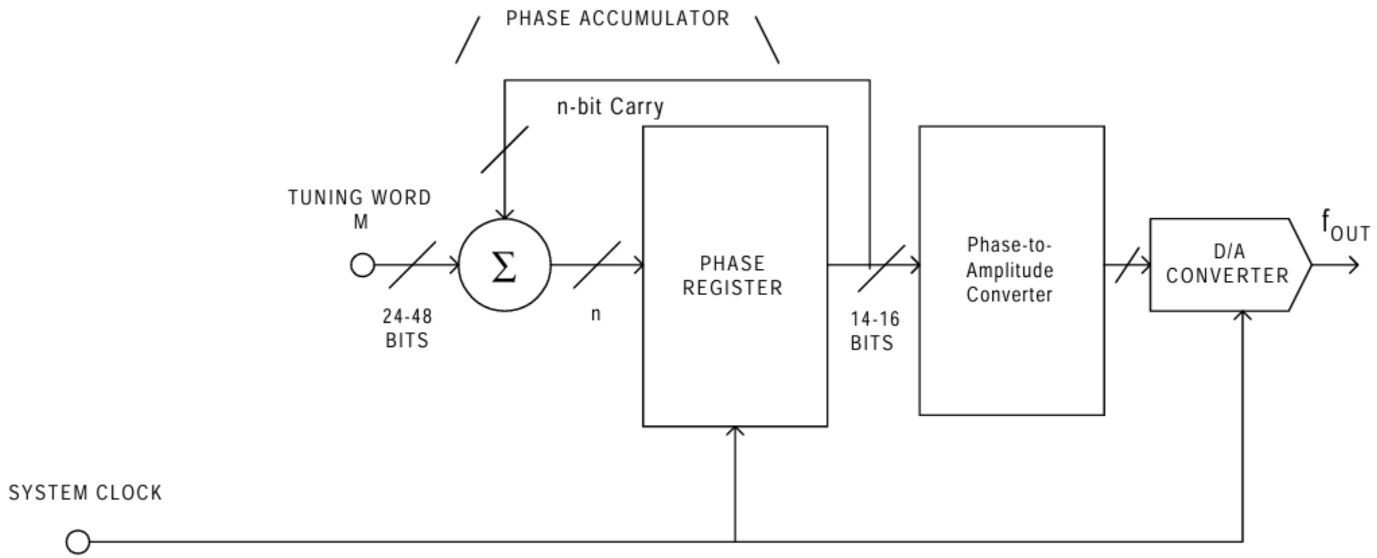


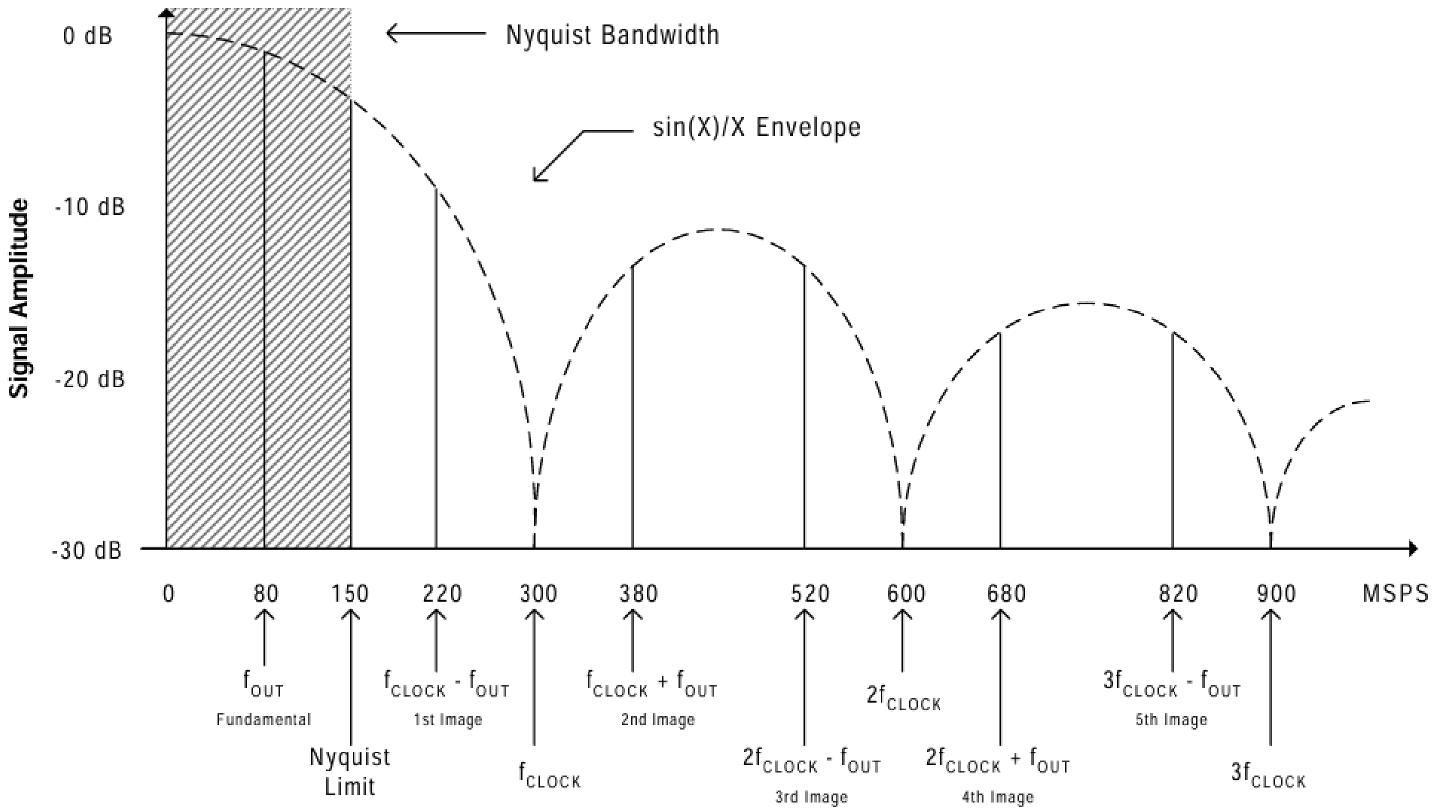
Figure 1-2. Frequency-tunable DDS System

DDS sampled output

- A DDS works by sending digital samples of a sine wave (from the lookup table) to a DAC.
- Each clock pulse produces one sample → that means the output is discrete in time, not continuous.

- **Theoretical** maximum output frequency is half the clock frequency (fclk/ 2).

- **Practical Reality:** In the real world, you can only use about **33%** of the clock frequency



DDS sampled output from ADI tool

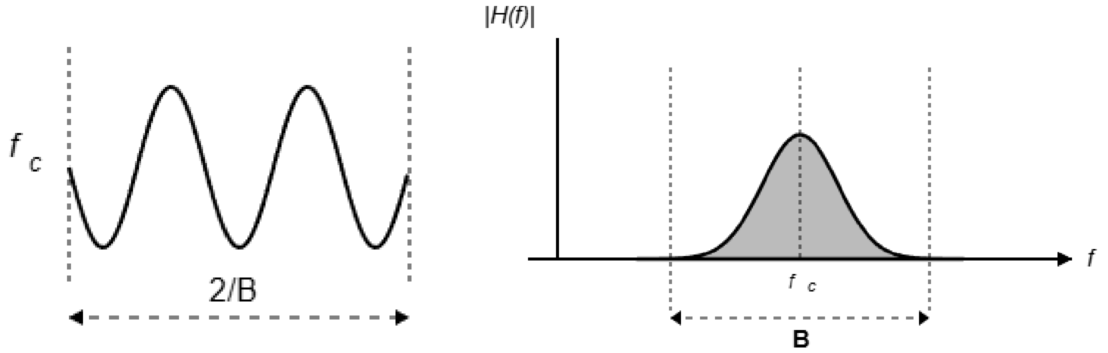
OFDM 1st part:
Moustafa Saad Dawood

Main concepts “OFDM”

- OFDM, or Orthogonal Frequency Division Multiplexing, is a key digital communication scheme. It functions as both:
  1. **A Modulation Technique:** It transmits data over many closely spaced, orthogonal subcarriers to Solve the problem of frequency-selective fading.
  2. **A Multiplexing Technique:** It efficiently shares the channel's time and frequency resources among multiple data streams or users

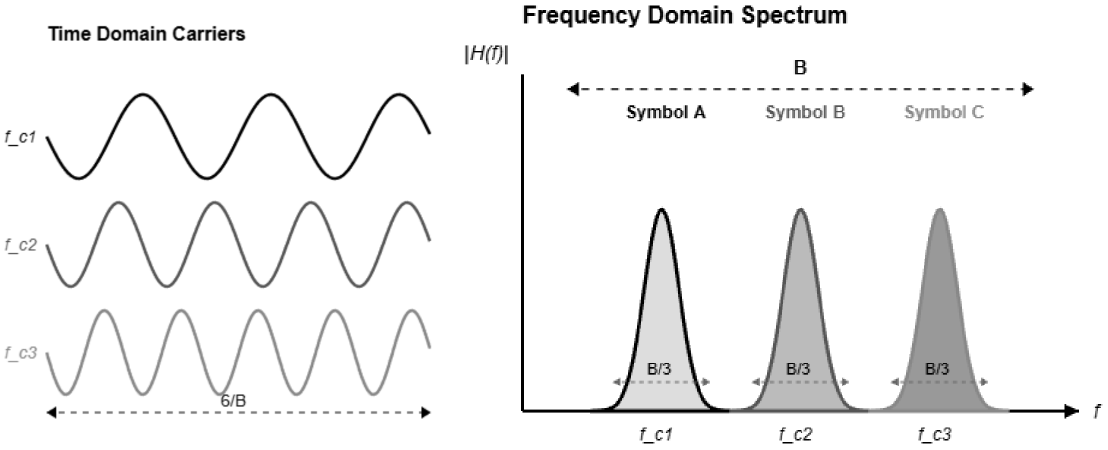
- **Problem -** Frequency-Selective Fading**:**
  - In time domain, the channel has a multi-path **impulse response**.
  - Convolution of a fast signal with this response causes **Inter-Symbol Interference (ISI)**.
  - Symbol energy disperses, smearing into neighboring time slots.

