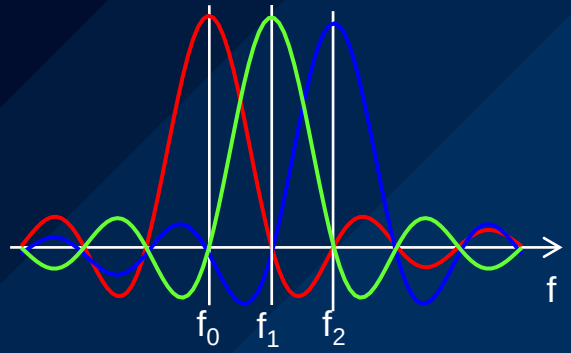
RF Fundamentals Seminar
Part 6: Intro to OFDMA
(Orthogonal Frequency Division Multiple Access)



Rick Daniel
Application Engineer

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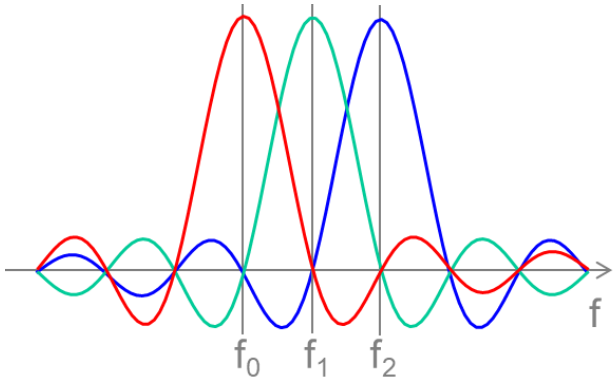
Make ideas real

Some Questions…

- What is OFDMA?
- What's the difference between Modulation and Channelization
- How does OFDMA work?
- What does this diagram represent?
- What is Cyclic Prefix/Guard Interval and why is it used?
- OFDM, OFDMA…What's the difference?
- What are the advantages of OFDMA?
- What are the disadvantages of OFDMA?
- What are some systems that use OFDMA?

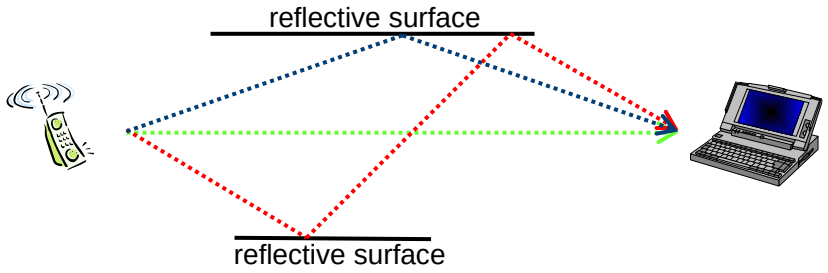


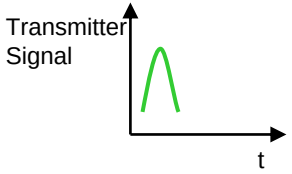
Evolution of Cellular Communications

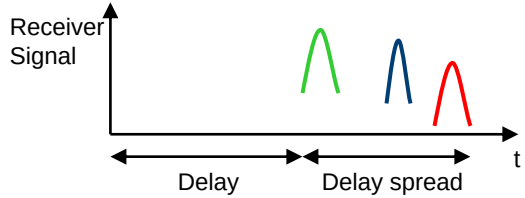
- **1G (voice based)**
  - 1980's
  - AMPS (Advanced Mobile Phone Service)
  - FM modulation, FDMA channelization
- **2G (voice and < 100 kbps data)**
  - 1990's
  - GSM (Europe), IS-136 (US Digital)
  - GMSK and QPSK modulation, TDMA channelization
  - "2.5G" EDGE (8PSK)
- **3G (voice and > 1 Mbps data)**
  - 2000's
  - 3GPP (UMTS/WCDMA), CDMA 2000, 1xEV-DO
  - QPSK and QAM modulation, CDMA channelization
- **4G (VoLTE and > 50Mbps data)**
  - 2010's
  - LTE
  - PSK and QAM modulation, OFDMA channelization
  - MIMO
- **5G (VoNR and > 1 Gbps data)**
  - 2020's
  - 5G NR
  - PSK/QAM modulation, OFDMA channelization
  - MIMO
  - mmWave frequency bands
  - Beamforming
- **6G (> 100 Gbps?)**
  - 2030's?
  - 100 – 300 GHz?

