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WI-FI: THE MOST TRAVELED ROAD TO THE INTERNET

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Wi-Fi is one of the great technology success stories of our time. Based on the IEEE 802.11 wireless communication standard, it has evolved and improved over two decades and is the world's most used wireless technology. It's also still growing, with over 4 billion devices shipping annually and 16 billion devices in use.

In this eBook, you'll find articles on various aspects of Wi-Fi technology:

- How the robustness of Wi-Fi connectivity can help ensure a future-proof IoT network
- The gains made in Wi-Fi 6 vs. Wi-Fi 5 that come from borrowing of 4G LTE techniques
- How Wi-Fi 6E can pose RF security challenges
- A survey of wireless communication standards from 1G cellular to Wi-Fi 6
- The importance of efficient spectrum utilization in coexistence of 5G and Wi-Fi

It's our hope that the information you'll find in these articles will be helpful to you in present and future design projects.

CHAPTER 1:

Good Wi-Fi Connectivity is Essential for IoT Product Success

SACHIN GUPTA, Staff Product Marketing Engineer, www.cypress.com

Factors that make for effective Wi-Fi include ample range, high throughput, low packet error rate, and suitable coexistence—all of which can be enhanced via 802.11ac.

Internet of Things (IoT) momentum is bringing connectivity to devices we never thought would ever be connected. Now you can prepare your coffee without walking to your coffeemaker. You simply send a command to the maker using your phone. It even learns your preferences and prepares your coffee the way you like, every time.

The number of connected devices and users continues to increase rapidly. And that's great! But, for a sustainable IoT infrastructure, it's necessary that an IoT device performs well in every environment. An IoT device that can't connect to the local access point (AP) is useless. System designers need to understand various Wi-Fi parameters such as transmit power, receive sensitivity, coexistence, and throughput while designing an IoT product. This article covers some of the important aspects that are essential for a successful IoT product.

2.4 GHz is a Crowd

Today, the most commonly used wireless technologies used in IoT devices are Wi-Fi and Bluetooth that utilize the 2.4-GHz spectrum. Not only is Wi-Fi implemented by IoT devices, but it's extensively used in every home for televisions, laptops, tablets, and mobile phones. The 2.4-GHz spectrum has become like a conference room where several people are all trying to have a conversation at the same time. For a conversation to be understood, though, only one device can talk at one time.

Now imagine a device that can't communicate efficiently and tries to talk continuously. No one else can talk, so no meaningful conversations can take place anywhere in the room. There's little in the Wi-Fi spec that emphasizes performance and spectrum utilization. With the increasing density of Wi-Fi devices, the Wi-Fi Alliance needs to add stringent requirements for good performance on top of adherence to the protocol to pass the certification process.

IoT device manufacturers need to get over the low-cost-only approach to make sure they're not designing Wi-Fi connected devices that are bad performers and bad neighbors for other Wi-Fi devices. Just one bad device is enough to bring down the customer's entire Wi-Fi network.

For a future-proof IoT network, it's important that system designers use robust Wi-Fi connectivity. It's of the utmost important for companies to understand the consequences of bad design as it directly relates to the product's success and the brand's reputation. An IoT product that's unable to connect to the AP is useless for the customer.

When customers face any issues with connectivity, they are likely to return the product or write a bad online review. These contribute to unsuccessful product and negative impact on brand name. Even with a well-designed product, it is necessary to provide extensive technical support for customers who are new to IoT.

The following are the key symptoms of bad Wi-Fi connectivity:

- Poor range
- Low throughput
- High packet error rate
- Bad coexistence

Poor Range

Poor range limits the distance at which your IoT product can connect to the AP. This is the very first experience your customer has with your product. If it doesn't even connect, in most cases the customer will return the product and slam a bad review. Your IoT product may not be able to connect to the AP at a distance because of low transmit power, poor sensitivity, or lack of transmit beamforming support.