- **Old Solution** - Low Data Rate**:**
  - Use a slow, narrowband signal where symbol duration **>>** channel delay spread.
  - Channel appears **flat** across this narrow bandwidth.
  - Pro: Simple single-tap equalizer suffices.
  - Con: Very low spectral efficiency (wastes bandwidth)



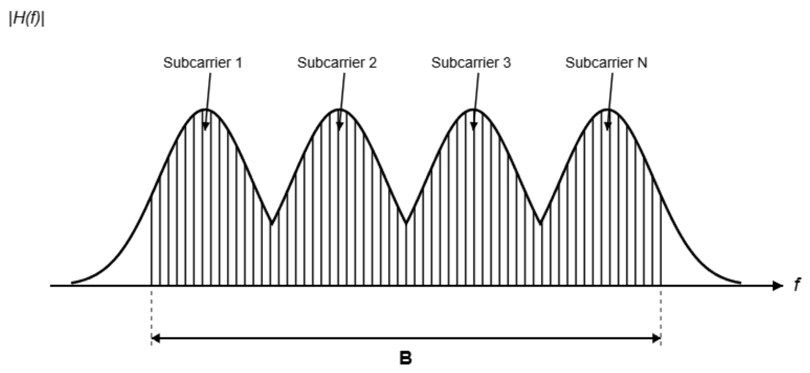
Multi-Carrier Modulation (MCM)

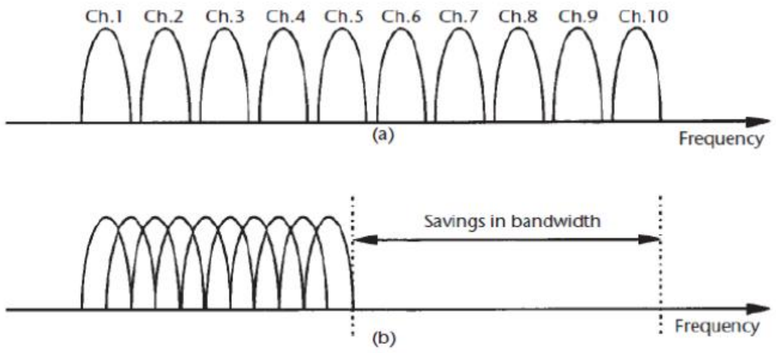
Multi-Carrier Modulation (MCM) solves that problem by, instead of transmitting one fast symbol over a wide, distorted channel, transmitting many slow symbols in parallel over narrow, flat sub-channels

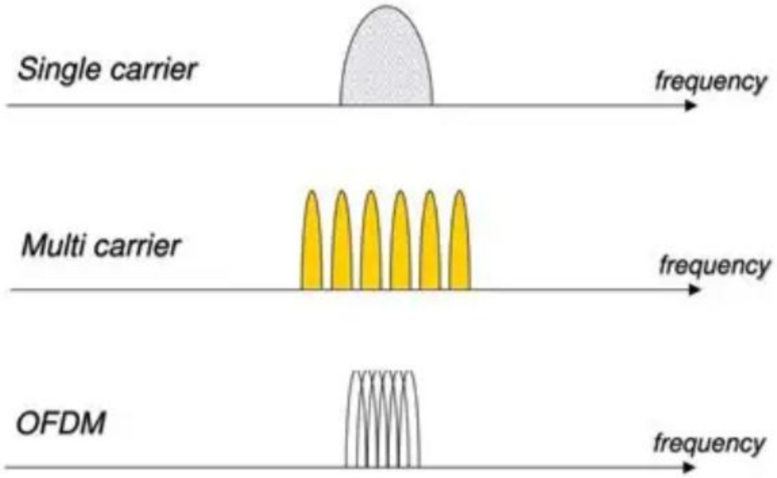


Main concepts “OFDM”

- A typical Multi-Carrier Modulation (MCM) system with guard bands doesn't save bandwidth. However, when we make the carriers **orthogonal**, we can pack them tightly without interference, which **saves significant bandwidth**.
- This is the **critical transition** from regular Frequency Division Multiplexing (FDM) to **Orthogonal** Frequency Division Multiplexing **(OFDM).** It's the "O" that makes the technology revolutionary.
- To ensure subcarriers don't interfere despite overlapping, they must satisfy $\Delta F = \frac{1}{T}$







Three Essential Requirements for Practical OFDM

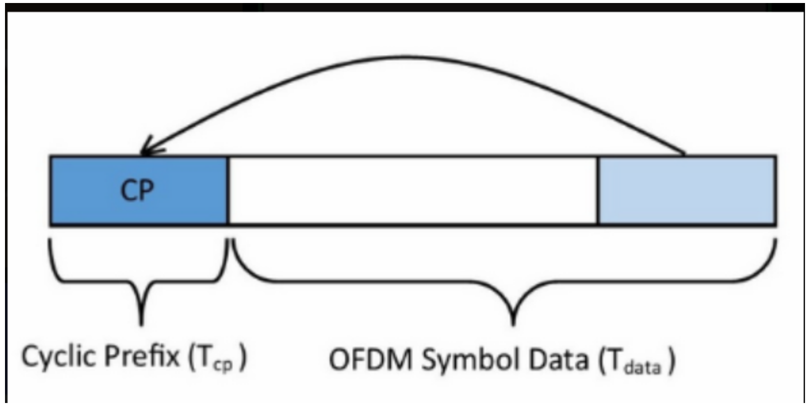
- **1. Orthogonal Subcarriers**
  - Subcarrier spacing: **Δf = 1/T**
  - Allows spectral overlap without interference.
  - Enables maximum bandwidth efficiency.
- **2. IFFT/FFT Implementation**
  - The OFDM signal equation is identical to an **Inverse Discrete Fourier Transform (IDFT)**.
  - Replaces banks of analog oscillators with a **single, efficient digital block**.
  - Makes the system practical and scalable.
- **3. Cyclic Prefix (CP)**
  - A guard period created by copying the **end of the symbol** to its **beginning**.
  - **Eliminates Inter-Symbol Interference (ISI)** from multipath delay.
  - Turns channel convolution into a **circular** form, enabling simple **one-tap frequency-domain equalization**

Cyclic Prefix in OFDM

- The Cyclic Prefix is a **copy of the end of an OFDM symbol** placed at its beginning.

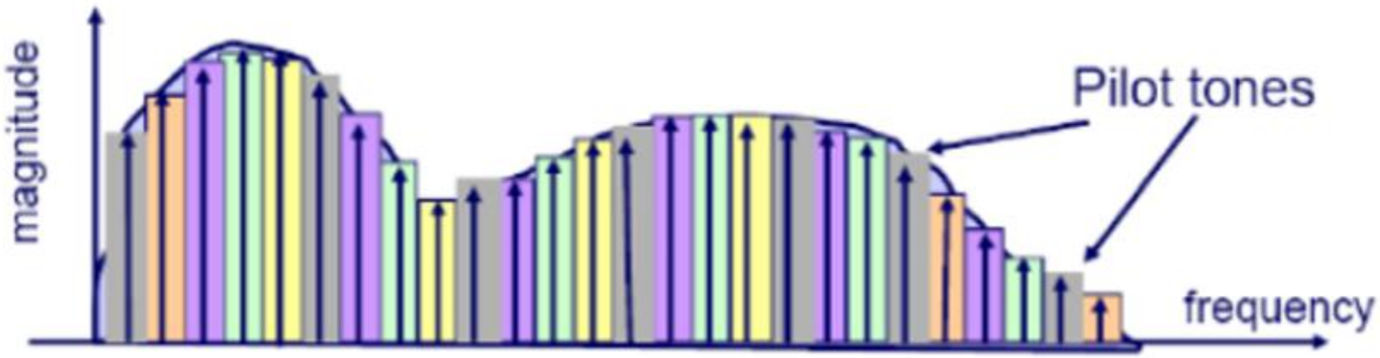
Its main jobs are:

- **Combat Inter-Symbol Interference (ISI):** It acts as a sacrificial buffer against signal echoes (multipath) from the previous symbol.
- **Maintain Orthogonality:** It helps preserve the mathematical orthogonality between subcarriers, preventing Inter-Carrier Interference (ICI).
- IT eliminates ISI but increased the length so decreased the Data rate



Pilot Tones in OFDM

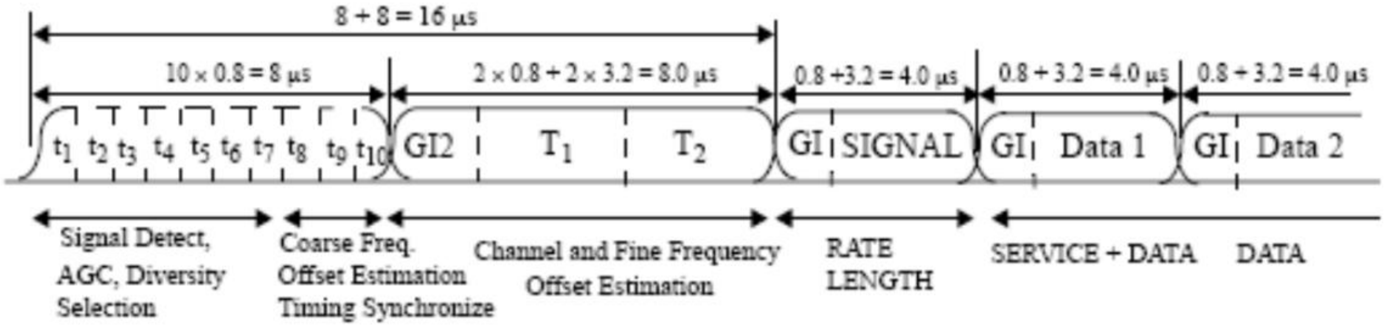
- Specific subcarriers reserved for transmitting **known reference symbols**
- Inserted at regular intervals in time and frequency



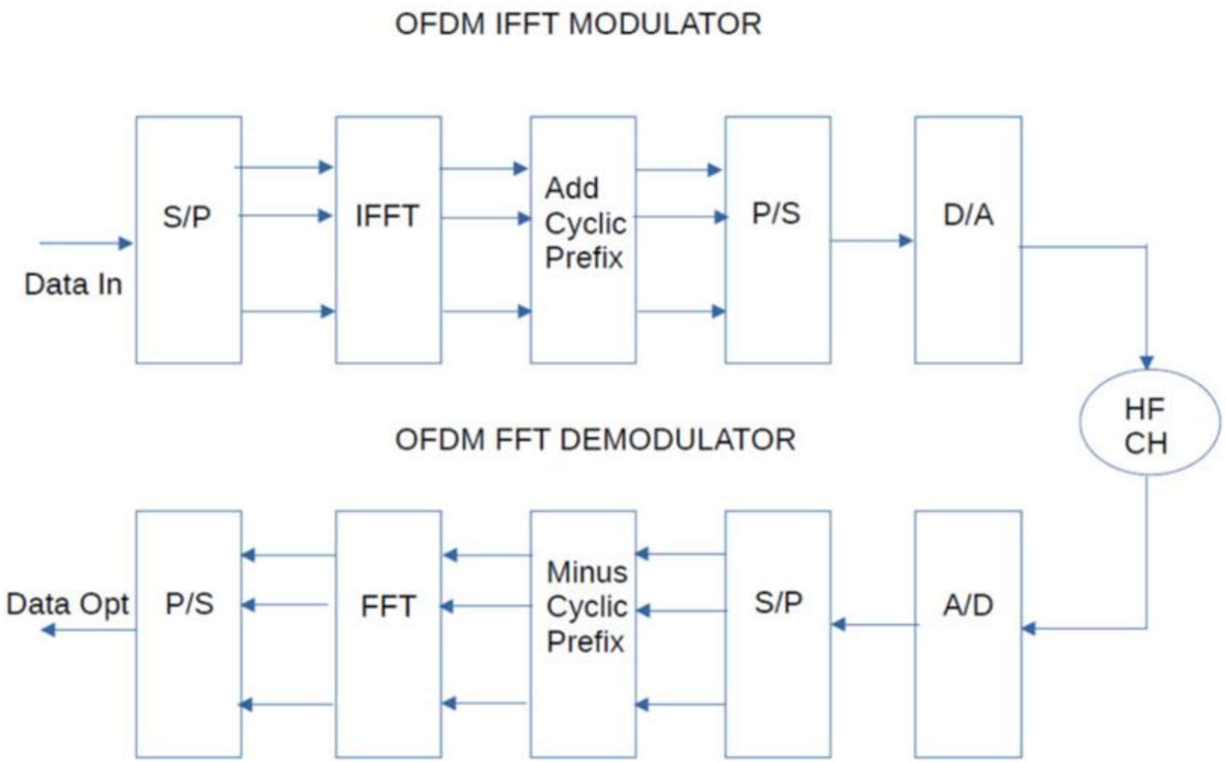
OFDM Frame Structure

- **Three Main Parts:**

1. **Preamble** – Synchronization & Initial Estimation
2. **Signal Field** – Frame Control Information
3. **Data Field** – Payload with Embedded Pilots