Multipath Interference

- Problem of multi-path interference in a single carrier transmission

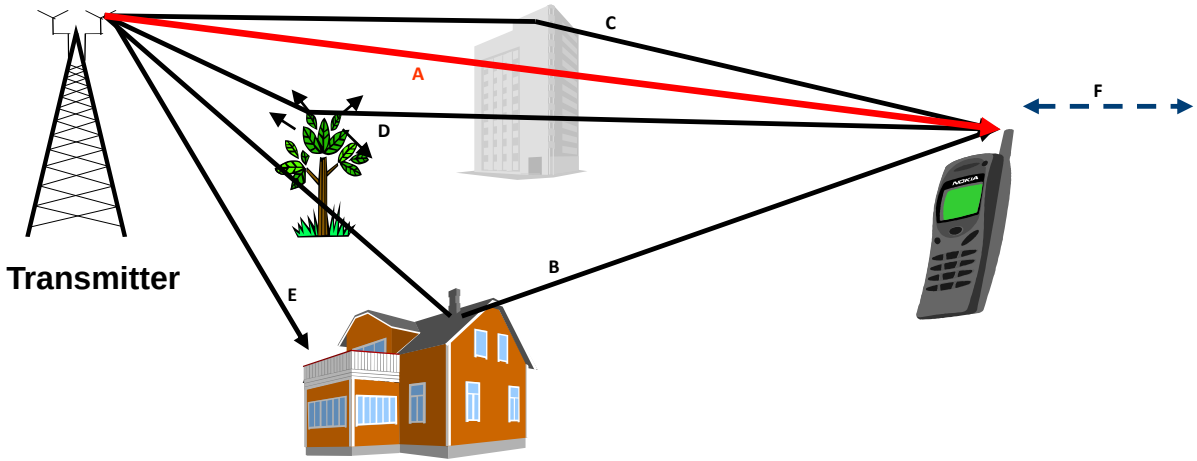


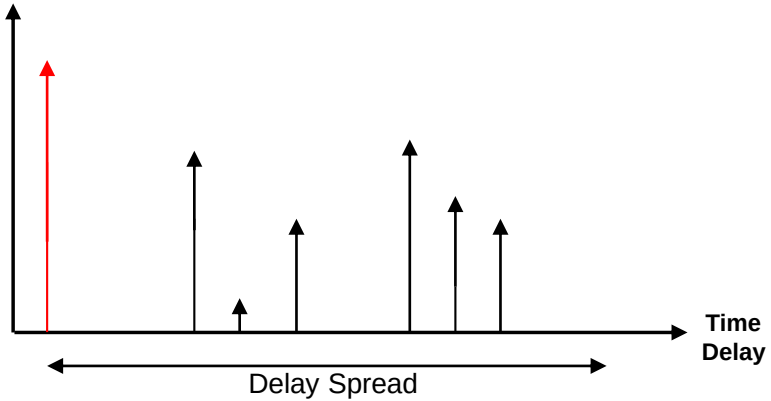




Multipath Interference

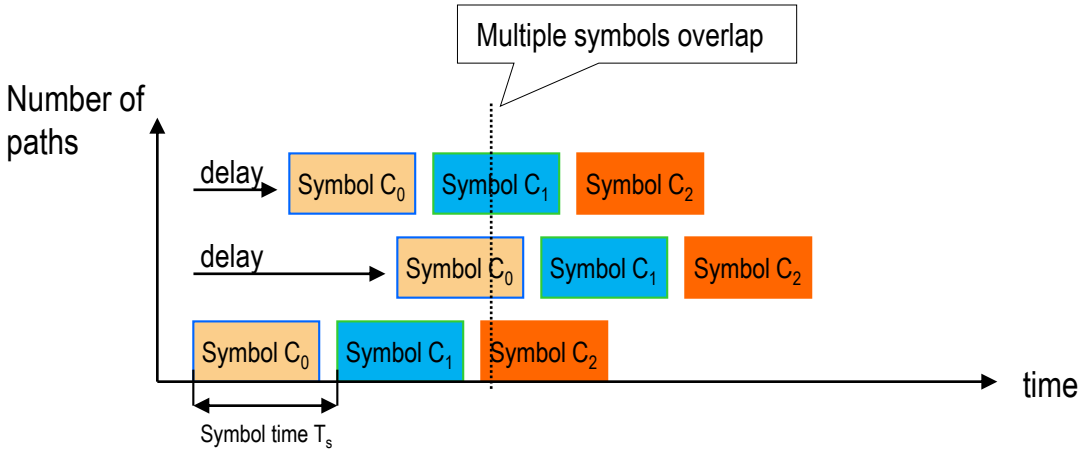
A: free space
B: reflection
(object is large compared to wavelength)
C: diffraction
D: scattering
(object is small or its surface irregular)
E: shadowing (birth death)
F: doppler





Inter-Symbol Interference (ISI)

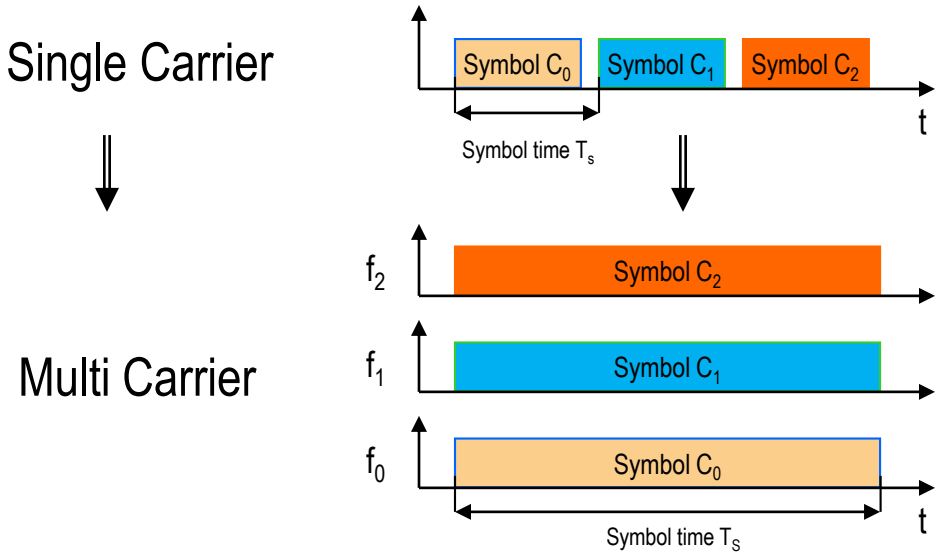
- In a high data rate single-carrier transmission the symbol duration is very short
- When delay spread is longer than the symbol duration the symbols overlap at the receiver
- This is called Inter-Symbol Interference (ISI)



Multipath interference in a high rate single-carrier system

OFDMA: Solution for inter-symbol interference

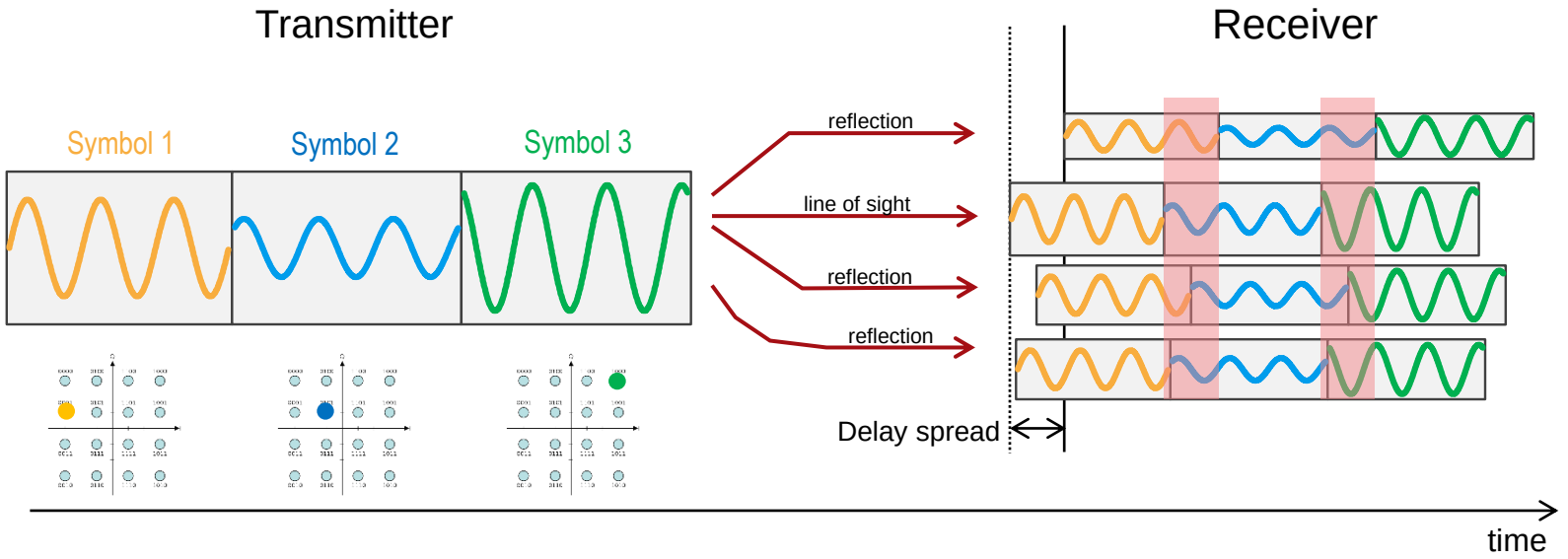
- Replace the single high data rate carrier with many low data rate subcarriers (can be thousands)
- Low data rate → Long symbol duration (longer than delay spread)
- ISI is significantly reduced



Due to the longer symbol time multi-path interference is reduced

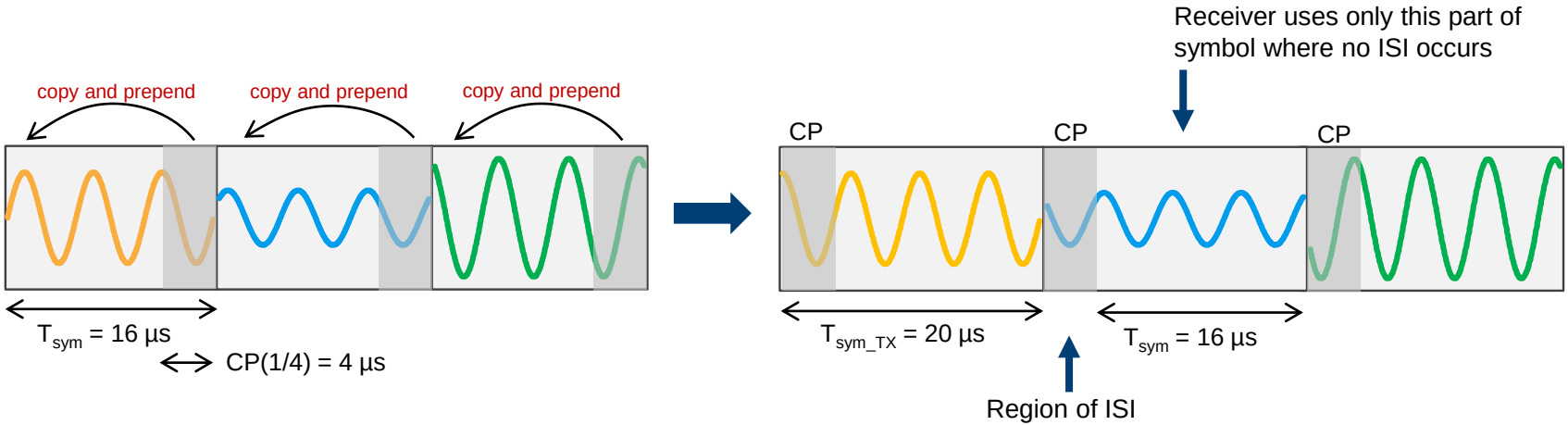
OFDMA: Still some ISI at symbol boundaries

