A quick dive into Wi-Fi

EURECOM, January 2025

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Algorithms & Signal Processing Engineer

Agenda

- CEVA Introduction
- Wi-Fi Introduction
  - Market and Timelines
  - WLAN Topology
  - CSMA/CA
  - Channels
- OFDM
  - Basics and hints
  - Advantages and disadvantages
- Wi-Fi PHY key features evolution
- OFDMA (in 11ax)
- 11ax Frame formats
- MIMO Channel Estimation
- Transmit Beamforming
- Wi-Fi 7 and Wi-Fi 8: Present and Future
  - Coordinated MU-MIMO Beamforming

Corporate Introduction

Licensing IP since 1991
Over **16bn** devices shipped
Powered > 1.7bn devices in 2022

NASDAQ:CEVA

Strong, profitable
~$160m cash, no debt

> 400 employees

> 200 registered patents

R&D centers
Israel, U.S., France, Serbia & U.K.

Worldwide Operations

Global Reach Through Local Presence;
All direct CEVA employees

Technology Portfolio Value Proposition

World's #1 5G & wireless communication IP

5G · Wi-Fi · UWB · Bluetooth

Powering >1B new connected devices annually

Scalable Edge AI Sensing IP

TinyML · DSP+AI · NPU

Addressing full gamut of Edge AI use cases with >500m devices shipped

Embedded Application Software

Sensor Fusion, Spatial Audio, Audio AI, Positioning

CEVA software IP powering >300m devices

Target markets:

Consumer IoT · Mobile · Automotive · Data Center & 5G infrastructure · Industrial · PC

Our Customers

CEVA IP powers the world’s leading semiconductors and OEMs

intel	UNISOC	NOKIA	ZTE	BROADCOM	NXP	BEKEN	BES TECHNIC
onsemi	socionext	LG	SAMSUNG	NOVATEK	ambiq	SEQUANS	sonova HEAR THE WORLD
iRobot	RENESAS	TOSHIBA	ST	SHARP	SONY	炬力 Actions	oticon
YAMAHA	Panasonic	Rockchip	MICROCHIP	INFOTM	FREQCHIP	MEDIATEK	nextchip
SigmaStar	Atmosic	GOODIX	INPLAY TECHNOLOGIES	LifeSignals	OPTEK	SatixFy	SRT
FUJIFILM	synaptics	artosyn 酷芯微电子	ESPRESSIF	SMIC	CERAGON	SCKIPIO	Itron
NORDIC SEMICONDUCTOR	VIA	SANECHIPS 中兴微电子	SUNPLUS	LEADCORE 联芯科技	Autotalks	iCatch Technology	GCT
ASR MICROELECTRONICS	ROHM SEMICONDUCTOR	CIRRUS LOGIC	VATICS	TEXAS INSTRUMENTS	Celeno Wireless Communications	Trademarks, trade names and logos (“Licensee Marks”) are the property of the respective Licensee	

Wireless IoT BU Introduction

Most advanced Wi-Fi IPs solutions

For Client devices and Access Points

All generations up to Wi-Fi 7

Ultra low power and cost-effective solution for NB-IoT

DSP & HW Accelerator for Cat-M/1

Positioning GNSS IoT IP

BLE and BT Dual Mode

802.15.4 add-on for IoT & smart home

High performance UWB PHY & MAC for ranging, AoA and Radar

Supports FiRa 2.0 & CCC's Digital Key 3.0 requirements

> 1.7bn CEVA-powered Devices Annually

harman/kardon®	soundcore	PHILIPS	RAZER	LG

HUAWEI	mi	MUDIX	iRobot	realme	ZTE	nubia Neo 5G

CEVA Inside!


Huawei Eyewear 2


JBL Live 770NC


Huawei Watch Ultimate


NearStream VM33


Lenovo Xiaoxin 100


Honor Watch 4


ZTE Blade A73 5G


Tmall Genie
IN Sugar 3 Pro


Tomtom Go Expert Plus

Plimpad tablet

DJI Osmo Action 4


Huawei Freebuds SE 2


Xiaomi
Smart Band 8


Xming Q3 MAX


Sharp Aquos Board

UWB most popular target applications

- “Find me” – track objects, already in market
- Secured Access
  - CAR Digital key
  - Home access
- HPD (Human Presence Detection)
  - Laptops – Auto log on\off
  - Automotive – Child presence detection
- Indoor positioning\RTLS (Real Time Locating System)
- Tap-free payments
  - Transit use case
  - Carpark payment
- Lossless low latency audio streaming







CEVA in France

- Located in the technological park of Sophia Antipolis (near Saint Philipe)
- New offices inaugurated in 2022
- Hybrid working policy

- Main R&D site for Wi-Fi and Bluetooth
- ~ 20 engineers on Wi-Fi, ~ 20 engineers on Bluetooth
- Small teams with long-lasting know-how

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What is Wi-Fi?

Wikipedia says:

“Wi-Fi is a family of wireless network protocols based on the IEEE 802.11 family of standards, which are commonly used for local area networking of devices and Internet access, allowing nearby digital devices to exchange data by radio waves. ”

Wi-Fi Applications

- Internet everywhere
  - Both indoor and outdoor as a Wireless LAN
- Internet of Things
  - Ex: Household appliances connected to a home wireless network
- Wi-Fi offloading for 5G
  - For overloaded cellular networks and limited coverage
- Medical and HealthCare
  - Wearable devices, monitoring patients, remote surgeries
- Industrial and logistics
  - Industry 4.0, robots can connect to central processing stations

Wi-Fi Advantages

- High data rates
- Unlicensed Spectrum
- “Low” Complexity
- Scalable and upgradeable
- Power efficient

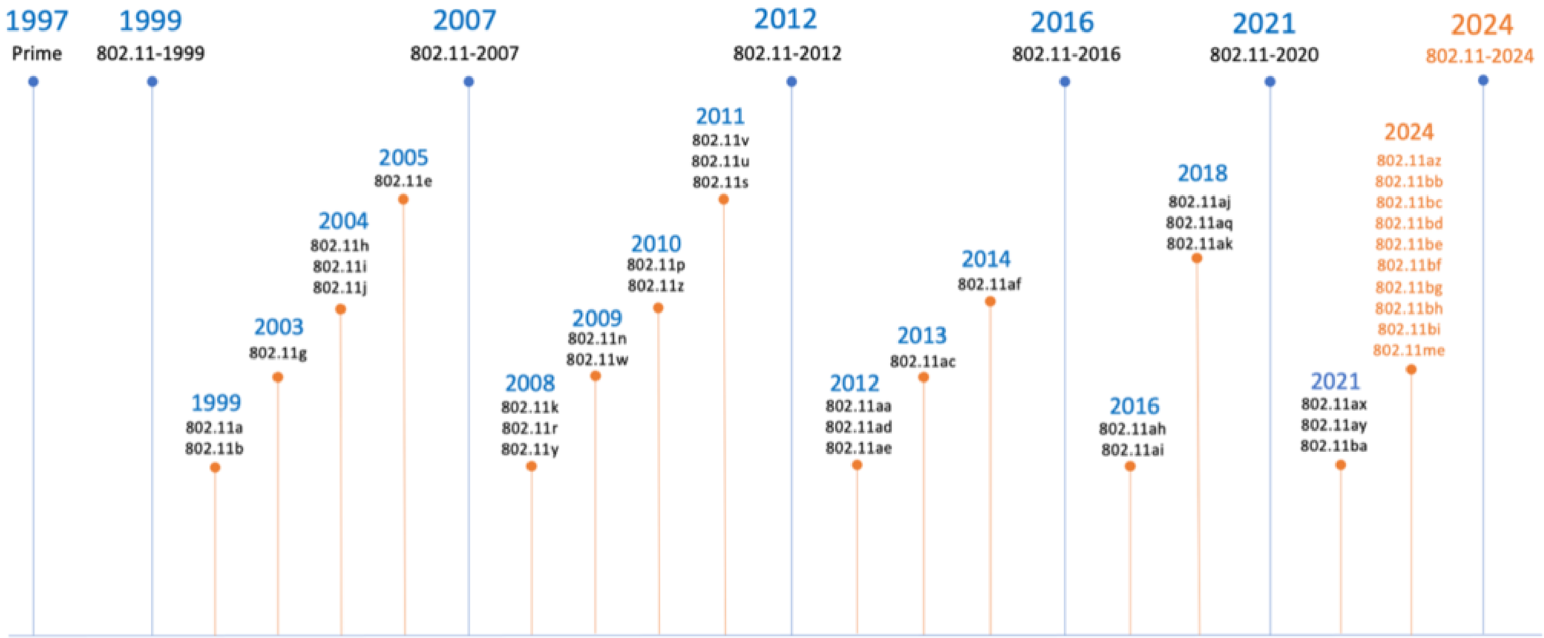
Wi-Fi Disadvantages

- Limited coverage/range
- Reliability
  - Due to interference
- Speed limitation
- latency

Wi-Fi Alliance generational branding

- Wi-Fi 1-3: 802.11a/b/g
- Wi-Fi 4: 802.11n (High Throughput)
- Wi-Fi 5: 802.11ac (Very High Throughput)
- Wi-Fi 6: 802.11ax (High Efficiency)
- Wi-Fi 7: 802.11be (Extremely High Throughput)
- Wi-Fi 8: 802.11bn (Ultra High Reliability)

IEEE 802.11 Standards Timeline

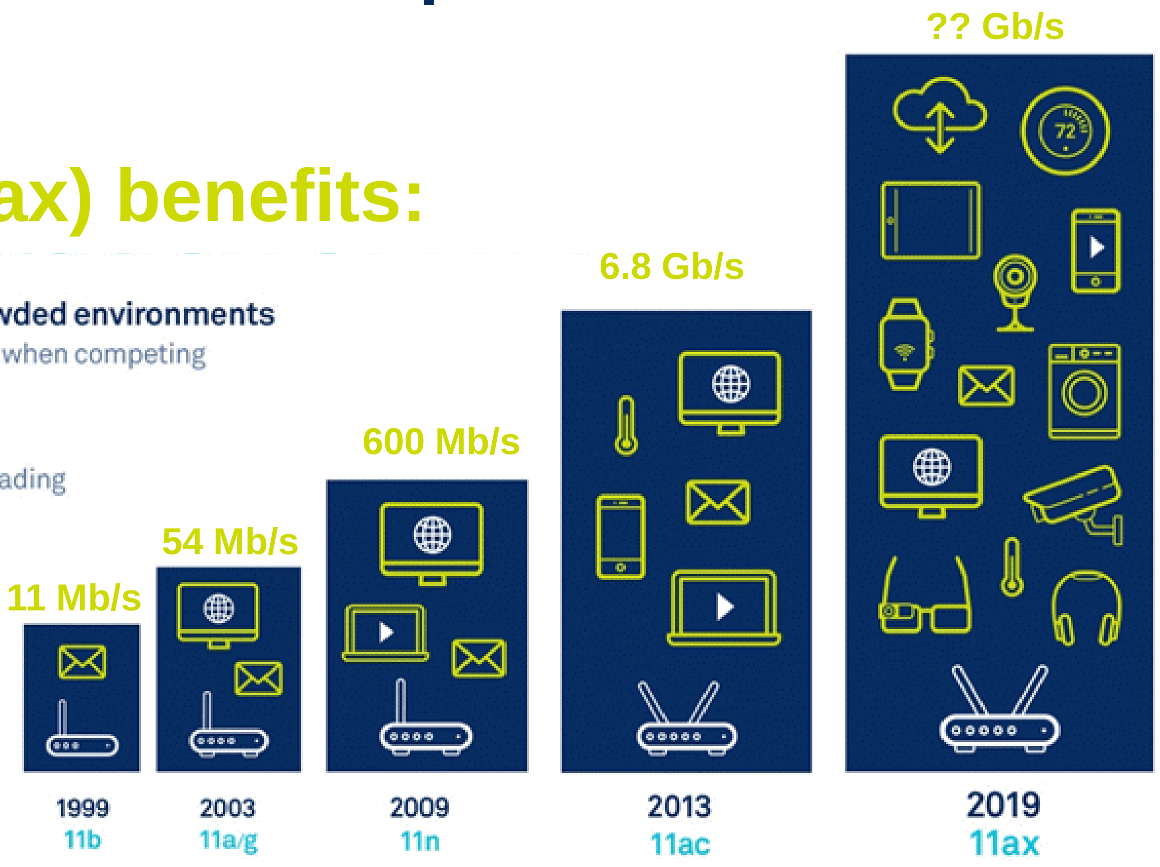


Source: https://grouper.ieee.org/groups/802/11/Reports/802.11_Timelines.htm

The Evolution of Wi-Fi up to 802.11ax

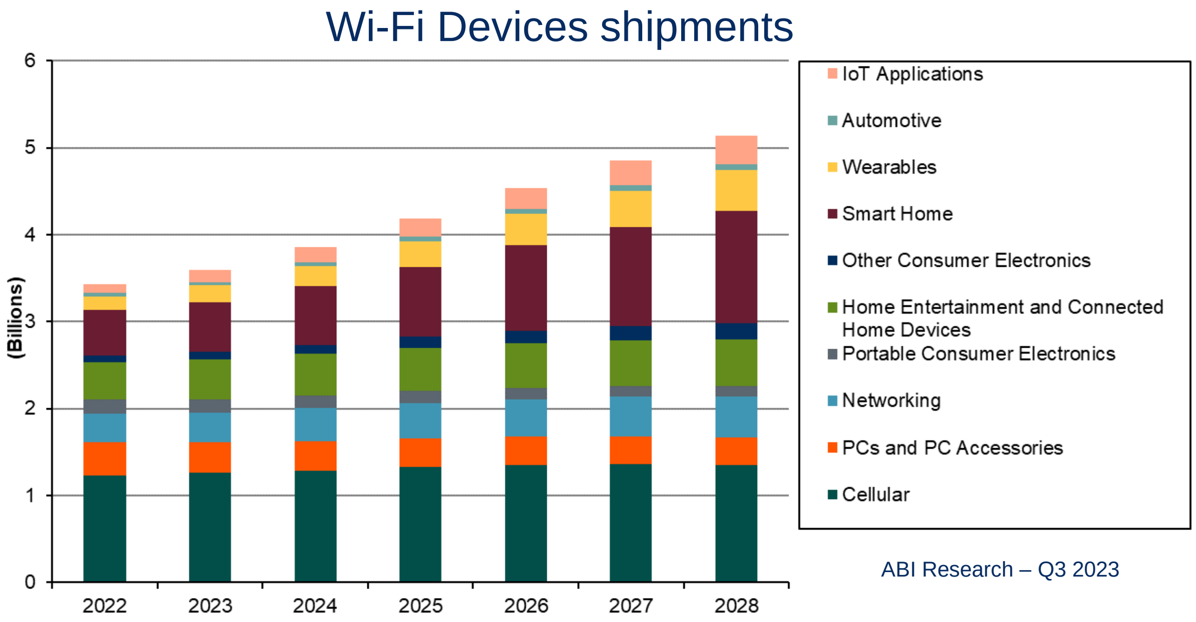
Wi-Fi 6 (11ax) benefits:

