UBIQUITY & EVOLUTION OF WI-FI

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TERMINOLOGY

- WLAN (wireless local area network) refers to IEEE 802.11 standards that define the physical (PHY) and medium access control (MAC) layers in implementations (chip, product)
- Wi-Fi (wireless fidelity) refers to products that are certified by Wi-Fi Alliance (WFA), a consortium of companies that provide certification to WLAN enabled products for inter-operability & sales to end customers

These terms are often used interchangeably!

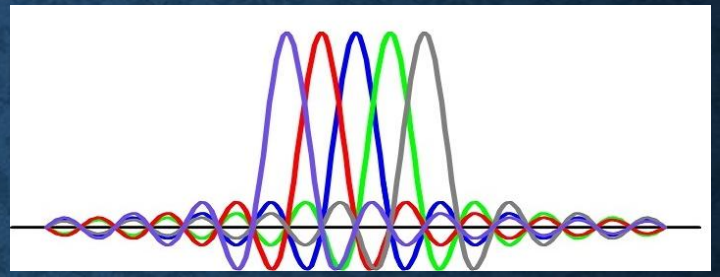
UBIQUITY OF WI-FI

- Wi-Fi chips are present across myriad devices like home/enterprise/campus routers, smartphones, laptops, tablets, printers, cameras, outdoor CPEs, TVs, drones, earbuds (!), security cameras … and many more!
- Key USPs of Wi-Fi
  - ✓ Decoupling of PHY/MAC standards (IEEE 802.11 WLAN) and device certification (Wi-Fi Alliance)
  - ✓ Hard PHY + Firm MAC + Soft higher layers
  - ✓ High throughput
  - ✓ Quick STA-AP connection time

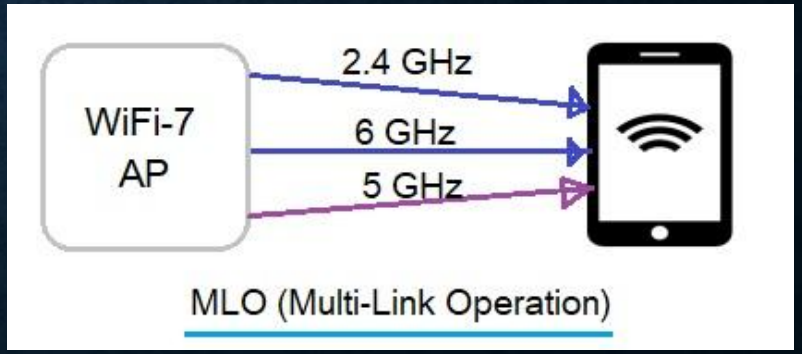
Image courtesy: Gemini

KEY USPS OF WI-FI

- @ Architecture level
  - PHY layer and MAC layer are highly decoupled (compared to xG cellular)
  - $\Delta(AP, STA) < \Delta(gNB, UE)$ → faster R&D and TTM!



- @ PHY layer (L1)
  - ✓ OFDM *(launched via IEEE 802.11a in 1999)*
  - ✓ MIMO (*launched via IEEE 802.11n in 2009)* → *SU TxBF* → *DL MU MIMO* → *UL MU MIMO*
  - ✓ Low TxEVM (leads to higher QAM) → 4k QAM
- @ MAC layer (L2)
  - ✓ CSMA/CA (*launched via IEEE 802.11 in 1997*) → bedrock of Wi-Fi MAC!
  - ✓ [QoS] EDCA (*traffic classification into VO, VI, BE, BK*) + TWT (*802.11ac*)
  - ✓ [Efficiency] Frame aggregation (*802.11n*) + Block ACK (*802.11ac*)
  - ✓ Multi link operation (MLO)