- Even when the symbol duration is longer than the delay spread, the symbols (as seen by the receiver in a multipath environment) still overlap and interfere with each other at the symbol boundaries



OFDMA: Use Cyclic Prefix to eliminate remaining ISI

- Cyclic Prefix: Prepend a copy of the last portion of a symbol to the beginning of the symbol
- Also called Guard Interval or Cyclic Extension



- Transmitted symbol is longer, but receiver looks only at the smaller symbol time (T_{sym}) where the symbol overlap doesn't exist
- Receiver ignores the region of ISI (Cyclic Prefix)

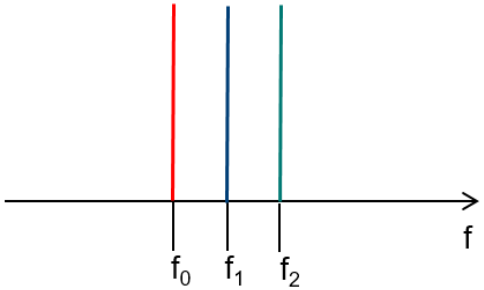
Some Terms Defined…

- FDM: Frequency Division Multiplexing
- FDMA: Frequency Division Multiple Access
- OFDM: Orthogonal Frequency Division Multiplexing
- OFDMA: Orthogonal Frequency Division Multiple Access

- This prompts some questions:
  - What does ‘Orthogonal’ mean?
  - How is OFDM different than FDM
  - How is OFDMA different than OFDM?

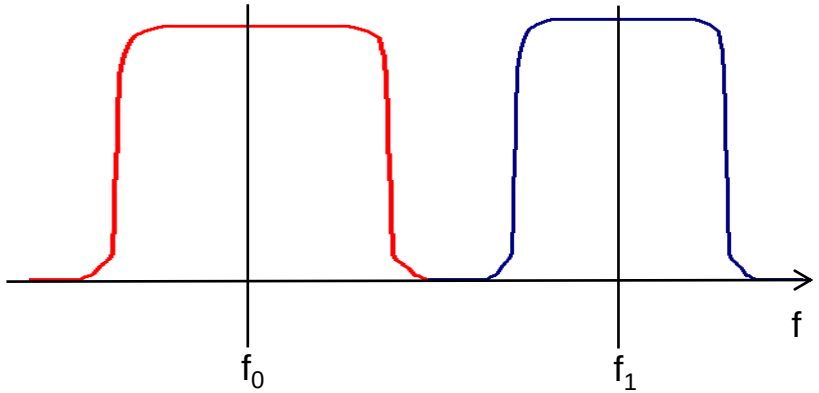
OFDMA: What is Orthogonal?

- Using many low data-rate carriers along with cyclic prefix works well to improve performance in multipath environments, but how does the ‘orthogonal’ part fit in?
- Mathematically, two signals A(t) and B(t), are orthogonal if: $\int A(t)B(t)dt = 0$
- If A and B are unmodulated CW carriers this becomes: $\int \sin(\omega_1 t)\sin(\omega_2 t)dt$
- Regardless of the spacing between the two frequencies, if the integration interval contains an integer multiple of cycles of both carriers, the integral is zero and the signals are orthogonal
- But, unmodulated carriers carry no information, so we apply modulation to carry information and their spectral width increases



OFDMA: What is Orthogonal?

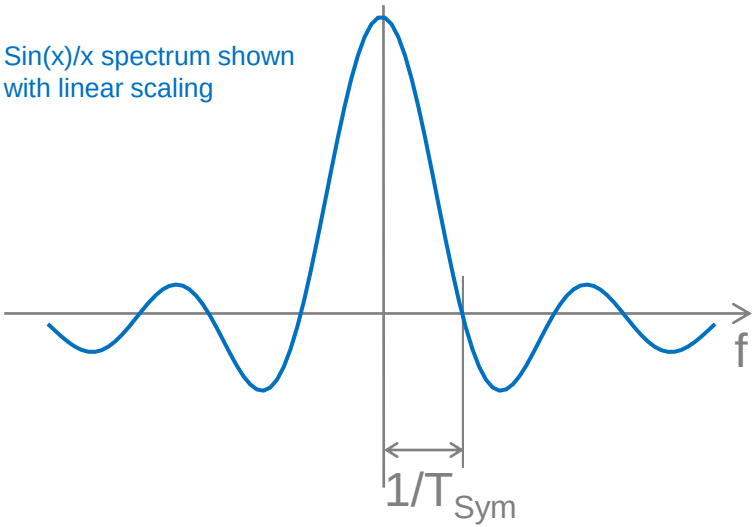
- In conventional FDMA systems (like broadcast AM, FM, TV, walkie-talkies, etc.) modulated signals are filtered and spaced far enough apart so they don't interfere with each other

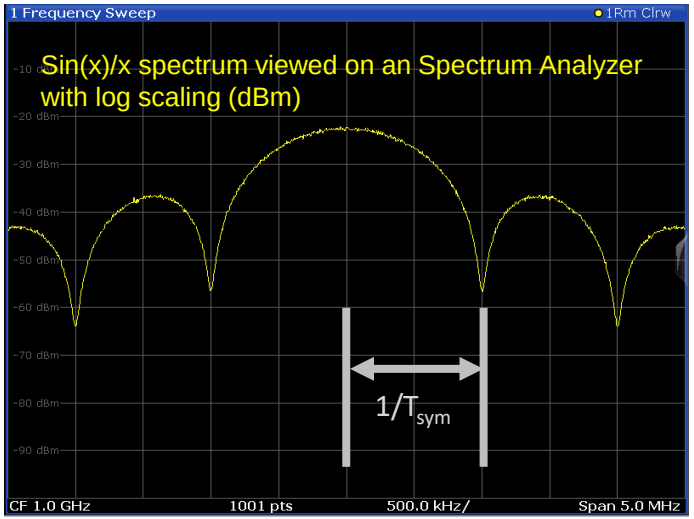


FDMA

OFDMA: What is Orthogonal?

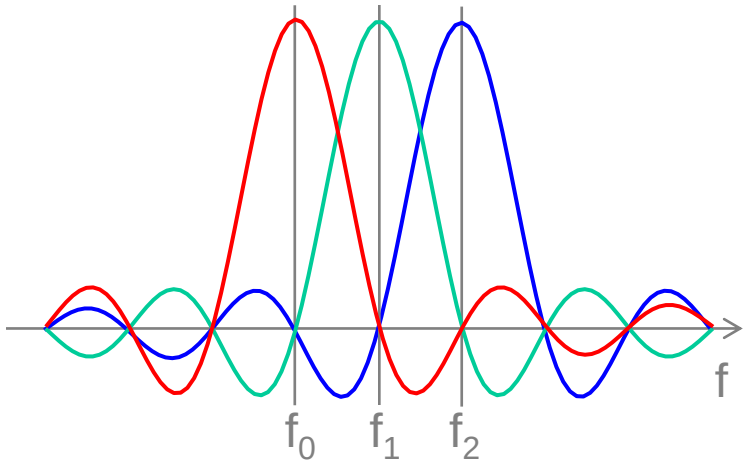
- Unfiltered digitally modulated carriers have spectral width with nulls spaced at the Symbol Rate ($1/T_{sym}$)
- Spectrum has a sin(x)/x characteristic





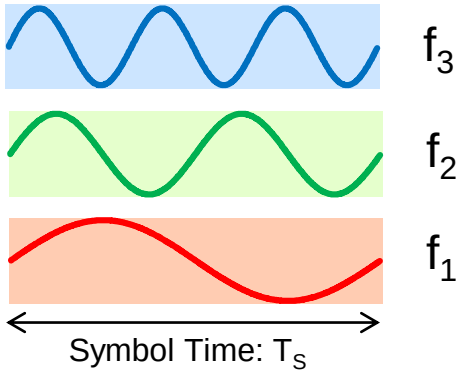
OFDMA: What is Orthogonal?