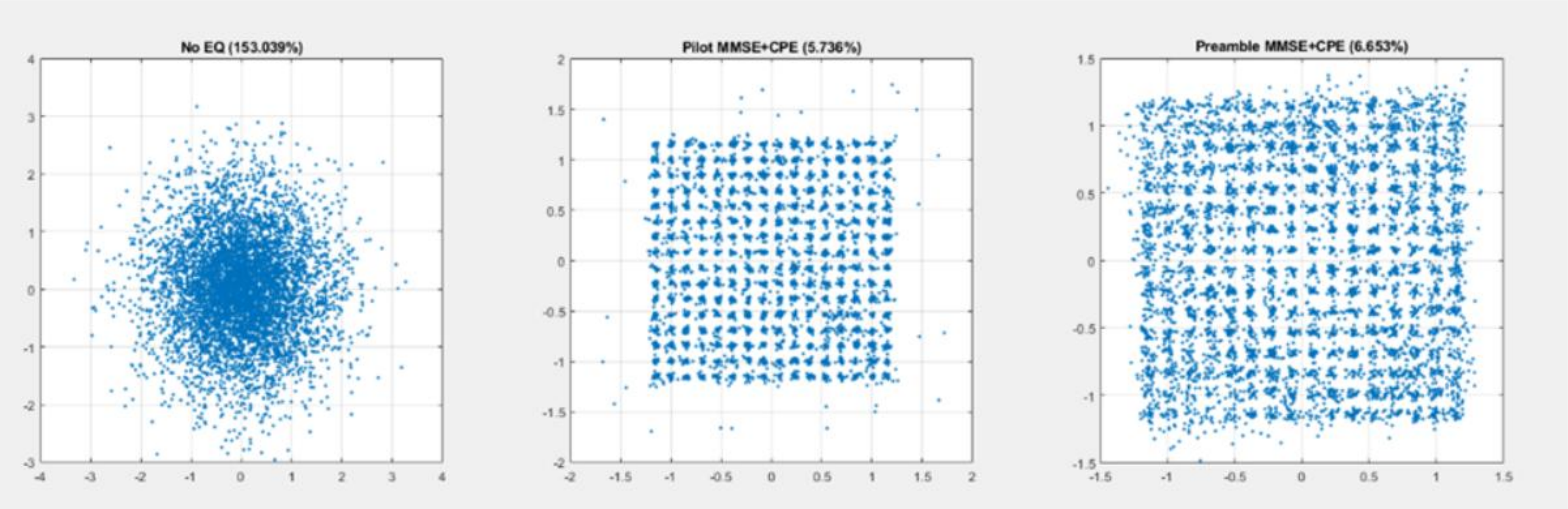
OFDM diagram



OFDM 2nd part:
Mohamed Adel Abdelrahem

Main concepts “EVM in OFDM”

- Error vector magnitude is the distance of the received wrong point in constellation diagram from the correct one.

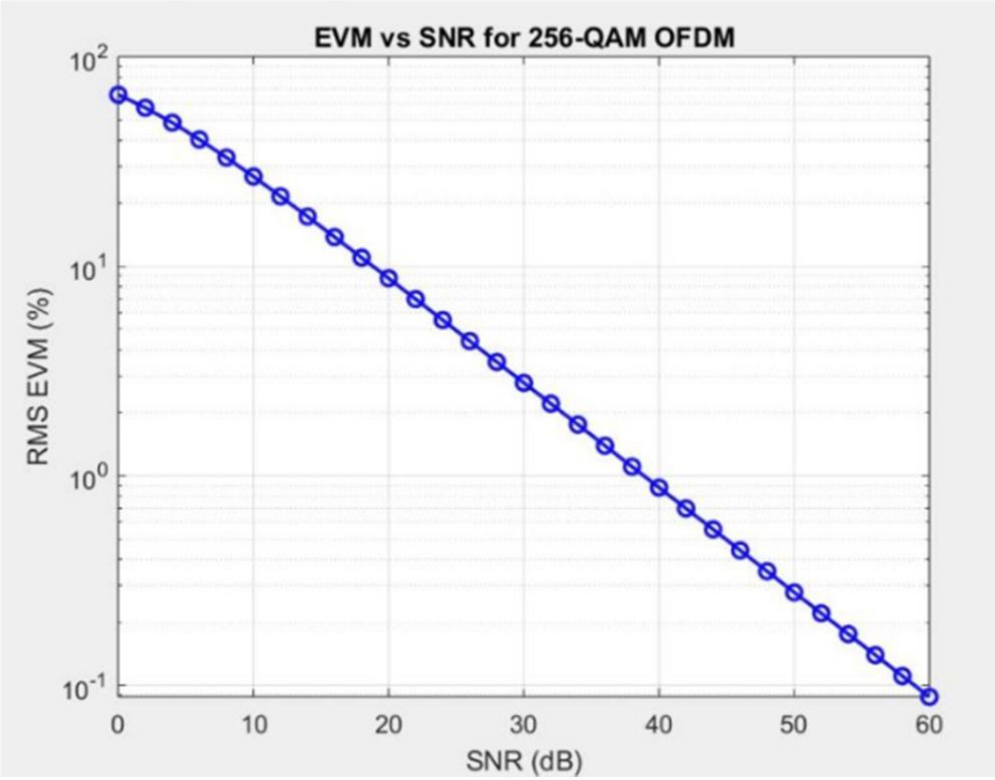


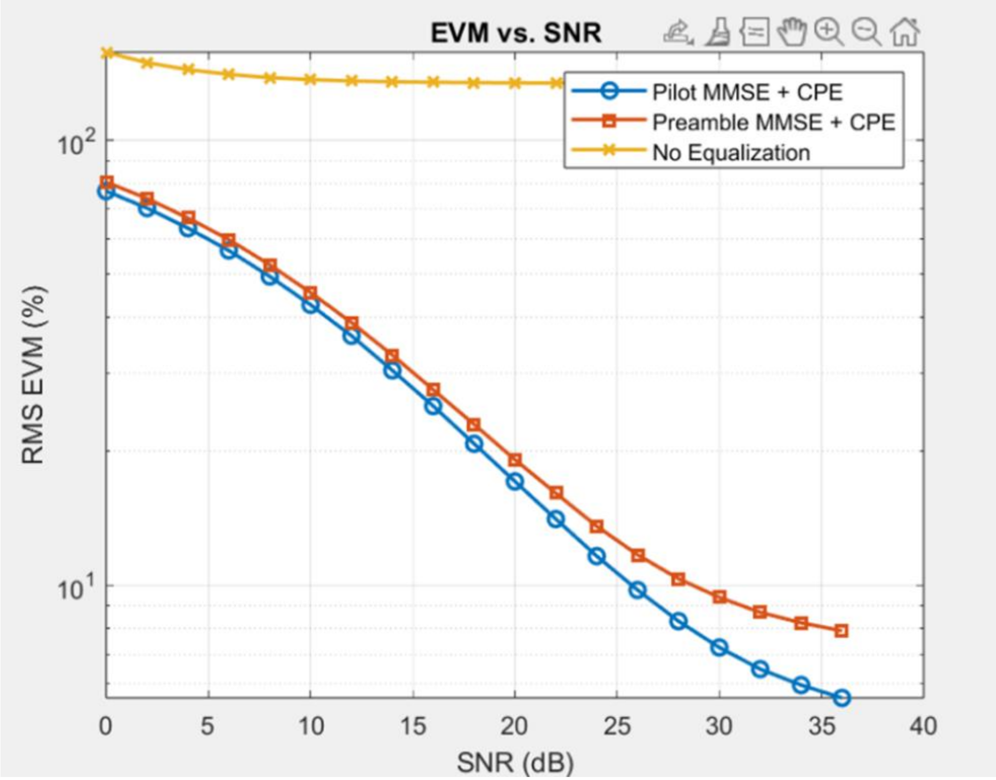
Main concepts “EVM in OFDM”

- Approximate equation from the simulation.

$$\mathrm{SNR_{lin}} = \frac{1}{\mathrm{EVM_{lin}^2}} \quad \text{or} \quad \mathrm{SNR_{dB}} = -20\log_{10}(\mathrm{EVM_{lin}}).$$

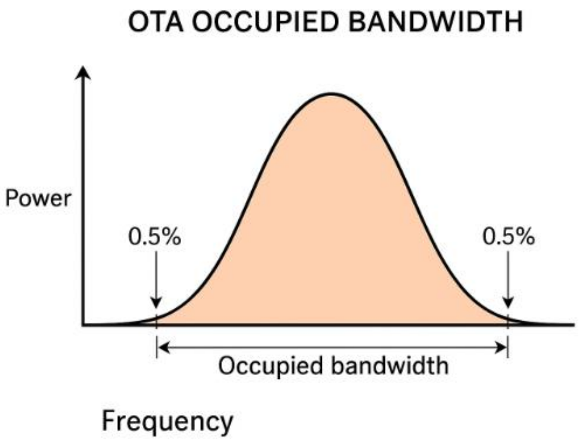
$$\mathrm{SNR_{dB}} = 40 - 20\log_{10}(\mathrm{EVM_{\%}}).$$





Main concepts “BW, ACLR”

- BW: The OTA occupied bandwidth is the width of a frequency band such that, below the lower and above the upper frequency limits, the mean powers emitted are each equal to a specified percentage β/2 (0.5 %) of the total mean transmitted power.
- ACLR : **Adjacent Channel Leakage Power Ratio** :It is the ratio of the filtered mean power (Power after applying a measurement filter (like: BPF) that isolates one channel) centered on the assigned channel frequency to the filtered mean power centered on an adjacent channel frequency.