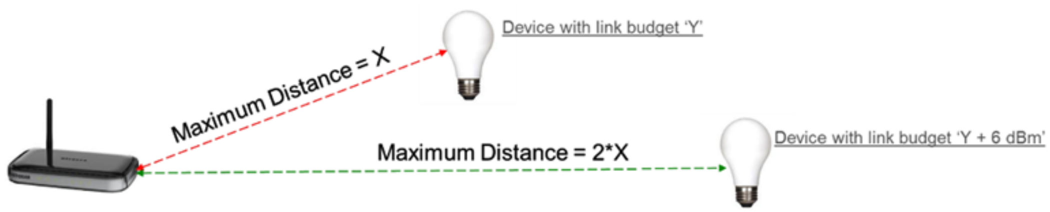
A Wi-Fi link requires two devices to exchange packets to establish a connection. The distance at which a device can connect to the AP is determined by factors listed below.

Transmit power

The transmit power of IoT devices impacts the ability of the AP to hear it. Beyond a certain level, the output of Wi-Fi's power amplifier starts to distort. To deal with this, most Wi-Fi devices limit Tx power. For instance, Cypress' Wi-Fi devices use proprietary methods to deal with this distortion and provide higher Tx power. Another challenge with Tx power is regulatory limitations imposed by different countries. This means that the maximum Tx power needs to be controlled based on the country to avoid regulatory violations. As a result, the Wi-Fi subsystem must provide an easy or automated method to control the transmit power so that the IoT device can transmit at the maximum Tx power level while avoiding any regulatory (FCC, CE, etc.) violations.

Receive sensitivity

Receive sensitivity is the device's capability to hear the AP. Good receive sensitivity in conjunction with good transmit power is the key to good range. Some Wi-Fi devices include algorithms that can process inputs with smaller signal-to-noise ratio than others. Thus, the receive sensitivity specification needs to be considered while selecting a device for an IoT product.



The link budget can have a significant impact on range.

Link budget

Transmit power, receive sensitivity, and environmental factors define the link budget between two Wi-Fi devices. Suppose one device has +3 dBm more Tx power than the other and −3 dBm better sensitivity. This results in a 6-dBm link budget improvement. Every 6-dBm increase in the link budget doubles the range (**see figure**).

Transmit beamforming

Transmit beamforming focuses transmit power in a given direction—it helps increase the range in that direction. For instance, if an IoT device supports transmit beamforming, it can connect to the AP at a longer distance. However, not all Wi-Fi devices support transmit beamforming. Beamforming was first introduced in 802.11n. However, its implementation was left to the vendors. This has made interoperability a challenge. In 802.11ac, this feature was well-defined in WLAN specification and allowed implementations that were interoperable. Considering this fact, 11ac becomes a necessity to increase range without requiring repeaters.

Low Throughput

Low throughput has a severe impact on performance, including:

- Latency: The lower the throughput, the higher the latency. Though most IoT devices require only a few bytes of data to be sent, higher latency can result in a poor user experience. Low latency also means reduced reliability in time-critical applications using sensors such as medical and industrial devices.
- Battery life: If the throughput/modulation index is low, the device takes longer to transmit and, hence, has longer active times. That directly translates into short battery life.
- Poor spectrum utilization: Low throughput increases the airtime needed for communication. This directly results in making the 2.4-GHz spectrum even more congested.

A device's throughput is impacted by several factors such as link budget, modulation index, and spectrum availability. Wi-Fi devices adjust their link data rate to accommodate the link budget. A higher modulation index means higher throughput. Higher modulation index support requires improved signal conditioning. So, some devices perform better at a lower modulation index versus a higher modulation index. Good sensitivity and good Tx power across various modulation and coding schemes translates into a good rate versus range.

For good throughput, it's important to investigate the device's throughput at all supported modulation index and coding schemes. Also, it's important to pick a device that supports a higher modulation index. 802.11ac supports 256-QAM (quadrature amplitude modulation) that enables higher throughput in 802.11ac devices compared to 64-QAM supported by 802.11n.

