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Wi-Fi 7 – Technology Realities and Way Forward

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***Abstract* With pre-standard Wi-Fi 7 products, based on the IEEE 802.11be amendment, already available in the market, and technology demonstrators showing data rates exceeding 5Gbps the technology is living up to its name of “Extreme High Throughput”. The key innovation of Wi-Fi 7, however, is not necessarily in achieving these high data rates, rather the introduction of a multi-link operation concept into Wi-Fi. In this paper we will provide a brief overview of the key Wi-Fi 7 technology innovations and discuss why we expect future Wi-Fi technologies will need to expand on the multi-link concept and new spectrum to continue deliver increasing end-user value with future Wi-Fi generations.**

***Index Terms* — 802.11be, Wi-Fi 7, Wi-Fi 8, Throughput, Quality of service, Multi-link communication.**

I. Introduction

Wi-Fi, based on the IEEE 802.11 family of standards is the predominant wireless networking technology, delivering more data than any other wireless access technology, cellular included [1]. One of the key pillars of the Wi-Fi success story has been its forward and backward compatibility – i.e., the latest Wi-Fi device is almost guaranteed to interoperate with devices designed to support older versions of the standard. This guarantee allowed organic network and device evolution since the early days of 802.11a/b/g with its 54Mbps peak data rates, to upcoming Wi-Fi 7 which is positioned to deliver peak data rates that are at least 100x higher (> 5 Gbps).

While it is easy to relate to Wi-Fi evolution mostly by peak data rate, this was never really the case, and more so starting Wi-Fi 6, with one of the key challenges in enabling some of these other innovations in cross-generational Wi-Fi networks. The introduction of the 6 GHz band in 2021 [2] presented an opportunity to break this mold, while still allowing legacy devices to operate in the 2.4 and 5 GHz bands. Another opportunity to accelerate the adoption of new Wi-Fi capabilities comes with the introduction of multi-link operation with Wi-Fi 7.

The rest of this paper will review the key innovations of Wi-Fi 7 and some of the expected challenges in their enablement. The paper starts with a brief introduction of the key features, describes the multi-link operation framework, followed by a discussion of PHY innovations and achievable data rates and MAC enhancements not related to multi-link operation. Following this introduction, the paper discusses some of challenges in achieving Wi-Fi 7 potential benefits and concluded with a brief discussion showing why Wi-Fi 7 is expected to set the stage for future Wi-Fi generations.

II. Key features

With draft 3.0 of the IEEE 802.11be amendment already available as of March 2023, the main standard development work is already done, and indeed some products have already been introduced to the market at the beginning of the year ahead of a Wi-Fi Alliance Certification.

The limelight features of Wi-Fi 7 are:

- 320 MHz wide channels.
- 4,096 Quadrature Amplitude Modulation (QAM).
- Multi-link operation, and related features.

In addition to these, Wi-Fi 7 promises:

- Improved coexistence with incumbents and other technologies using Multi-RU (MRU) allocations.
- Delivery of services with deterministic latency using restricted target wake time (rTWT).

and

- Improved area capacity and reduced latency in multi-AP mesh and mixed networking/peer-to-peer scenarios through the introduction of shared Transmission opportunities (TxOPs).

III. Multi-Link Operation

Current Wi-Fi connections use a single logical link over a single radio frequency (RF) channel per connection where any change in the connection configuration between two Wi-Fi devices (e.g., change in the RF channel) requires a MAC level reassociation or a roaming flow. In general, an 802.11 link is a MAC level logical entity between two devices that operate on a given RF channel, or subset of the RF channel (e.g., in the case that only a portion of the channel is available for use).

Wi-Fi 7 is changing this paradigm through the introduction of a multi-link operation (MLO) framework. MLO maintains on one hand the existing per-link connection, allowing interoperability with “legacy” pre-MLO devices, but introduces, however, a new multi-link device (MLD) logical entity that manages the multiple links a device supports, and exposes a single MAC data service access point (SAP) across all links as shown in Fig. 1. Note that the MLO framework does not require a device to integrate multiple transceivers. The standard defines the following MLD types or MLO modes of operation [3],[4].