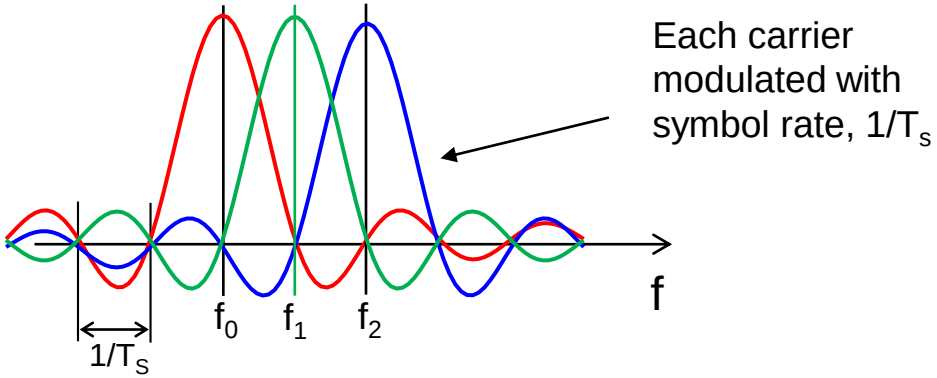
- What if the unfiltered carriers are spaced such that the peak of each carrier is exactly at the nulls of all the other carriers?
- Now the modulated carriers are tightly spaced, but do not interfere with each other



OFDMA: What is Orthogonal?

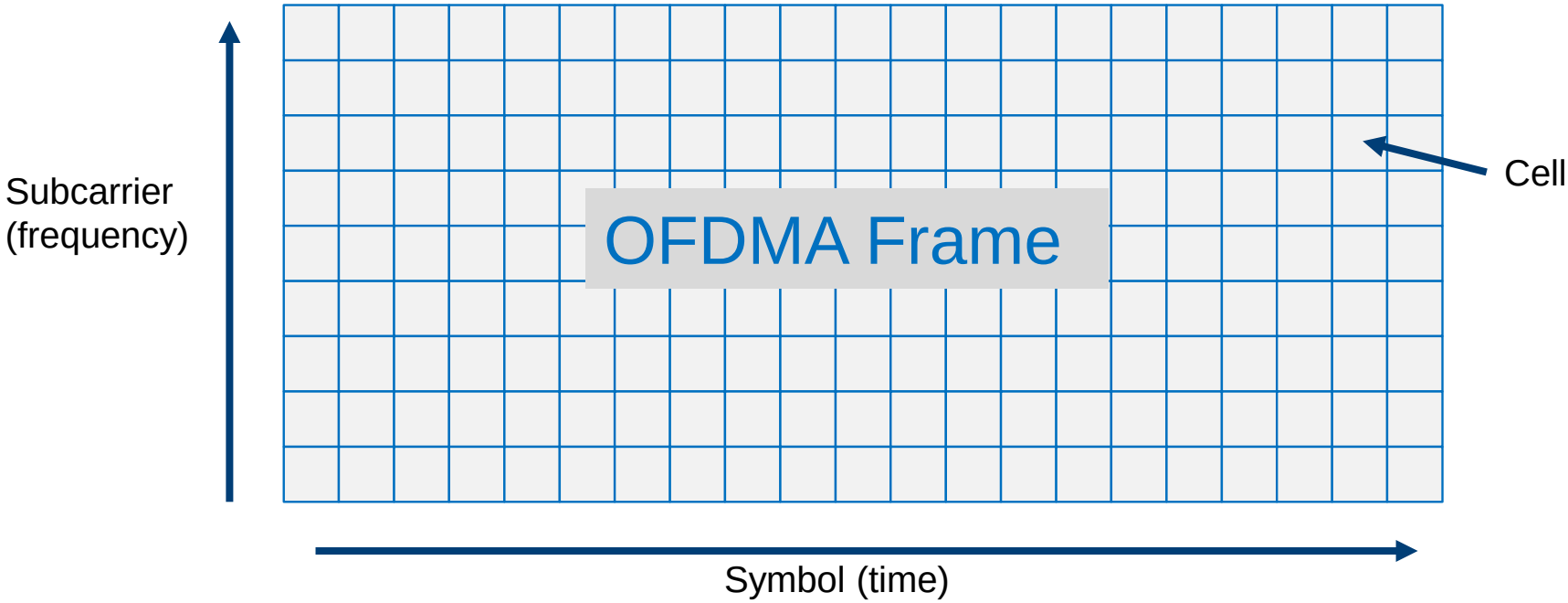
- OFDMA Concept: Use unfiltered carriers spaced at $1/T_s$
  - Spacing is much closer than in filtered FDMA systems where guard band must be used
  - $f_{subcarrier} = f_0 + n/T_S$ where n is an integer (subcarriers are harmonically related at baseband)
  - The peak of each carrier is at the nulls of all others
  - This is ensured by spacing the subcarriers at $\Delta f = 1/T_S$
  - These subcarriers are orthogonal





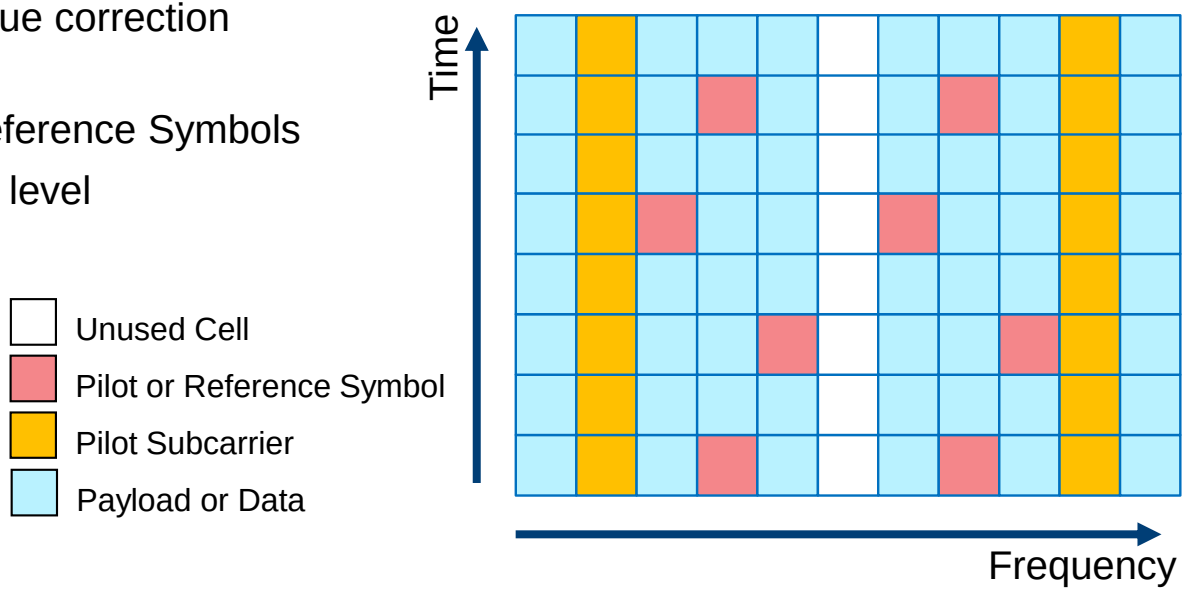
OFDMA: Time and Frequency Cells

- An OFDMA signal has many orthogonal subcarriers each sending symbols at the same rate
- Each cell can have a different power level and modulation type