- **Better efficiency in crowded environments**
  4X better throughput per user when competing for bandwidth
- **Higher peak data rates**
  25% faster than the today's leading 11ac standard
- **Backward compatible**
  Coexist with older networks, accelerate as they upgrade
- **More power-efficient**
  Extends battery life in user devices



Wi-Fi Market - Devices Shipments

- Growing TAM, driven mostly by IoT, smart home, wearable and home entertainment markets

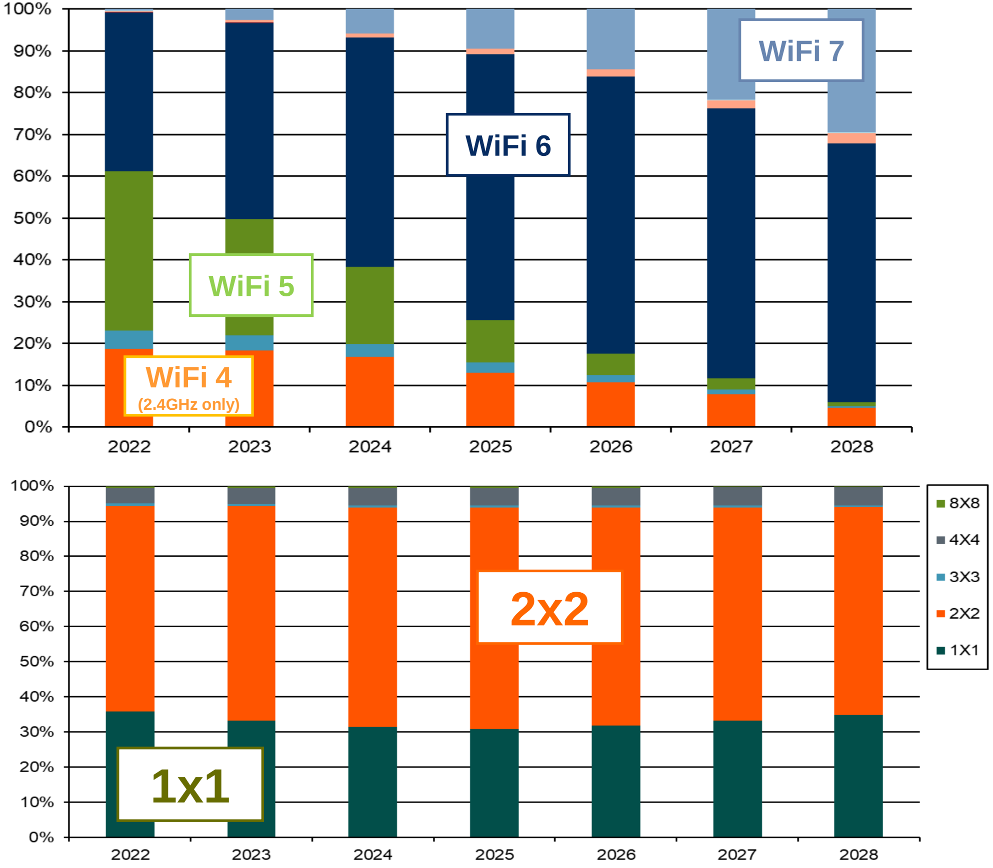


ABI Research – Q3 2023

Wi-Fi market growing at 7% CAGR (23-28) >5.1B units by 2028

WiFi Market

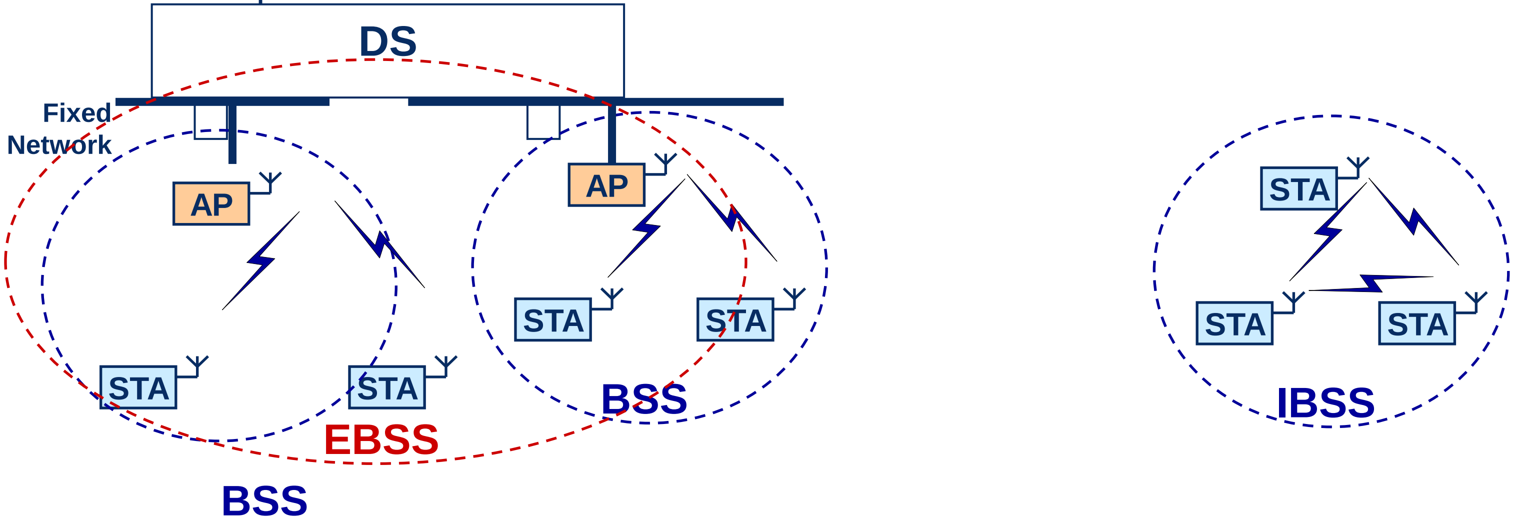
- Wi-Fi market moving fast to Wi-Fi 6
  - Wi-Fi 5 declining sharply in high end / high throughput applications
  - Wi-Fi 4 showing some resistance but eventually declining in low power devices
- First Pre Wi-Fi 7 chipsets reached the market in 2023
  - Partial support of Wi-Fi 7 features before official ratification in Q2 2024
- Wi-Fi shipments dominated by 2x2 & 1x1 configurations (total > 95%)
  - 2x2: smartphone, tablet, PC, laptop, AP
  - 1x1: low power devices, feature phones
  - Access Points:
    - Still 40% of AP are 2x2
    - 4x4 & 8x8 configurations exclusively for AP



ABI Research – Q3 2023

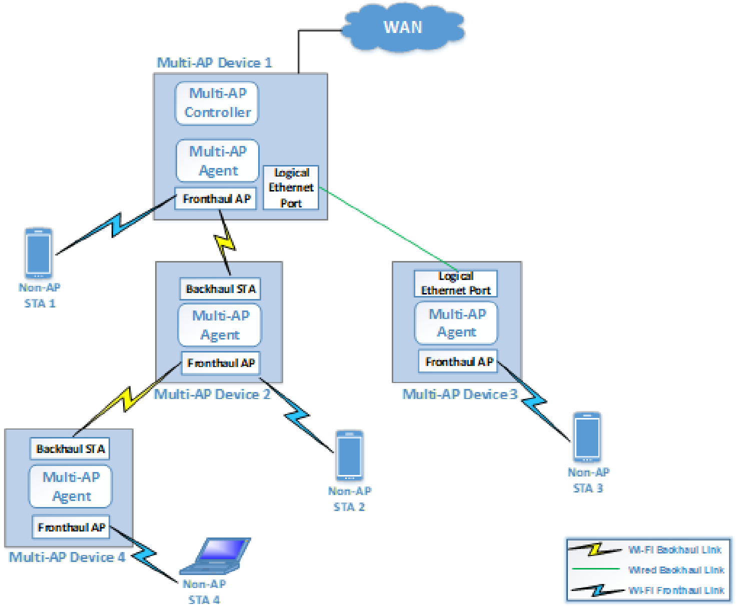
WLAN Topology

- Access to a infrastructure network via an Access Point (AP)
  - BSS – Basic Service Set
  - DS – Distribution service
- Ad-hoc network of mobile stations (STA)
  - IBSS – Independent Basic Service Set



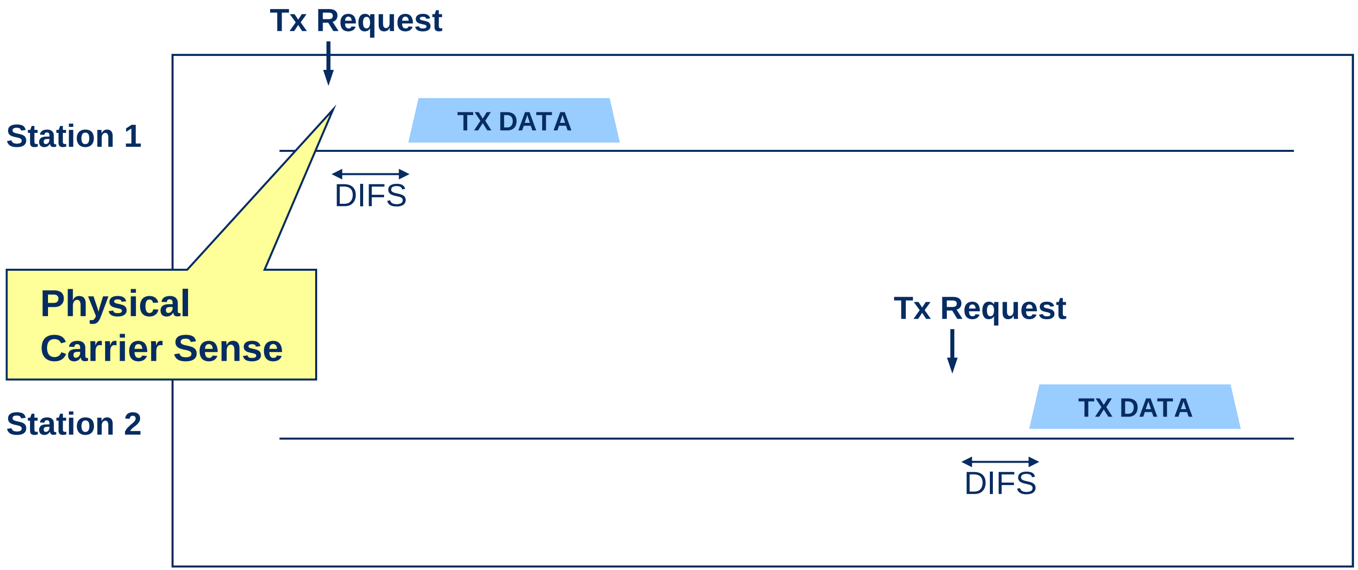
EasyMesh

- A Multi-AP network consists of two types of logical entities:
  - One Multi-AP Controller and
  - One or more Multi-AP Agents
- Two Multi-AP devices with Multi-AP Agents connect to each other over a backhaul link, which could be either a Wi-Fi link or a wired Logical Ethernet Link



