ECE 447 Communication Systems

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Lesson 39 Objectives (!)

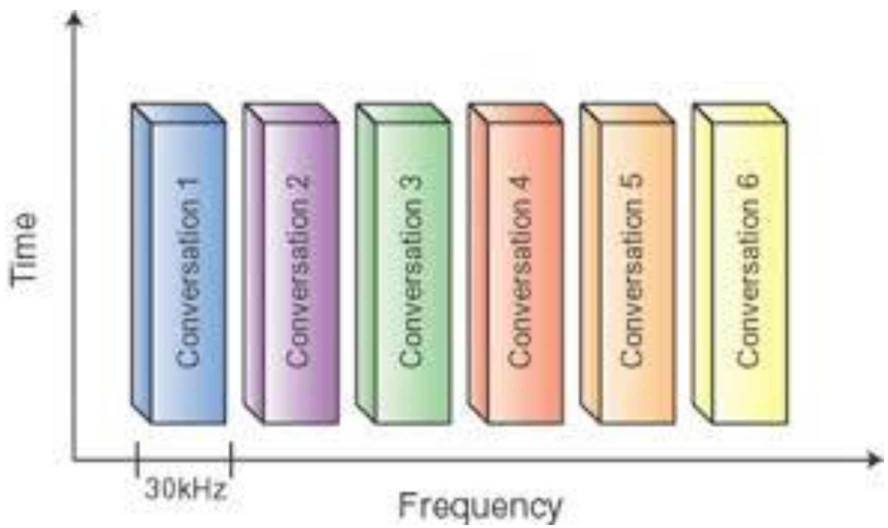
- Understand the different methods for multiplexing/multiple access
  - FDM/A – Frequency Division Multiplexing/Multiple Access
  - TDM/A – Time Division Multiplexing/Multiple Access
  - CDM/A – Code Division Multiplexing/Multiple Access
  - SDM/A – Space Division Multiplexing/Multiple Access
  - PDM/A – Polarization Division Multiplexing/Multiple Access
  - OFDM/A – Orthogonal Frequency Division Multiplexing/Multiple Access
- Understand what orthogonal frequency division multiplexing (OFDM) is and why modern digital comm systems use it
- Understand what a cyclic prefix is and why it must be used in OFDM
- Understand how OFDM mitigates the effects of frequency selective fading through equalization
- Understand the importance of pilot signals in an OFDM symbol
- Understand what MIMO is and why it was such an important innovation for communication systems
  - Spectral efficiency improvement
  - Gains (array, diversity, coding)

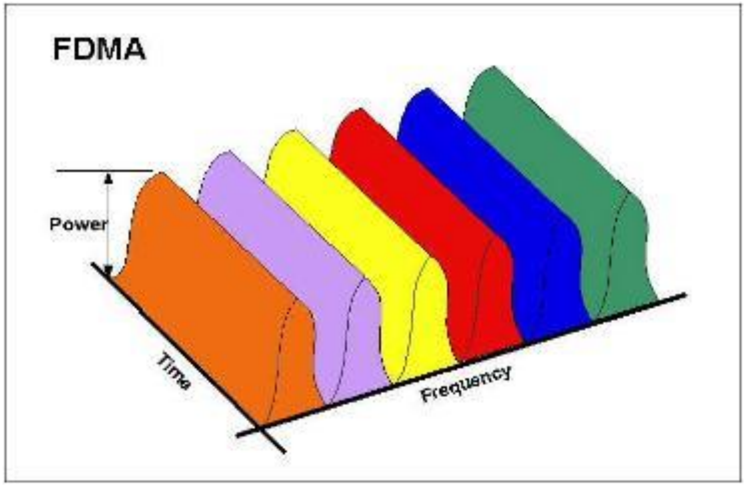
Multiplexing or Multiple Access?

- Both refer to how resources in a communication system are shared
- Multiplexing
  - Fixed or slowly changing allocation
  - Assigned *a priori*
- Multiple access
  - Dynamic allocation
  - Controller must be aware of each user's needs
    - How? Through control signals that run in background
    - Why? Enables *efficient* utilization of resources

FDM/A

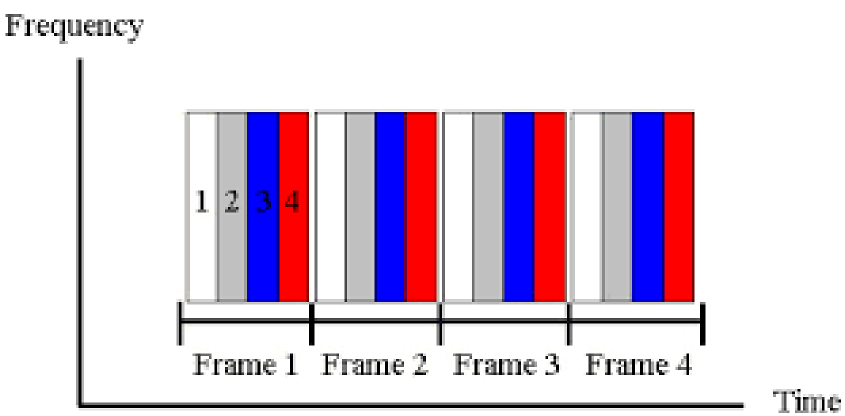
- **Allowing multiple users to use the same channel by splitting up frequency channels**
  - **Separation done in the frequency domain**