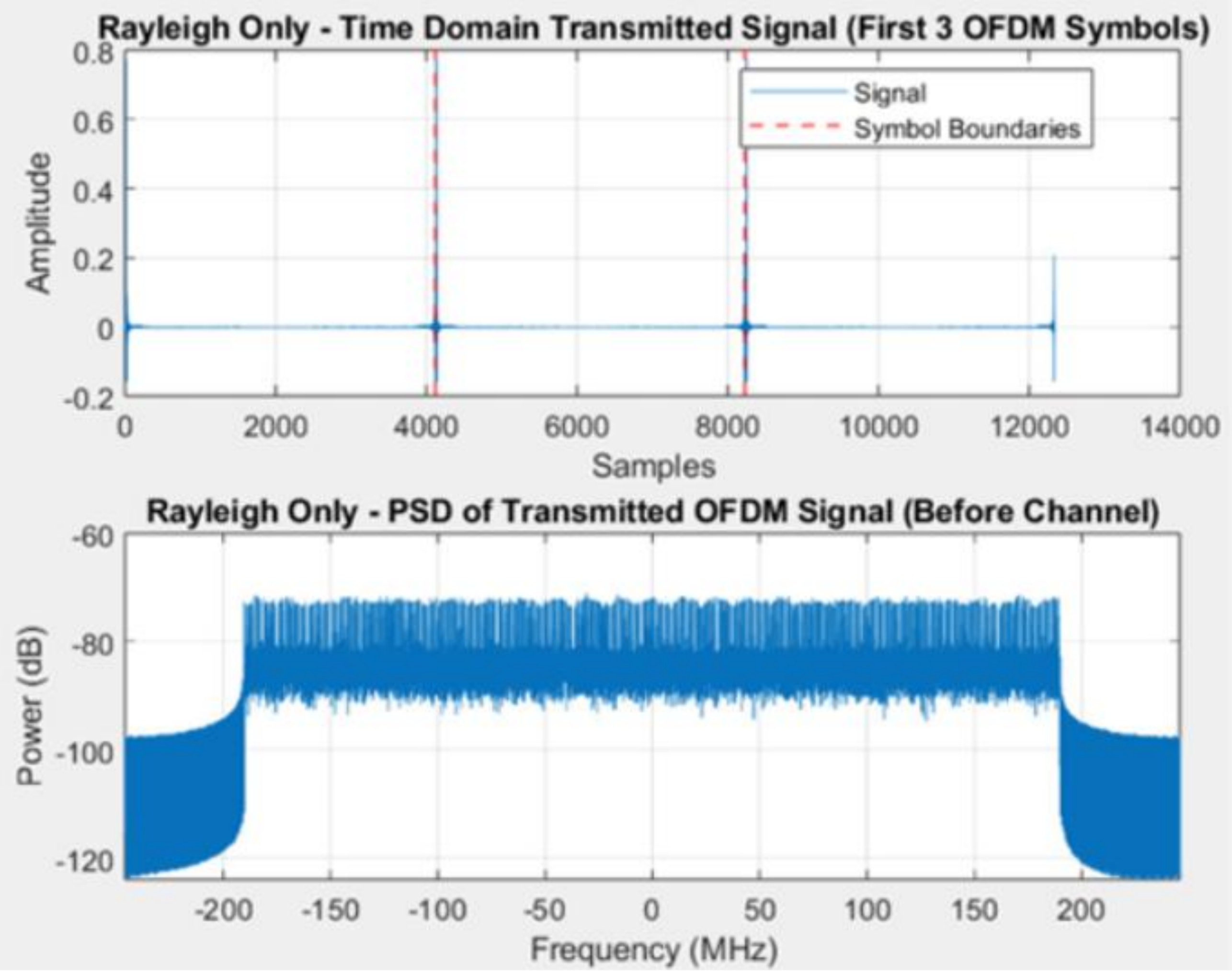
BW for FR2-2

SCS (kHz)	100 MHz	400 MHz	800 MHz	1600 MHz	2000 MHz
	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}
120	66	264	N/A	N/A	N/A
480	N/A	66	124	248	N/A
960	N/A	33	62	124	148

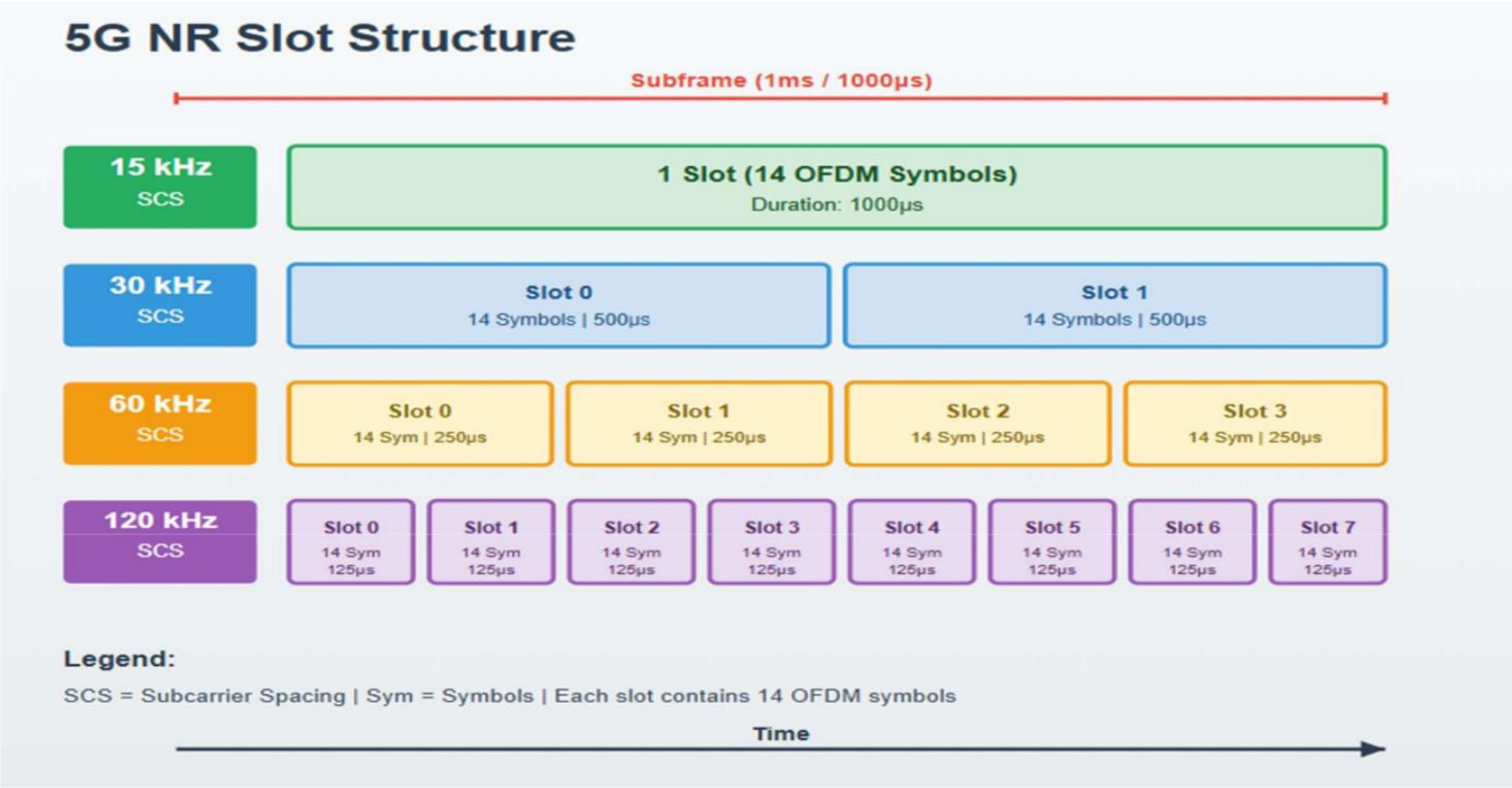
Main concepts "OFDM"

- Matlab Simulation for OFDM in FR-2.

```
%% ---------------- Parameters ----------------
NFFT = 4096;
SCS = 120e3; % Subcarrier spacing [Hz]
NumSCinRB = 12;
NusedFFT = 264 * NumSCinRB; % active subcarriers
NGuardSC = NFFT - NusedFFT;
NSymbols_data = 100; % number of data symbols
% number of identical preamble OFDM symbols (will average)
numPreamble = 3;
% OFDM modulator NumSymbols
totalSymbols = numPreamble + NSymbols_data;
ModOrder = 256; % 256-QAM
```

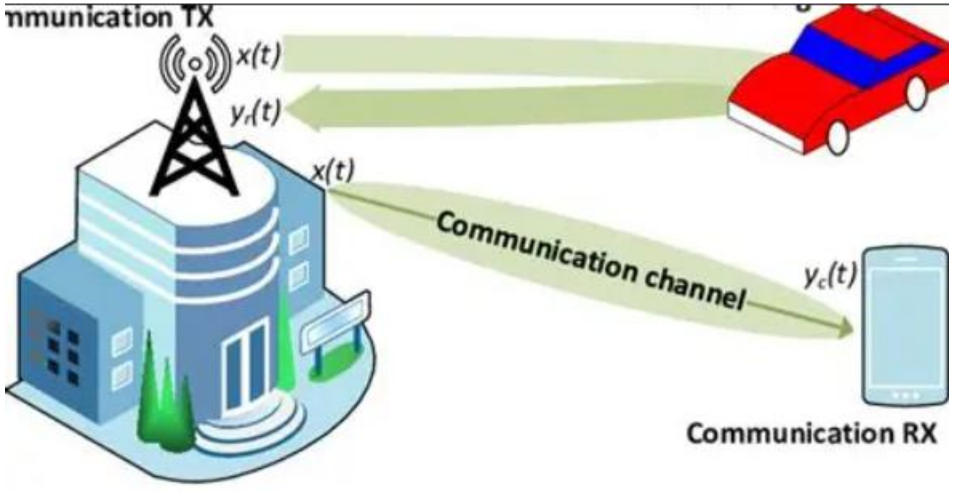


Main concepts “5G frame structure”



Main concepts “JCAS”

- Joint communication and sensing
- JCAS makes 6G systems act like a pair of **“eyes and mouth” in one device** — they can **talk and sense** at the same time, using the same signal.
  This leads to smarter, faster, and more efficient wireless networks capable of understanding and reacting to the physical world.
- JCAS waveforms can be designed to **favor communication** (OFDM-based), **favor radar** (chirp-based), or **jointly optimize both** depending on the use case.

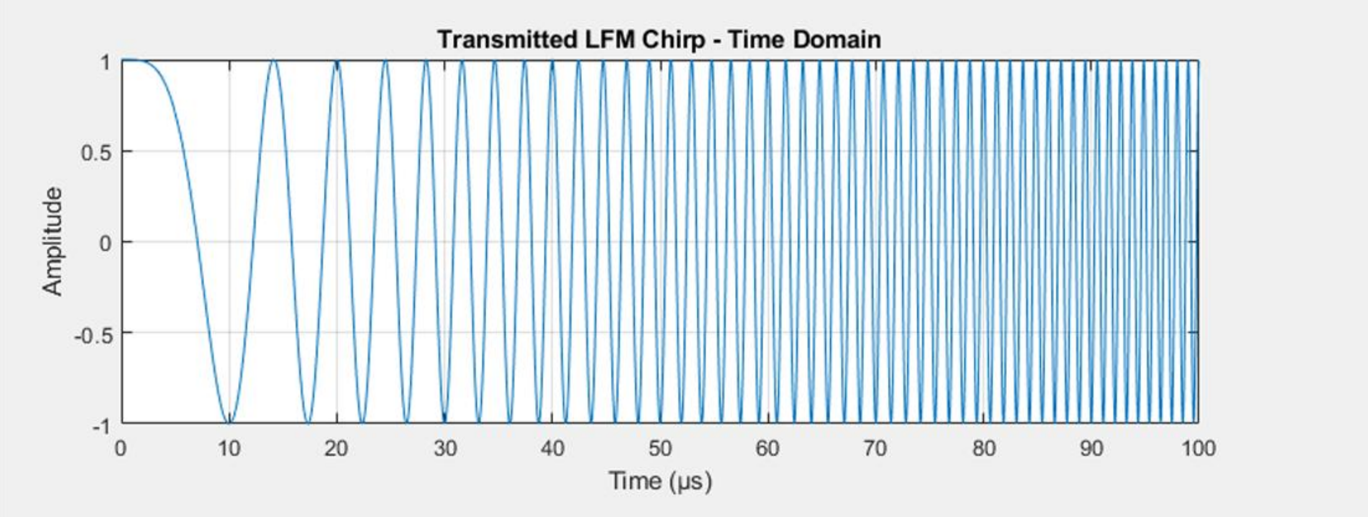


Chirp and TDM:
Ahmed Haitham Othman

Main concepts “Chirp signal”