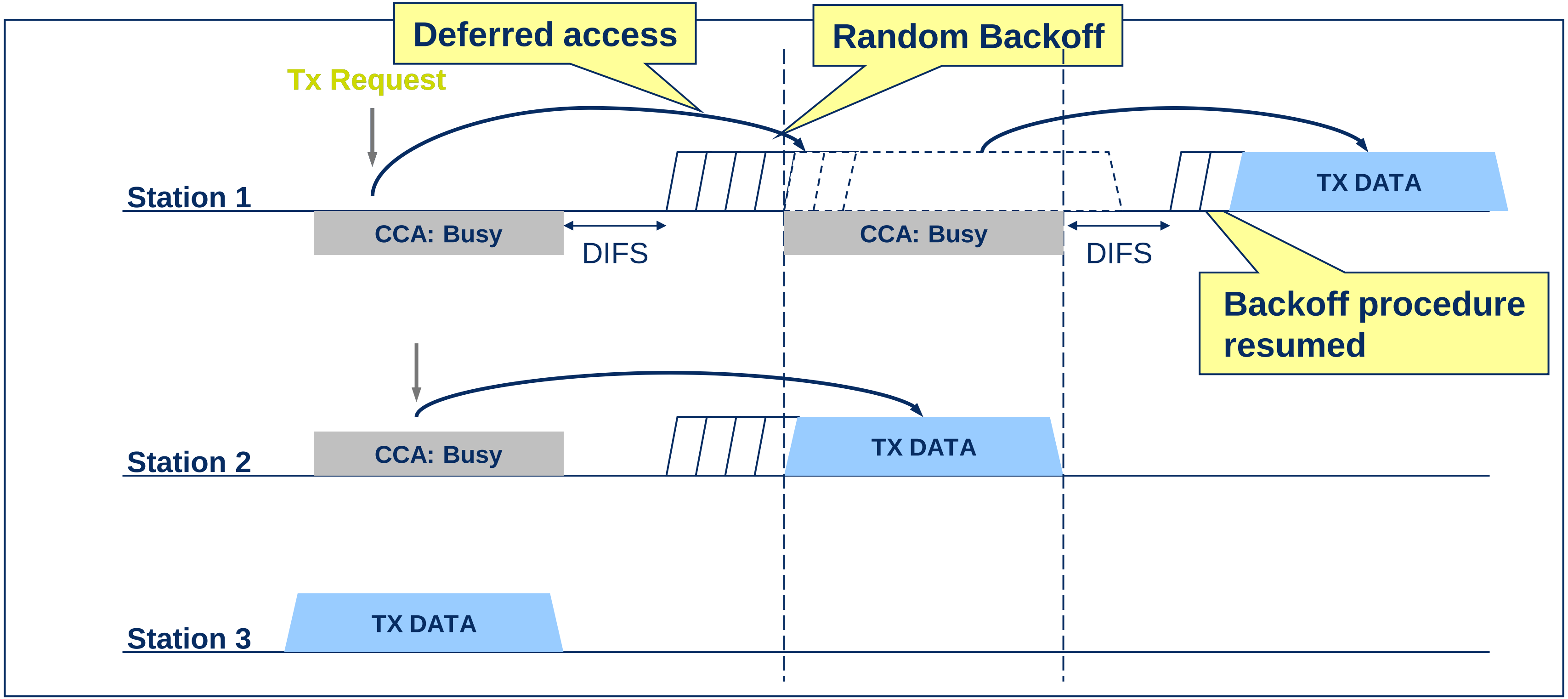
Carrier Sense Multiple Access / Collision Avoidance

- Listen before talking



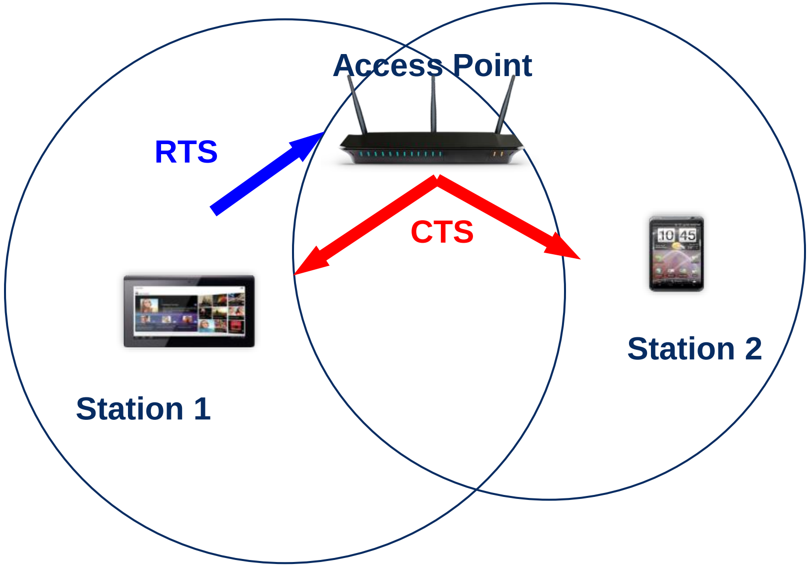
DIFS: Distributed Inter-Frame Space

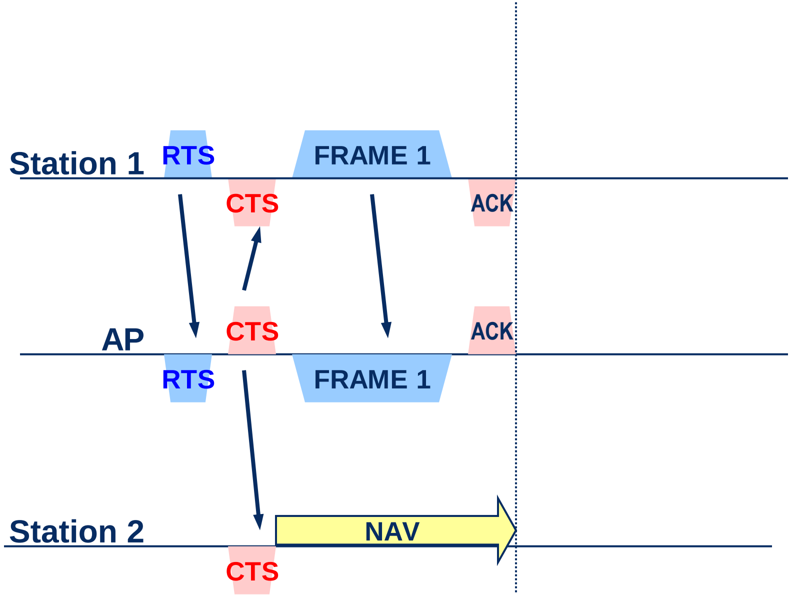
Carrier Sense Multiple Access / Collision Avoidance



- BACKOFF is the reason why Wifi cannot have deterministic delay and guarantees and why in the past as long as you were connecting many devices to the same AP the throughput was dropping drastically!

Hidden Station Problem

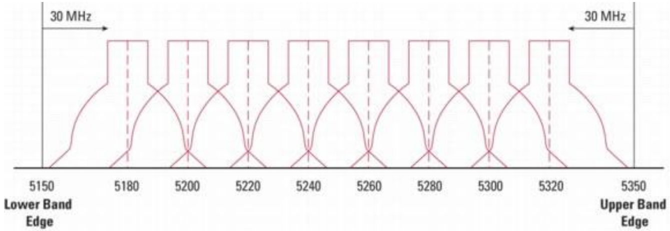


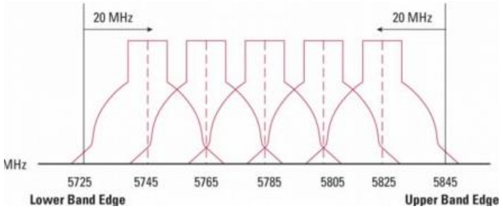


- RTS: Request To Send
- CTS: Clear To Send

Channels in legacy 802.11

- The 802.11 defines two frequency bands split in several channels
  - 2.4GHz band (up to 40 MHz/AP)
    - For 802.11b/g/n/
    - 11 channels of 20MHz with 5MHz space, only 3 non-overlapping
  - 5GHz band (up to 160 MHz/AP)
    - For 802.11a/n/ac/ax
    - 25 channels of 20 MHz with 20MHz space, split in two bands
      - Lower Band from 5150MHz to 5350MHz (channels from 34 to 60)
      - Lower Band from 5725MHz to 5845MHz (channels from 100 to 165)





WiFi 6E

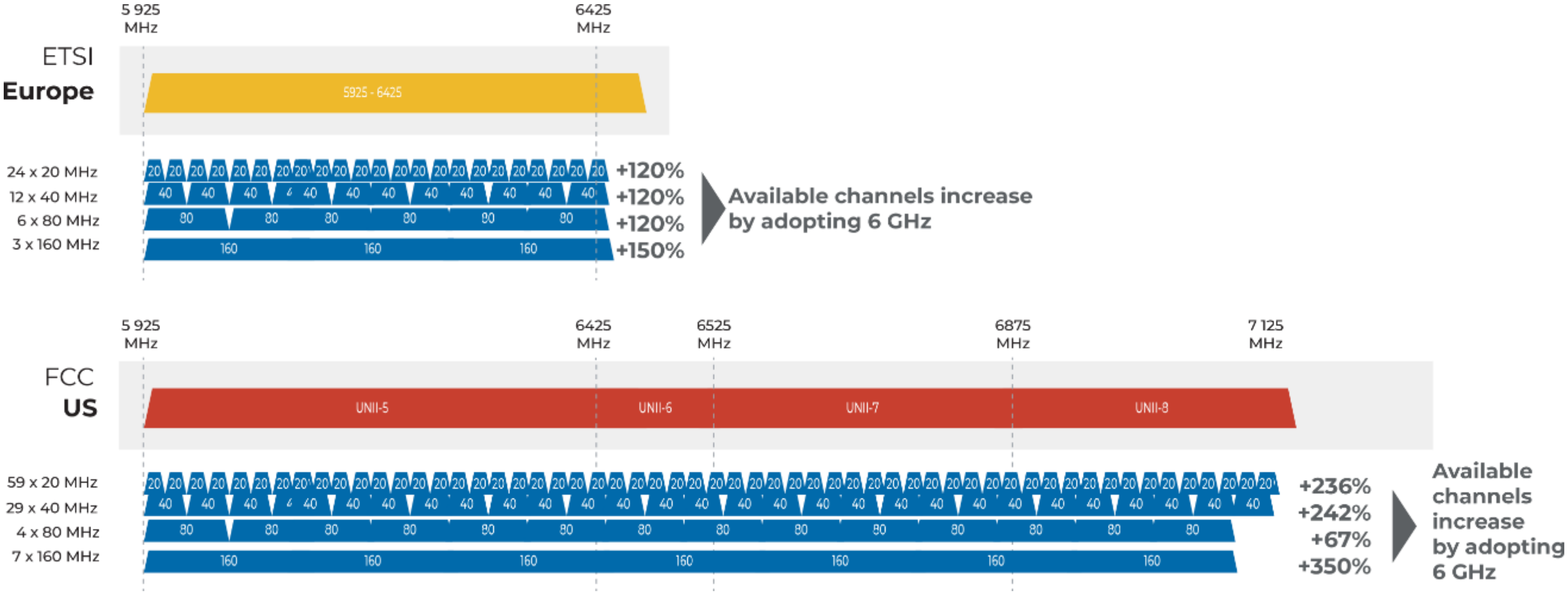
- The 2.4 GHz band for Wi-Fi has become crowded, competing with other technologies such as Bluetooth
- Traffic offloaded to 5 GHz band, but demand is now overflowing capacity of Wi-Fi 4, 5 and 6 due to increased internet connection
- Wi-Fi 6E on 6GHz adds up to 1.2GHz bandwidth (USA)
  - Up to 7 channels of 160MHz each
  - Or up to 14 channels of 80MHz each





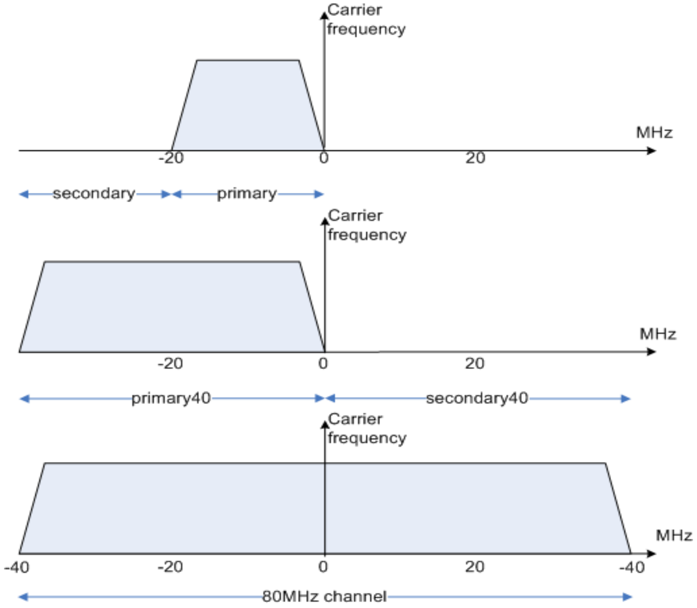

Wi-Fi 6E: 6GHz band for more throughput and lower latency

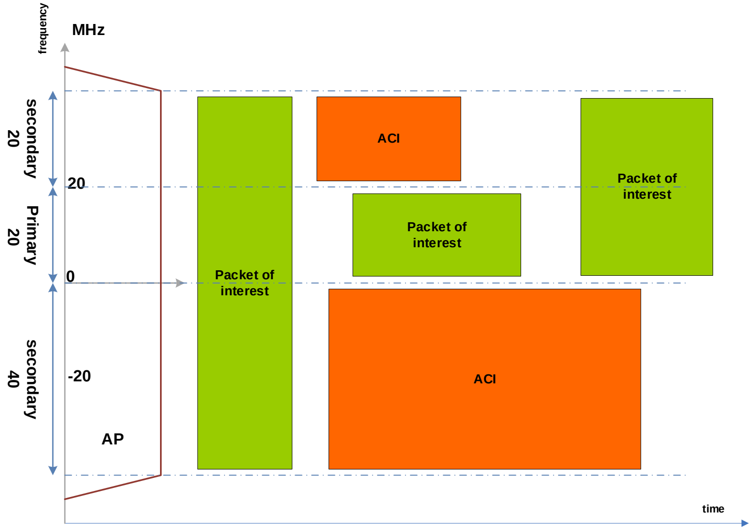
WIFI 6E: channels in EU and US



Channel Bounding

- In a 80MHz capable BSS, a 80MHz capable STA or AP shall be able to transmit and receive
  - 80MHz frame in the 80MHz wide channel
  - 40MHz frames in the primary 40MHz channel
  - 20MHz frames in the primary 20MHz channel