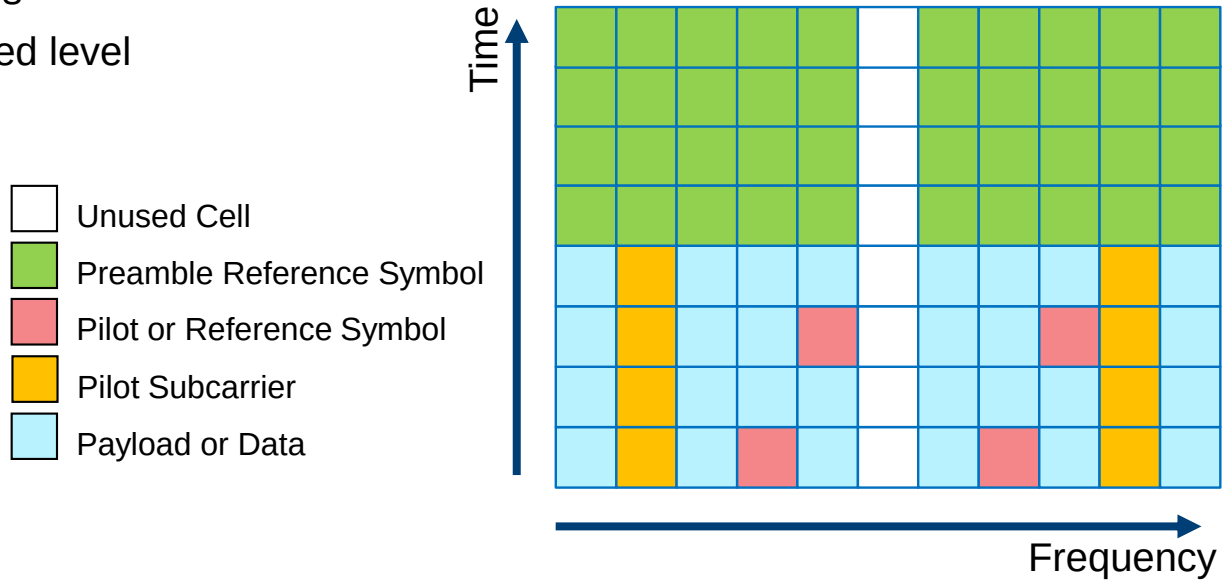
OFDMA Channel Equalization – Pilots

- OFDMA systems can have wideband channels – how do we equalize the channel?
- Send a known bit pattern on fixed OFDMA carriers (Pilot Subcarriers) or periodically in time and frequency (Pilot Cells)
- Use them to estimate channel response
- Each cell gets a complex value correction coefficient
- Pilot Cells are also called Reference Symbols
- Often transmitted at boosted level



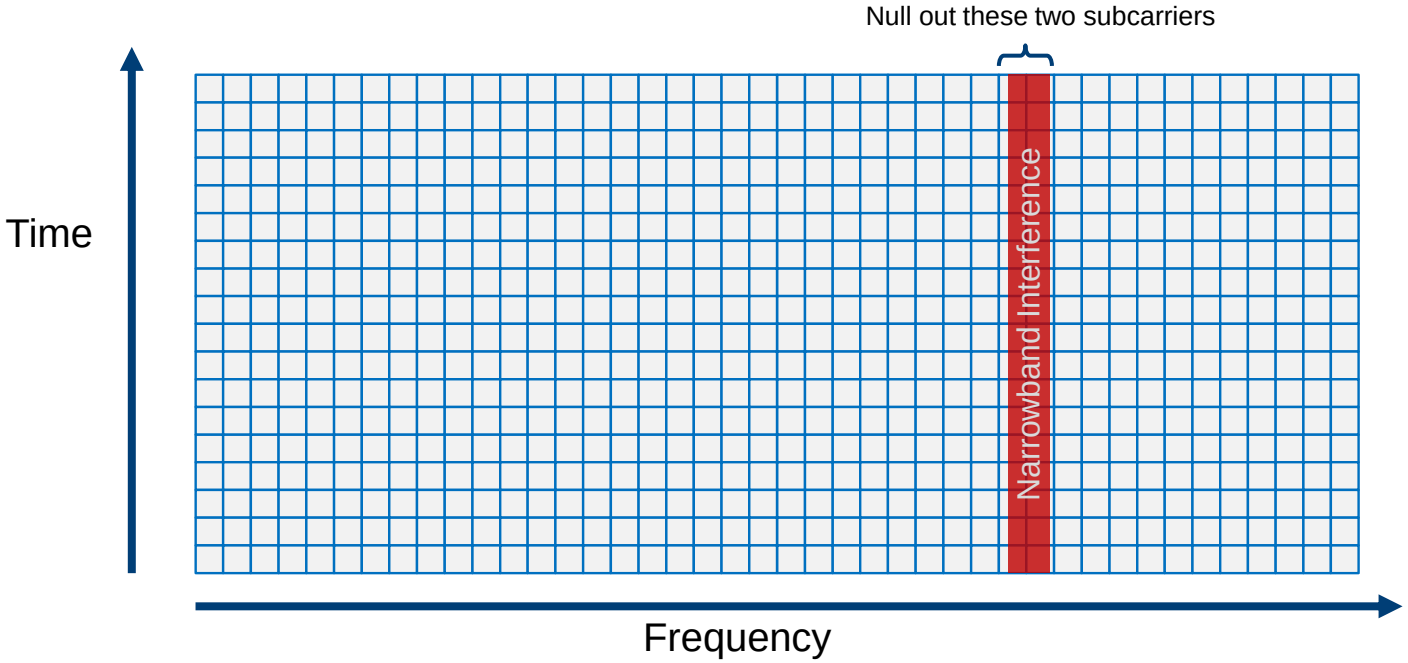
OFDMA Timing Synchronization – Preamble

- Synchronization in the Receiver is accomplished with a “preamble”
- The preamble bit pattern is known by the receiver
- Preamble is several symbols in duration
- Use most or all sub-carriers
- Often transmitted at boosted level