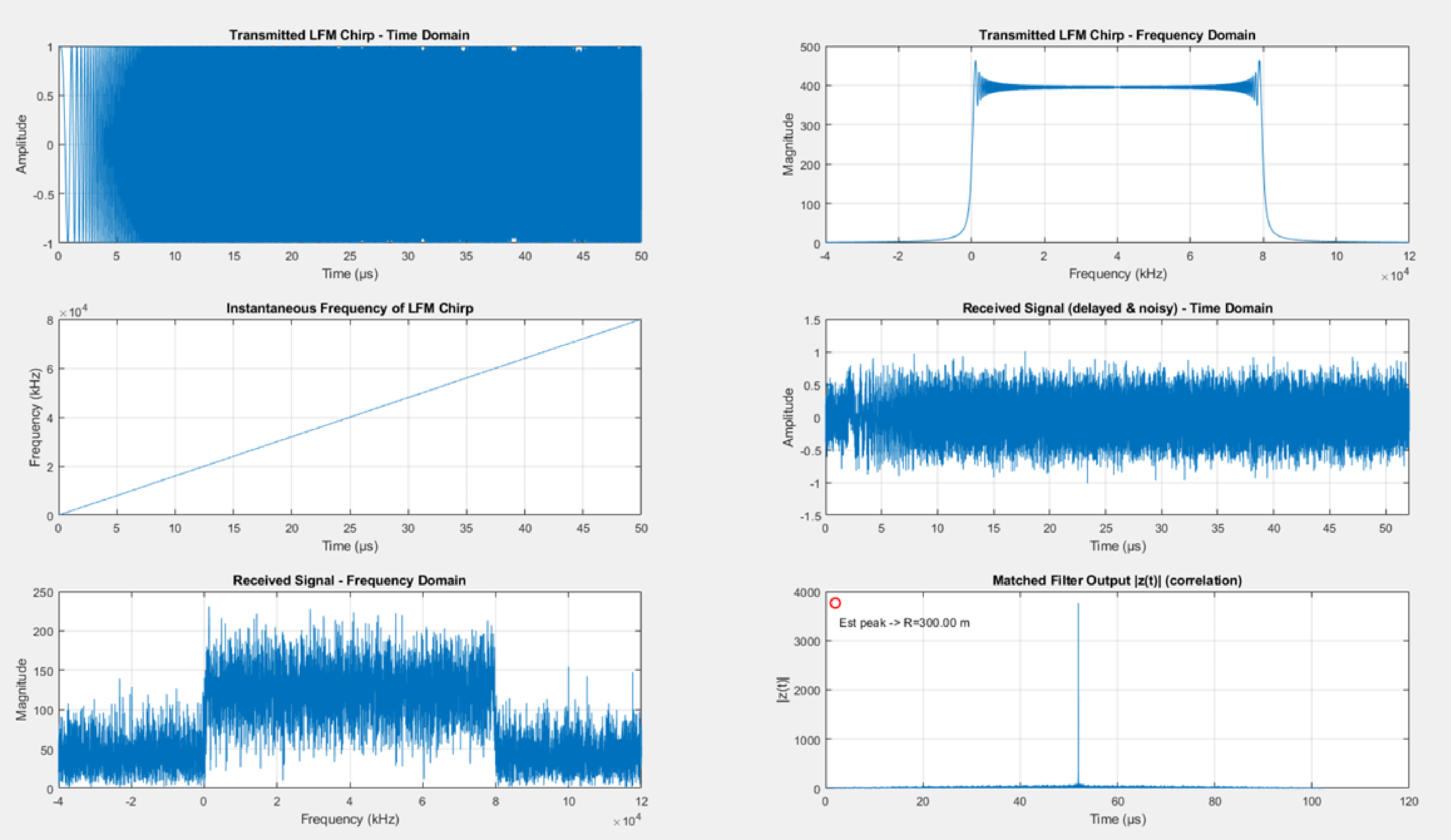
$$s(t) = A\cos(2\pi(f_0 t + (K/2)t^2) + \theta)$$

- f_0: start frequency
- $K = B/T$: chirp rate
- B: bandwidth



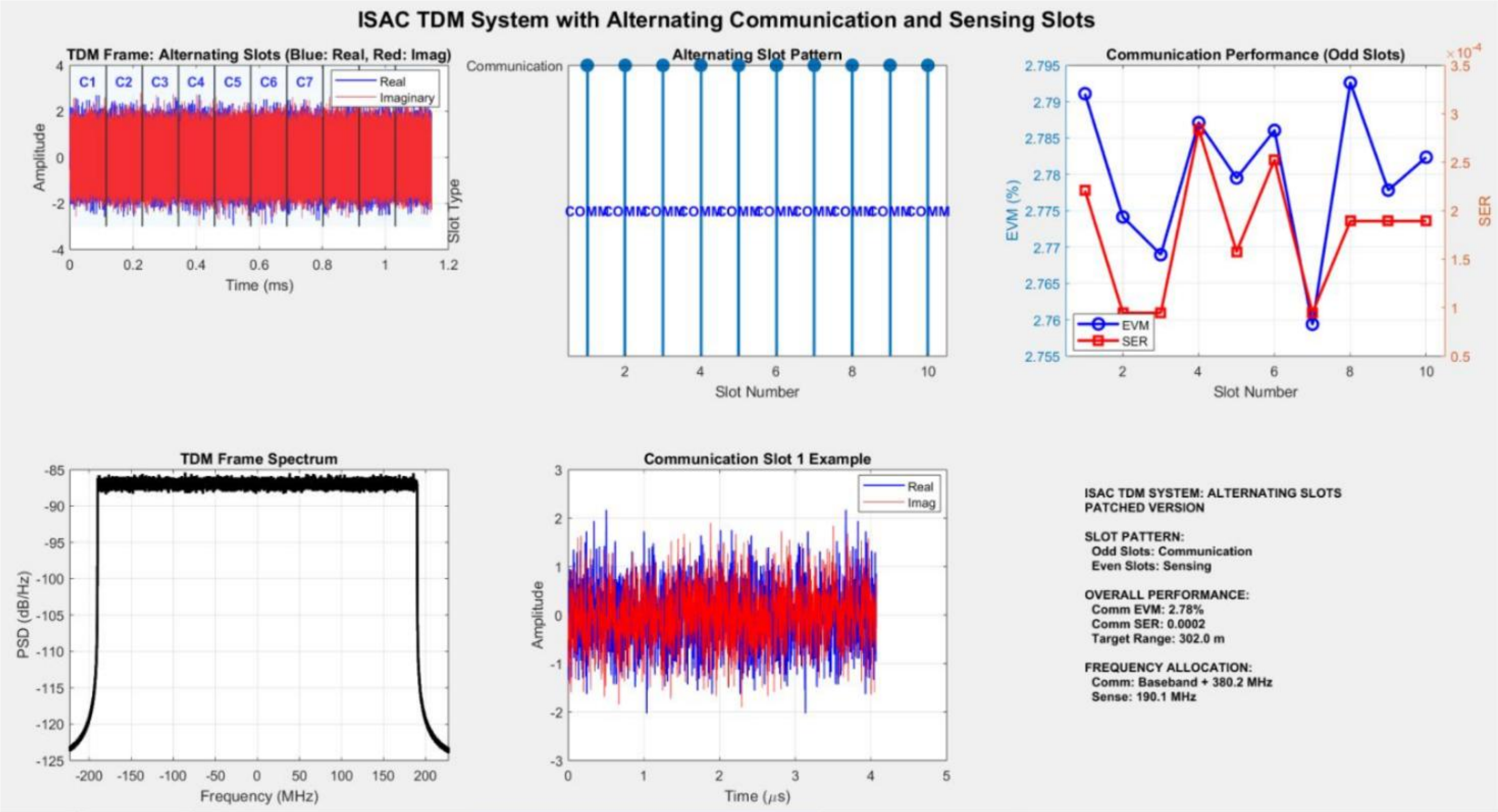

```
%% ----------------- Parameters -----------------
c = 3e8;                     % speed of light (m/s)
A = 1;                       % amplitude of transmitted chirp
f0 = 0;                    % start frequency (Hz) (baseband-ish example)
B = 80e6;                     % bandwidth (Hz)
T = 50e-6;                  % pulse duration (seconds)
K = B / T;                   % chirp rate (Hz/s) -> K = B/T
theta = 0;                   % initial phase (rad)
Fs = 5e8;                    % sampling frequency (Hz) (must be >> f0+B)
SNR_dB = 0;                 % desired SNR at the receiver (dB) for the echo
R_true = 300;                % true target range in meters
alpha = 0.3;                 % target amplitude attenuation (reflection coef)
```

Main concepts “Chirp signal”

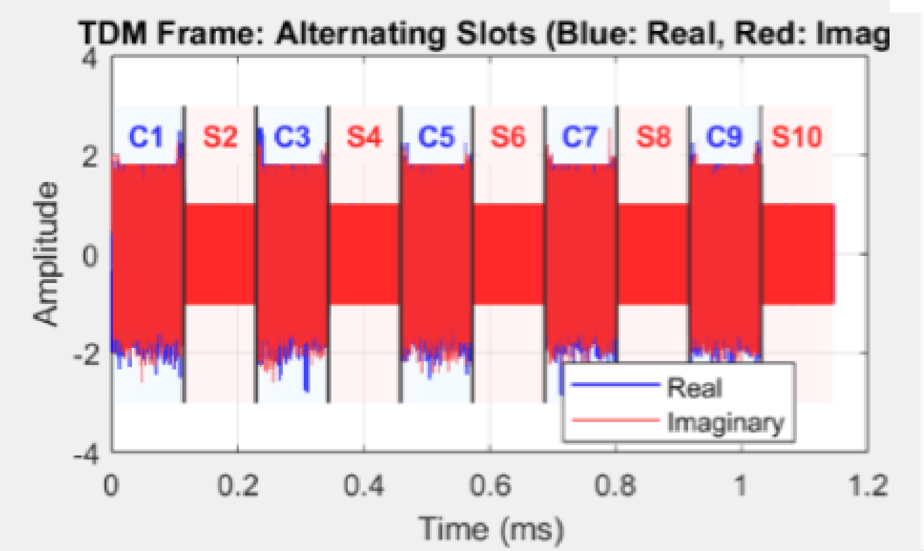


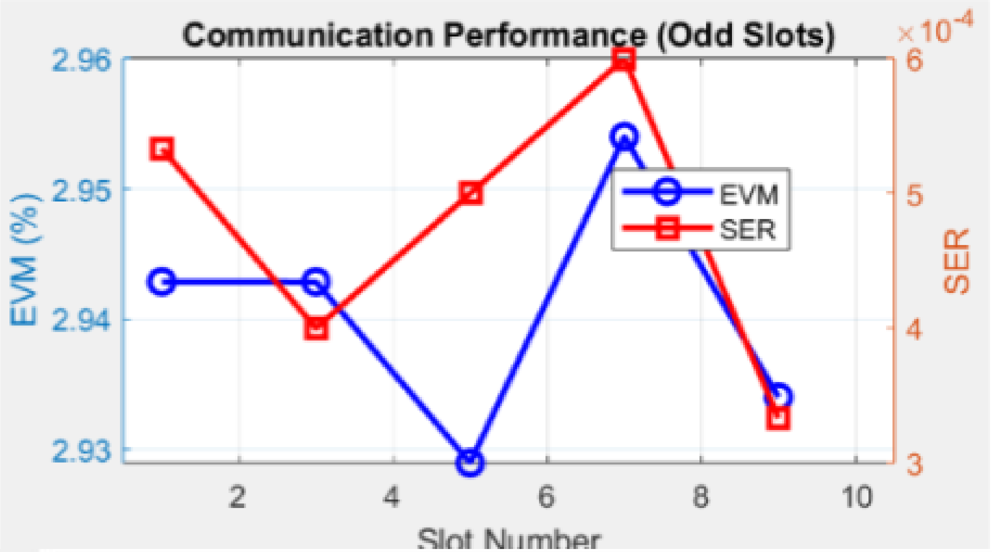
Main concepts “TDM”

