Wi-Fi advancements and the potential use of Wi-Fi 7 in crisis situations

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Abstract: *This paper explores the IEEE 802.11be standard, also known as Wi-Fi 7 Extremely High Throughput (EHT), the latest iteration of Wi-Fi technology. Comparing it to its predecessors to highlight the significant technical and performance differences, with a focus on the capabilities and advantages compared to 802.11ax, upon which it is built. The analysis includes improvements in transfer speeds, energy efficiency and network capacity particularly through the enhanced use of Multi-User MIMO (MU-MIMO), which allows simultaneous communication with multiple devices, increasing overall network efficiency and performance. Additionally, it discusses the Multi-Link Operation (MLO) technology, which enhances connectivity by allowing devices to maintain multiple simultaneous connections across different channels and bands. It also introduces the Multi Resource Units (MRU) technology which represents an advanced technology that enables more efficient use of radio resources in wireless networks. Furthermore, it examines the potential application of Wi-Fi technology in crisis situations, such as natural disasters, emphasizing its role in ensuring reliable communication and connectivity. Through an in-depth analysis of technical specifications this paper provides insight into the possibilities and challenges in implementing Wi-Fi 7 technology, considering its security aspects and its ability to address challenges in crisis scenarios.*

Keywords: *IEEE 802.11be, Wi-Fi 7, Multi-User MIMO, Multi-Link Operation, Multi Resource Units*

1. INTRODUCTION

Wi-Fi, short for Wireless Fidelity, revolutionized networking by enabling seamless wireless data transfer using radio frequency waves between devices. In a typical setup, a wireless router acts as the gateway to the Internet, connecting various devices wirelessly. Developed in the late 1990s, Wi-Fi has evolved into a cornerstone of modern network infrastructures, facilitating access to both the Internet and local area networks without the constraints of physical cables. The inception of Wi-Fi began with the adoption of the IEEE 802.11 standard in 1997, which initially supported data transfer speeds of up to 2 Mbps over the 2.4 GHz band. Since then, Wi-Fi standards have undergone significant advancements, continually improving in speed, range, and reliability. These enhancements have been crucial in meeting the diverse connectivity needs across homes, offices, schools, and public spaces, offering users unparalleled flexibility and mobility. With each successive iteration, such as Wi-Fi 6 and the latest Wi-Fi 7 standards, the technology has evolved to deliver not only faster speeds but also enhanced performance in environments bustling with numerous connected devices. These newer standards incorporate innovations that optimize network efficiency, minimize latency, and maximize throughput, catering to the growing demand for seamless connectivity in both residential and industrial settings. This paper employs literature review and comprehensive technical analysis of Wi-Fi 7 (802.11be) to compare it to previous standards such as Wi-Fi 6, highlighting key advancements in speed, efficiency, and capacity. Additionally, the potential applications of Wi-Fi 7 in crisis situations are explored through scenario-based evaluation, emphasizing its role in maintaining communication and connectivity under challenging circumstances. These methodologies provide a foundation for understanding both the technical specifications and the practical implications of this cutting-edge wireless technology.

2. WI-FI 7

Wi-Fi 7 (802.11be) stands as the latest pinnacle in wireless networking technology, building upon the foundational advancements of Wi-Fi 6 (802.11ax) while introducing substantial technical enhancements. These include advanced Multi-user Multiple-input and Multiple-output (MU-MIMO) capabilities and the adoption of a wider channel bandwidth of up to 320 MHz. Additionally, Wi-Fi 7 pioneers new technologies such as Multi-Link Operation (MLO), Multi Resource Unit (MRU), and 4K quadrature amplitude modulation (4K-QAM), collectively revolutionizing the capabilities and efficiency of wireless networks (Wi-Fi Alliance, 2024). A standout feature of Wi-Fi 7 is its remarkable increase in data transfer speeds, reaching up to 46 Gbps (gigabits per second), which represents a significant leap of 4.8 times faster than Wi-Fi 6. This enhancement is pivotal in meeting the escalating demand for high data throughput and in mitigating latency and jitter issues, particularly in dynamic home and industrial environments. These advancements are critical for supporting time-sensitive applications such as augmented reality (AR), virtual reality (VR), and mobile gaming, where seamless and robust connectivity is essential for optimal user experience. The industry's growing interest in advanced Wi-Fi capabilities across the 2.4 GHz, 5 GHz, and 6 GHz bands underscores the need for more efficient and reliable wireless communication infrastructures. Wi-Fi 7's technological advancements not only cater to current demands but also pave the way for future innovations, ensuring that wireless networks can sustainably support the evolving needs of diverse applications and environments.