The number of devices trying to communicate in a given area also directly affects throughput. The more devices, the less time there is for each device to send/receive data. This limits the effective throughput. The problem becomes severe in the 2.4-GHz band, where most legacy Wi-Fi devices are trying to communicate along with other wireless devices such as Bluetooth and Zigbee. So, along with higher modulation index to improve throughput, 802.11ac's support for the less-crowded frequency band—5 GHz—also helps in improving throughput.

High Packet Error Rate

In Wi-Fi, whenever there's a packet error, it needs to be resent. A device with a high packet error rate (PER) causes all devices to perform poorly in the network because it takes longer to transmit a packet successfully. It potentially increases the number of collisions, thus requiring other devices to retransmit as well, which further impacts PER. The table shows the airtime usage based on different PER. It reveals the percentage of airtime per second that will be taken to transmit 1000 bytes of data by 20 nodes transmitting one packet per second.

Packet Error Rate vs. Airtime Usage

Network scenario	Airtime usage				
Wi-Fi Packet Error Rate (PER)	~10%	~30%	~50%	~70%	~90%
Network airtime usage at given PER	9% per second	11.7% per second	16.5% per second	27.3% per second	81% per second
Additional airtime needed compared to 10% PER	-	130%	183%	303%	900%

Looking at the **table**, a device with a 90% error rate takes about 900% of the airtime compared to a device that has 10% PER. High PER also increases the latency; the packet needs to be retransmitted if there's a packet error. It becomes a challenge in time-critical applications. Therefore, it's important to understand the Wi-Fi device's PER before selecting it for an IoT application. 802.11ac can be very useful—it supports the 5-GHz band, which is less congested and results in fewer packet collisions.

Bad Coexistence

IoT devices often require Wi-Fi and Bluetooth wireless technologies to be co-located. The challenge is that they operate in the same frequency band, so if they're not coordinated, they can clobber each other. Bad coexistence means Wi-Fi throughput suffers significantly.

There are several coexistence schemes, and their performance varies significantly. It takes hundreds of man-years to create a coexistence algorithm that makes real-time decisions in granting medium access to Wi-Fi and Bluetooth. RF chains of Wi-Fi and Bluetooth radios must be optimally controlled to minimize the interference and maximize the performance. A good arbiter needs a lot of information from both Wi-Fi and Bluetooth core to implement coexistence.

Some Wi-Fi and Bluetooth combo devices come with integrated coexistence, which allows an arbiter to communicate with the Wi-Fi and Bluetooth cores over a parallel bus. 5-GHz support for Wi-Fi in 802.11n and 802.11ac is very useful in applications that require both Wi-Fi and Bluetooth to operate at the same time. So, in addition to good coexistence mechanism, a device with 5 GHz should be used for the best coexistence.

Good Wi-Fi connectivity is the backbone of a successful IoT product. It's important to select a device that has a good range, high throughput, low PER, and good coexistence support. 802.11ac helps in increasing range by means of transmit beamforming, higher throughput due to improved modulation index, and low PER and coexistence due to support for the less-congested 5-GHz band. Combo devices with proven coexistence can provide significantly better Wi-Fi throughput even in the presence of Bluetooth. All of these factors should be considered when selecting a connectivity solution for an IoT product.

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CHAPTER 2:

What's the Difference Between Wi-Fi 5 and Wi-Fi 6?

JACK BROWNE, Technical Contributor

The enhanced efficiency and capacity of Wi-Fi 6 compared to Wi-Fi 5 promises to support the growing needs of wireless network users.

Wireless local-area networks provide internet access for many users in rapidly growing numbers in homes, offices, factories, and public places. The growth rate is so fast, in fact, that what had been the international standard for wireless networking, IEEE 802.11ac, released in 2014, can no longer keep up. It's now being replaced by a new version of the standard, IEEE 802.11ax. In other words, IEEE 802.11ac is Wi-Fi 5 and IEEE 802.11ax is Wi-Fi 6. The standards are compatible but also different in many ways, with enough disparities to combine for significant improvements in wireless network capacity and efficiency for all users, even in crowded places (**Table 1**).