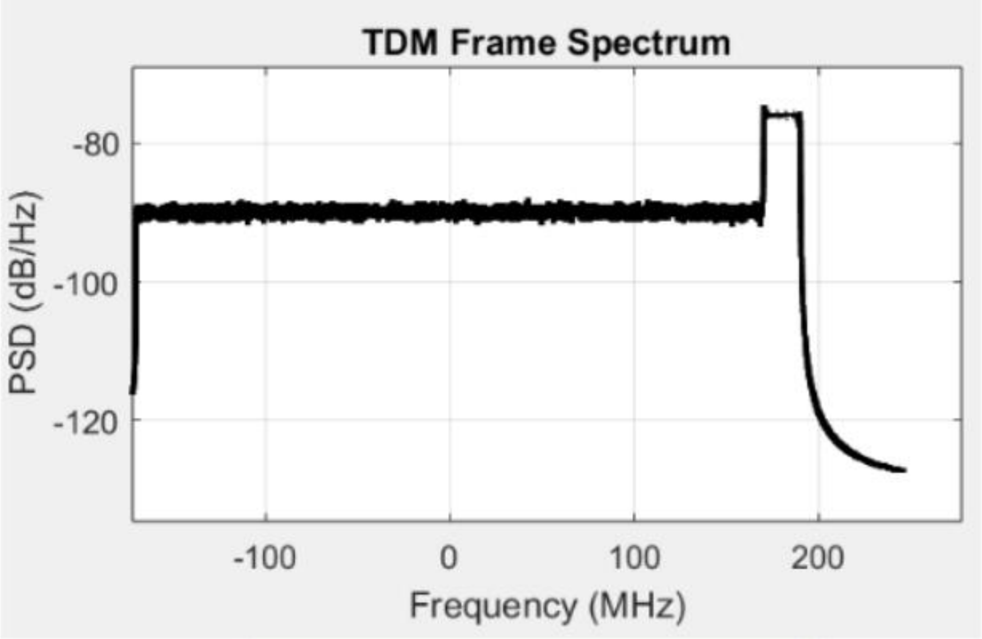
- OFDM + Chirp (different timeslots).



Main concepts "TDM"







ISAC TDM SYSTEM: ALTERNATING SLOTS
PATCHED VERSION

SLOT PATTERN:
- Odd Slots: Communication
- Even Slots: Sensing

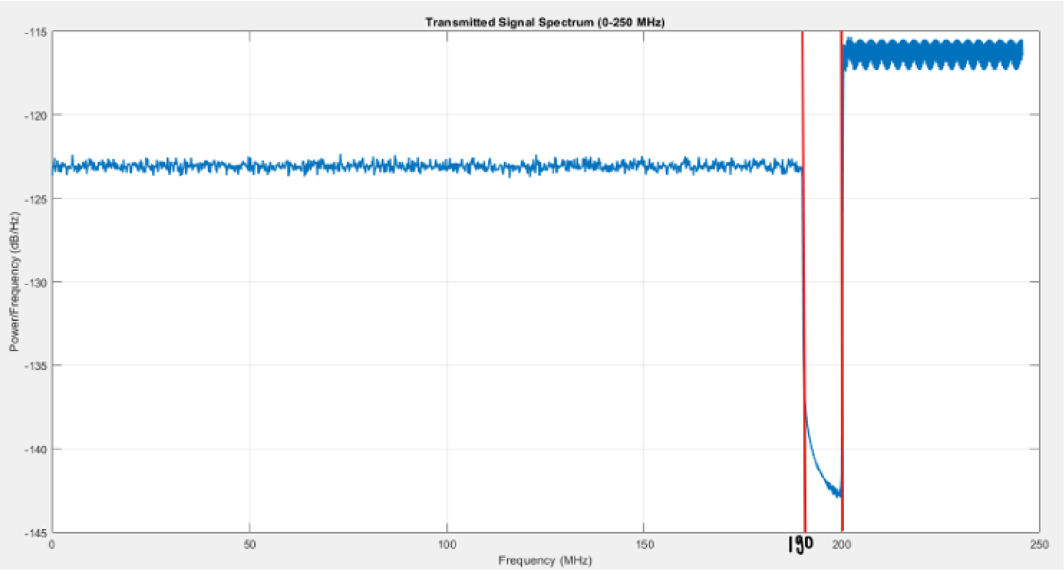
OVERALL PERFORMANCE:
- Comm EVM: 2.94%
- Comm SER: 0.0005
- Sense Range Error: 0.12 m
- Target Range: 302.0 m

FREQUENCY ALLOCATION:
- Comm: Baseband + 360.2 MHz
- Sense: 190.1 MHz

FDM and overlapping BW:
Youssef Mohamed Mamdouh

Main concepts “FDM”

- Sending OFDM communication signals and an LFM radar chirp simultaneously in the same time slot
- OFDM BW = 380 MHZ , Chirp BW = 80 MHZ
- Guardband = 20 MHZ
- If small GB : EVM increases due to leakage of power from Chirp to OFDM
- If GB increases : EVM decreases and ranging is not affected in either case

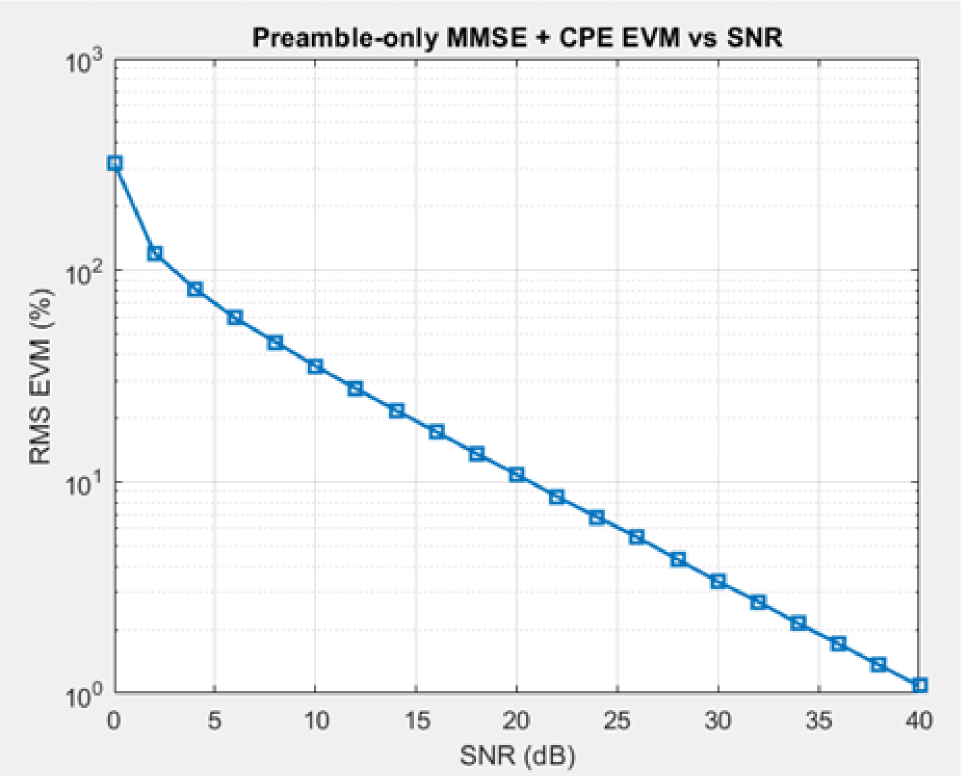


- SO, EVM is sensitive to guard band size and Radar sensing is robust in both cases
- Sensing is affected by channel effects. If there’s AWGN, sensing error is relatively acceptable and if there’s doppler effect, Sensing is affected significantly

Main concepts “FDM”

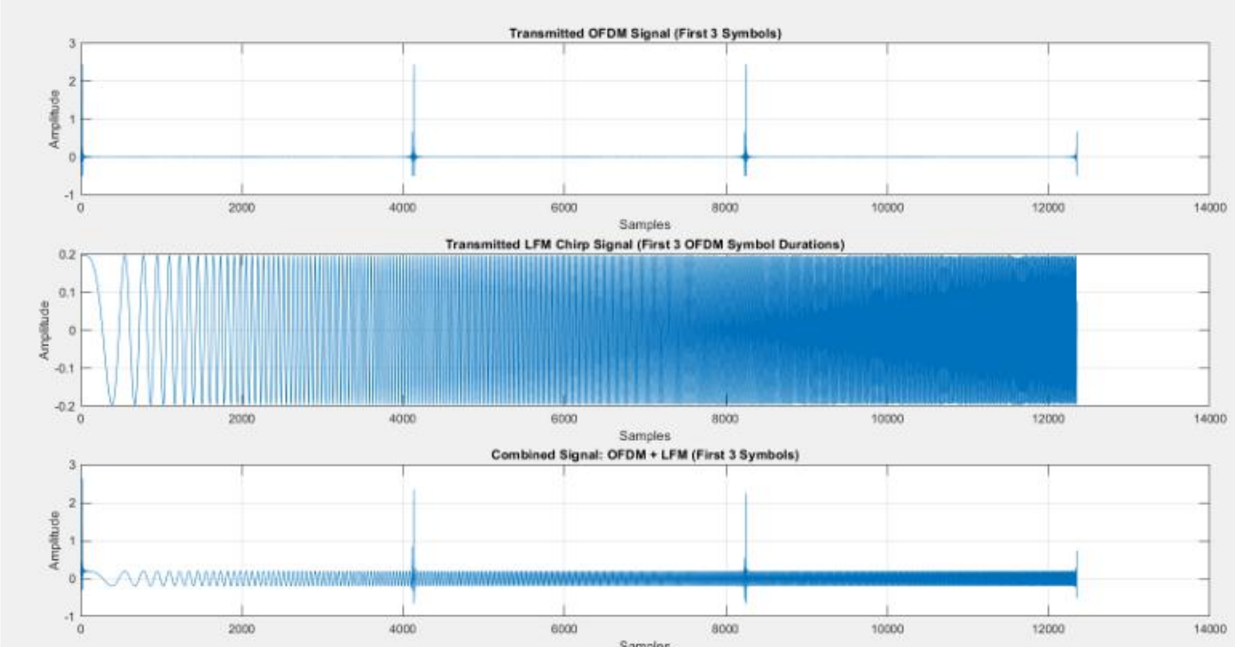
- By increasing SNR, EVM decreases as noise power is relatively low with respect to signal power