3. Multi-User MIMO

MU-MIMO is a wireless networking technology that enables a Wi-Fi access point to communicate with multiple client devices simultaneously, rather than sequentially. This improves network efficiency and overall throughput, especially in environments with a high density of connected devices. It offers key advantages such as the elimination of bottlenecks which means that devices connect and disconnect from the network more quickly, allowing a greater number of devices to be efficiently served. Legacy devices operating on older standards experience enhanced performance and no longer slow down the overall downlink throughput for other devices on the network. With the optimization of frequency bands newer devices which support 5 GHz and 6 GHz such as smartphones, laptops and tablets will utilize those bands, freeing up the 2.4 GHz band for older devices, leading to better overall network performance and management (Commscope, 2022). As the band increases so are the transfer speeds but higher bands provide less coverage. One of the key improvements in Wi-Fi 7 compared to Wi-Fi 6 is the support for a larger number of simultaneous spatial streams, as shown in figure 1, increasing the number from 8 to 16 which theoretically doubles its capabilities allowing for more efficient handling of multiple data streams and boosting overall network capacity.
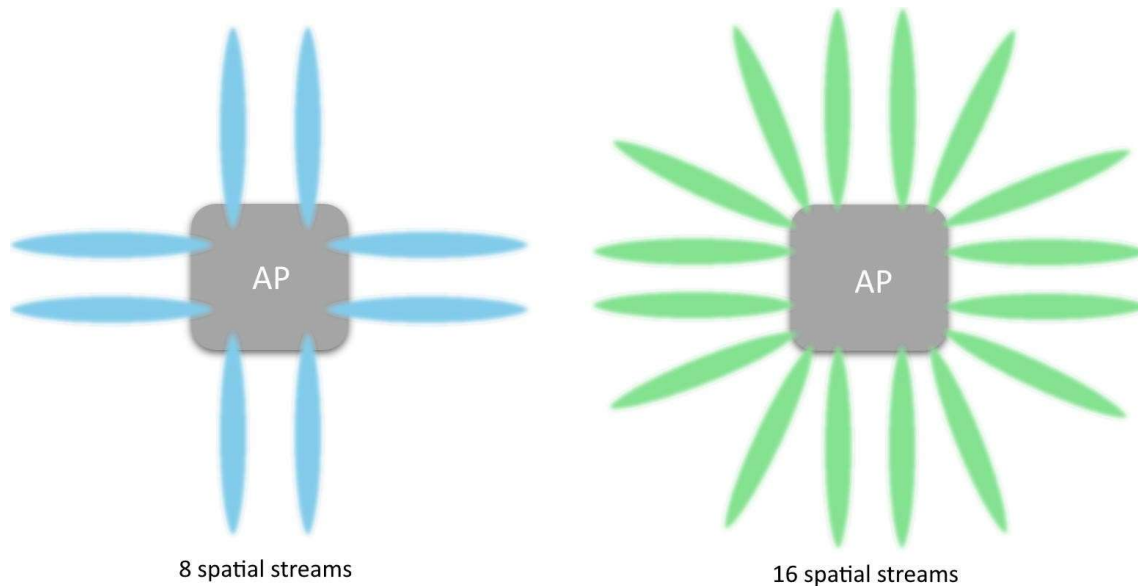
Figure 1 Wi-Fi 6 & Wi-Fi 7 Spatial Streams
Source: Author's own work.