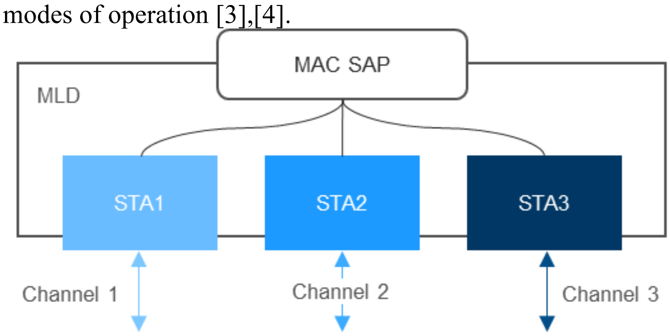

Fig. 1 Wi-Fi 7 multi-link framework

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1) Multi-Link Single Radio (MLSR) devices have a single radio interface and have a single active link at a given time, i.e., these devices can only receive or transmit over a single channel at a given time.
2) Enhanced Multi-Link Single Radio (eMLSR) devices can be available on more than one link at any given time (are able to listen to multiple links) but can only transmit or receive data through a single link at a given time.
3) Multi-Link Multi-Radio (MLMR) devices can receive and transmit concurrently on more than one link. There are two flavors of MLMR devices – simultaneous and non-simultaneous transmit-receive (STR and NSTR) MLMR devices. STR-MLMR devices can operate their multiple links asynchronously, potentially transmitting on one link while receiving on the other, while NSTR MLMR devices must synchronize the operation of their multiple links. A MLMR device could be STR capable in some link configurations while being constrained to NSTR mode for others.
4) Enhanced Multi-Link Multi-Radio (eMLMR) devices can dynamically reconfigure their multiple radios across the different links (e.g., support either of 2-spatial stream operation on a single link or two single spatial streams operation across two different links). Like MLMR devices, eMLMR devices could be constrained to operate in STR or in NSTR modes.

MLO is expected to deliver multiple benefits starting with faster connection transitions between the different links an access point (AP) supports, reduced latency and increased throughput in congested environments, and all the way to data rate aggregation across multiple links that are possible with STR-MLMR devices. It should be noted that the MLO framework may need to be configured differently (potentially per connection) to optimize for the wanted benefit.

Important, if less mentioned, aspects of the MLO framework are multi-link discovery, multi-link setup, multi-link block ack and power save, as well as multi-link specific QoS enhancements. A Wi-Fi 7 MLD AP is required to advertise the basic information for all its links in each of the individual AP beacons. Further, a non-AP MLD can request detailed information for all the links an AP MLD supports – significantly reducing multi-link discovery time and overheads. The multi-link setup process was defined to have a single association and authentication process for all the links an AP supports. Here, the association flow was enhanced to relate to the link specific STA information and the device level MLD MAC. Further the Wi-Fi 4-way security handshake was extended to relate to the multi-link aspects. The security handshake establishes a unified security context across all links, sharing the pairwise master key (PMK), pairwise transient key (PTK) and packet number (PN) space across all links. At the same time, and to better interoperate with legacy devices, the MLD security framework maintains per-link broadcast and multicast context with a per-link group temporal key (GTK), integrity group temporal key (IGTK), and beacon integrity temporal key (BIGTK), as well as per-link broadcast and multicast PN space.

IV. PHY ENHANCEMENTS AND ACHIEVABLE DATA RATES

The primary PHY enhancements of Wi-Fi 7 are the introduction of 320 MHz wide channels that when combined with the 4,096 QAM modulation scheme the standard introduces, increases the per-link data rate by a factor of 2.4x. This puts the peak PHY data rate of a single 2-spatial stream link at 5.76 Gbps, and that of an 8 spatial stream (the maximum supported by the standard) link at just over 23 Gbps.