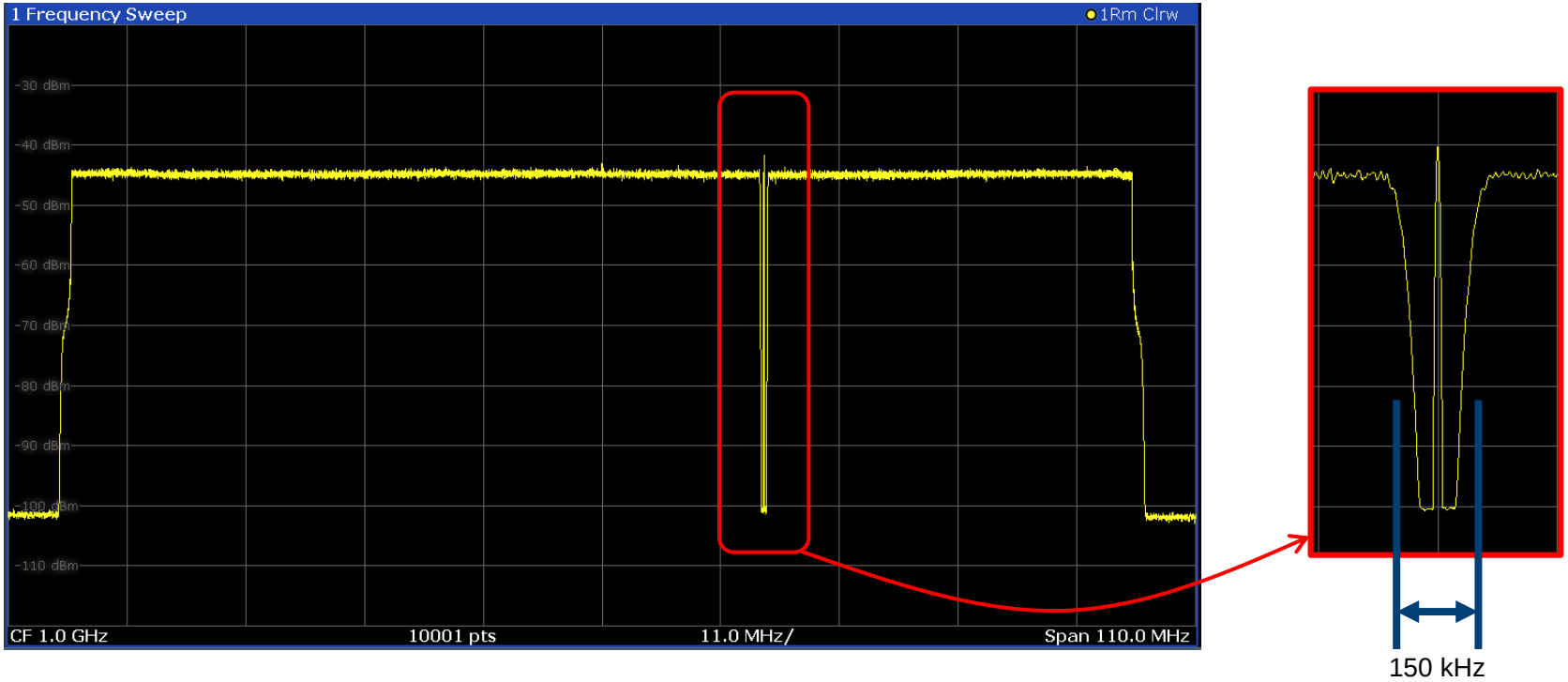
OFDMA: Flexible with Interference

- Narrowband interference can be a severe impairment on a single carrier signal
- In an OFDMA system, the affected subcarriers can be nulled out until interference is identified and eliminated

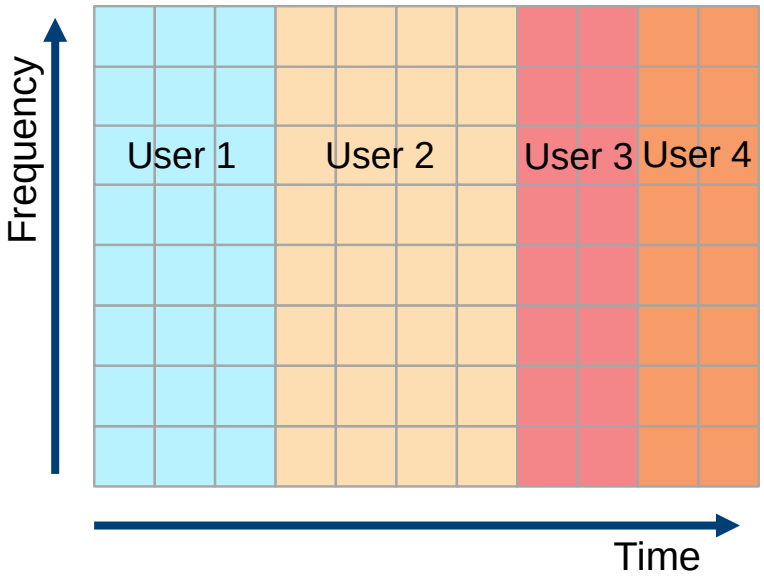


OFDMA: Robust against Interference

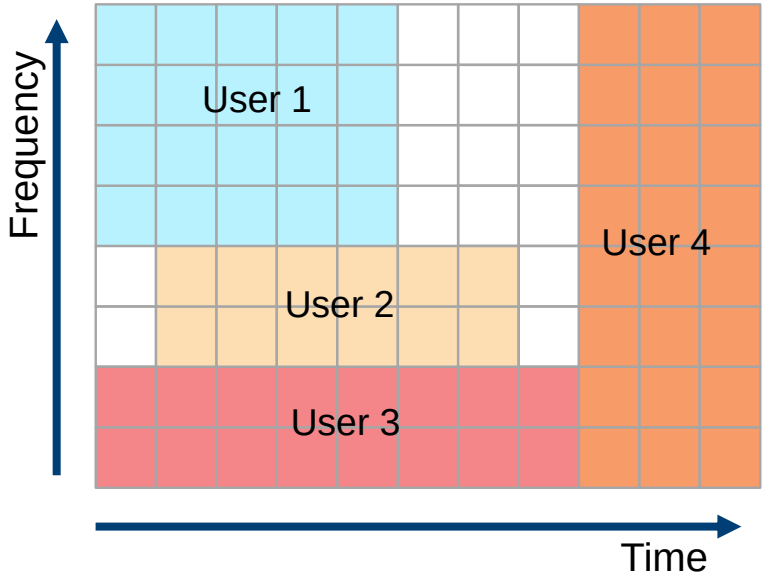
- Spectrum showing nulled subcarriers in the presence of a narrowband interferer



OFDM vs OFDMA



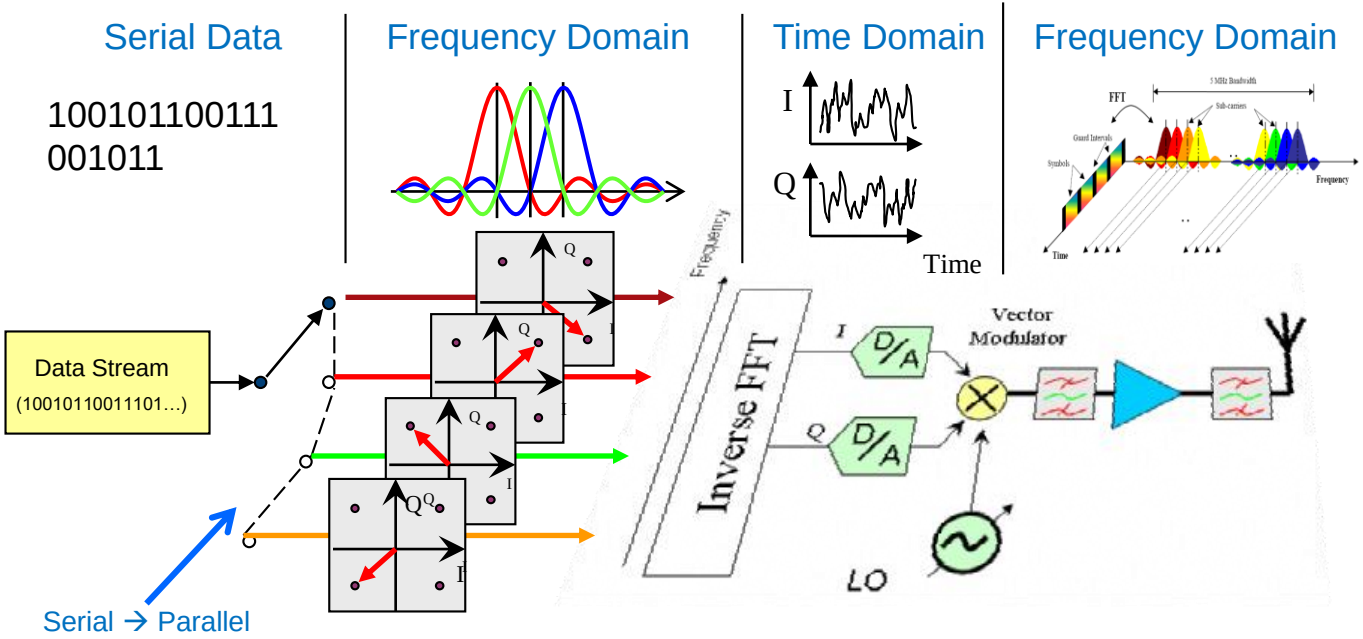
- OFDM allocates users in the time domain only
- Entire channel (all subcarriers) assigned to one user at a time