4. Wider channel bandwidth (320 MHz)

Let's imagine Wi-Fi channels as roads and data as cars. In this analogy, 80 MHz, 160 MHz, and 320 MHz channels can be likened to different types of roads with 2, 4, or more lanes, respectively. The wider the road (or channel), the more cars (or data) can travel at faster speeds with fewer traffic jams. For instance, an 80 MHz channel is akin to a neighborhood street, able to accommodate a moderate amount of traffic. Moving up to a 160 MHz channel is like having a 4-lane road, allowing for more cars to move simultaneously, thus increasing capacity and speed. In contrast, a 320 MHz channel in Wi-Fi 7 resembles an 8-lane superhighway (tp-link, 2022).
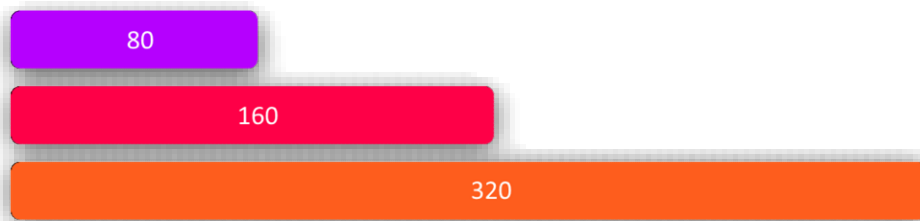

Figure 2 80 MHz, 160 MHz, 320 MHz channels
Source: Author's own work.

As shown in figure 2, this wide channel can handle a significantly larger volume of data transmission at once, facilitating faster speeds and reducing congestion. It provides ample room for multiple devices to communicate simultaneously without slowing down, enhancing overall network efficiency and performance. By extending to the 6 GHz frequency band, it doubles the capacity compared to the 160 MHz channels in the 5 GHz band and thereby doubles the data transmission speed. Therefore, Wi-Fi 7's 320 MHz channel width acts as a crucial upgrade, transforming the network into a high-capacity superhighway capable of supporting intensive data applications with ease, while also optimizing traffic flow and reducing   potential

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bottlenecks. This enhancement marks a substantial advancement in wireless technology, catering to the growing demand for faster and more reliable connectivity in various industrial applications.

5. Multi-Link Operation

Multi-Link Operation (MLO) represents a key innovation that significantly improves the performance, reliability and flexibility of wireless networks, enabling better adaptation to different conditions and user requirements. It is an advanced technology introduced in Wi-Fi 7 that allows devices to use multiple links simultaneously over different channels and frequency bands (Wi-Fi Alliance, 2024). MLO enables devices to establish and maintain multiple simultaneous connections over different frequency bands (2.4 GHz, 5 GHz and 6 GHz). This increases overall throughput and improves connection reliability. In Wi-Fi 6 a device connects either on the 2.4 GHz or the 5 GHz band whilst on Wi-Fi 7 with MLO a device simultaneously connects on all available bands.
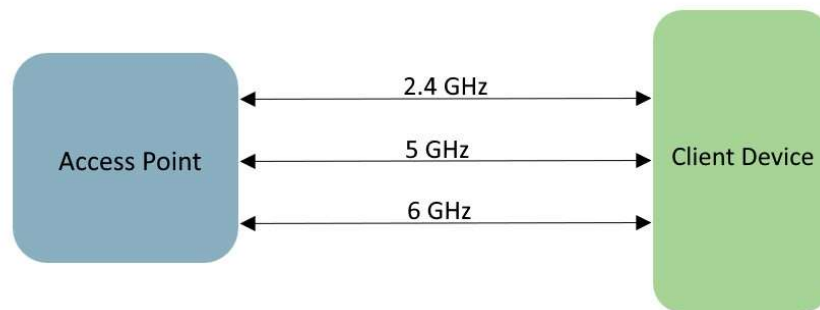

Figure 3 Connecting on all bands simultaneous
Source: Author's own work.