Further, Wi-Fi 7 MLMR devices, can deliver much higher aggregate data rates with a potential 8.65 Gbps peak data rate between a 2-antenna Wi-Fi 7 station (STA) and a Wi-Fi 7 AP (using one 160MHz channel in the 5GHz band and one 320MHz channel in the 6GHz band). This is only a shade lower than the 9.6 Gbps peak achievable Wi-Fi 6 data rate over an 8-spatial stream connection, as shown in Fig. 2.

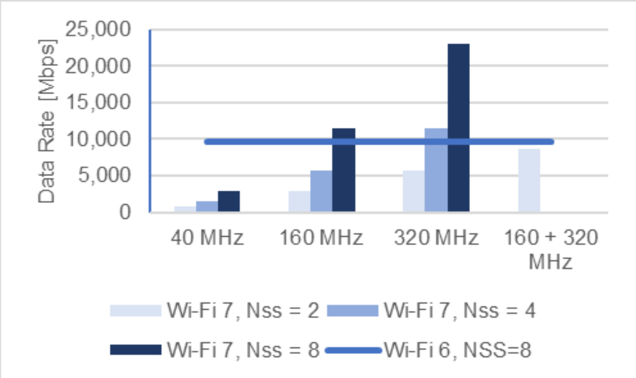

Fig. 2 Wi-Fi 7 usable data rates compared to Wi-Fi 6 peak data rate.

Another key Wi-Fi 7 PHY enhancement is the capability of an AP to allocate multiple resource units (MRUs) to a single station. Through MRU, Wi-Fi 7 devices can better utilize wide-band channel connections even in the presence of incumbent services (in the 6 GHz band), or interference (from other Wi-Fi or other transmitters), increasing the overall spectral efficiency of Wi-Fi networks, even when a limited number of STAs are connected to an AP.

Several of the PHY enhancements targeted for Wi-Fi 7 did not make it into the specification. These include an increase in the maximum allowed MIMO order from 8 spatial streams to 16 spatial streams [3],[4], and the introduction of a distributed tones OFDMA resource unit (RU). Distributed tones RU was expected to allow a STA to increase its overall transmit power, when operating under the constraints of a power spectral density (PSD) limit and reduce required transmissions times at low data rates. Further, distributing the used subcarriers over the complete channel bandwidth provides better link reliability over frequency selective channels due to the greater frequency diversity. Distributed RU may yet be introduced in a future Wi-Fi amendment. On the other hand, there are limited expectations to see a future increase in the maximum spatial stream order to 16, given the related cost and complexities that make even 8-spatial streams APs rare products.

V. BEYOND MULTI-LINK

In addition to the introduction of the MLO framework and higher data rates, Wi-Fi 7 extends the Wi-Fi quality of service (QoS) framework to further reduce data delivery latency and jitter through the introduction of a new QoS provisioning scheme and channel access management mechanisms.

To help AP schedulers, Wi-Fi 7 implements and extends the stream classification service (SCS) protocol. SCS allows non-AP STAs to provide the AP with IP traffic classifications rules using the traffic classification (TCLAS) element to assign per-application user priorities (and related access categories) [5]. In addition, Wi-Fi 7 SCS allows a STA to add a comprehensive description of the service requirements, including service interval and data rate information. This extra information, in conjunction with the existing traffic specification (TSPEC) element, provides the necessary information for AP schedulers to efficiently schedule trigger-based uplink (UL) traffic and prioritize downlink (DL) traffic to the different STAs it serves.

In addition to extending the SCS framework, Wi-Fi 7 introduces several features targeted to reduce jitter and enhance reliability. One such key feature is restricted target wake time (rTWT) that complements the existing target wake time (TWT) mechanism. Whereas TWT can be used to manage STA power save and availability as well as to group STAs into availability groups, to help with multi-user scheduling, with rTWT, the AP can reserve service periods (SP) for STAs and applications that require the increased reliability and reduced jitter. To guarantee the reservation, any Wi-Fi 7 non-AP STA that supports rTWT is required to end any transmissions before the rTWT SP starts, and the AP can further protect the rTWT SP with a quite time interval which prohibits STAs that are not members of the rTWT SP from accessing the channel. rTWT is especially useful in managed environments (e.g., factory floors) where it can be ensured that all STAs in the area support the feature, and through that almost eliminate latency and jitter.