Images courtesy: EverythingRF

EVOLUTION OF SUB-7GHZ INDOOR WI-FI

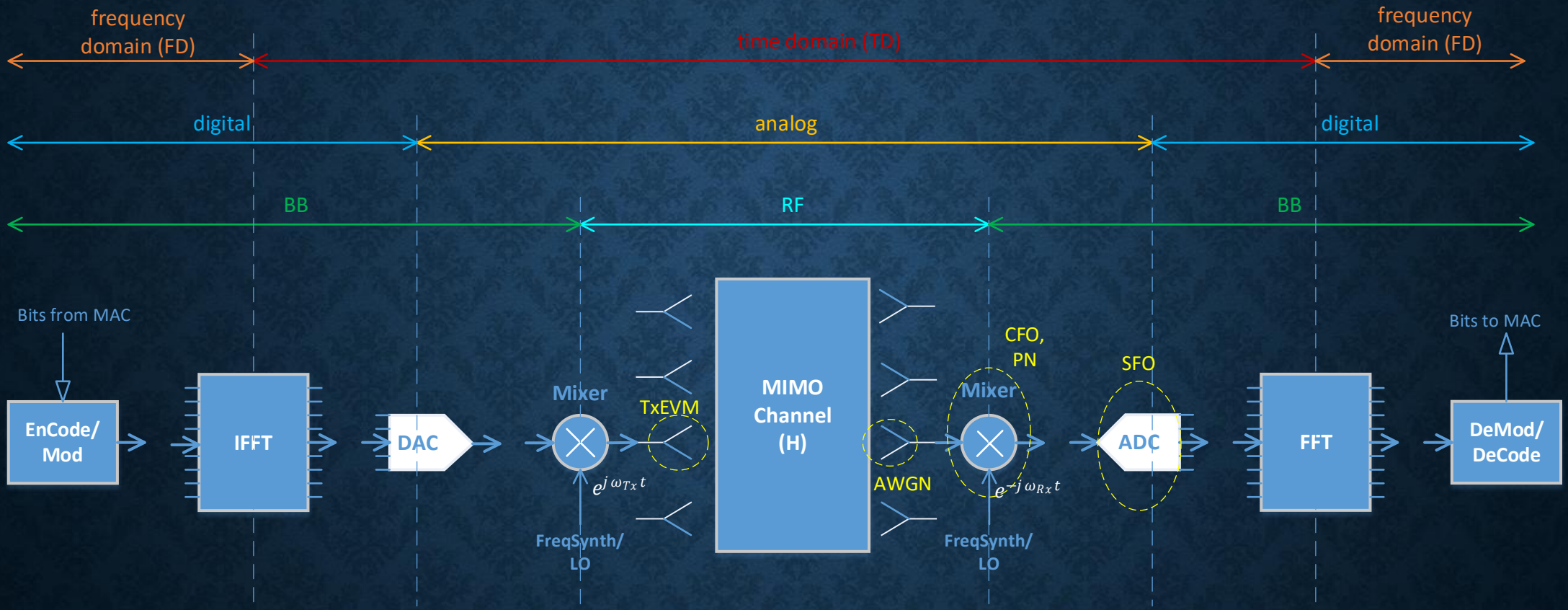
- Most Wi-Fi evolution studies (and product sheets!) only focus on
  - Peak PHY rate for 1 AP, 1 STA with max BW and max # spatial streams
  - Key PHY features, Key MAC features, # clients supported, …

Wi-Fi generation	PHY PPDU type	IEEE Standard	PHY USP	Max. BW (MHz)	Max. QAM	Max. MIMO $N_{Tx} \times N_{Rx}: N_{SS}$	Max. PHY rate	Max. STAs/AP	MAC USP
Wi-Fi 1	DSSS	802.11b		22	N/A	1 x 1: 1	2 Mbps	1	
Wi-Fi 2	CCK	802.11b		22	N/A	1 x 1: 1	11 Mbps	1	
Wi-Fi 3	LEG	802.11a/g	OFDM	20	64	1 x 1: 1	54 Mbps	1	
Wi-Fi 4	HT	802.11n	MIMO, SU TxBF	40	64	4 x 4: 4	600 Mbps	1	
Wi-Fi 5	VHT	802.11ac	DL MU MIMO	160	256	8 x 8: 8	7 Gbps	4	BA
Wi-Fi 6	HE	802.11ax	UL MU MIMO, OFDMA	160	1k	8 x 8: 8	9.6 Gbps	37	TWT
Wi-Fi 7	EHT	802.11be	DL/UL SU/MU MIMO+OFDMA	320	4k	8 x 8: 8	30 Gbps	37	MLO
Wi-Fi 8	UHR	802.11bn	Multi-AP CoBF ELR	320	4k/8k	8 x 8: 8	30+ Gbps	37	Seamless roaming

Tough questions to ask:

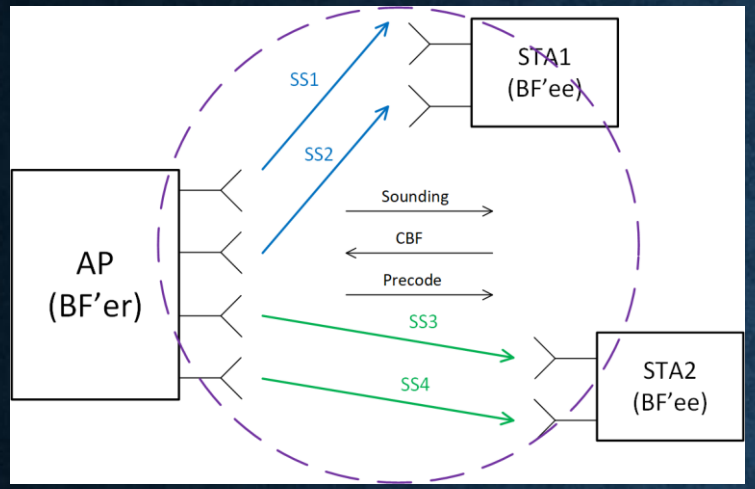
1. Can we sustain the above PHY rates in DL/UL when # STAs increases from say 1 to 16?
2. What are the UL latencies experienced by various clients with heterogeneous QoS requirements?

ANATOMY OF WLAN PHY LAYER



Dominant impairments:

- **CFO** (carrier frequency offset) $= \Delta f = f_{Rx} - f_{Tx}$ → this needs to be estimated & compensated
- **SFO** (sampling frequency offset) $= F_{samp,ADC} - F_{interp,DAC}$ → needs to be estimated & compensated
- **TxEVM** (transmitter error vector magnitude) → can be reduced with better RFIC design
- **AWGN** → necessary "kTB" evil, unless you operate at 0K !
- **NF** (noise figure) → due to non-linearities in Rx RFIC components along the signal path