Through load balancing based on traffic demands, MLO assists congested networks in achieving substantially increased throughput, reduced latency and improved reliability. There are several types of MLO modes:

1. Multi-Link Multi-Radio modes: The links are statically assigned and do not have the capability to dynamically switch to other frequencies.
2. Simultaneous Transmit and Receive (STR) mode is utilized when there is ample isolation, enabling links to operate independently without experiencing loss due to Interference Detection and Cancellation (IDC).
3. Enhanced Multi-Link Single Radio (MLSR) modes enable links to dynamically switch to other frequencies. This mode is specifically defined to allow all radios and antennas capable of multi-link operations to dynamically consolidate into a single link as needed. This flexibility enhances network efficiency and adaptability, optimizing performance in varying conditions without compromising on connectivity or throughput.
4. Non-STR (NSTR) mode coordinates synchronous transmission across the band links, ensuring efficient utilization of available spectrum resources.

6. Multi-Resource Units

Multi-Resource Units (MRU) is an advanced mechanism for a more efficient and flexible use of available radio resources. The technology is designed to enhance the performance and adaptability of wireless networks. As shown in figure 4, in Wi-Fi 6 systems, if any part of a large high-speed channel is in use by another device, the entire channel becomes unavailable, necessitating the use of a different channel. This scenario is analogous to a moving truck in legacy Wi-Fi being unable to access a multi-lane highway and needing to find an alternative route because passenger cars occupy one of the lanes (Intel, 2024). However, with Multi-RU Puncturing introduced in Wi-Fi 7, devices will gain the capability to utilize other parts of the same high-speed channel that are not in use.
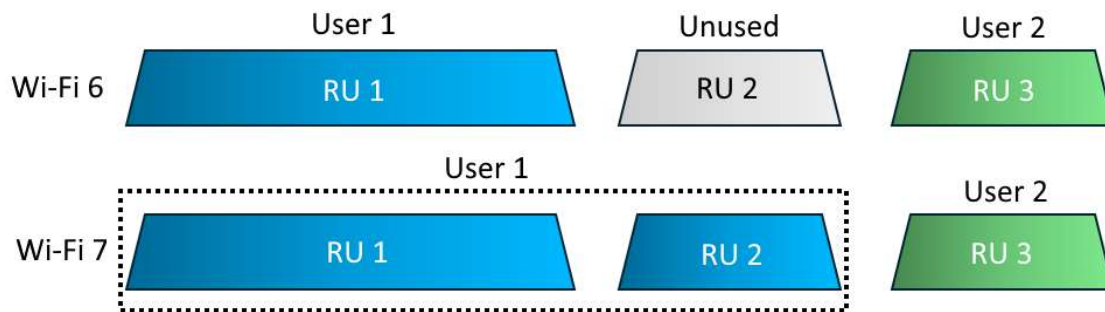

Figure 4 Multi-RU
Source: Author's own work.

This innovation allows for the establishment of very large channels, even if they are smaller than the maximum 320 MHz size. This capability is akin to Wi-Fi 7 movers being able to redistribute most of the contents from a truck into smaller trucks without having to avoid a partially occupied multi-lane highway. As a result, they can deliver boxes to their destination more swiftly and reliably. This advancement in Wi-Fi 7 technology enhances spectrum efficiency by enabling devices to dynamically utilize available portions of high-speed channels, optimizing data transmission and network performance. It represents a significant improvement over previous Wi-Fi standards, offering greater flexibility and reliability in crowded wireless environments.