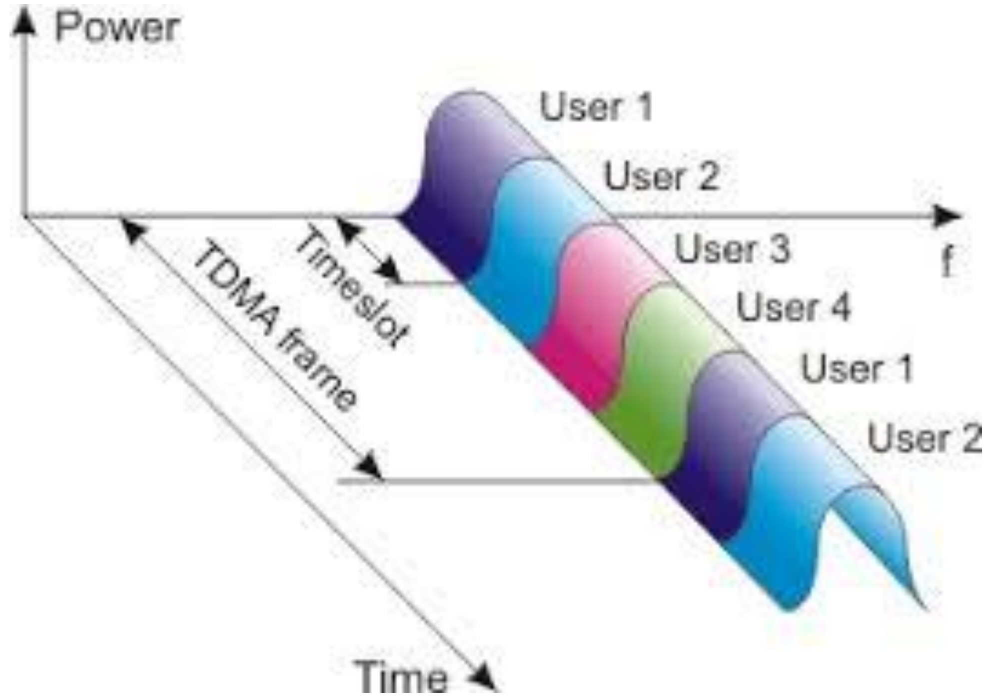




TDM/A

- Allowing multiple users to use the same channel by splitting up time slots
  - Separation done in the time domain



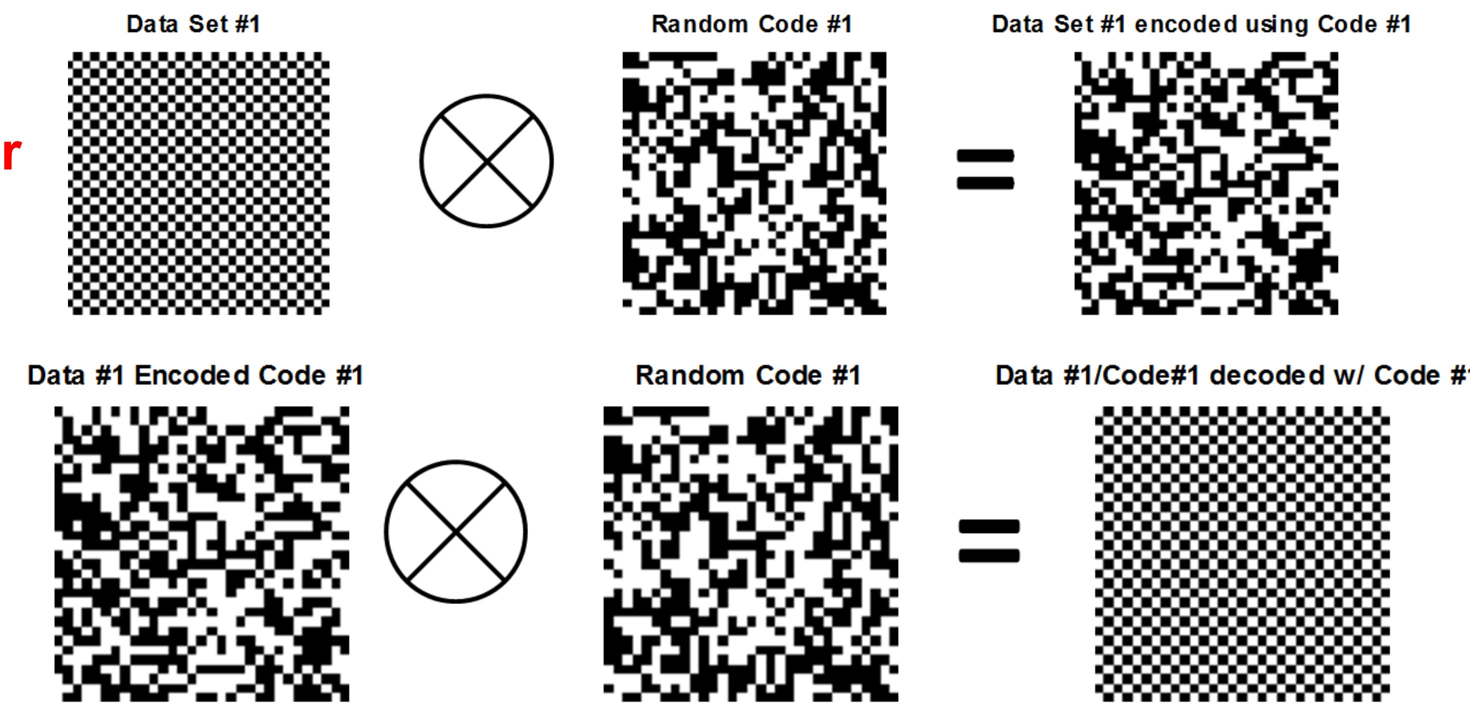


CDM/A

- **Share communications resources by using special non-interfering/orthogonal codes that can be transmitted at the *same time* and on the *same frequency***