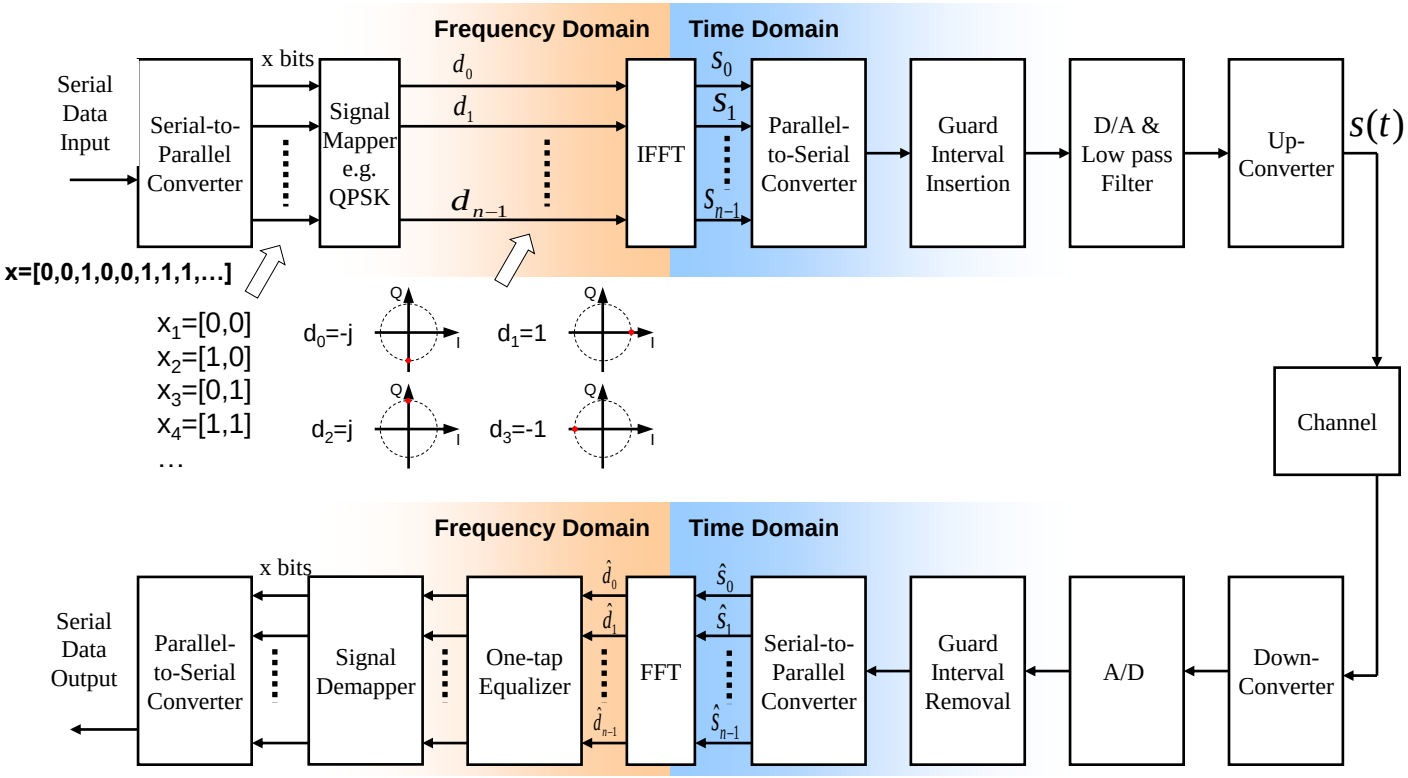
- OFDMA allocates users in the time and frequency domains
- Subcarriers can be allocated to multiple users

OFDMA Transmitter

- From Data to OFDMA carriers



OFDMA Transmitter & Receiver



OFDMA Transmitter

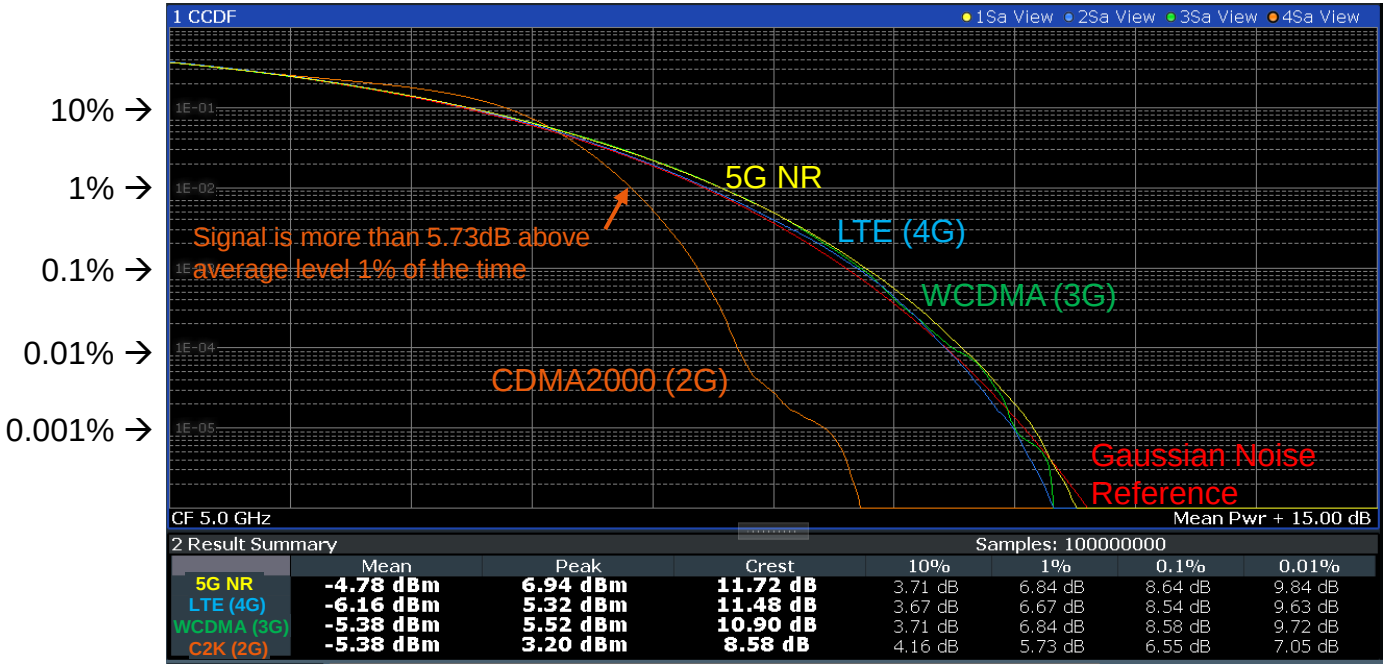
- Each OFDMA subcarrier can have any digital modulation
  - BPSK, QPSK, 16 QAM, 64 QAM, etc. (dynamically set based on channel quality)
- Data is divided up among the subcarriers (Serial to Parallel conversion)
- Subcarriers are modulated with the data symbols
- Each subcarrier has a magnitude and phase (or I/Q) value for the duration of the symbol (including CP)
- Use IFFT to convert from frequency domain to time domain
  - The number of subcarriers (FFT size) must be a power of 2.
  - Any carriers can be nulled (always done at channel edges)
- At this point we have a complex IQ time domain signal
  - Vector modulate it onto an RF carrier and transmit