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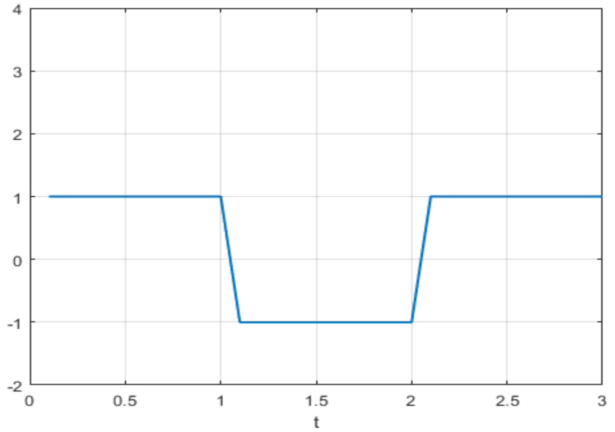
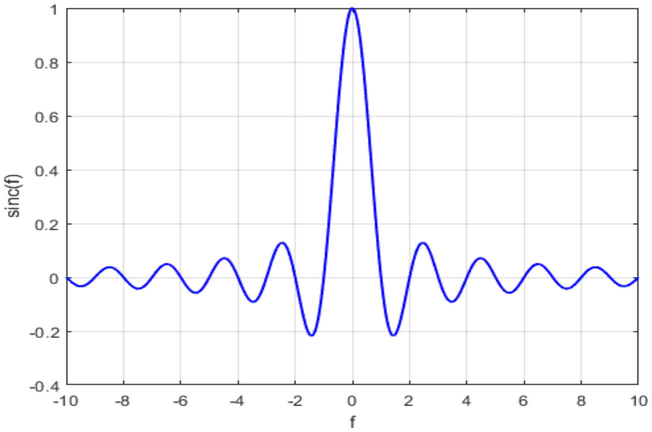
OFDM Basics

- The simplest transmission strategy is a train of BPSK modulated rectangular pulses g(t) of duration T



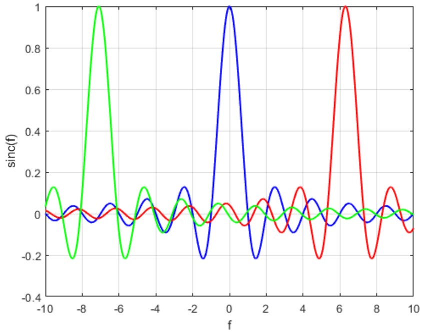


$$s(t) = \sum_{m=1}^{N} d_m g(t - mT)$$

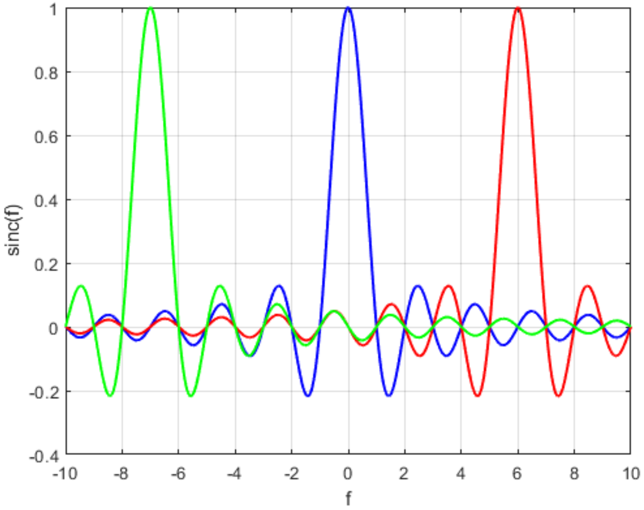
TX rate is 1/T bps, and the occupied spectrum is a sinc with first null at 1/T

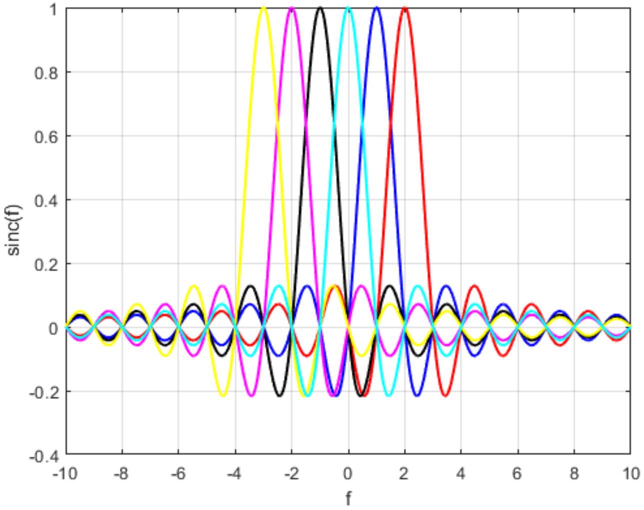
OFDM Basics

- Alternatives to increase the rate
  - Shorter symbols (higher frequency occupancy)
  - Higher modulation (requires higher SNR)
  - Add more pulse trains at other frequencies (FDM)



OFDM Basics

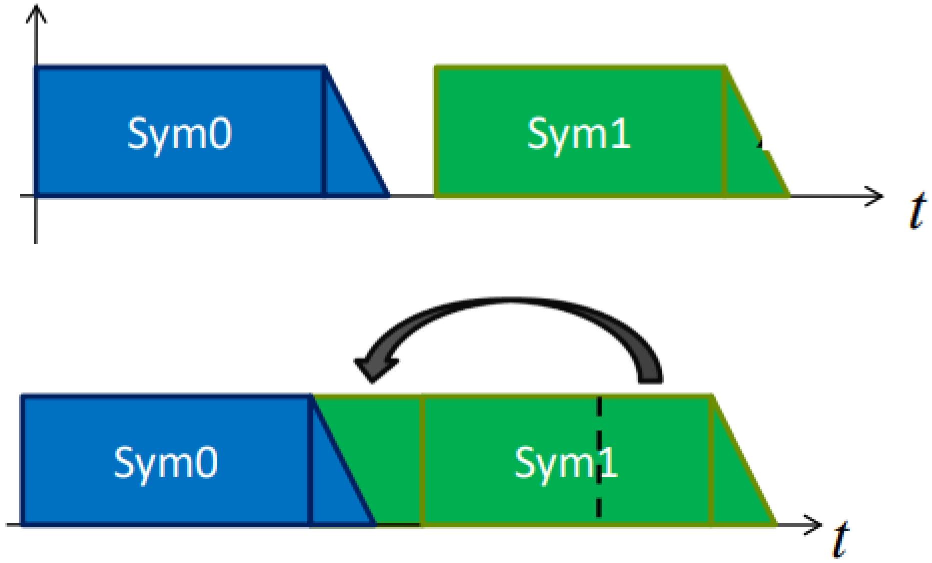




We created several orthogonal channels!

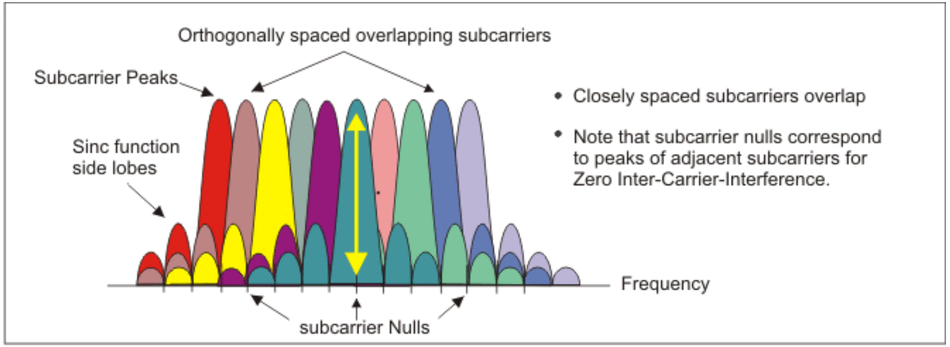
OFDM Basics

OFDM symbols are separate by guard intervals to eliminate ISI and they are meant to accommodate the delay spread of the wireless channel

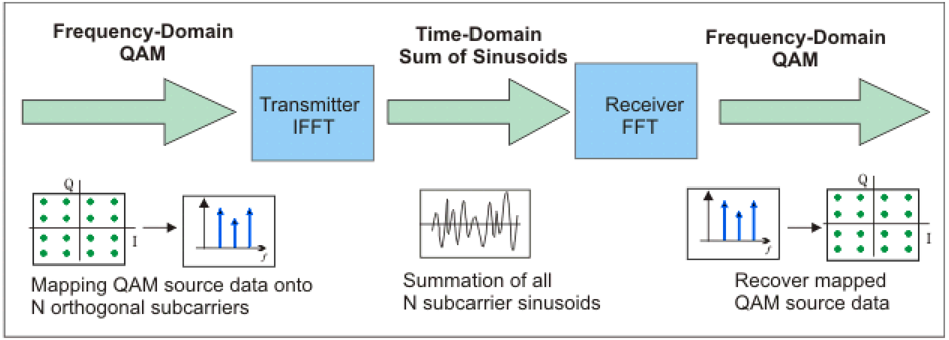


The guard is chosen to be a cyclic extension of the symbols

Orthogonal Frequency Division Multiplexing (OFDM)



OFDM Signal Frequency Spectra



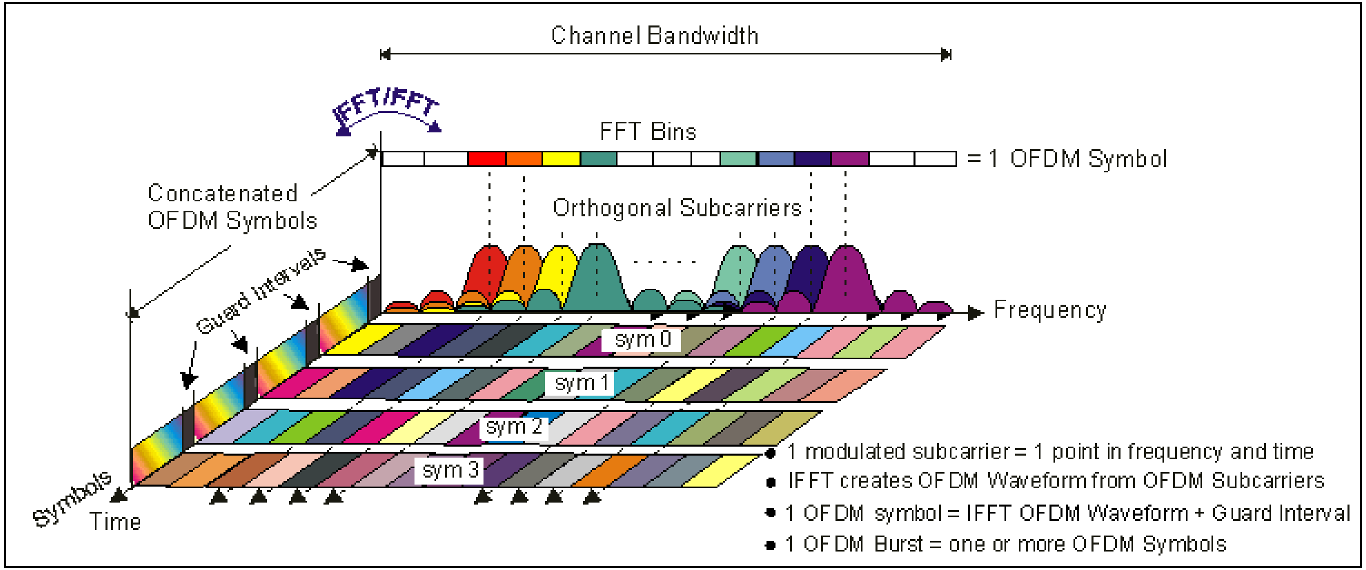
Simplified OFDM System Block Diagram

- Subcarriers are orthogonal to each other
- Each symbol is mapped into a specific subcarrier

IDFT: $$x(n) = \frac{1}{N}\sum_{k=0}^{N-1} X(k)e^{\frac{i2\pi kn}{N}}$$

DFT: $$x(k) = \sum_{n=0}^{N-1} x(n)e^{-\frac{i2\pi kn}{N}}$$

OFDM



Frequency-Time Representative of an OFDM signal

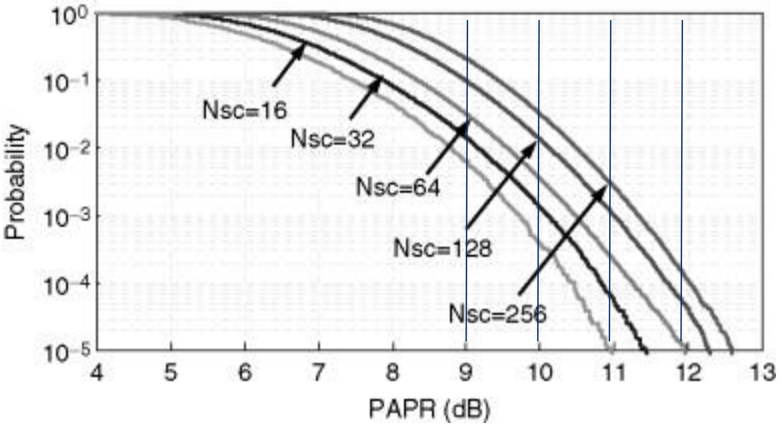
Peak-to-Average Power Ratio in OFDM

$$PAPR = \frac{P_{peak}(t)}{P_{average}(t)}$$

- OFDM is a sum of complex tones (*subcarriers*), each one of those has maximum amplitude 1
  - If at any given time instant all sinusoids sum in phase, the peak power is equal to Nsubcarriers
  - Average Power is relatively constant

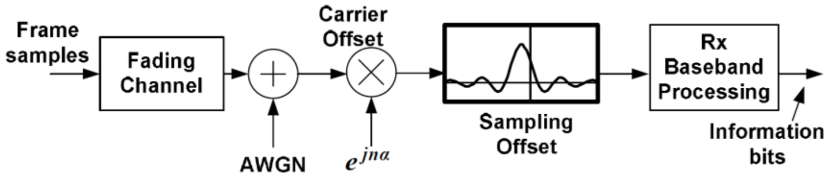
$$PAPR \approx \frac{N_{sc}}{P_{average}}$$

- Typical OFDM systems are characterized by a relatively high PAPR (**ie ~10dB**) that results in a required high dynamic range requirements for the system.
  - This is particularly bad for power amplifiers, resulting in poor power efficiency.