Data at Transmitter

Data at Receiver



CDM/A Example – Spread Spectrum

<u>Direct-Sequence Spread Spectrum example:</u>

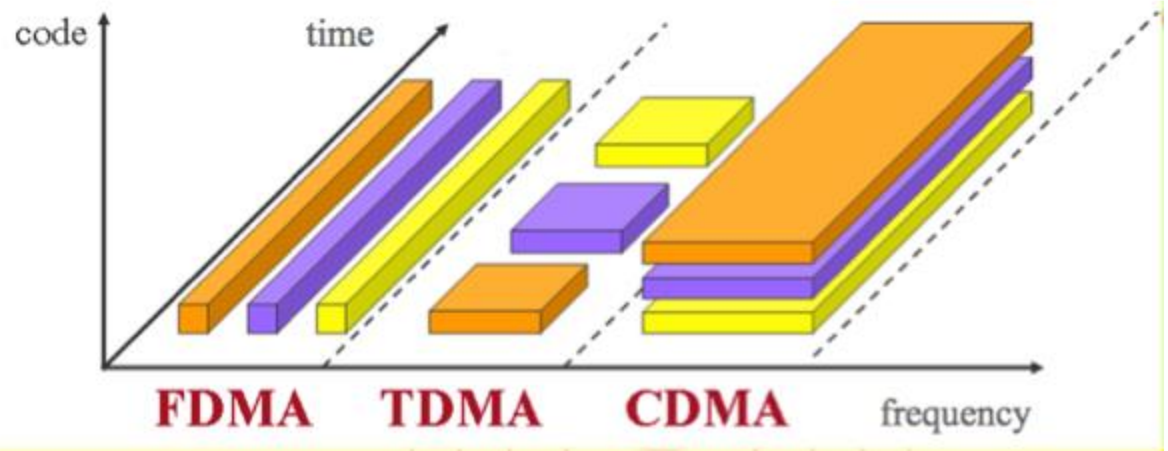
Bit to be transmitted:	1	(this bit lasts 10 μs)
Chipped bit (resampled)	1111111111	(each “chip” is 1 μs)
PRN	<u>1011010101</u>	
XOR result	0100101010	Note: XOR: one + one = 0; one + zero =1

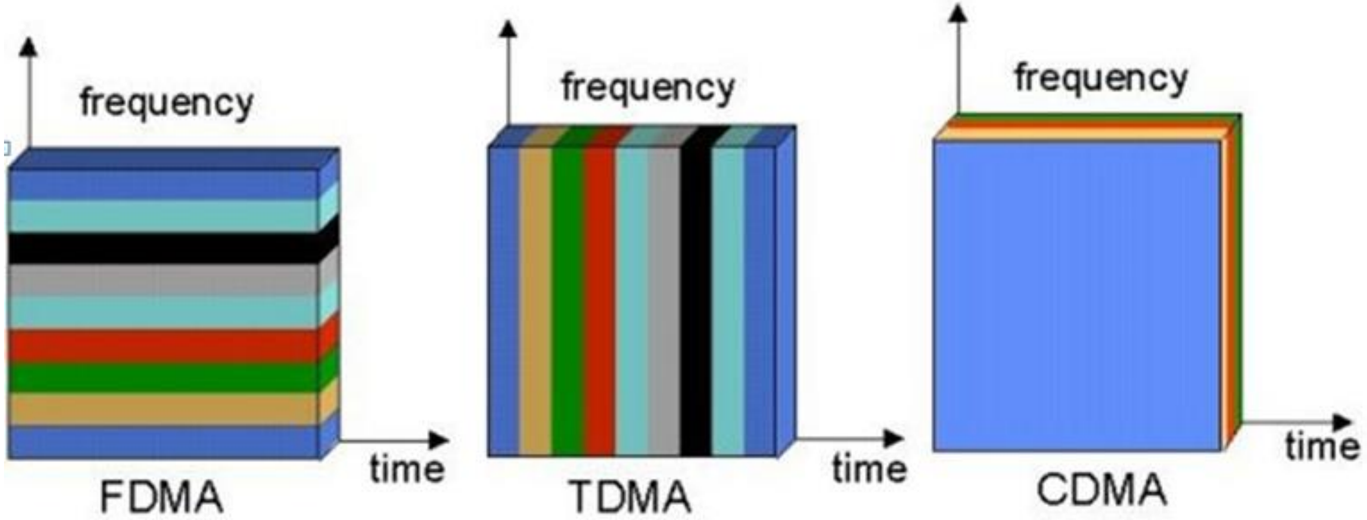
The sequence of 0100101010 is transmitted to the receiver:

Bits received:	0100101010	
Receiver applies PRN	<u>1011010101</u>	Note: PRN is exactly the same as above
XOR result	1111111111	