Wi-Fi 6 improves on the performance of Wi-Fi 5 by borrowing useful techniques from 4G Long Term Evolution (LTE) cellular radio technology, in the hopes that Wi-Fi 6 will provide the increased capacity needed for a growing number of interconnected wireless devices (**Fig. 1**). These range from Internet of Things (IoT) sensors and smarter 5G wireless cellular telephones to even connected cars.

In addition to operating within narrow channel bandwidth at 2.4 GHz along with the 5-GHz spectrum already occupied

TABLE 1: COMPARING WI-FI-5 AND WI-FI 6 STANDARDS

Parameter	Wi-Fi 5 (802.11ac)	Wi-Fi 6 (802.11ax)
Frequency	5 GHz	2.4 and 5.0 GHz
Bandwidths (channels)	20, 40, 80+80, 160 MHz	20, 40, 80+80, 160 MHz
Access	OFDM	OFDMA
Antennas	MU-MIMO (4 × 4)	MU-MIMO (8 × 8)
Modulation	256QAM	1024QAM
Maximum data rate	3.5 Gb/s	9.6 Gb/s
Maximum users/AP	4	8

1. Wi-Fi 6 is a wireless networking standard conceived and developed because of the rapidly growing worldwide reliance on wireless devices. (Courtesy of the Wi-Fi Alliance)

by Wi-Fi 5 at 5 GHz, perhaps the biggest difference between the two Wi-Fi standards is the use of orthogonal frequency-division multiple access (OFDMA) in Wi-Fi 6 compared to orthogonal frequency-division multiplexing (OFDM) in Wi-Fi 5. OFDMA is essentially a multiple-user version of OFDM, making it possible to increase the capacity of a Wi-Fi 6 access point (AP) compared to a Wi-Fi 5 AP.

In both multiplexing formats, a wideband wireless carrier signal at a high data rate is divided into a large set of closely narrowband subcarriers at much lower data rates and then transmitted. To avoid interference between subcarriers, they are orthogonal to each other. The data is divided among all of the subcarriers whereby if any of the subcarriers is degraded or corrupted because of interference, the data can be restored by means of error-correction techniques. At the receiver, the subcarriers with their data contributions are combined to restore the initial high-speed transmission and its full data.

By using the orthogonal, low-data-rate subcarriers rather than the single high-data-rate carrier, the transmissions can minimize the effects of signal fading, multipath distortion, and interference from other signals within the same or nearby frequency spectrum. The low data rates of the subcarriers reduce the effects of intersymbol interference (ISI) that are typically more pronounced at higher data rates.

One drawback to OFDM is that a single user occupies each carrier with all its subcarriers at any one time. Multiple users are possible by means of static multiple-access schemes, such as having different transmission times per carrier/subcarriers for each user in a time-division-multiple-access (TDMA) scheme or different transmission frequencies in a frequency-division-multiple-access (FDMA) approach. However, these methods are not efficient in their use of time and/or frequency.

To develop a more efficient version of Wi-Fi 5, having multiple-user APs was an important consideration for Wi-Fi 6—in OFDMA, a single user does not occupy all of the subcarriers at any one time. For enhanced efficiency, the subcarriers are themselves divided among multiple users. Multiple users can access their assigned subcarriers by means of TDMA or FDMA, or both techniques simultaneously. APs use segments of frequency and time known as resource units (RUs) to manage multiple simultaneous users. Because the subcarriers are subdivided in this way, timing synchronization of the multiple Wi-Fi 6 users for a single AP is critical compared to Wi-Fi 5, adding to the complexity of transmitters, receivers, and APs (**Fig. 2**).

2. Wi-Fi 6 adds capacity by using access points that enable many simultaneous users. (Courtesy of Cisco Systems)

Timing is Everything

Since multiple users will connect to a Wi-Fi 6 AP simultaneously, timing across the different users must be precise to minimize interference among subcarriers. For Wi-Fi 6 wireless networks to achieve the highest capacity, it's essential to minimize interference between simultaneous users.

Synchronization of multiple users is achieved by a trigger frame broadcast by the AP. The trigger frame contains information about when different users and devices can transmit and which subsets of OFDMA subcarriers' RUs to use. The precise timing required among different users and within each AP emphasizes the importance of the reference-clock oscillators within Wi-Fi 6—they must have extremely low phase noise and low jitter with excellent long-term frequency stability.