7. 4096 Quadrature Amplitude Modulation

4K-QAM is an advanced modulation scheme used in communication systems, including Wi-Fi technologies like Wi-Fi 7, to achieve higher data rates over wireless channels. 4K-QAM allows a carrier waveform to exist in one of 4096 possible discrete and measurable states in a constellation plot, which consists of two orthogonal axes: the in-phase (x axis) and quadrature (y axis) shown in figure 5. Each symbol in a 4K-QAM scheme represents a constellation point consisting of 12 bits, enabling 4096 different combinations. This modulation scheme leverages binary data, with each symbol corresponding to 12 bits ($2^{12} = 4096$). The maximum data rate achievable with 4K-QAM is notably high, reaching up to 575 Mbps over a channel bandwidth of 56 MHz. This modulation scheme is integral to technologies like Wi-Fi 7, which utilize multiple channels, MU-MIMO and other advanced algorithms to further enhance data rates and

network efficiency. Increasing the order of QAM, such as moving from lower-order schemes like 16-QAM or 64-QAM to 4096-QAM, significantly boosts link capacity. For example, transitioning from 1024-QAM to 4096-QAM typically offers an approximately 20% capacity gain (Sbeglia, 2022).
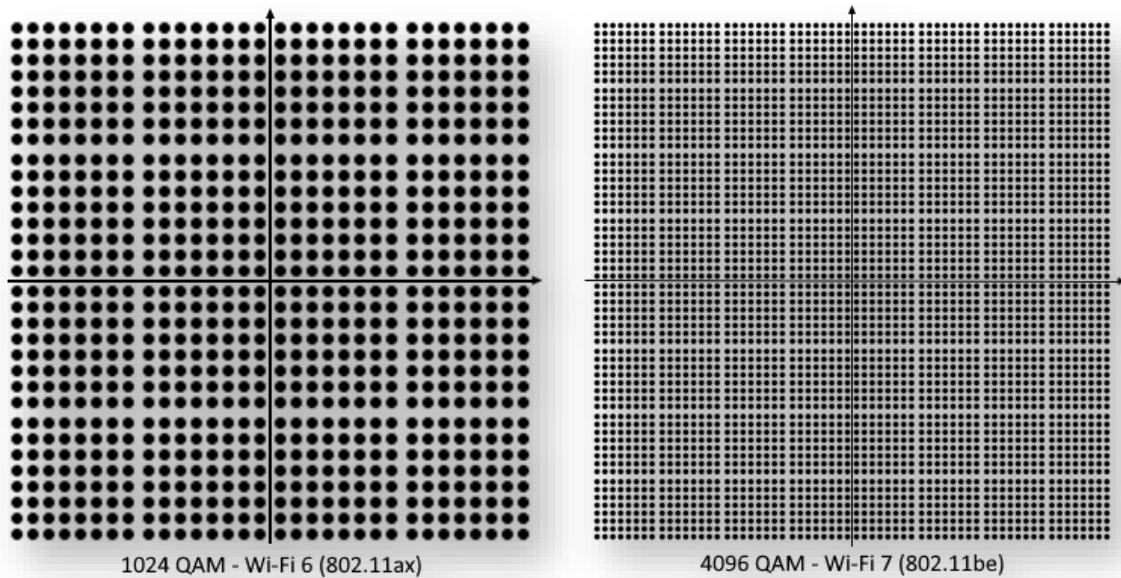

Figure 5 1024 vs 4096 QAM
Source: Author's own work.

However, as QAM complexity increases, incremental capacity gains diminish due to factors like signal-to-noise ratio (SNR) and potential for constellation point overlap in noisy environments. In environments with noise and multipath interference, maintaining signal integrity in 4096-QAM becomes challenging. The closeness of constellation points increases the likelihood of errors, necessitating careful management of transmit power and system linearity to preserve signal quality. Adaptive Coding and Modulation (ACM) techniques are employed to mitigate these challenges, adjusting modulation schemes dynamically based on channel conditions to optimize performance. Wi-Fi 7 is set to adopt 4096-QAM to achieve throughput rates exceeding 30 Gbps with minimal latency. This next-generation Wi-Fi technology integrates 4096-QAM to encode up to 12 bits per symbol per OFDM (Orthogonal Frequency Division Multiplexing) sub-carrier, representing a 20% increase in data rate compared to its predecessors. By leveraging 4096-QAM, Wi-Fi 7 enhances spectral efficiency and overall network performance, catering to the increasing demands for high-speed data transmission in dense and dynamic wireless environments.