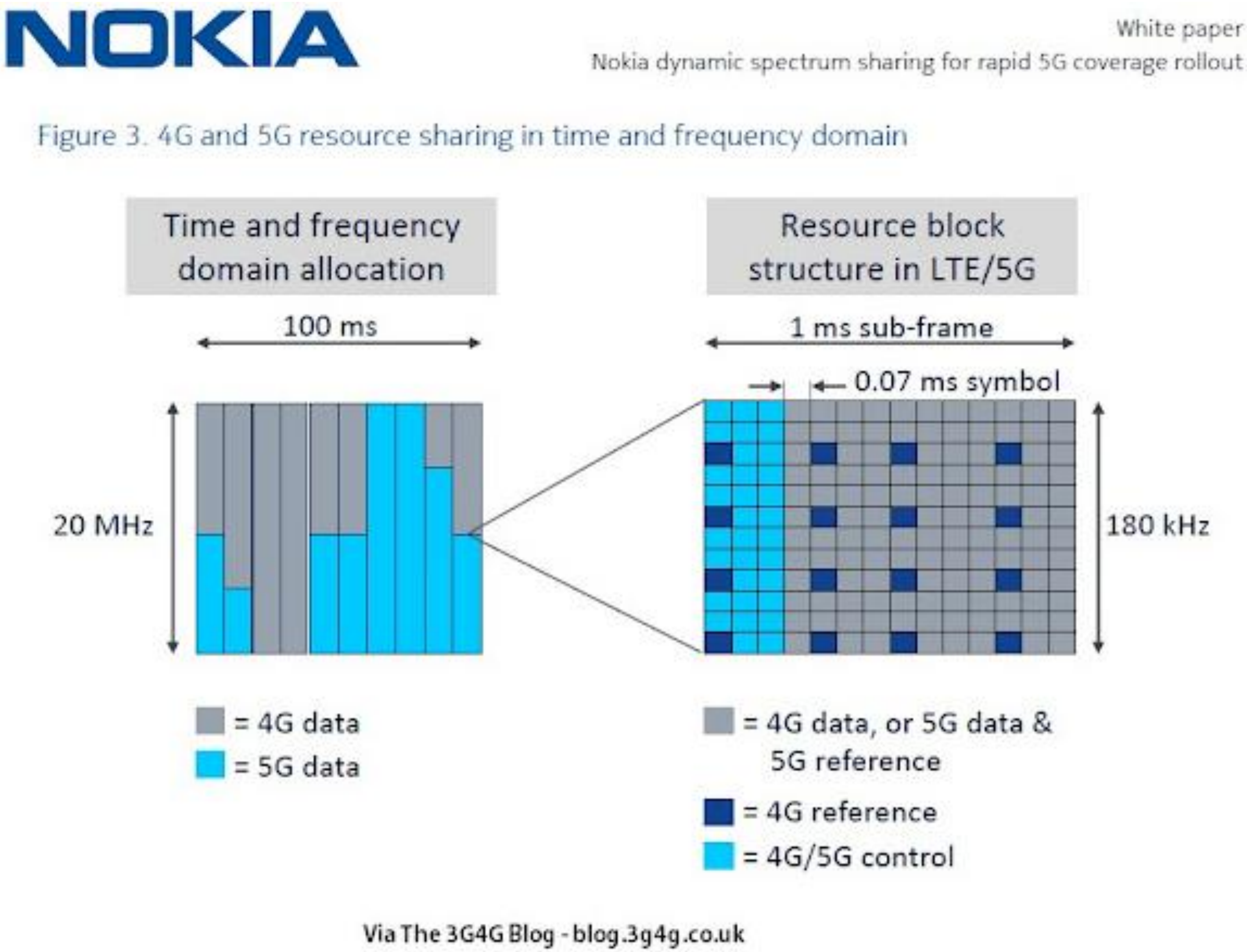
This string of ten “1”s is passed through a low pass filter which recreates the original 10 μs-long bit.

Comparing Methods





Example: 5G Resource Blocks



SDM/A and PDM/A

- **SDM/A**
  - Use multiple antennas with different beams separated spatially
  - Prevalent in satellite and 4G LTE/5G cellular systems
- **PDM/A**
  - Antenna polarization determined by direction of electric field
  - Antennas with ideal orthogonal polarizations do not interfere with each other
  - Examples include satellite TV and cellular backhaul (microwave antennas)