Carrier and Sampling Frequency Offset

- Local Oscillator is not perfect!
  - ▷ DownConversion and sampling from same LO



CFO Model

- ▷ $f_c \rightarrow (1+\varepsilon)f_c$
- ▷ $\bar{x}(n) = x(n)e^{jn\alpha}$ where $\alpha = 2\pi\varepsilon f_c T_s$

SFO Model

- ▷ $T_s \rightarrow (1-\varepsilon)T_s$
  - ▸ n-th sample is taken at time $n\varepsilon T_s$ earlier than it should be

CFO and SFO causes Inter-Carrier Interference (ICI)

E. Sourour et al., "Frequency Offset Estimation and Correction in the IEEE 802.11a WLAN" in IEEE 60th Vehicular Technology Conference, 2004. VTC2004-Fall.

Transmitter Diagram Example

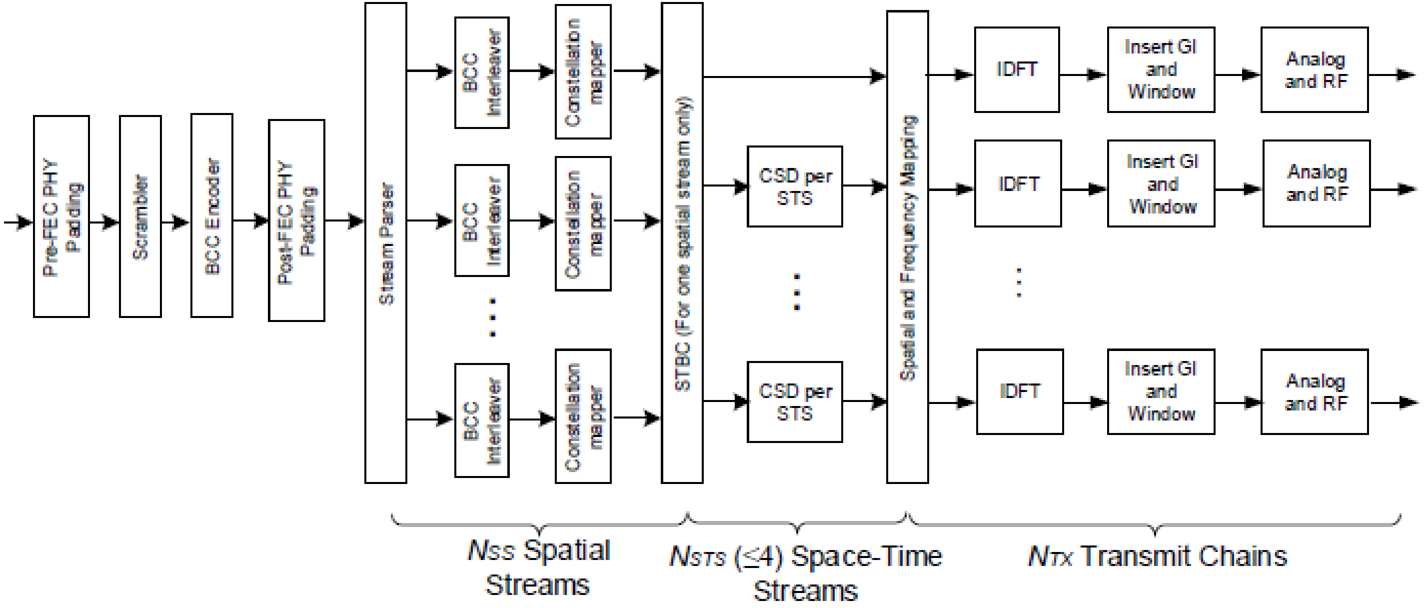


Figure 27-17—Transmitter block diagram for UL transmission or DL non-MU-MIMO transmission of a Data field with BCC encoding on a 26-, 52-, 106-, or 242-tone RU

WLAN-PHY features

802.11b

- DSSS / CCK modulation
- 22MHz bandwidth
- Up to 11Mbps

802.11a/g – Legacy (L)

- OFDM
- Convolutional coding
- 64-QAM
- 20MHz bandwidth
- Up to 54Mbps

802.11n – High Throughput (HT)

- OFDM with Short-Guard interval
- MIMO & STBC up to 4 spatial streams
- Convolutional coding + LDPC
- 64-QAM
- 20 & 40MHz bandwidth
- Up to 600Mbps

802.11ac – Very High Throughput (VHT)

- OFDM with Short Guard interval
- MIMO up to 8 spatial streams & STBC
- MU-MIMO DL
- Convolutional coding + LDPC
- 256-QAM
- 20, 40, 80, 160MHz & 80+80 MHz bandwidth
- Up to 7GHz

802.11ax – High Efficiency (HE)

- “4x” OFDM
- MIMO up to 8 spatial streams & STBC
- OFDMA & MU-MIMO DL
- OFDMA & MU-MIMO UL
- Convolutional coding + LDPC
- 1024-QAM
- 20, 40, 80, 160MHz & 80+80 MHz bandwidth

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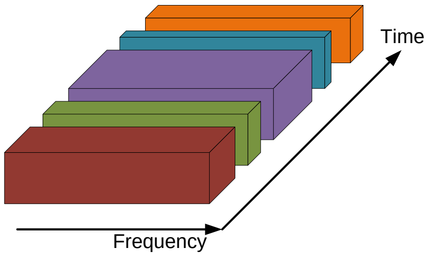
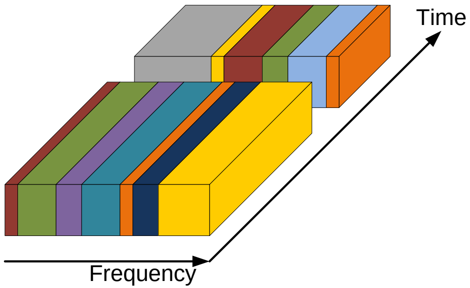
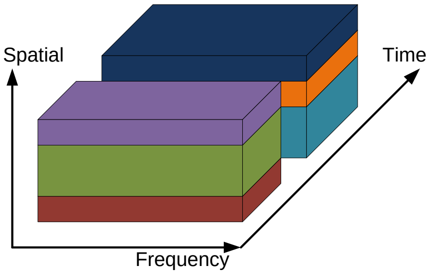
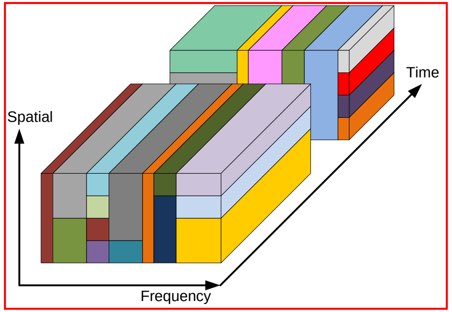
Multiplexing

TDM	OFDMA	MU-MIMO
▶ Users served successively ▶ Full bandwidth allocated to one user	▶ Users share bandwidth ▶ 802.11ax basis	▶ Users served simultaneous in same band → Increase spectral efficiency !! ▶ Key feature of 802.11ac ▶ Use the spatial dimension i.e. multiple antennas



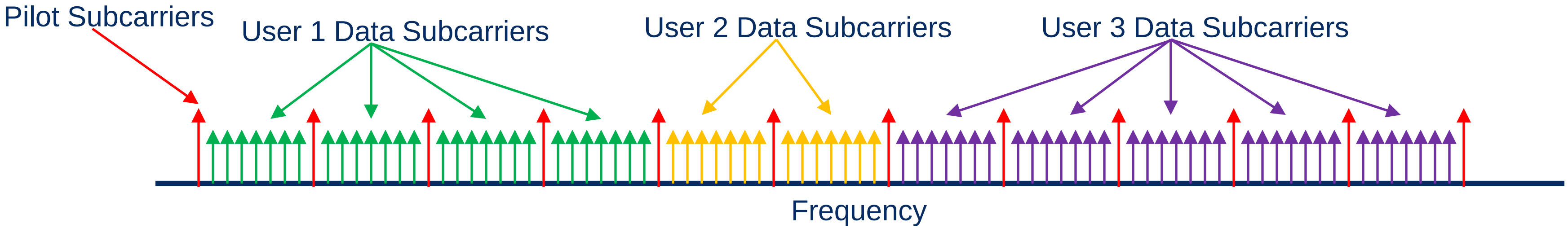






OFDMA

- Orthogonal Frequency Division Multiple Access (OFDMA) is the multi-user variant of the OFDM whereby assigning subsets of subcarriers to different users~~,~~ allows simultaneous transmissions to several users
- The OFDMA consists of frequency sub-blocks called Resource Units (RUs).
- OFDMA reduces preamble overhead and channel access overhead (CSMA) by amortizing those overheads across several users.



Resources Allocation in 11ax

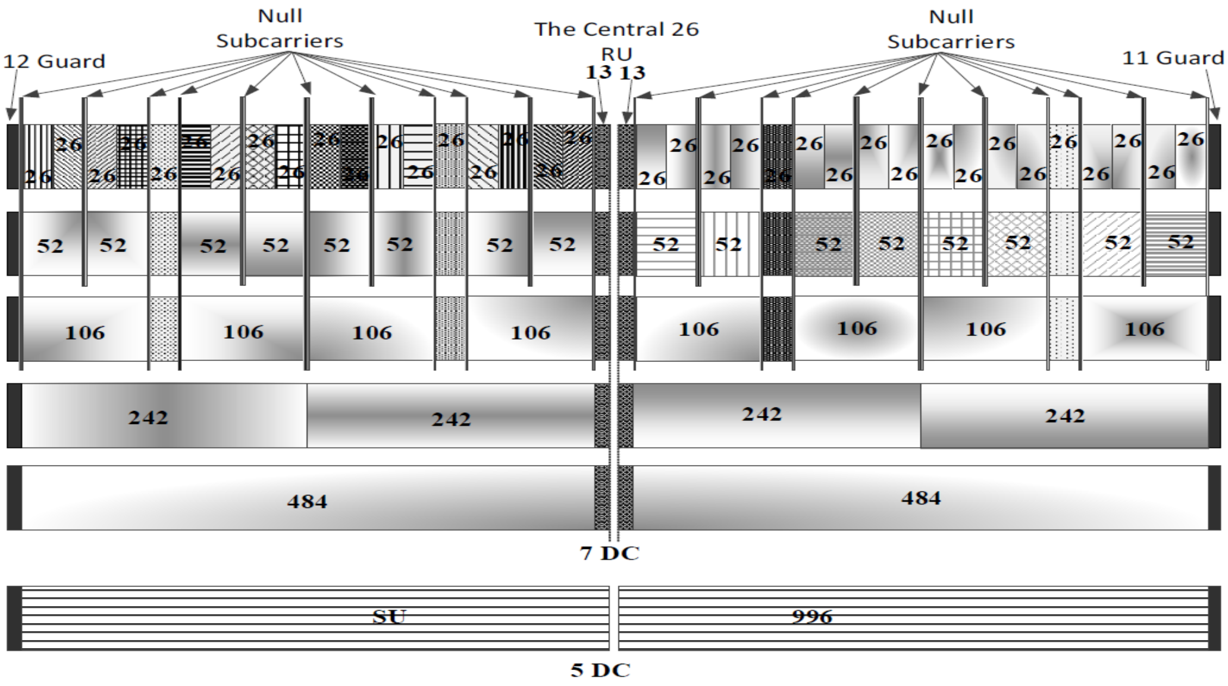
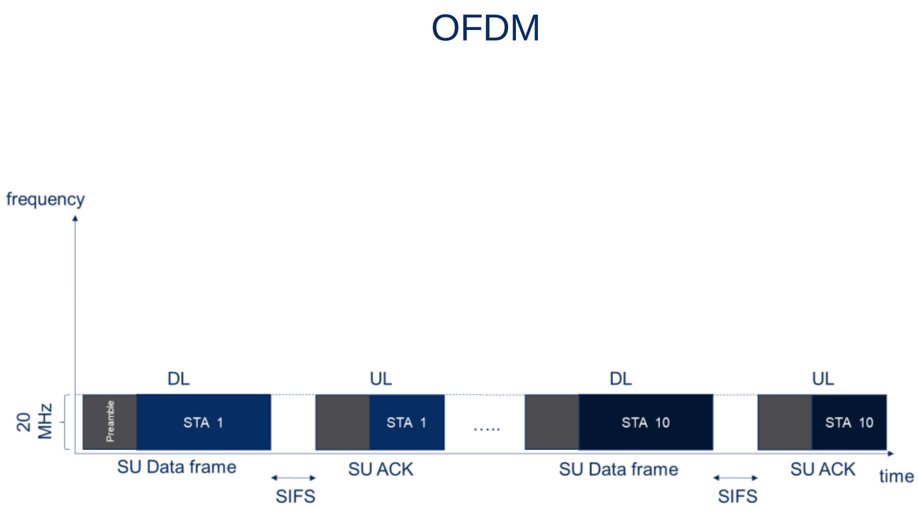
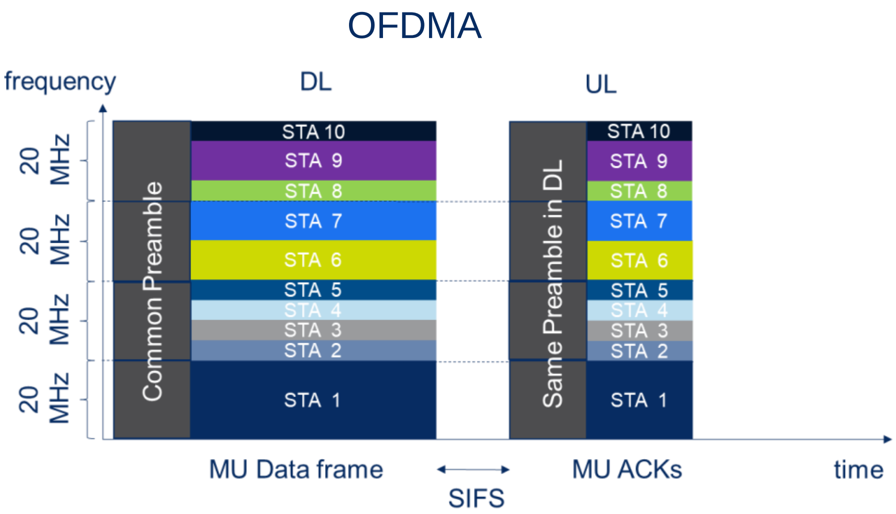