Another QoS enhancing feature is traffic identifier (TID) to link mapping (T2LM). Through T2LM, the AP can define on which links specific QoS classes (access categories) can be transmitted on. Through T2LM a Wi-Fi 7 AP can, e.g., dedicate its 6 GHz link to latency sensitive traffic, and through that further help reduce its jitter. When used in conjunction with link steering and the other QoS enhancing Wi-Fi 7 features, a Wi-Fi 7 AP can effectively manage the latency and jitter of services across its network.

VI. TECHNOLOGY CHALLENGES

There are several challenges related to the development and deployment of new technologies, and Wi-Fi 7 is no exception. Further, due to the Wi-Fi promise of backward and forward compatibility, Wi-Fi 7 technology and products face some unique related challenges. At least some of these, as we will show, are due to implementation in older devices that did not relate to the forward compatibility promise.

A. PHY Challenges

The introduction of 320 MHz wide channels, and 4,096 QAM (also known as 4K-QAM), brings with it a set of implementation challenges that may make it difficult for Wi-Fi technology to evolve to allow higher data rates in future generations.

The signal to noise (SNR) requirement of supporting a 4,096 QAM with a 5/6 rate are such, that the standard mandates meeting a modulation accuracy of -38 dB relative constellation error (or error vector magnitude (EVM)) for this modulation scheme. This, of course, directly impacts the implementation complexity of the transmitter and receiver. Comparing this requirement, to the -35 dB EVM requirement for the 5/6 encoded 1,024 QAM scheme introduced with Wi-Fi 6, we can see this is already a compromise, given the straightforward information theoretical requirement is 5 dB more stringent. As a result, the receiver implementation complexity of Wi-Fi 7 is expected to be higher than that of previous Wi-Fi receivers.

When considering the link-budget for 320 MHz wide channels, and the regulatory limits on Tx power Wi-Fi operates under, we can see that the effective distance for delivering the maximum throughputs with Wi-Fi 7 is expected to be limited. This also limits the potential for future data rate growth in the current frequency bands.

- Maximum allowed Tx power (6 GHz band, Standard power AP [6]): 36 dBmi
- Thermal noise floor at 320 MHz: -88.9 dBm
- SNR required at the receiver input to achieve 1 dB degradation (vs -38 dB required transmitter EVM): 43.9 dB.
- Required signal strength at receiver input: -45 dBm.

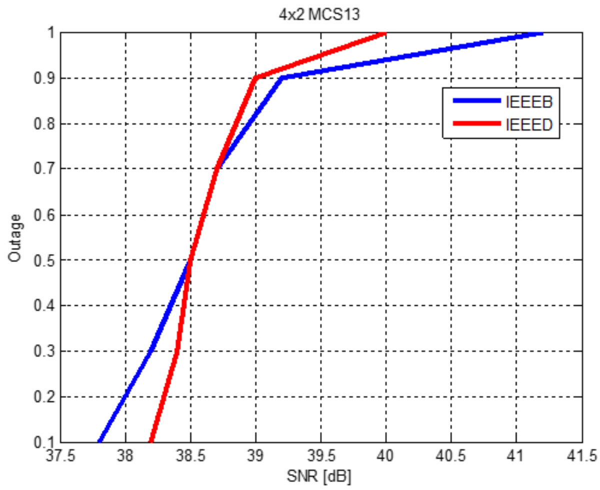

Fig. 3 Wi-Fi 7 4K-QAM Outage Performance over IEEE B and D channel models

As the received signal strength for real-world Wi-Fi devices is typically lower than -50 dBm (which indeed is assigned a receive signal strength indication (RSSI) of 100% in some implementations). It should be noted that the IEEE 802.11be reference channel model [7], with an Outage performance demonstrated over both the IEEE indoor residential and office environment channel models (IEEE 802.11 channel B and D respectively), allows for a significant link loss variability due to shadow fading that makes it hard to estimate the real-world range targets. If we do take the -50 dBm RSSI value as a target, it is easy to see that regardless of channel availability, the potential to benefit from increasing channel bandwidth or modulation scheme is going to be limited, given the existing regulatory constraints.