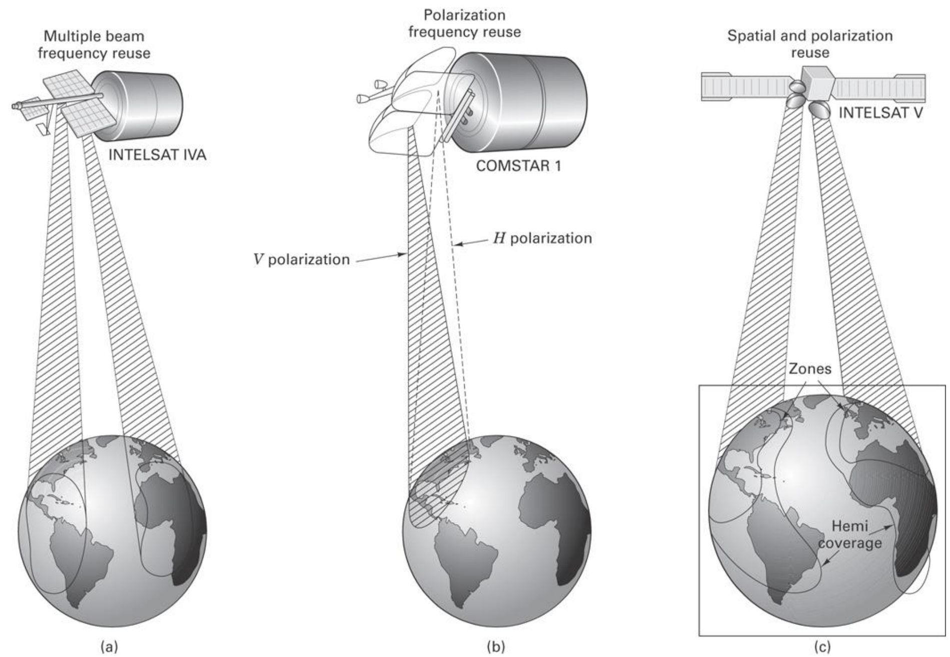
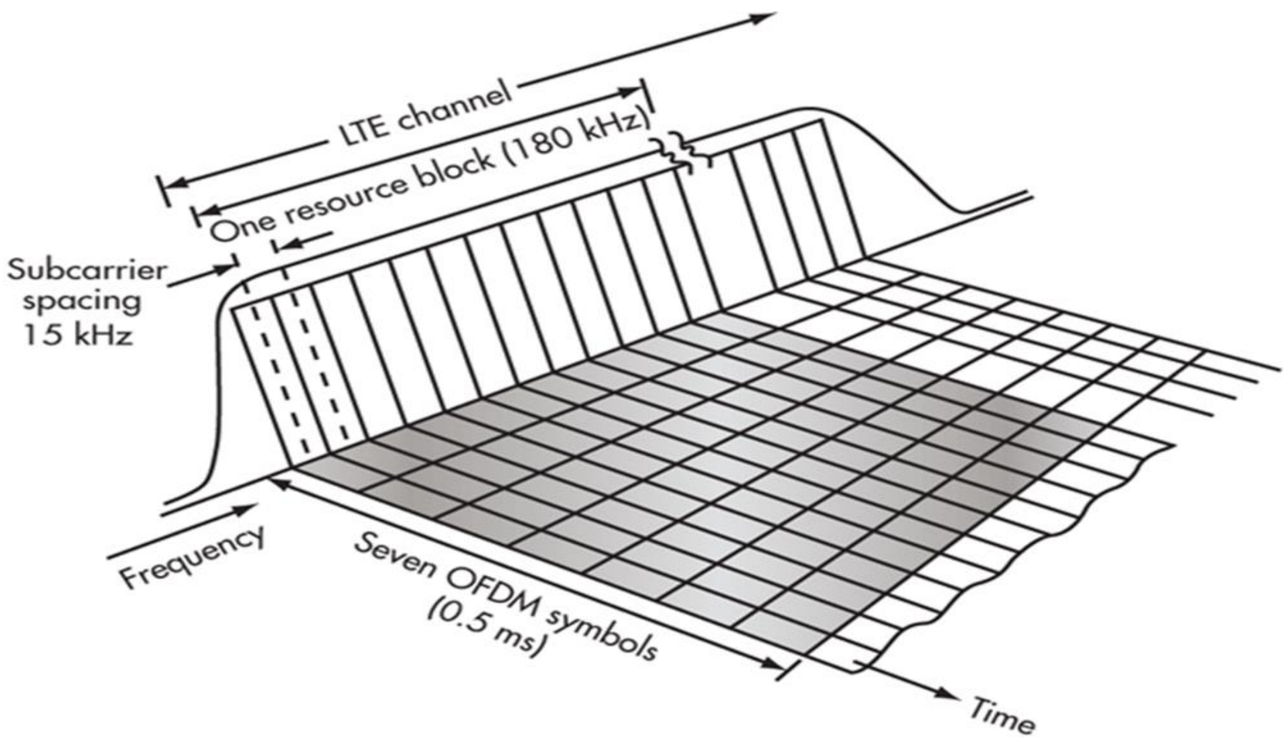


Figure 11.15 from Sklar

OFDM/A

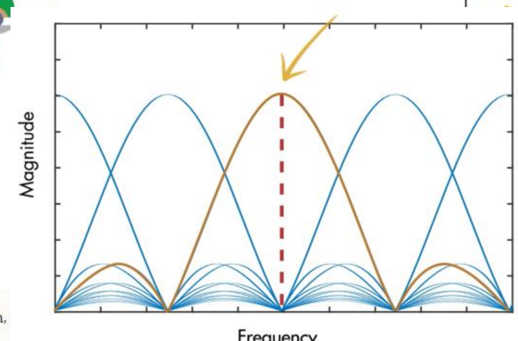
- **Share communications resources in the both the frequency and time domains simultaneously, by transmitting on separate channels during specific time slots**

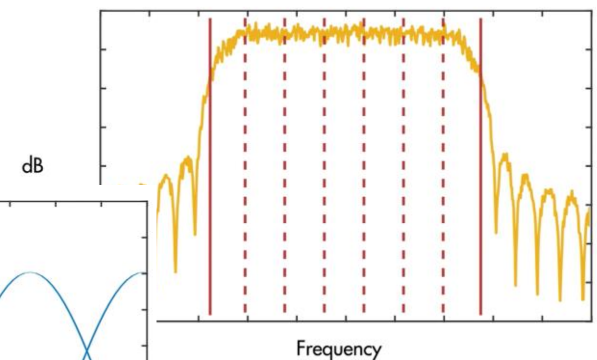


What is OFDM?