OFDMA Disadvantage

- A major disadvantage of OFDMA is high crest factor (Pk/Avg ratio, PAPR)
- Since all subcarriers are coherent their phases can add constructively which causes high peak signal levels
- High crest factor requires highly linear amplifiers with high peak power capability
- Theoretical crest factor is 10 log ($N_{carriers}$)/2
  - Theoretical value for 1000 carriers is 15 dB
  - Probability of all carriers adding constructively is extremely small
  - In practice, crest factor is similar to that of Gaussian noise: ~12 dB
- Crest factor can be measured using CCDF (Complementary Cumulative Distribution Function)

CCDF: Complementary Cumulative Distribution Function

- CCDF measurement is used to quantify the probability of peaks levels within a signal (relative to its average level)



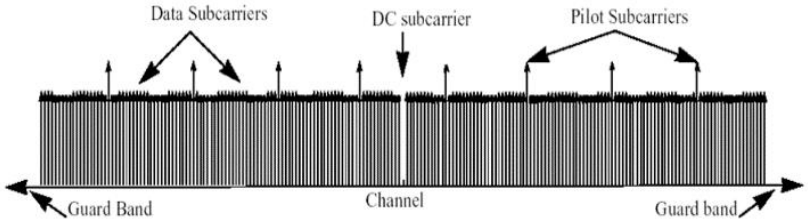
	Mean	Peak	Crest	10%	1%	0.1%	0.01%
5G NR	-4.78 dBm	6.94 dBm	11.72 dB	3.71 dB	6.84 dB	8.64 dB	9.84 dB
LTE (4G)	-6.16 dBm	5.32 dBm	11.48 dB	3.67 dB	6.67 dB	8.54 dB	9.63 dB
WCDMA (3G)	-5.38 dBm	5.52 dBm	10.90 dB	3.71 dB	6.84 dB	8.58 dB	9.72 dB
C2K (2G)	-5.38 dBm	3.20 dBm	8.58 dB	4.16 dB	5.73 dB	6.55 dB	7.05 dB

Where is OFDMA used?

- 5G NR
- LTE
- WLAN
- DVB digital video broadcast
- DAB digital audio broadcast
- MoCA (HD video distribution over coax)
- DOCSIS 3.1 (cable internet)
- Ultra Wideband (UWB)
- WiMAX
- VDSL2 (broadband over POTS)
- Flash-OFDM (Nextel)

OFDMA System Example: 802.16-2004 WiMAX

- Sub-carrier spacing is 45 kHz
- FFT size is 256 (192 carriers used, others nulled)
  - Bandwidth is 8.7 MHz (uses 10 MHz channel)
- Fundamental Sample Rate = 45 kHz * 256 = 11.52 MHz
- Useful symbol length is 22.22 us (1 / 45 kHz)
- Cyclic Prefix is 1/32 to 1/4 * Symbol length
- Data Modulation Order: BPSK to 64QAM
- Preamble consists of 1 or 2 symbols
- Pilots use 8 sub-carriers with BPSK modulation



OFDMA System Example: 802.11a WLAN

- Sub-carrier spacing is 312.5 kHz
- FFT size is 64 (52 carriers used)
  - Bandwidth is 16.25 MHz (uses 20 MHz channel)
- Fundamental Sample Rate = 312.5 kHz * 64 = 20 MHz
- Symbol length is 3.2 us (1 / 312.5 kHz)
- Cyclic Prefix is ¼ * Symbol length (0.8 us)
- Data Modulation Order: BPSK to 64 QAM
- Preamble consists of 5 symbols
- Pilots use 4 sub-carriers at all times

Data Rate (Mbps)	Modulation	Code Rate	Code Bits Per Subcarrier	Code Bits Per OFDM Symbol	Data Bits Per OFDM Symbol
6	BPSK	1/2	1	48	24
9	BPSK	3/4	1	48	36
12	QPSK	1/2	2	96	48
18	QPSK	3/4	2	96	72
24	16 QAM	1/2	4	192	96
36	16 QAM	3/4	4	192	144
48	64 QAM	2/3	6	288	192
54	64 QAM	3/4	6	288	216

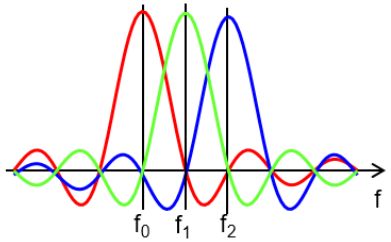
OFDMA System Example: LTE

- Sub-carrier spacing is 15 kHz
- FFT size up to 2048 (1201 carriers are used)
  - Max Bandwidth is 18 MHz (uses 1.4 MHz to 20 MHz channel)
- Fundamental Sample Rate = 15 kHz * 2048 = 30.72 MHz
- Useful symbol length is 66.6 us (1/15 kHz)
- Normal Cyclic Prefix is ~4.77 us
- Data Modulation Order: QPSK to 256 QAM
- Embedded sync channels
- Pilots at regular intervals

Frequency Range	UMTS FDD bands and UMTS TDD bands (see previous slides)					
Channel bandwidth 1 Resource Block (RB) =180 kHz	1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
	6 RB	15 RB	25 RB	50 RB	75 RB	100 RB
Modulation Schemes	Downlink	QPSK, 16QAM, 64QAM				
	Uplink	QPSK, 16QAM, 64QAM (⇨ optional for handset)				
Multiple Access	Downlink	OFDMA (Orthogonal Frequency Division Multiple Access)				
	Uplink	SC-FDMA (Single Carrier Frequency Division Multiple Access)				
MIMO technology (see next slide for details)	Downlink	Wide choice of MIMO configuration options for transmit diversity, spatial multiplexing, and cyclic delay diversity (max. 4 antennas at base station and handset)				
	Uplink	Multi-user collaborative MIMO				
Peak Data Rate (depending on UE category)	Downlink	150 Mbps (UE category 4, 2x2 MIMO, 20 MHz) 300 Mbps (UE category 5, 4x4 MIMO, 20 MHz)				
	Uplink	75 Mbps (20 MHz)				

OFDM / OFDMA Summary

- OFDMA uses many low data-rate subcarriers (long symbol time) along with cyclic prefix to mitigate multipath effects
- Subcarriers are orthogonal and closely spaced – spectrally efficient
- OFDMA signals can have high crest factor (~12 dB)
- Subcarriers can individually have any order of digital modulation (BPSK to 16384 QAM)
- OFDMA subcarriers can be nulled to avoid narrowband interference
- Pilots (or Reference Symbols) are used for channel estimation (equalization) at the receiver
- Preamble (known data sequence) is used for timing synchronization at the receiver
- OFDMA offers extreme flexibility for network operators for serving a wide variety of users and applications
- OFDMA is commonly used in a variety of modern communication systems



Have we answered our questions?

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- What's the difference between Modulation and Channelization
- How does OFDMA work?
- What does this diagram represent?
- What is Cyclic Prefix/Guard Interval and why is it used?
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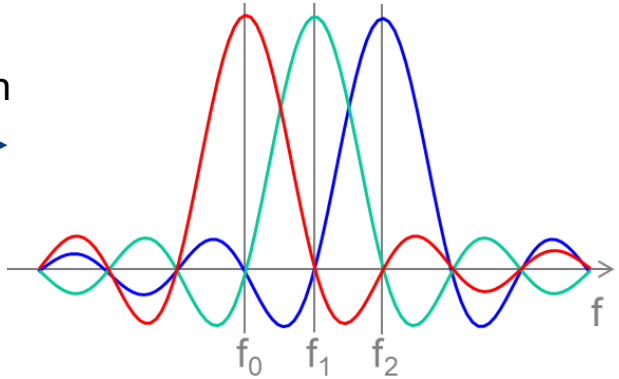

Thank You!

ROHDE&SCHWARZ

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