Figure 28-4—RU locations in an 80 MHz HE PPDU

- Very large set of options for RUA
- Full optimization is NP-hard

OFDM vs OFDMA (w/ MU-BA)



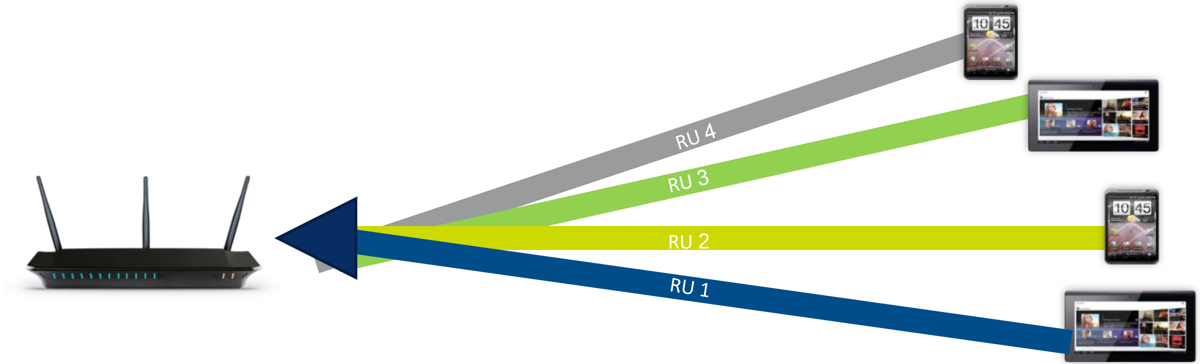


- OFDM:
  - (1SIFS + 1ACK) x #users

- **OFDMA+MU-BA can effectively improve network efficiency by reducing protocol time required by SIFS + ACK**

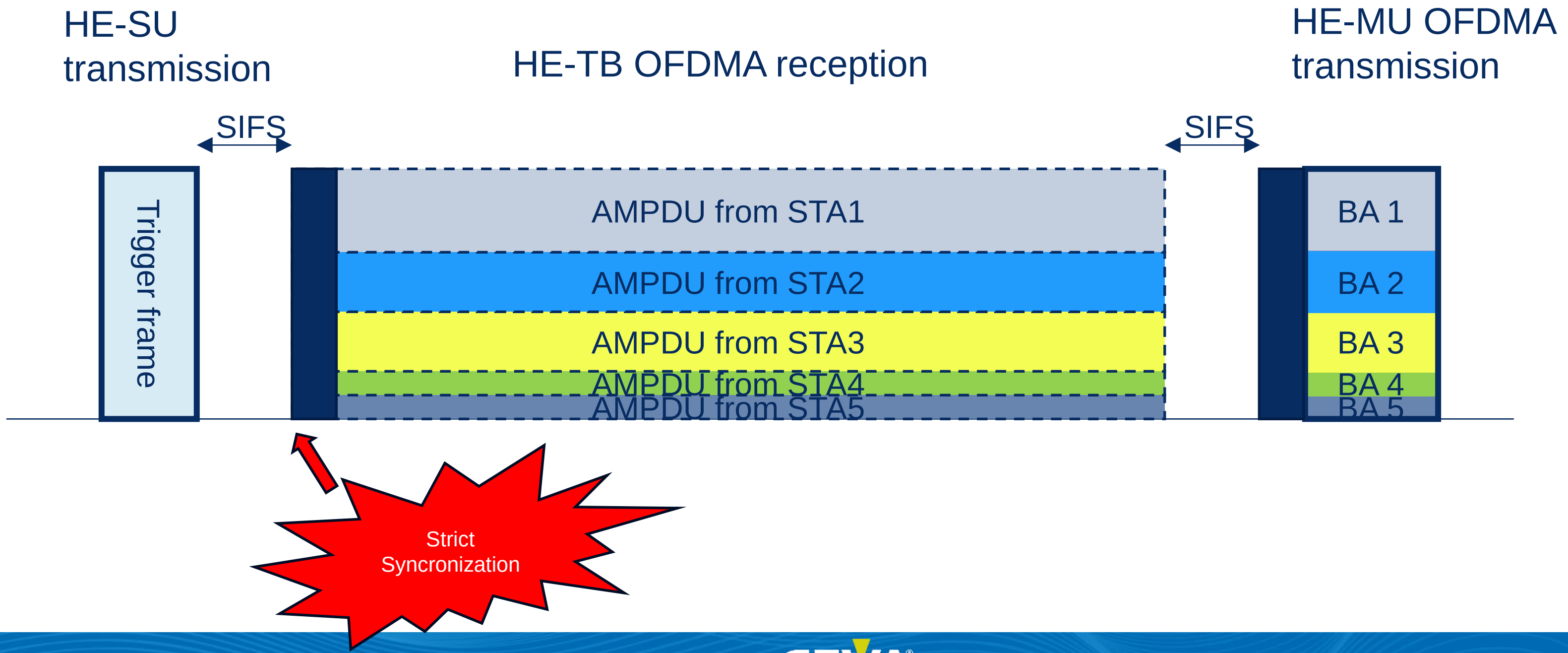
UL OFDMA

- UL OFDMA means that several STAs transmit frames to the AP at the same time, each STA transmitting in a dedicated RU.
  - gains are mainly due to the aggregation of multiple users.
  - reduces channel access overhead (CSMA) by amortizing those overheads across several users.
- UL MU-MIMO allows several STA to TX in the same RU, each on his dedicated SS



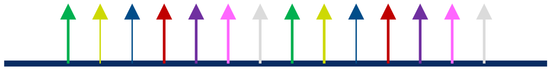
UL OFDMA

- The Trigger frame solicits and allocates resources for UL MU transmissions a SIFS after the PPDU that carries the Trigger frame



Dual Carrier Modulation (DCM)

- 11ax introduces dual sub-carrier modulation (DCM) to enhance the robustness of transmissions in low SNR regions.
- DCM is an optional modulation scheme for any OFDMA and non OFDMA transmissions but is only applied up to 4-QAM.
- DCM modulates the same information on a pair of sub-carriers. It is a repetition scheme in frequency domain to enhance the performance.
- DCM with BPSK provides about 3.5dB gain.

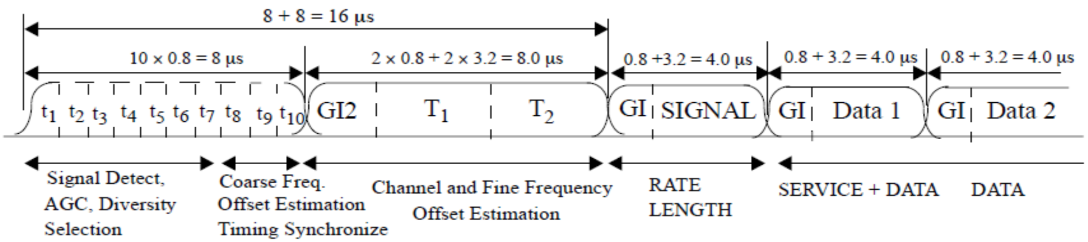


48

Legacy Frame Format and timings

11a/g

LM 20	L-STF	L-STF	L-LTF	L-LTF	L-SIG	L-Data	L-Data	L-Data	L-Data	L-Data	L-Data	L-Data	L-Data



Parameter	Value
N_{SD}: Number of data subcarriers	48
N_{SP}: Number of pilot subcarriers	4
N_{ST}: Number of subcarriers, total	52 ($N_{SD} + N_{SP}$)
Δ_F: Subcarrier frequency spacing	0.3125 MHz (=20 MHz/64)
T_{FFT}: IFFT/FFT period	3.2 μs ($1/\Delta_F$)
$T_{PREAMBLE}$: PLCP preamble duration	16 μs ($T_{SHORT} + T_{LONG}$)
T_{SIGNAL}: Duration of the SIGNAL BPSK-OFDM symbol	4.0 μs ($T_{GI} + T_{FFT}$)
T_{GI}: GI duration	0.8 μs ($T_{FFT}/4$)
T_{GI2}: Training symbol GI duration	1.6 μs ($T_{FFT}/2$)
T_{SYM}: Symbol interval	4 μs ($T_{GI} + T_{FFT}$)
T_{SHORT}: Short training sequence duration	8 μs ($10 \times T_{FFT}/4$)
T_{LONG}: Long training sequence duration	8 μs ($T_{GI2} + 2 \times T_{FFT}$)

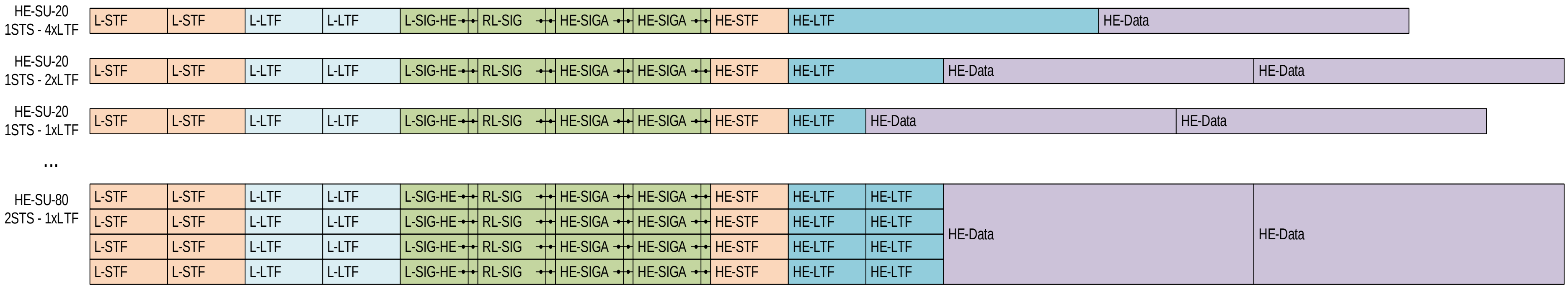
$$N_{FFT} = 64$$

11ax PHY Introduction

Up to … Gbit/s

- The main features of 802.11ax:
  - Frequency Bands: 2.4GHz, 5GHz, 6GHz
  - 4 times FFT size, i.e. 1/4 subcarrier spacing.
    - $N_{FFT} = 256$ for 20MHz . Subcarrier Frequency spacing 78.125 KHz for HE-Modulated fields
  - Modulation: Same as 11ac + 1024QAM
  - No. of spatial stream: 1-8 (as 11ac)
  - Guard Intervals: 0.8, 1.6, 3.2 µs
  - Channel Bandwidth(MHz): 20, 40, 80, 160, 80+80 (as 11ac)
    - max $N_{SD} = 1960$
  - Max coding rate: 5/6 (as in 11ac)
  - New technologies: downlink and uplink OFDMA, Uplink MU MIMO, Spatial Reuse, Extended Range

11ax Frame formats



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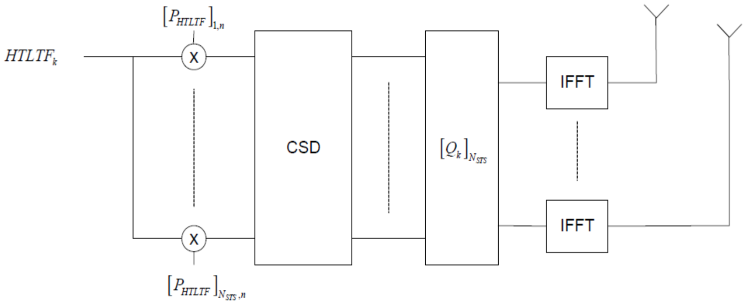
LTF for MIMO & Channel Estimation

- Example: 2x2 case
- $$\begin{bmatrix} y_1^{(k)}(t) \\ y_2^{(k)}(t) \end{bmatrix} = \begin{bmatrix} h_{11}^{(k)} & h_{12}^{(k)} \\ h_{21}^{(k)} & h_{22}^{(k)} \end{bmatrix} \begin{bmatrix} x_{SS1}(t) \\ x_{SS2}(t) \end{bmatrix} + \begin{bmatrix} n_1^{(k)}(t) \\ n_2^{(k)}(t) \end{bmatrix}, \qquad \mathrm{k} = 1, \dots, \mathrm{N_{FFT}}$$
- Channel Estimation can be performed on each subcarrier independently
- LTF field is used for this purpose

LTF for MIMO & Channel Estimation



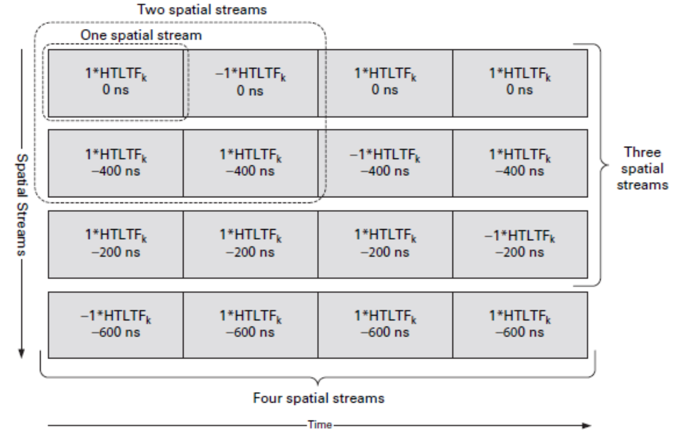


Figure 4.20 Construction of the HT-LTF.