For environments with obstructions or interference sources, using different subcarriers per user can be programmed by location to avoid the loss of data due to multipath or fading. In contrast to OFDM, in which all subcarriers are transmitted at the same power level, the subcarriers in ODFMA can be broadcast at different power levels. It's an additional weapon against fading that might occur in part of the frequency spectrum in an operating environment. As with OFDM, in OFDMA, each user's multiple low-data-rate subcarriers are combined at the receiver to form the high-speed data that was originally transmitted for access by that user.

An OFDMA AP can change the amount of frequency spectrum or subchannels occupied by each user depending on the demands of their wireless connections. For example, less bandwidth is needed to send an e-mail than to send streaming video to a Wi-Fi receiver. This functionality boosts the efficiency of Wi-Fi 6 compared to Wi-Fi 5, but also increases the complexity of the hardware in terms of frequency alignment, stability, and accuracy, timing synchronization, and response time of wireless-network system components.

Achieving Control of Power

Power control is needed in Wi-Fi 6 systems because of its OFDMA and due to multiple users with simultaneous access to the wireless network. A user close to the AP would present a higher-power signal to the AP than a user operating at the outer sensitivity limits of the AP. If the power levels of multiple users are not balanced, network performance will be compromised by intercarrier interference (ICI) and compression when a Wi-Fi receiver attempts to process multiple signals across a wide dynamic range. Wi-Fi 6 devices will increase or decrease their transmit power levels within a certain response time according to downlink signals from an AP.

This dynamic transmit power control (DTPC) feature of Wi-Fi 6 networks can, of course, be compromised by devices that ignore the power-control instructions in a downlink signal or because they simply lack the power-control capability (as with earlier-generation Wi-Fi devices). The amount of power control and how accurately power is controlled for each device is defined within the Wi-Fi 6 (802.11ax) standard. Devices with tight control of power, within ±3 dB, are considered Class A devices, while devices capable of ±9 dB control of power are referred to as Class B devices, somewhat in the manner of amplifier linearity classes.

Wi-Fi 6 includes several unique features to help boost capacity in dense environments, such as convention centers and other public meeting places, and save power for devices like IoT sensors that may only require occasional network access. Basic service set (BSS) coloring identifies shared frequency spectrum by a number or "color code" included within the network physical-layer (PHY) header that's communicated between each device and its AP. BSS makes it possible for Wi-Fi 6 devices to communicate and negotiate with each other to optimize use of shared channel bandwidth. BSS coloring indicates when a channel is unavailable—when two or more devices are coded by the same color. It also provides information to manage multiple devices and users in congested areas by adjusting clear-channel-assessment (CCA) parameters, including dynamic range and power control.

Another unique feature of Wi-Fi 6—target wake time (TWT)—is a method for an AP to monitor device requirements and turn its Wi-Fi 6 radio on and off as needed. For example, one of the devices within range of a Wi-Fi 6 AP may be an IoT proximity sensor that does not require continuous radio contact with the network. The TWT feature can be used to periodically activate the IoT sensor. In working this way, the TWT function can improve network efficiency and conserve battery life in portable/mobile devices.

For multiple users in dense environments with a great many wireless devices, Wi-Fi 6 builds upon the multiple-user, multiple-input, multiple-output (MU-MIMO) antenna configurations used in Wi-Fi 5, with extended capabilities. Wi-Fi 5 routers, with their multiple antennas, are designed to handle as many as four simultaneous users or data streams. Large data transfers are possible, but only on downlinks from routers or APs to user devices.

In contrast, the MU-MIMO antenna arrangements of Wi-Fi 6 support as many as eight simultaneous spatial data streams for eight simultaneous users, without buffering delays, on both downlinks and uplinks between APs and wireless devices. As a result, Wi-Fi 6 wireless networks can handle large data transfers back and forth between wireless devices and APs without data buffer delays. Therefore, a greater number of users (than Wi-Fi 5) per AP can enjoy even data-intensive applications, such as video streaming, simultaneously.