8. Potential use in crisis situations

In times of crisis, Wi-Fi 7's advanced capabilities play a pivotal role in maintaining effective communication and operational efficiency. Its ability to support data rates of up to 46 Gbps, significantly surpassing previous standards, becomes crucial for ensuring rapid and reliable data transfer essential for coordinating emergency responses swiftly and efficiently. Features like MU-MIMO enhance network management by enabling simultaneous communication with

multiple devices, ensuring seamless connectivity for emergency personnel and facilitating real-time information sharing without encountering network congestion. Moreover, Wi-Fi 7's utilization of wider channel bandwidths, extending up to 320 MHz, combined with its support for multiple frequency bands (2.4 GHz, 5 GHz, and 6 GHz), enhances coverage and reliability. This capability allows Wi-Fi 7 to provide extended connectivity even in environments where infrastructure may be compromised, thereby ensuring uninterrupted communication across diverse and challenging conditions. Technological innovations such as Multi-Link Operation (MLO) further bolster Wi-Fi 7's resilience by enabling dynamic utilization of available spectrum resources. This flexibility optimizes network performance in response to fluctuating demands and environmental challenges, ensuring consistent connectivity when it is needed most. Wi-Fi 7's integration of advanced modulation schemes like 4096-QAM enhances its capacity to efficiently handle large volumes of data, supporting the seamless transmission of multimedia content, sensor data, and critical medical telemetry during crises. These capabilities are essential for maintaining situational awareness and facilitating timely decision-making processes under challenging circumstances. Continual advancements in features such as Multi-Resource Units (MRU) and adaptive modulation techniques ensure that Wi-Fi 7 remains adaptable to emerging technologies and evolving crisis response needs. This ongoing innovation effectively future-proofs communication infrastructure investments, ensuring compatibility with future technological developments and enhancing overall resilience in crisis management scenarios (IEEE Access. 2018).

9. Conclusion

From its humble beginnings in the late 1990s, Wi-Fi has evolved into an indispensable pillar of modern networking, facilitating seamless wireless connectivity across diverse environments. The journey from IEEE 802.11's modest 2 Mbps speeds on the 2.4 GHz band to the cutting-edge capabilities of Wi-Fi 7 (802.11be) represents a testament to relentless innovation and technological advancement. Wi-Fi 7 stands at the forefront of wireless networking, leveraging advanced Multi-user Multiple-input and Multiple-output (MU-MIMO) technologies, wider 320 MHz channel bandwidths, and pioneering features like Multi-Link Operation (MLO) and Multi Resource Unit (MRU). These advancements not only elevate data transfer speeds to an unprecedented 46 Gbps but also enhance network efficiency, coverage, and reliability across the 2.4 GHz, 5 GHz, and 6 GHz bands. In crisis situations, Wi-Fi 7 emerges as a critical asset, enabling high-speed, resilient communication essential for emergency response coordination. Its robust capabilities, including dynamic spectrum utilization through MLO, ensure uninterrupted connectivity amidst challenging conditions. Features like 4096-QAM modulation further bolster Wi-Fi 7's ability to handle large volumes of data swiftly and reliably, supporting crucial applications such as real-time video feeds and medical telemetry. As Wi-Fi technology continues to evolve, driven by the demands of an increasingly interconnected world, Wi-Fi 7 remains poised to meet future challenges head-on. Its adaptability to emerging technologies and ongoing enhancements in network efficiency underscore its pivotal role in shaping the future of wireless communication, ensuring that connectivity remains a steadfast ally in addressing both everyday needs and unforeseen crises.

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