B. Deployment Challenges

As described in section III above, Wi-Fi 7 MLO uses the same security credentials for all the links. This effectively mandates using the same security scheme across all links. With many Wi-Fi 7 APs expected to support operation in the 6 GHz band and Wi-Fi Protected Access 3 (WPA3) mandated in the band, Wi-Fi 7 essentially mandates use of WPA3. On one hand, moving the network security baseline to WPA3 is a good thing, on the other hand, there is the Wi-Fi promise of maintaining backward compatibility, and specifically ensuring older devices that may not support the latest Wi-Fi technologies (including WPA3), could still connect to Wi-Fi 7 networks. While the Wi-Fi standard has addressed this concern introducing the WPA3 transition mode [8], there are multiple devices (e.g., Internet of things (IOT) devices, and even older Smartphones) that can only connect to WPA2 networks and would not connect to networks configured for WPA3 transition mode. As a result, many internet service providers (ISPs) and AP vendors configure their APs today to WPA2, regardless of the availability of updated Wi-Fi security standards. This creates two contradicting requirements:

1) Use a single WPA3 security scheme across all bands of operations.
2) Use only WPA2 network security in 2.4, 5GHz bands.

A related complication is that Wi-Fi 7 adds support for a WPA3-Personal flavor using GCMP256 encryption. Therefore, for a Wi-Fi 7 AP to support both Wi-Fi 7 and older STAs supporting WPA3, it needs to support multiple authentication and key management (AKM) suites within WPA3. This is like the WPA3 transition mode scheme that was designed to address a similar issue (where one AKM was the WPA2 AKM, and another the WPA3 AKM). As the main issue with STAs that were not designed with forward compatibility in mind is that they do not connect to a network supporting multiple AKMs, a potential solution could be to configure Wi-Fi 7 APs to have two different networks (service set identifiers, or SSIDs), one "legacy" SSID configured in WPA2 only mode in the 2.4 and 5 GHz bands, to support legacy devices, and a second, WPA3 SSID configured with multiple AKMs to support newer, standard compliant STAs.

This proposed scheme creates further potential complexities. The first is the need to configure two different networks, each with its own SSID. The second would be to design APs to allow devices on one network/SSID to discover and access devices on the other network/SSID, creating a unified network. Further, users will need to be educated that the two different networks form a single network. When considering that in many deployments there are also Guest networks, and that there are cases where there is interest to create further isolated networks (e.g., for utility companies, etc.), this may require each AP to be configured with a multiplicity of SSIDs and virtual networks.

This discussion specifically relates to "personal" (home, or small venue) networks, as in most IT deployed networks, and regardless of WPA3 transition mode applicability to networks using WPA3-Enterprise, in many cases IT managers already deploy dedicated network per Wi-Fi security protocol version and configure IT peripherals with the right credentials to access the network / SSID that best fits the device capabilities and usages.

An unrelated challenge, which is relevant for both "personal," and "enterprise" Wi-Fi 7 APs, that will need to be addressed by AP vendors is the network MLO configuration. As mentioned above, there are multiple different flavors of Wi--Fi 7 MLO STAs, and as mentioned multiple, sometimes mutually exclusive potential benefits. As an example, one way to achieve high transmission reliability is to transmit the data on all available links. This scheme does not allow, for example, to also gain the potential throughput benefit due to transmitting different data on each link.

An interesting side effect of the proposed solution to the Wi-Fi 7 deployment challenges is that since the situation almost mandates separating networks into Wi-Fi 7 networks and legacy networks (which is technically not hard to implement), Wi-Fi 7 networks could find themselves in the unique position of not being burdened by the need to support the legacy devices with their idiosyncrasies, and allow the deployment of features that these older devices are incompatible with, on the new Wi-Fi 7 dedicated network.