- **A technique used to transform a single serial high-rate data stream into many parallel low-rate data streams**
- **Each QAM symbol from serial stream is assigned to a different frequency within the signal bandwidth known as a *subcarrier***
  - **The OFDM symbol is the sum of all frequency-translated QAM symbols**
- **Each subcarrier peak lines up at the zero crossing of the others → this makes them orthogonal!**

Figure 15.1 Transport analogy: One large delivery vehicle depicts ordinary FDM. Many small vehicles depict OFDM. (Charan Langton, www.complextoreal.com)

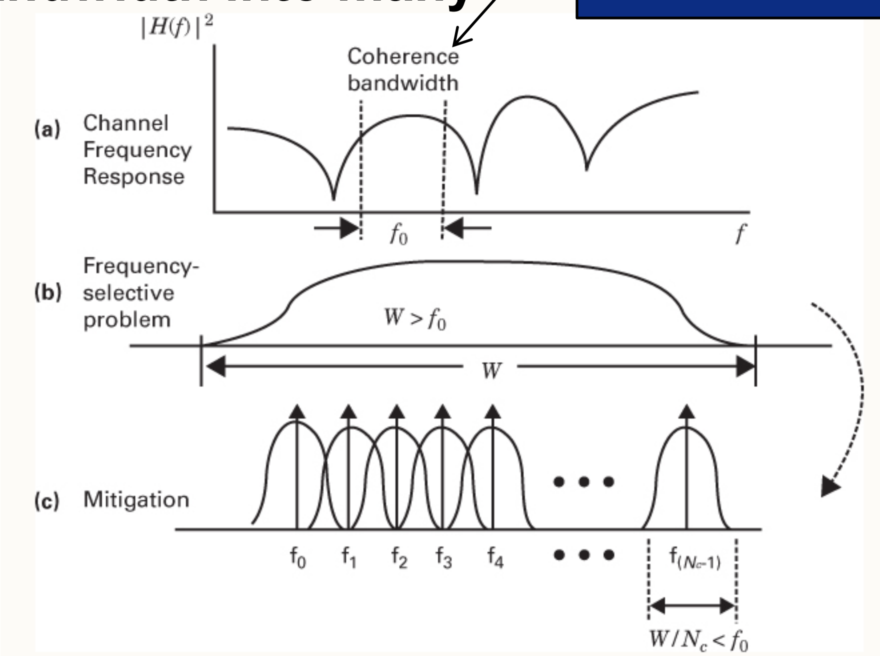




Why OFDM?

- Need coherence bandwidth of channel to be greater than signal bandwidth
  - High data rates → wideband signals → large coherence BW
  - Unlikely…why?
- Instead OFDM divides signal bandwidth into many small narrowband channels with BW less than channel coherence BW
- Why do we care if these sub-carriers are orthogonal or not?

BW over which the channel's amplitude response is flat and phase response is linear (relatively)



OFDM allows us to send spectrally-efficient, wideband (high data rate) signals across channels we normally would not be able to

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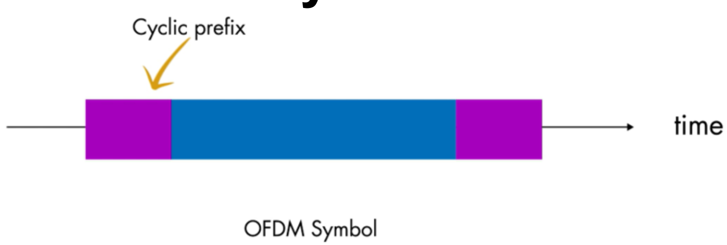
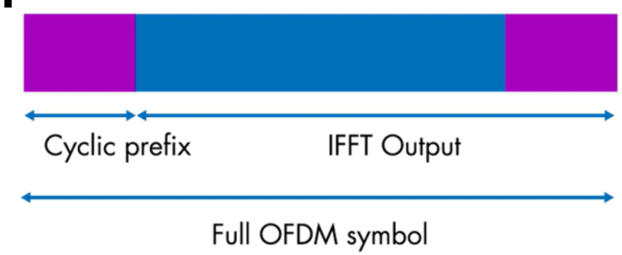
How do we make and transmit OFDM symbols?

1. **Move QAM symbols to subcarrier frequencies and sum together**

$$s(k) = \sum_{m=0}^{N-1} a_m e^{j2\pi\left(\frac{mk}{N}\right)}$$

2. **Add cyclic prefix**
   - **Necessary for accurate channel equalization**

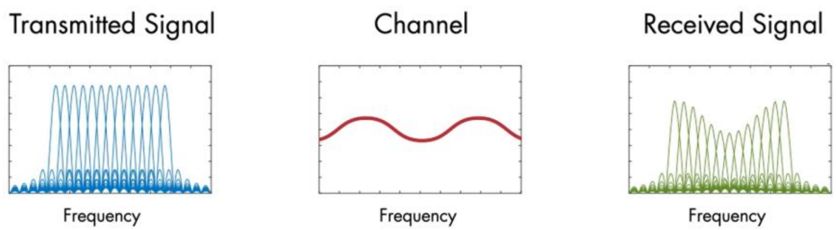




3. **Then upconvert to desired transmission frequency, amplify to desired power, and transmit**

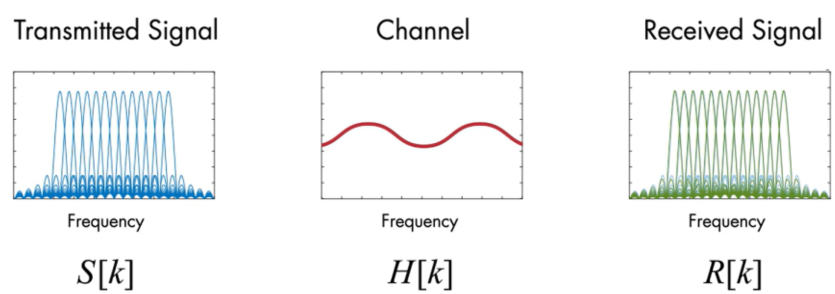
What about the channel distortion?

- **Recall that the channel will affect the subcarrier amplitudes**



- **We use our knowledge of the channel, or the channel model $H[k]$, to perform *equalization* on the received OFDM symbols**

Remember: in the time domain the received signal is the convolution of the transmitted signal and the channel's impulse response. What is convolution in the frequency domain?