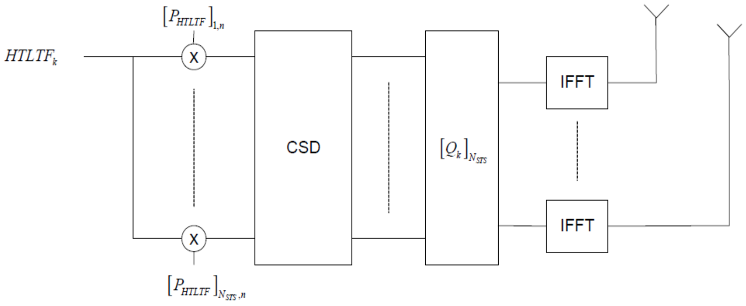
$$\boldsymbol{P} = \begin{bmatrix} 1 & -1 & 1 & 1 \\ 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & -1 \\ -1 & 1 & 1 & 1 \end{bmatrix}$$

Example: $N_{TX} = 2, N_{RX} = 2, N_{STS} = 2$

$$\begin{bmatrix} y_1(t_1) & y_1(t_2) \\ y_2(t_1) & y_2(t_2) \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} s_{LTF}$$

$$\hat{h}_{11} = \frac{y_1(t_1) - y_1(t_2)}{2S_{LTF}}$$

LTF for MIMO & Channel Estimation



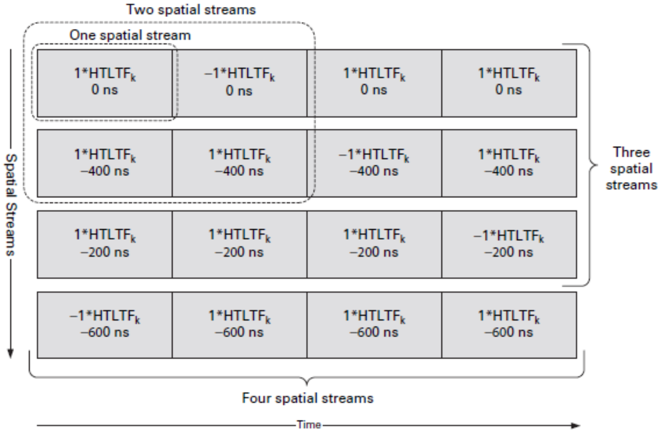


Figure 4.20 Construction of the HT-LTF.

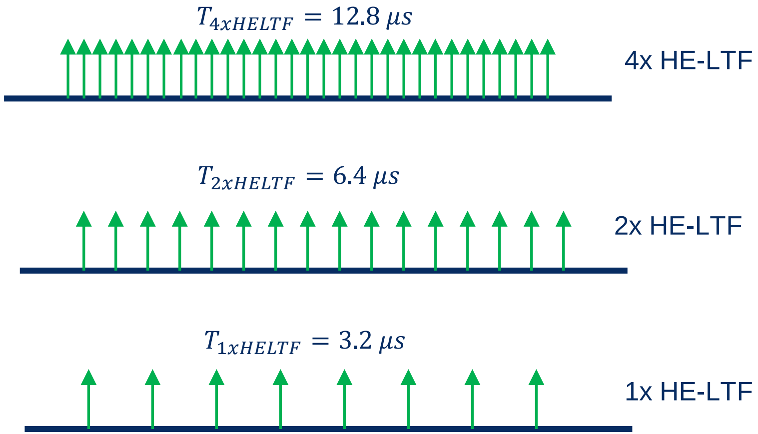
$$\boldsymbol{Y} = \boldsymbol{HPS}_{LTF} + \boldsymbol{Z}$$

- **Y** is N_{RX}x $\mathrm{N_{LTF}}$
- $\boldsymbol{H}$ is N_{RX}x $\mathrm{N_{STS}}$
- **P** is N_{STS}x $\mathrm{N_{LTF}}$

$$\widehat{\boldsymbol{H}} = \boldsymbol{YP}^T \frac{1}{N_{LTF} S_{LTF}}$$

(11ax) HE-LTF Modes

- Channel coherence BW usually > 78.125 KHz
- 11ax defines 4x, 2x, 1x HE-LTF modes
- Channel estimates require interpolation over frequency



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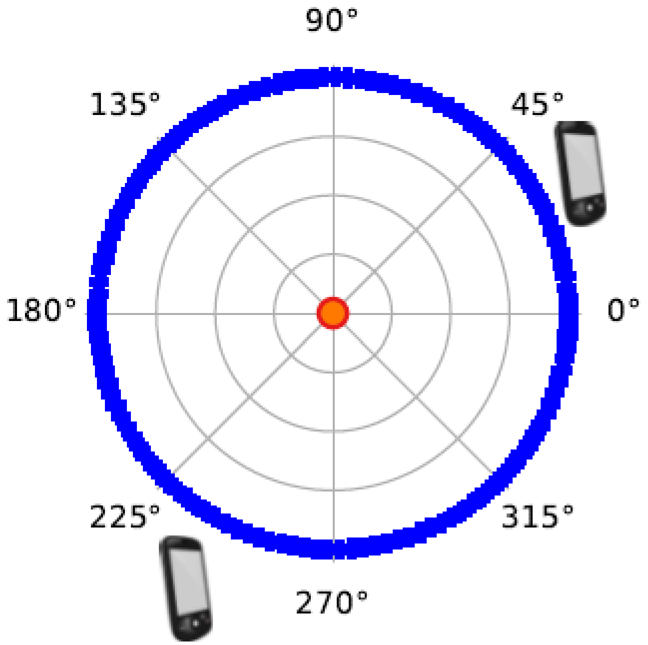
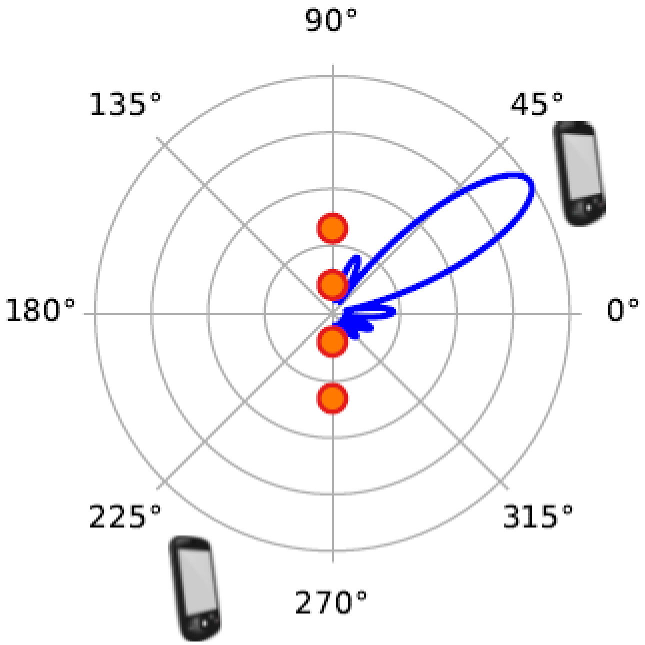
Beamforming





Transmit Beamforming

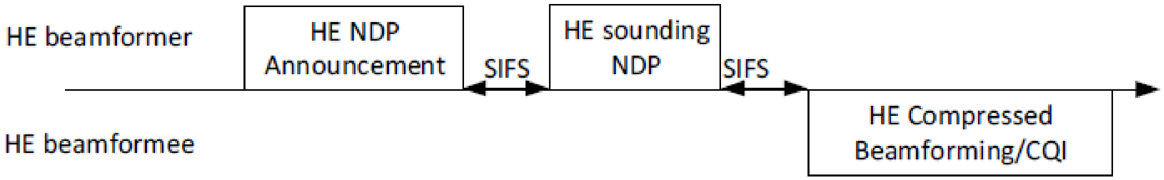
Implicit Beamforming

- Beamformer acquires CSI from LTF transmitted by beamformee
- It assumes channel reciprocity
- Calibration of RX/TX chains should be done to improve performance.

Explicit Beamforming

- Beamformee estimates CSI from LTF transmitted by beamformer
- Beamformee send a feedback response to Beamformer, which uses the feedback to beamform the subsequent packet
- Feedback Response type:
  - *CSI:* channel coefficients sent as they are
  - *Noncompressed beamforming:* The beamformee sends calculated BF feedback matrices to the beamformer.
  - *Compressed beamforming:* The beamformee sends compressed BF feedback matrices to the beamformer.
  - CQI: Average SNR per STS averaged over the subcarriers of each RU

Beamforming Calibration



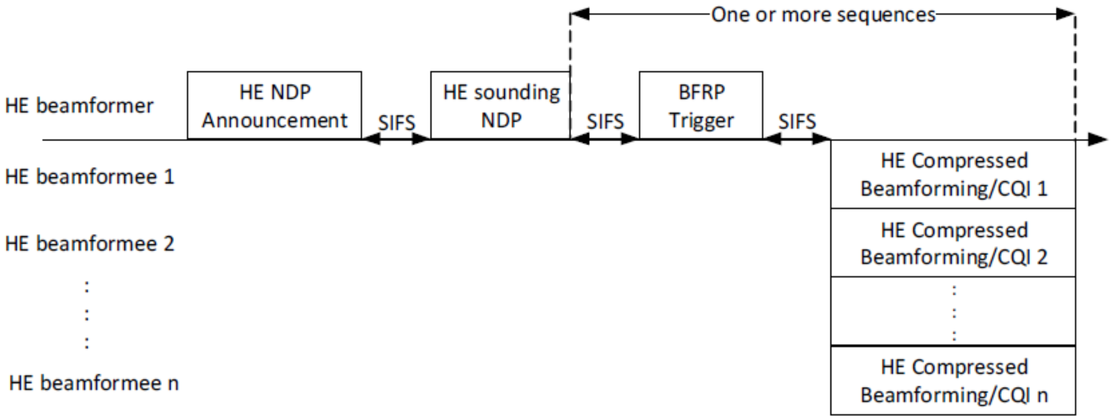


Figure 26-8—Example of HE TB sounding

SU Frequency Domain Model

- $\boldsymbol{Y}_k = \boldsymbol{H}_k \boldsymbol{Q}_k \boldsymbol{X}_k + \boldsymbol{N}_k, \qquad k = 1, \ldots, N_{FFT}$

- **Y** is $N_{RX}\mathrm{x}1$ and corresponds to the received vector for a given subcarrier *k*
- $\boldsymbol{H}$ is the $N_{RX}\mathrm{x}\ \mathrm{N_{TX}}$ channel matrix
- **Q** is the $N_{TX}xN_{STS}$ spatial mapping matrix
- **X** is $N_{STS}\mathrm{x}1$ and contains the QAM-Modulated symbols

- $\widetilde{\boldsymbol{H}} = \boldsymbol{HQ}$ corresponds to the equivalent channel

SU Explicit Beamforming with Feedback Matrix

$$\boxed{\boldsymbol{Y}_k = \boldsymbol{H}_k \boldsymbol{Q}_k \boldsymbol{X}_k + \boldsymbol{N}_k}$$

- STA A wants to beamform to STA B
- STA B estimates the channel coefficients matrix $\boldsymbol{H}$ for each subcarrier k
- STA B calculates feedback matrix $\boldsymbol{V}$ of size $N_{STS} \mathrm{x} N_{SS}$ from $\widehat{\widehat{\boldsymbol{H}}} = \widehat{\boldsymbol{HQ}}$
- STA B sends matrix **V** to STA A in the form of data
- STA A generates $\boldsymbol{Q}_{steer} = \boldsymbol{QV}$ to transmit to STA B

Compressed Feedback Matrix

$N_{TX} = 4, N_{RX} = 2$

$$V = \begin{bmatrix} e^{j\phi_{11}} & 0 & 0 & 0 \\ 0 & e^{j\phi_{21}} & 0 & 0 \\ 0 & 0 & e^{j\phi_{31}} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} \cos\psi_{21} & \sin\psi_{21} & 0 & 0 \\ -\sin\psi_{21} & \cos\psi_{21} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}^T \times \begin{bmatrix} \cos\psi_{31} & 0 & \sin\psi_{31} & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\psi_{31} & 0 & \cos\psi_{31} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}^T \times \begin{bmatrix} \cos\psi_{41} & 0 & 0 & \sin\psi_{41} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\sin\psi_{41} & 0 & 0 & \cos\psi_{41} \end{bmatrix}^T$$

$$\times \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{j\phi_{22}} & 0 & 0 \\ 0 & 0 & e^{j\phi_{32}} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\psi_{32} & \sin\psi_{32} & 0 \\ 0 & -\sin\psi_{32} & \cos\psi_{32} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}^T \times \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\psi_{42} & 0 & \sin\psi_{42} \\ 0 & 0 & 1 & 0 \\ 0 & -\sin\psi_{42} & 0 & \cos\psi_{42} \end{bmatrix}^T \times \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

- Only ψ and ϕ are fed back to the beamformer which will reconstruct the precoding matrix $\boldsymbol{V}$
- Precoding matrix $\boldsymbol{V}$ can be sent only for 1 out of 2 or 4 subcarriers