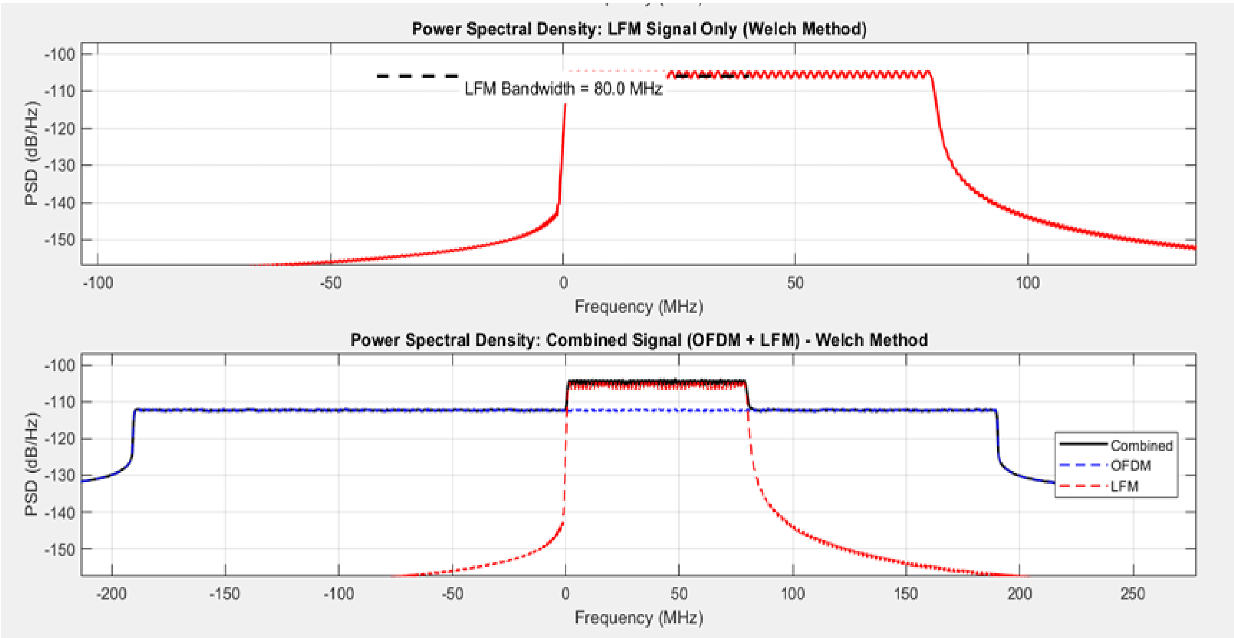
```
CP length = 128 samples
OFDM Band: +/- 190.08 MHz
LFM Band: 200.08 MHz to 280.08 MHz (BW=80.00 MHz)
OFDM Power: 0.00 | LFM Power: 0.00
SNR:  0 dB | Preamble EVM: 191.285 %
SNR:  2 dB | Preamble EVM: 126.653 %
SNR:  4 dB | Preamble EVM: 83.729 %
SNR:  6 dB | Preamble EVM: 67.723 %
SNR:  8 dB | Preamble EVM: 44.940 %
SNR: 10 dB | Preamble EVM: 35.343 %
SNR: 12 dB | Preamble EVM: 27.335 %
SNR: 14 dB | Preamble EVM: 21.579 %
SNR: 16 dB | Preamble EVM: 17.321 %
SNR: 18 dB | Preamble EVM: 13.753 %
SNR: 20 dB | Preamble EVM: 10.848 %
SNR: 22 dB | Preamble EVM: 8.591 %
SNR: 24 dB | Preamble EVM: 6.796 %
SNR: 26 dB | Preamble EVM: 5.447 %
SNR: 28 dB | Preamble EVM: 4.287 %
SNR: 30 dB | Preamble EVM: 3.399 %
SNR: 32 dB | Preamble EVM: 2.735 %
SNR: 34 dB | Preamble EVM: 2.164 %
SNR: 36 dB | Preamble EVM: 1.721 %
SNR: 38 dB | Preamble EVM: 1.356 %
SNR: 40 dB | Preamble EVM: 1.084 %
--- LFM Radar (Correlation) ---
True R = 302.00 m | Estimated R = 302.12 m | Error = 0.12 m | Radar resolution = 1.88 m
```



Main concepts “overlapping bandwidth”

- The matched filter receives the LFM signal after a time delay and performs correlation between the received LFM and originally transmitted LFM signals
- The maximum peak out of correlation represents the right LFM signal after certain time delay which represents the round trip time then distance is calculated by the relation: d = (round trip time * c) / 2





Main concepts “overlapping bandwidth”

- if the LFM power is near or higher than the OFDM signal power it will make significant interference with the OFDM symbols at the receiver so, the receiver can’t distinguish them from each other and EVM gets worse
- Distance is affected by number of multipath components that face the LFM signal during its propagation through the channel as the transmitter receive replicas of LFM with variable delays and peaks, so it searches for maximum peak that gives the least error in distance calculation

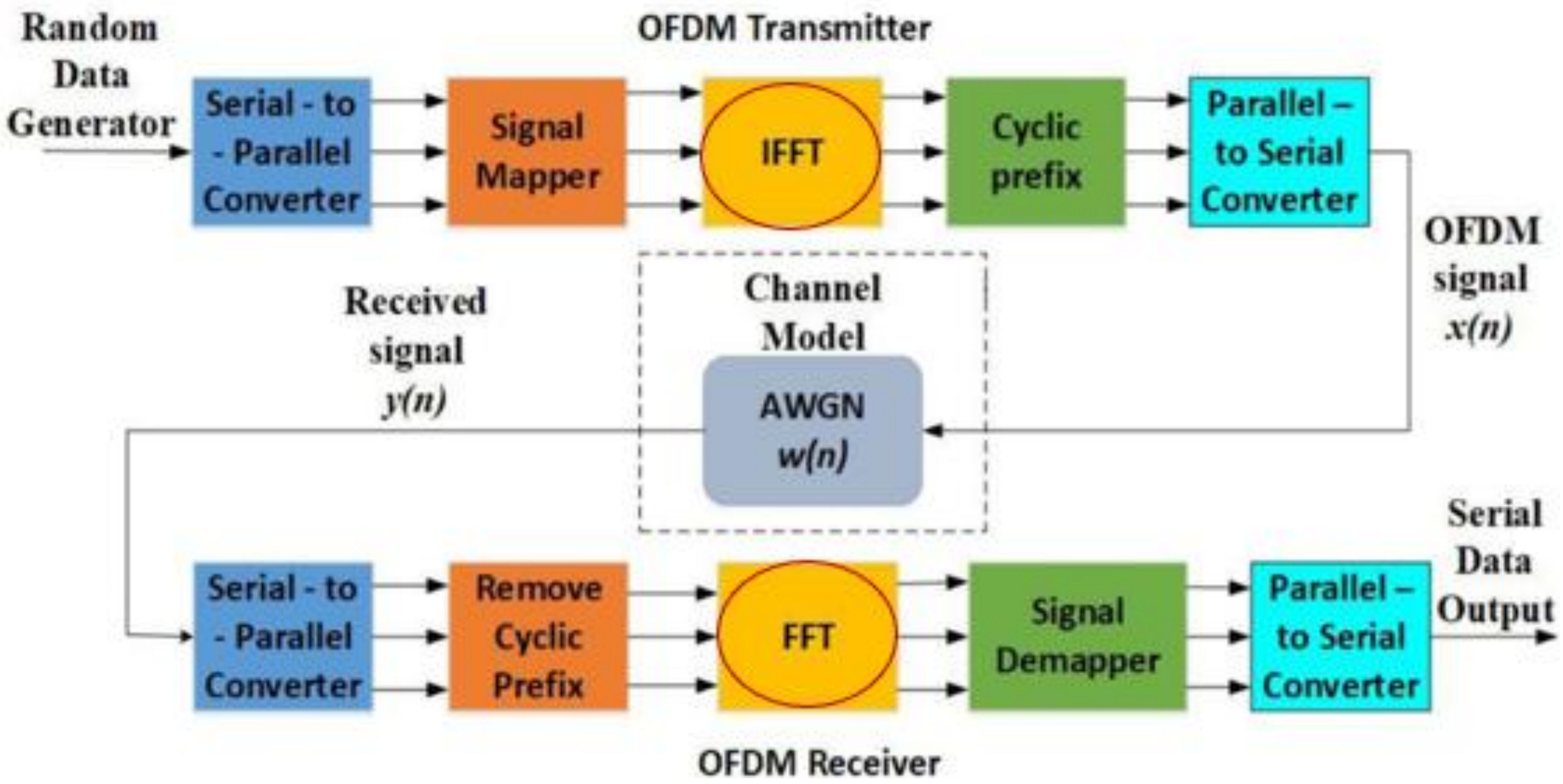
LFM relative power (dB)	EVM
-10	4.17%
-5	6.26%
0	10.33%
5	17.76%
10	31.62%
15	56.66%
20	101.26%

Number of multipath components	Distance error (m)
0	0.1363
1	7.5
2	15
3	67.5

FFT, IFFT & conclusion: Mohamed Ahmed Hussein

Main concepts “FFT,IFFT”

In modern communication systems—especially OFDM and chirp-based sensing systems, the Fast Fourier Transform (FFT) is one of the most critical building blocks.



Main concepts “Butterfly operation”

- A butterfly is the fundamental building block of the FFT.
- The Discrete Fourier Transform (DFT) is given by:

$$X[k] = \sum_{n=0}^{N-1} x[n] W_N^{kn}, \quad 0 \leq k \leq (N-1)$$

$$W_N = e^{-j\frac{2\pi}{N}}$$

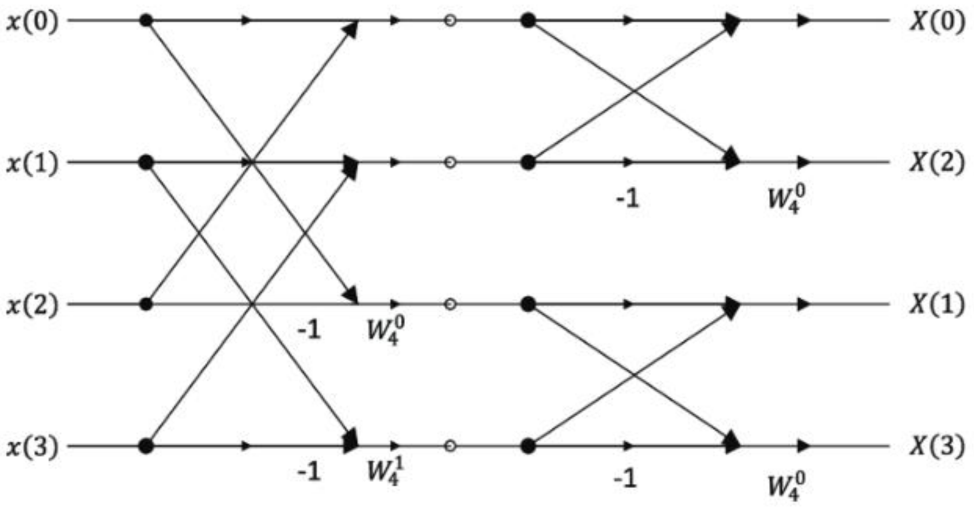
Main concepts "DIF vs. DIT FFT"

Decimation in Frequency (DIF)

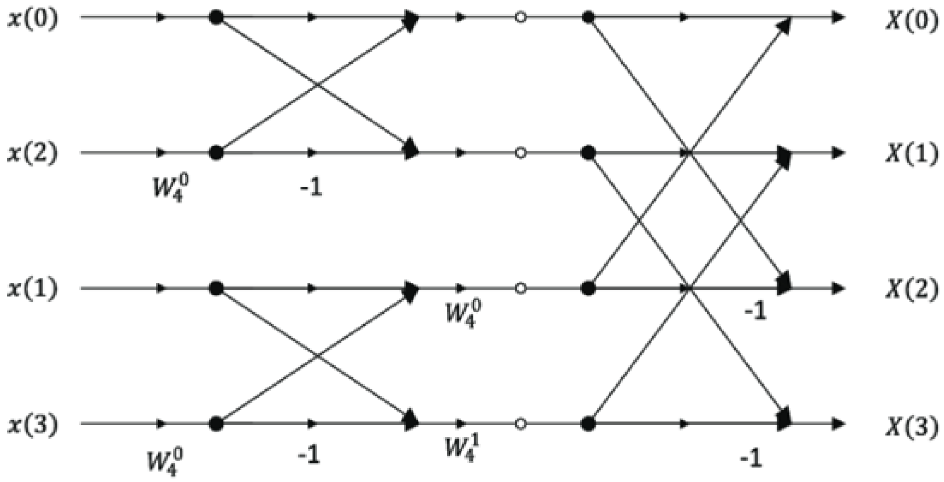
- Splits the output spectrum into even- and odd-indexed parts.
- Bit-reversal applied at the output.
- Twiddle factors multiply later.

$$A = x[n] + x[n + N/2]$$

$$B = (x[n] - x[n + N/2]) \cdot W_N^k$$



Length-4, DIF radix-2 FFT



Length-4, DIT radix-2 FFT

Decimation in Time (DIT)

- Splits input sequence into even and odd indices.
- Bit-reversal required at the input.
- Twiddle factors multiply early.