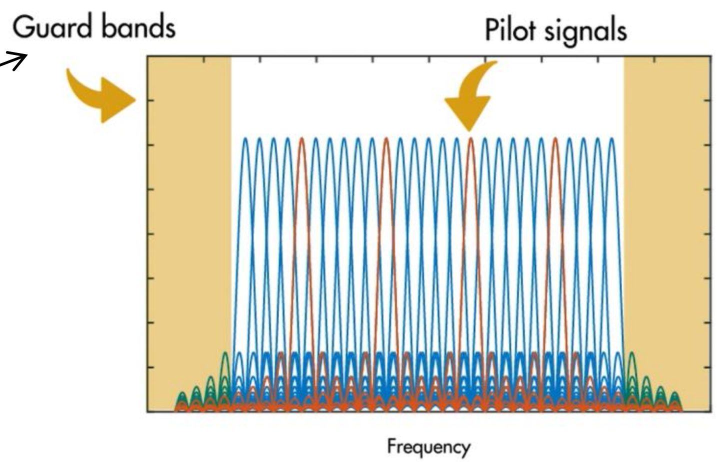


$$\hat{S}[k] = \frac{R[k]}{\hat{H}[k]}$$

How do we find out what the channel is?

- Evenly space subcarriers in the OFDM symbol are designated as pilot signals

Guardbands separate OFDM symbols



`ofdmmod`

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- Known pilot signals are used to estimate the channel model ($\widehat{H}[k]$) to get the Channel State Information (CSI)
  - Decisions on modulation order, rate allocation, power level, scheduling, and more based on CSI
- So … what happens if CSI is wrong?

How do we receive OFDM symbols?

1. Downconvert from carrier frequency
2. Remove cyclic prefix
   - Doesn’t affect OFDM symbol since cyclic prefix is redundant
3. Use CSI to equalize received QAM symbols at their respective subcarrier frequencies
4. Demodulate QAM symbols to bits

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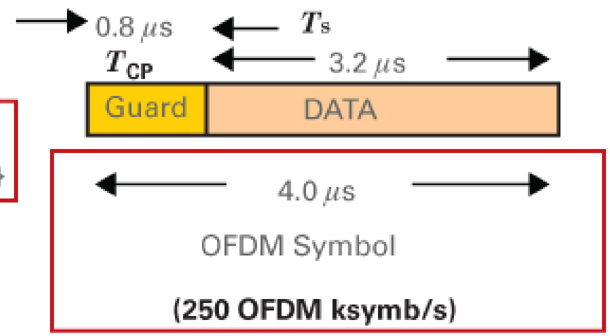
OFDM in 802.11a (WiFi)

OFDM 802.11a

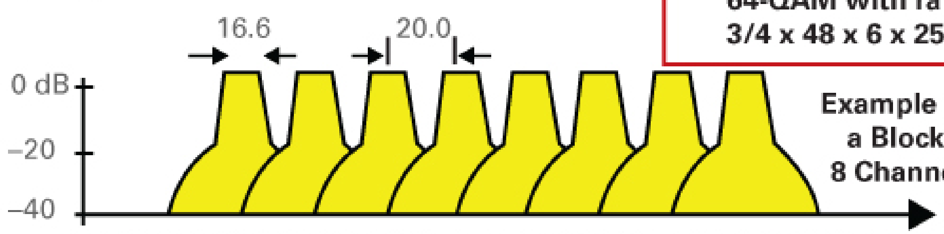
Uplink and Downlink are Symmetrical

OFDM SYMBOL DURATION	4 μsec T_{OFDM}
Guard Interval	800 nsec
Orthogonal Tone Duration	3.2 μsec
Tone Center Spacing **between DFT bins**	312.5 kHz {1/3.2 μsec}
Number of Data Tones	48
Number of Pilot Tones	4
Total Number of Tones	Nc = 52
Total Bandwidth $(Nc + 1)\,\Delta f$	16.56 MHz {(52+1)*312.5 kHz)}
Modulation	BPSK, QPSK, 16-QAM, 64-QAM
Coding Rate	1/2, 2/3, 3/4
Data Rates	6, 9, 12, 18, 24, 36, 48, 54 Mbps
Channel Spacing	20 MHz



BPSK with rate 1/2 code
1/2 x 48 x 250 ksymb/s = 6 Mbps

64-QAM with rate 3/4 code
3/4 x 48 x 6 x 250 ksymb/s = 54 Mbps



Example of: a Block of 8 Channels

Each channel shown with two-sided BW around its center frequency

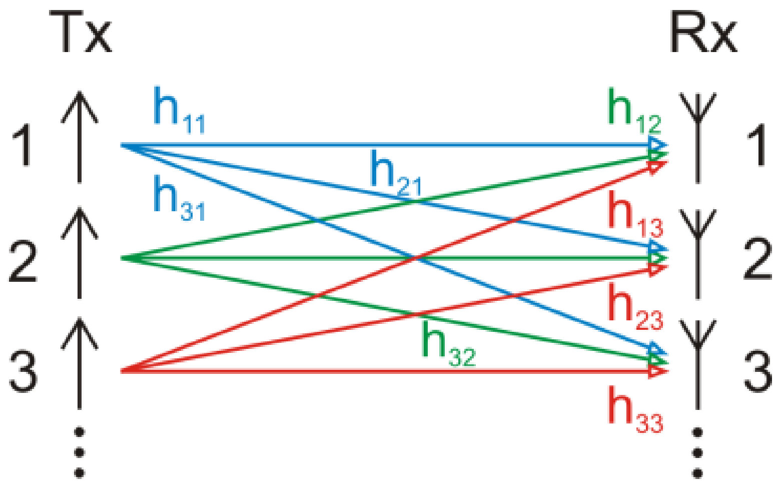
N_c = 52 Subcarriers (48 data + 4 pilot) in each 20 MHz Channel

Typical N-point DFT used is N = 64 or N = 128

E?cient overlap of OFDM orthogonal tones. The spectral tails necessitate 4 MHz guard bands.