VII. BEYOND WI-FI 7

With Wi-Fi 7 technology nearing its market intercept, the IEEE 802.11 work group (WG) has initiated a study group towards the next Wi-Fi generation following Wi-Fi 7. The formation of the 802.11 Ultra High Reliability (UHR) study group (SG) was approved in the IEEE 802.11 July 2022 meeting [9], and the Project Authorization Request (PAR) and the Criteria for Standard Development (CSD) documents were developed and finalized during the March 2023 SG meeting [10], with a target standard completion date of March 2027. Considering that Wi-Fi 6 technology and products were introduced in 2019, and with early Wi-Fi 7 products introduced in 2023, it is reasonable to assume that the next Wi-Fi generation, based on the UHR project will indeed see a 2027 market intercept.

While traditionally each Wi-Fi standard generation brought with it a growth in the supported data rates, as shown in section V above, there are significant challenges to continue this trend. Indeed, the proposed UHR PAR [11] acknowledges this, and proposed the following enhancements for the upcoming generation:

- Increasing throughput at different Signal to Interference and Noise Ratio (SINR) levels (Rate-vs-Range).
- Reducing worst case latency and jitter

and

- Improving spectrum usages efficiency

It is further interesting to note that the proposed PAR relates to Wi-Fi operation in channels in the 1 GHz to 7.250 GHz frequency range, which is an extension of current Wi-Fi related spectrum that only goes up to 7.125 GHz.

Another point of interest that might be found in the proposed UHR PAR is that it also targets to deliver these performance improvements in the case of overlapping networks, including reduced latency and jitter in conjunction with mobility between APs. This can be taken as a hint that UHR specifications may generalize the Wi-Fi 7 MLO framework to support links that do not necessarily terminate in the same MLD, rather at the network level. If this indeed is the case, then the Wi-Fi 7 MLO will become the foundation of a new paradigm that may enable further growth in Wi-Fi performance in the current bands of operation.

In addition to considering the existing bands of operation the UHR SG also considered the inclusion of mmWave band support as part of the upcoming standard. This concept was eventually rejected [10] and instead a proposal for the formation of a new, dedicated study group was approved. While Wi-Fi operation in the unlicensed mmWave bands is potentially already feasible through the IEEE 802.11ad and 802.11ay amendments, the new direction proposed for future 802.11 work on mmWave Wi-Fi is to integrate this band as another link in the overall MLO framework, further emphasizing the importance of the framework for the future growth of Wi-Fi.

VIII. Summary

Wi-Fi, being the predominant networking technology, has delivered an ever-increasing value to users over the past decades, with its 7th generation, Wi-Fi 7, seeing early market intercept as of early 2023. Wi-Fi 7 brings with it a significant increase in supported data rates and reduced latency, as well as a paradigm shift. While still significantly improving the per-channel link performance, Wi-Fi integrates multiple links into a single logical connection, with a potential to deliver further throughput improvements as well as reduced latency, and improved reliability. At the same time, and given the regulatory and constraints for unlicensed operation, it will be more than difficult for future Wi-Fi technologies to further increase link data rates beyond those available with Wi-Fi 7, and future Wi-Fi generations will need to improve performance by extending Wi-Fi operation to new bands, and by extending the multi-link framework with its potential for link aggregation to relate to the complete network as a virtual multi-link device.

As with any technological evolution, Wi-Fi 7 brings with it an extensive set of challenges in both device implementation and network deployment and configuration. As one of the key challenges relates to some device implementations not adhering to the forward compatible spirit of the standard, it looks as if there is a real need to configure Wi-Fi 7 capable networks as two separate networks – one for legacy devices, and the other for Wi-Fi 7 (or other forward compatible) devices. This potentially problematic situation, if managed properly, may allow Wi-Fi 7 networks to increase the pace of Wi-Fi 7 innovation and implement features that otherwise might not have been deployed due to incompatibility of these older devices.

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