Serial Vs. Parallel FFT Architectures

Serial FFT Architecture	Parallel FFT Architectures
Huge area reduction because only one butterfly is reused	Large area
Very efficient for ASIC and FPGA	One FFT per clock (if fully parallel)
Fits low-power or resource-constrained systems	Suitable for high bandwidth systems (5G NR, WiFi 6, radar processing)
Higher latency	Very high throughput
Throughput limited to "one output every clock" after pipeline fill	Higher power consumption & Requires many multipliers + adders

FFT Serial Architectures

- These process one sample per clock cycle. They are resource-efficient and ideal for low-to moderate throughput designs.
- Serial pipelined architectures include:

1. SDF – Single-Path Delay Feedback

- Most widely used low-complexity architecture
- Uses feedback registers to store delayed samples
- Very area-efficient

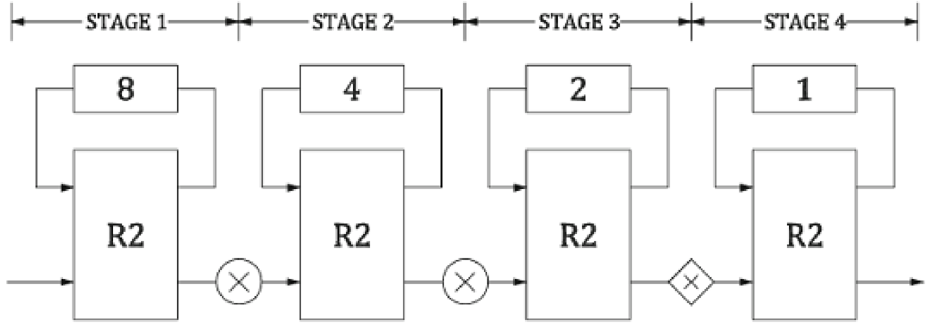
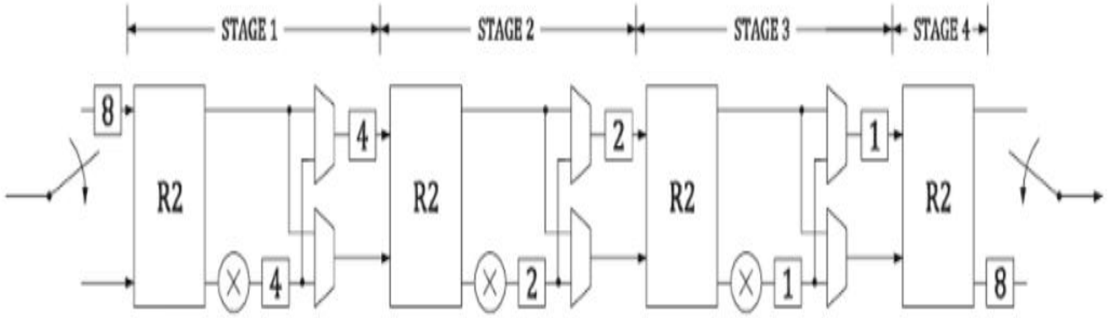


Figure 7 16-point radix-2 SDF FFT architecture.

2. SDC – Single-Path Delay Commutator

- Uses commutators (switch networks) instead of feedback loops
- Often higher throughput than SDF
- Regular structure → good for high-speed FFTs



16-point radix-2 SDC FFT architecture.

Serial Radix-2^2 (Radix-22) SDF Architecture

- Based on memory efficiency, hardware simplicity, computational savings, and suitability for high-throughput OFDM systems, The radix-22 SDF architecture offers the best balance between performance and implementation complexity.
- For a 4096-point serial FFT core in a 6G ISAC system, it is the optimal architecture from both an engineering and research standpoint.

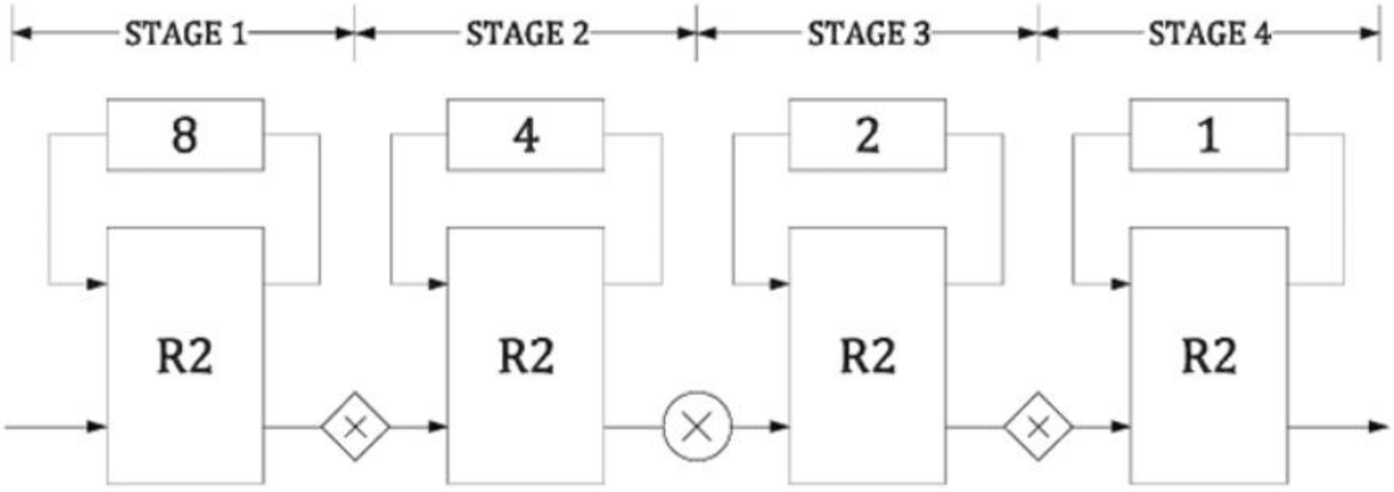
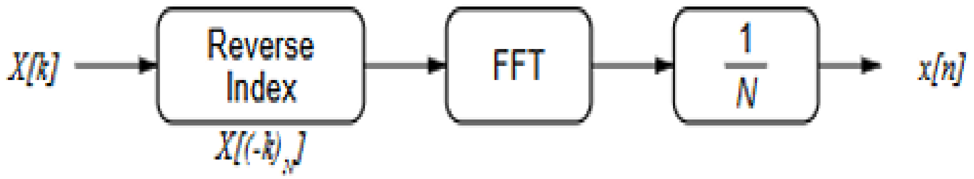
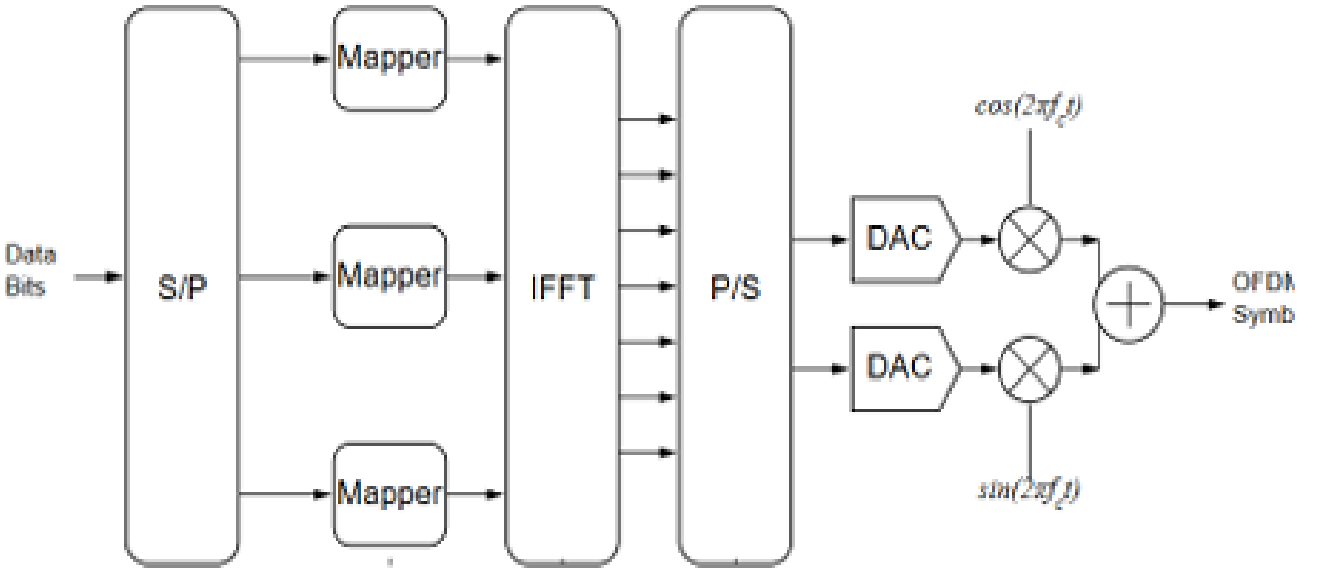


Figure 13 16-point radix-2^2 SDF FFT architecture.

IFFT

- The IFFT's job is to transform digital data into a transmittable waveform
- It takes parallel frequency-domain QAM symbols and converts them into a serial time-domain signal that can be modulated and sent over the air





Conclusion

We have done the following so far:

- Designed a DDS-based waveform generation and correlation system for 5G/6G ISAC applications
- Studied ISAC fundamentals and wireless channel effects
- Implemented OFDM and analyzed 5G NR standards (FR2)
- Evaluated DDS and FFT architectures for hardware suitability
- Simulated signal processing strategies (TDM/FDM) in MATLAB
- Quantified trade-offs between communication (EVM) and sensing accuracy

Future Work

- Finishing the modeling phase we started
- Starting RTL Design and Verification for The specified blocks
- ASIC Flow and FPGA Prototyping

Timeline

Phase	Weeks	Key Deliverables
Project Kickoff	Week 0	System overview document
Specs & Architecture	Weeks 1	DDS specification document
RTL Block Implementation	Weeks 2–6	Verified RTL blocks
Modeling & Algorithm Validation	Weeks 2–6	Final golden Model vs spec plots
Integration & System Verification	Weeks 2-8	Integrated DDS RTL Verification report
FPGA Mapping & Optimization	Week 9	Timing-closed FPGA design
ASIC flow	Week 10	Completed ASIC flow of the design
Demo & Documentation	Week 11	Final report & thesis

Thank You!