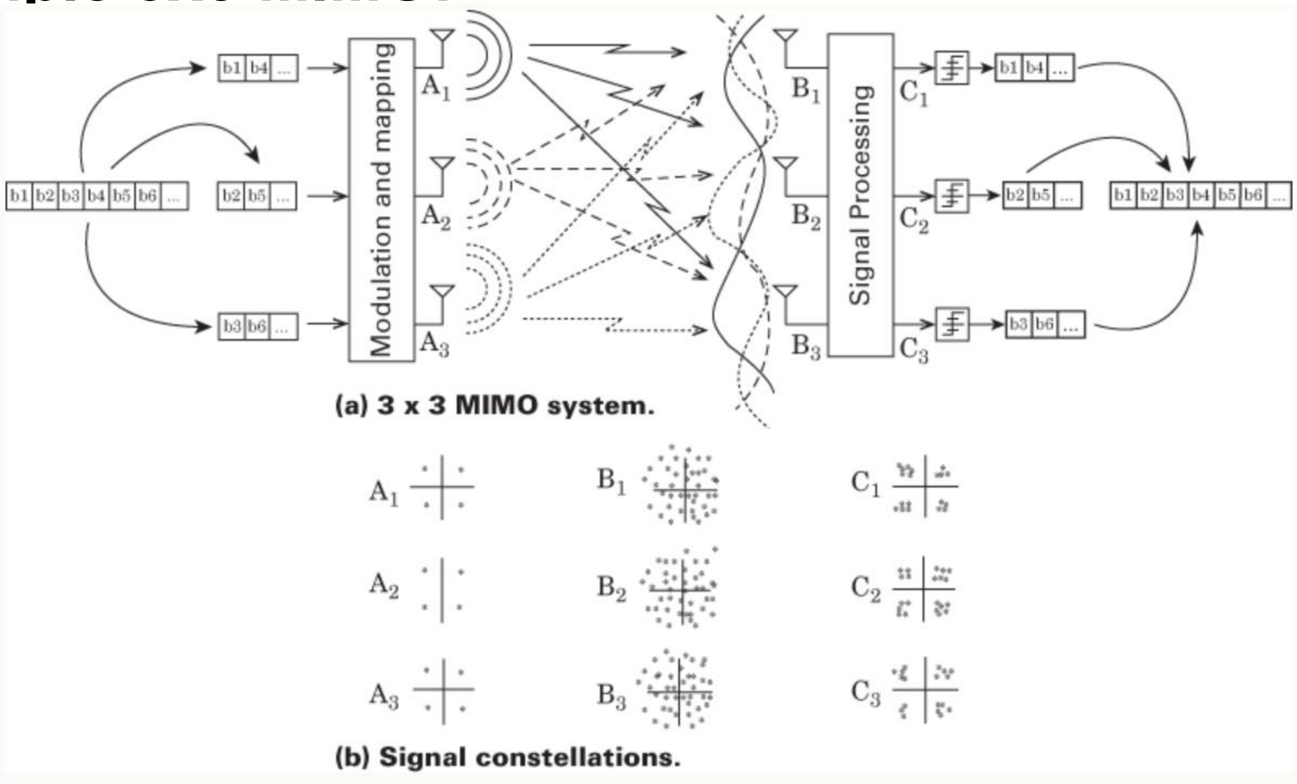
What is MIMO?

- **MIMO systems employ multiple antennas at the Tx and Rx**
- **Space-time signal processing – includes spatial component where previously we only used time/freq**
  - **<u>Improves BER and/or increases channel capacity (theoretical data rate) *without* requiring more power or additional bandwidth</u>**
  - **Instead of "fixing" multipath environment – requires it**
- **Channel state information represented by matrix H**
  - **Linear algebra! SVD! PCA!**



What is MIMO?

- **Example 3x3 MIMO:**



(a) 3 x 3 MIMO system.

(b) Signal constellations.

- **Spread spectrum analogy: instead of different signals sent with different codes sharing same BW at a cost of expanded BW, different signals sent over different paths share same BW at a cost of additional antennas**

Importance of MIMO

- Foschini (Bell Labs) demonstrated spectral efficiency greater than 40 bits/s/Hz in 1996
  - Appeared to defy theoretical "Shannon limit"
  - For a conventional single antenna system, each bit/s/Hz requires doubling the constellation size starting with BPSK
  - Extreme spectral efficiency made possible using multiple antennas at the Tx and Rx
- Space-time coding provides coding gain, but not from using additional bits like in FEC
  - Uses additional antennas
  - Diversity gain improves robustness across varying channels

Other MIMO concepts

- If Rx and Tx have CSI…
  - Tx able to optimally allocate power to channels with high SNRs
  - Called water-filling algorithm
- Multi-User MIMO (MU-MIMO)
  - More complicated
  - Can't perform joint computations (channel matrix inversions)
  - Requires cross-layer design
  - PHY layer modulation and coding, Link layer multiple-access channel
  - WiFi 802.11ac standard uses beamforming MU-MIMO in downlink direction