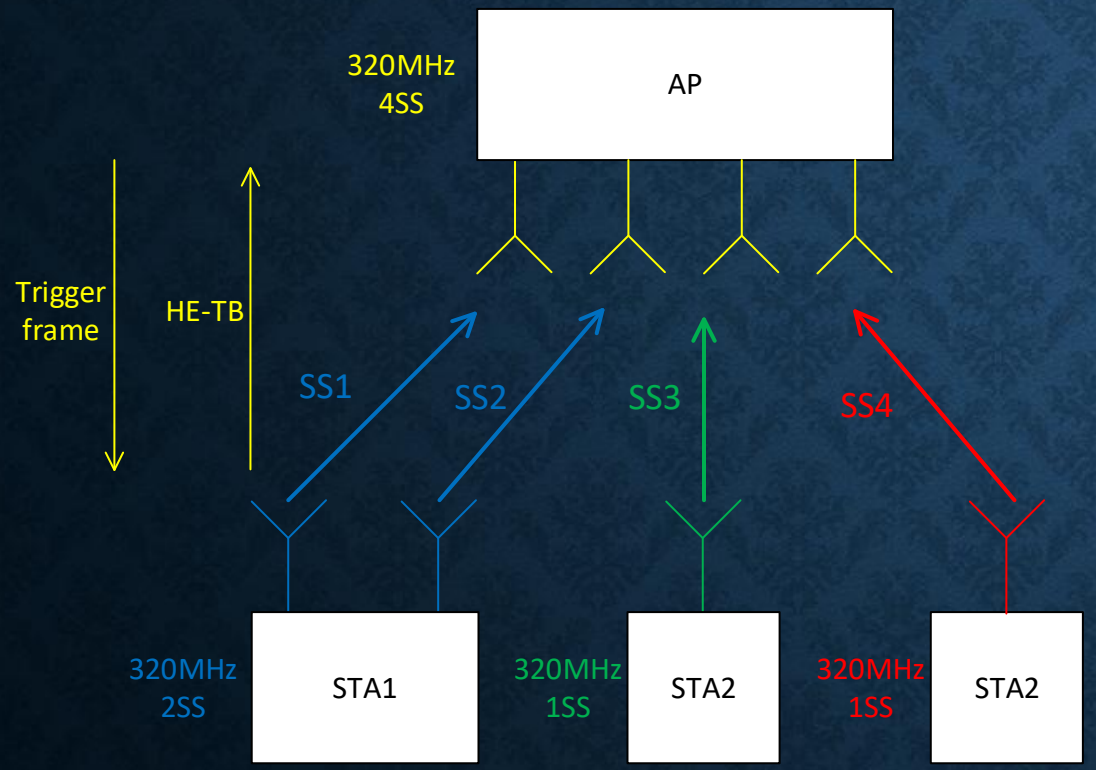
ON DL MU MIMO PRECODING

$$\begin{bmatrix} y_{1,a} \\ y_{1,b} \\ y_{2,a} \\ y_{2,b} \end{bmatrix} = \begin{bmatrix} [V_1]_{2\times2} & [\sim 0]_{2\times2} \\ [\sim 0]_{2\times2} & [V_2]_{2\times2} \end{bmatrix} \begin{bmatrix} x_{1,a} \\ x_{1,b} \\ x_{2,a} \\ x_{2,b} \end{bmatrix} + \begin{bmatrix} n_{1,a} \\ n_{1,b} \\ n_{2,a} \\ n_{2,b} \end{bmatrix}$$

- Enables AP to simultaneously transmit PHY DATA to 2 or more STAs via DL FD precoding matrix V
- DL MU MIMO is very sensitive to the channel estimates from BF'er (AP) to each of the BF'ees (STAs)
  - STAs that are co-located / near-located yield "similar" DL channel estimate matrices
- In practice, DL MU MIMO does not scale well beyond 2 STAs and $N_{SS,total} > 4$
- ∵ DL MU MIMO works best when there is sufficient "separation" between the channel estimate matrices from AP to each of the STAs..
  - ..else it can perform worse than SU TxBF !!!
  - ..we cannot guarantee "sufficient" channel separation when the two STAs are in close physical proximity!
- For large # users with heterogeneous QoS requirements, DL MU MIMO performance optimization ultimately becomes a user grouping problem for which optimal solutions do not exist!

FFT: This may be a good problem to solve using AI!

UL MU MIMO: PRACTICAL ASPECTS



- Uplink MU MIMO (full BW) & UL MU OFDMA (fractional BW) are WLAN PHY features introduced from Wi-Fi 6 (11ax) onwards
- Engineering challenges:
  - UL MU performance (@ AP) is highly sensitive to efficient CFO & SFO pre-correction (@ STA_k Tx) when all N STAs are transmitting simultaneously on UL
  - Wi-Fi 6 mandates residual xFO < 350 Hz
  - What if there is a rogue STA? (*FFT: Can we use AI in addition to PHY techniques?*)

Tough questions:

1. Have UL MU MIMO & UL MU OFDMA features been successful in commercial Wi-Fi deployments?
2. Indoors as well as outdoors…?

EVOLUTION OF MMWAVE WLAN

- ∃ 2 IEEE standards for mmWave WLAN: 802.11ad (2012) & 802.11ay (2021)
- Frequency range: 57 – 71 GHz
- Salient features of these "WiGig" standards
  - ❖ Band: Unlicensed 60GHz mmWave
  - ❖ PHY rates: 8 Gbps (11ad), 100 Gbps (11ay)
  - ❖ SigBW: 2.16 GHz (11ad), 8.64 GHz (11ay)
  - ❖ Range: 10m (11ad - indoors), 300m (11ay - outdoors)
- Why haven't 11ad/11ay been a commercial success?
  - × LoS dependency, O_2 absorption
  - × High manufacturing costs
  - × Lack of ecosystem (consumer electronics manufacturers)
  - × [Indoor] Competition from Wi-Fi 6 & Wi-Fi 7 !!!
- There are silver linings though!
  - ✓ Terragraph project (by Meta) adopted 11ay for high-speed links b/w buildings & poles
  - ✓ TG uses Cambium's cnWave technology & Edgecore hardware to create mesh networks

Image courtesy: terragraph.com

Google: Is Terragraph a commercial success?