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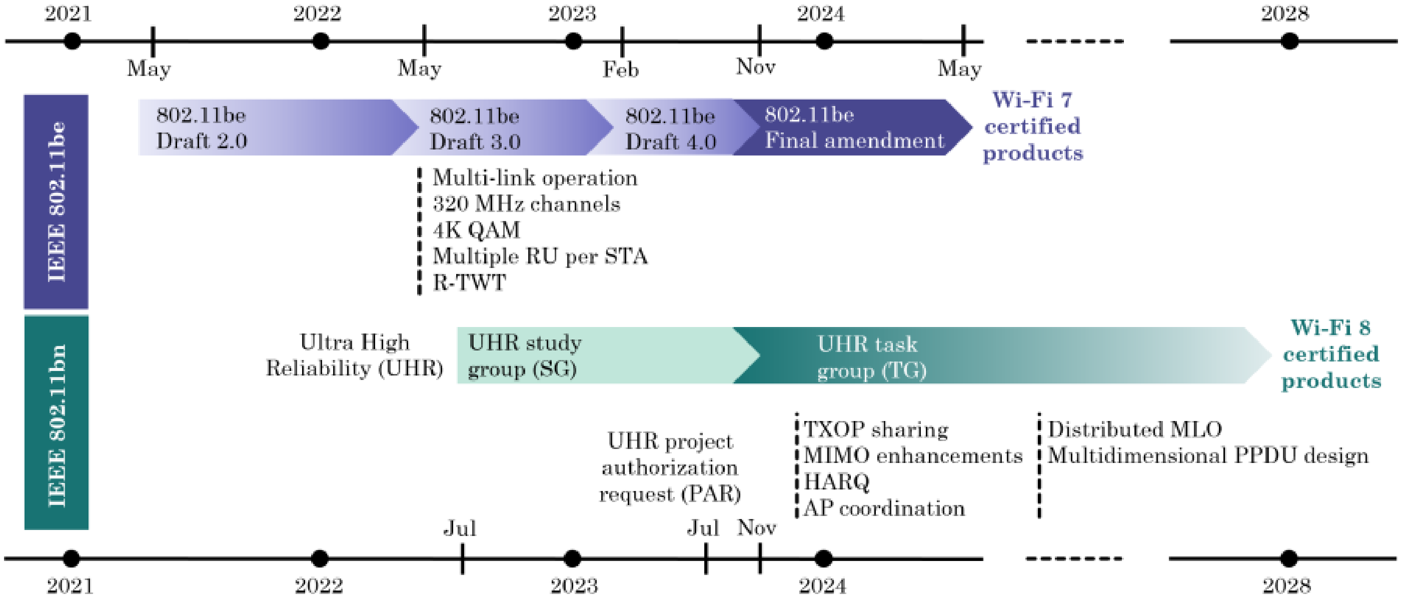
Wi-Fi 7 and Wi-Fi 8 timeline



Source: What Will Wi-Fi 8 Be? A Primer on IEEE 802.11bn Ultra High Reliability", in arxiv

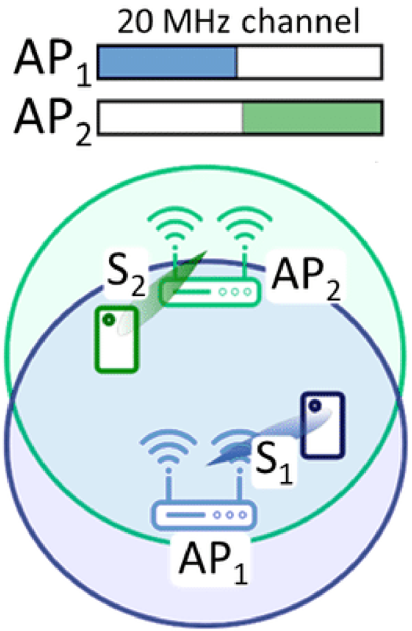
Multi-AP Coordination

- Near-by APs coordinate wireless in time, frequency, space and power
  - Avoid inter-BSS interference
  - Improve Resources Sharing
- Higher throughput and reduced latency
- Low and high complexity techniques are discussed
  - Low-complexity: C-OFDMA, Coordinate Spatial Reuse
  - High-complexity: C-BF, Joint-TX

Source: “IEEE 802.11be – Wi-Fi 7: New Challenges and Opportunities”, https://arxiv.org/pdf/2007.13401.pdf

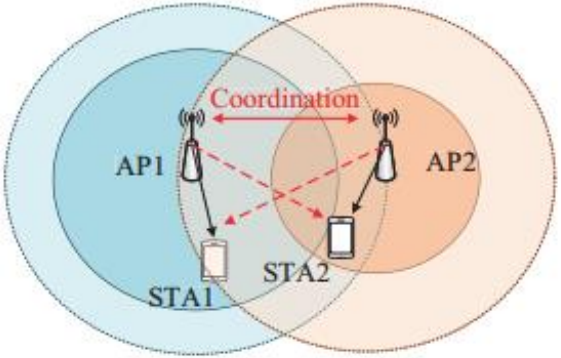
Coordinated OFDMA

- Time and Frequency coordination in OFDMA
- Reduces interference between BSSs
- More efficient use of the available spectrum



Coordinated Spatial Reuse

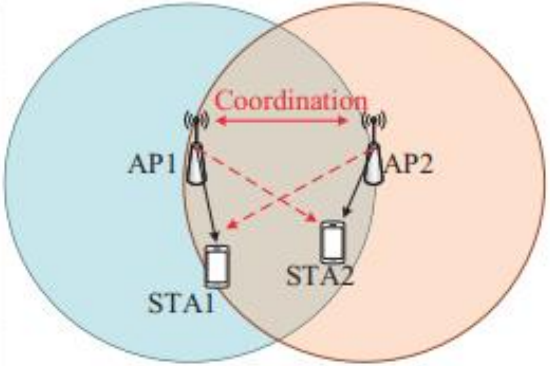
- Power Coordination
- Prevents collisions at the edge
- Less flexibility but little complexity (low overhead)



(b) CSR

Coordinated Beamforming

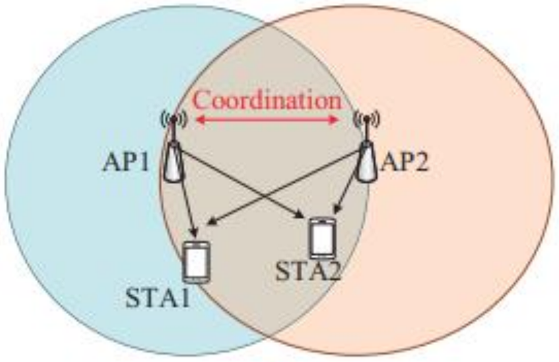
- Suppress interference at STAs served by nearby APs
- Boosted Spatial Reuse with simultaneous transmissions
- Requires exchange of CSI
- Requires joint scheduling



(c) CBF

Joint Transmission (D-MIMO)

- Each STA served by 2 APs simultaneously through BF
- Near-by APs are converted from “Interferering” to “Serving”
- Provides extended coverage
- Highest coordination complexity
  - Both CSI and Data exchange

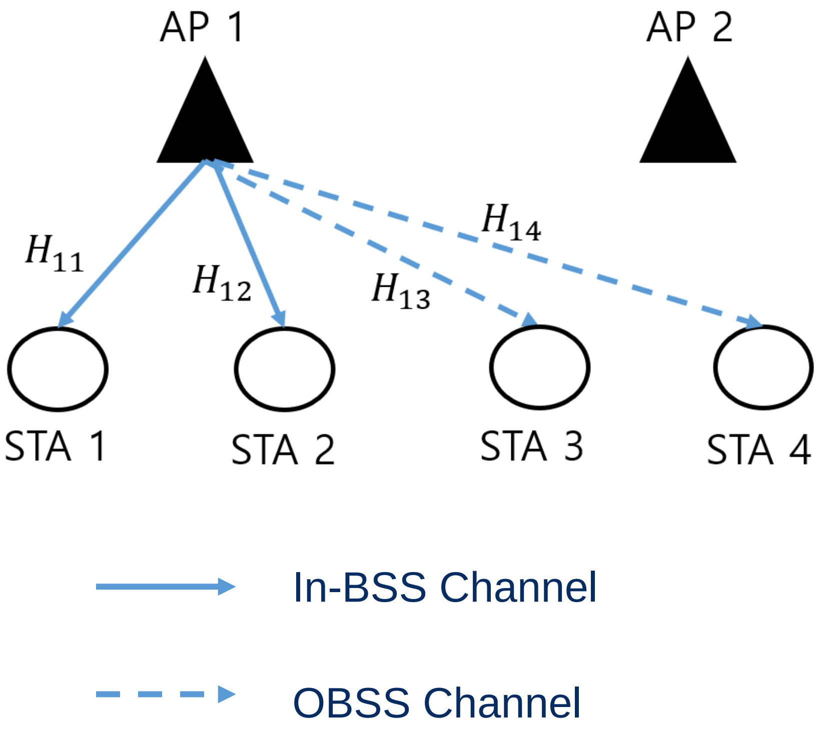


(d) JTX

Source: “IEEE 802.11be – Wi-Fi 7: New Challenges and Opportunities”, https://arxiv.org/pdf/2007.13401.pdf

Coordinated MU-MIMO BF (full nulling)

- Topology
  - 8 antenna AP, 2 antenna STAs
  - 2 spatial streams for each STA (2+2+2+2)
  - We focus on investigating AP 1's behavior



- Two-step Precoder Matrix

$$\begin{bmatrix} H_{11} \\ H_{12} \end{bmatrix} [P_{Null}][P_{SVD}]x + n$$

Interference Nulling

beamforming gain

- Interference Nulling Precoding (P_{Null})
  - In-BSS inter-user-interference
    - In STA 1 side, interference matrix can be decomposed as $H_{12} = U_{12}\Lambda_{12}V_{12}^H$
    - In STA 2 side, interference matrix can be decomposed as $H_{11} = U_{11}\Lambda_{11}V_{11}^H$
  - OBSS inter-user-interference
    - $H_{13} = U_{13}\Lambda_{13}V_{13}^H$,$H_{14} = U_{14}\Lambda_{14}V_{14}^H$
  - Null Precoder
    - For STA 1, $\widetilde{P_1} = Null\left(\begin{bmatrix} H_{12} \\ H_{13} \\ H_{14} \end{bmatrix}\right)$. For STA 2, $\widetilde{P_2} = Null\left(\begin{bmatrix} H_{11} \\ H_{13} \\ H_{14} \end{bmatrix}\right)$ $\rightarrow P_{Null} = [\widetilde{P_1} \quad \widetilde{P_2}]$

- After Null precoding, equivalent matrix becomes as follows
  - $$\begin{bmatrix} H_{11} \\ H_{12} \end{bmatrix} \begin{bmatrix} \widetilde{P_1} & \widetilde{P_2} \end{bmatrix} = \begin{bmatrix} H_{11}\widetilde{P_1} & H_{11}\widetilde{P_2} \\ H_{12}\widetilde{P_1} & H_{12}\widetilde{P_2} \end{bmatrix} = \begin{bmatrix} H_{11}\widetilde{P_1} & 0 \\ 0 & H_{12}\widetilde{P_2} \end{bmatrix}$$

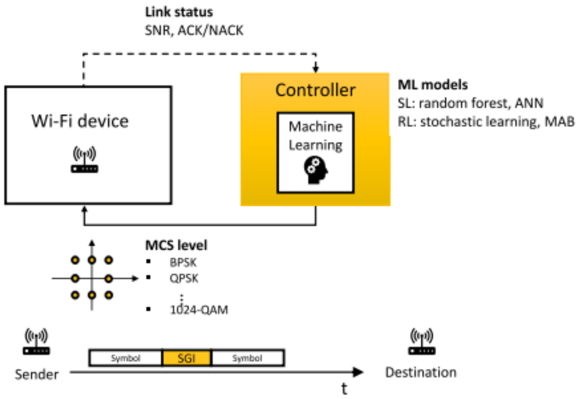
BSS IUI is nullified

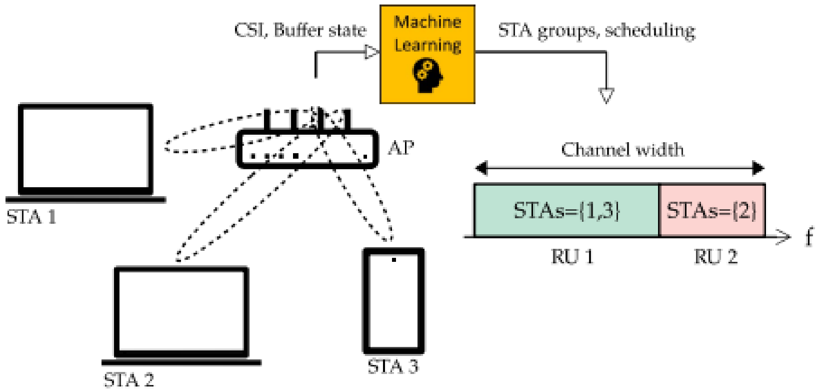
- SVD Precoding for each STA (P_{SVD})
  - We then apply SVD beamforming to each user for the BF gain
    - For STA 1, equivalent channel $H_{11}\widetilde{P_1} = \widetilde{U_1}\widetilde{\Lambda_1}\widetilde{V_1^H}$
    - For STA 2, equivalent channel $H_{12}\widetilde{P_2} = \widetilde{U_2}\widetilde{\Lambda_2}\widetilde{V_2^H}$

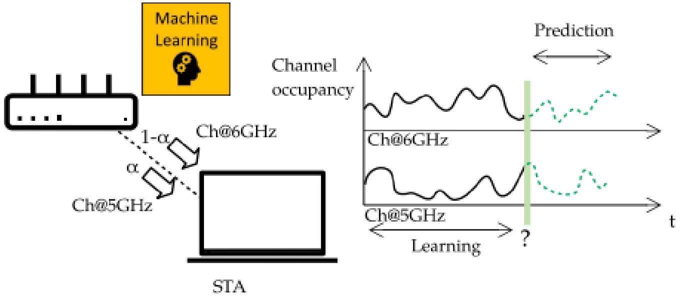
$$P_{SVD} = \begin{bmatrix} \widetilde{V_1} & 0 \\ 0 & \widetilde{V_2} \end{bmatrix}$$

- Total precoding matrix becomes:
  - $\begin{bmatrix} \widetilde{P_1} & \widetilde{P_2} \end{bmatrix} \begin{bmatrix} \widetilde{V_1} & 0 \\ 0 & \widetilde{V_2} \end{bmatrix}$

Is there space for ML in Wi-Fi?







Source: “Wi-Fi Meets ML: A Survey on Improving IEEE 802.11 Performance With Machine Learning”, IEEE communications surveys & tutorials

Thank you

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