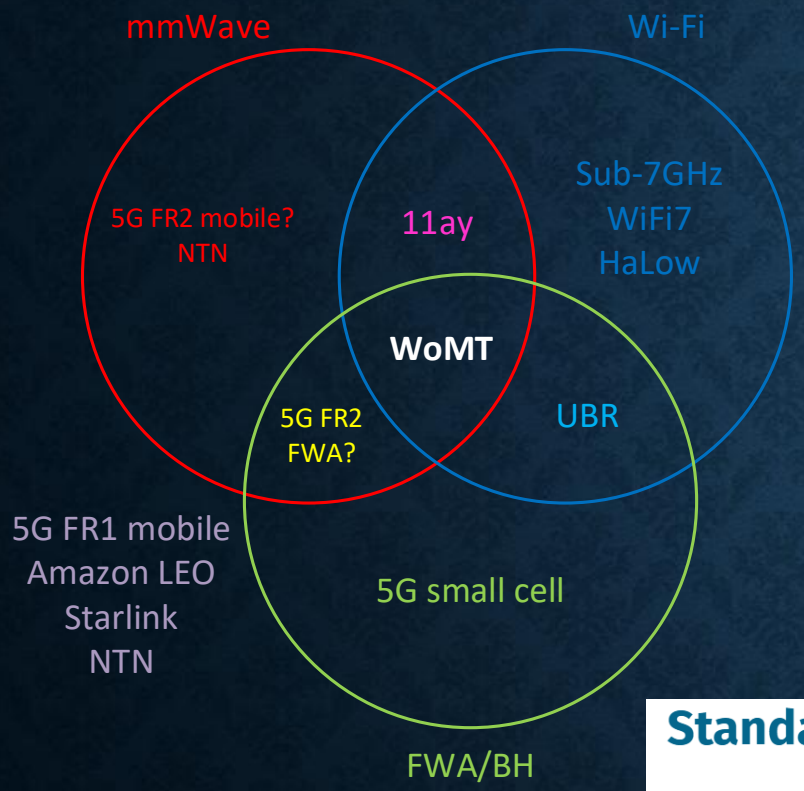
FFT: Can mmWave Wi-Fi be used for fixed wireless access & backhaul applications? Achieve commercial success?

EVOLUTION OF OUTDOOR SUB-7GHZ WLAN

- Multiple companies have commercialized the use of unlicensed sub-7GHz Wi-Fi for outdoor FWA (fixed wireless applications), *e.g. Cambium networks, Tarana wireless, Jio AirFiber*
- This is equivalent to a 4G/5G cellular network where xG PHY/MAC has been replaced by Wi-Fi PHY/MAC
- Key points to consider while deploying Wi-Fi outdoors
  - ✓ Operate in unlicensed ISM bands (2.4, 5, 6 GHz) only
  - ✓ Ensure that in-band EIRP is within regulatory limits
  - ✓ Ensure that out-of-band RF emissions into IMT bands are within 3GPP specified limits (*Tip: Work in 5GHz band*)
- Engineering challenges:
  - ➢ Develop channel & rate adaptation algorithms to mitigate interference from indoor Wi-Fi networks
  - ➢ Range extension by increasing EIRP (@ Tx) and using parabolic reflector (@ Rx)
  - ➢ Network planning by an operator to manage CCI from its own AP-STA devices as well as AP-STA devices of other operators (*… it is an unlicensed band after all!*)

FFT: Can outdoor unlicensed band WiFi guarantee consistent high throughput in spite of unexpected interference?

OUTDOOR MMWAVE WLAN: THE NEXT FRONTIER?



- Few companies/operators are developing products & services that leverage Wi-Fi tech in **licensed mmWave bands** for providing **multi-Gbps data rates** for **outdoor fixed wireless access** and **backhaul** applications
- Discussions are ongoing in:
  - **TEC/DoT** to release a GR (generic requirements) standard for **WoMT** (Wi-Fi over Millimeter wave Technology)
  - **TSDSI** (India's SDO) to draft a technical specifications (TS) standard for WoMT
- Progress: TEC/DoT has recently released a **provisional GR** for WoMT!

Ref: https://tec.gov.in/standards-specifications

Standards/ Specifications

Show 10 entries Search: mmWave

S.No.	Name of Standard	StandardNumber	Old Document Number	Date of Issue	Standard Type	Validation	Division	Download Standard	Download TSTP
530	AP (Access Point)-STA(Station) for Licensed mmWave Band	TEC 21150:2026		14-08-2026	Provisional Standard for Generic Requirements		MT	PDF	

Thank you! Questions?