Using the Bandwidth

Although Wi-Fi capacity and efficiency will be enhanced by OFDMA and MU-MIMO technologies, the number of users that can be supported per channel starts with available spectrum and channel bandwidth. While Wi-Fi 6 shares the frequency spectrum used by Wi-Fi 5 in the 5-GHz band, from 5.170 to 5.185 GHz with some small gaps, it also takes advantage of the legacy available frequency spectrum in the unlicensed 2.400- to 2.483-GHz portion of the industrial, scientific and medical (ISM) bands. With four spectral streams in the 2.4-GHz band and eight more possible in the 5-GHz range, and channel bandwidths of 20, 40, 80, and 160 MHz available (with wider-bandwidth channels supporting higher data rates), many more users can be supported with Wi-Fi 6 than the four spectral streams of Wi-Fi 5.

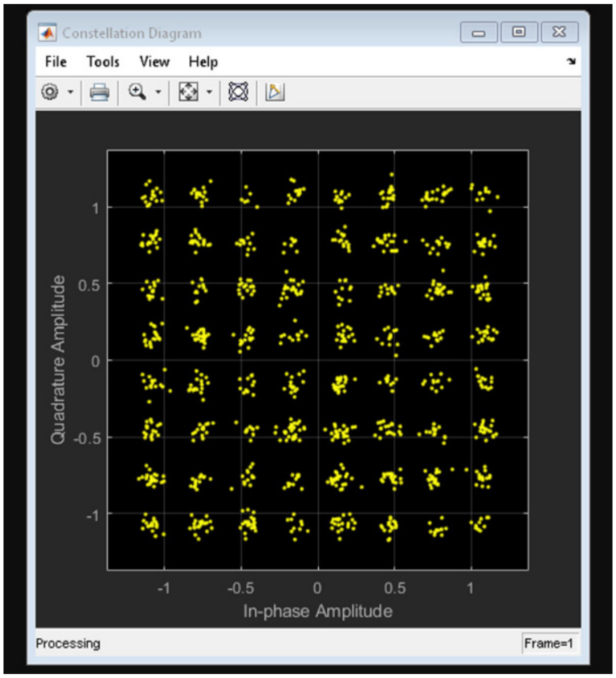
To add to the capacity of Wi-Fi 6, regulatory agencies such as the Federal Communications Commission (FCC) in the U.S. and European Telecommunications Standards Institute (ETSI) throughout Europe have approved the use of wide contiguous bandwidth in the 6-GHz range starting in 2022. The additional bandwidth is for use by Wi-Fi 6 devices and 5G cellular wireless networks, but not by earlier-generation Wi-Fi systems, such as Wi-Fi 4 (IEEE 802.11n) and Wi-Fi 5.

The 6-GHz band approved by the FCC for Wi-Fi 6 spans 1200 MHz from 5.925 to 7.125 GHz and is identified by Unlicensed National Information Infrastructure (UNII) radio-frequency bands 5 through 8 (**Table 2**). This generous portion of contiguous bandwidth at 6 GHz will make possible more wideband (160-MHz) channels for high-data-rate transmissions than at the lower-frequency 2.4- and 5-GHz bands, where the Wi-Fi channels tend to compete with more legacy applications and must operate within more narrowband channels.

TABLE 2: SPECTRUM TO COME FOR WI-FI 6—THE 6-GHz BAND

UNII band	Frequency range (MHz)	Bandwidth (MHz)
5	5925 to 6425	500
6	6425 to 6525	100
7	6525 to 6875	350
8	6875 to 7125	250

To efficiently use the available bandwidth with enhanced data throughput, Wi-Fi 6 employs quadrature-amplitude-modulation (QAM) formats at levels as high as 1024-state QAM (1024QAM). This contrasts with the lower-order 256-state QAM (256QAM) of Wi-Fi 5. 1024QAM enables digital bit resolution of 10 bits per symbol in a constellation diagram (**Fig. 3**), for as much as 25% more data-handling capacity than the 8-bit-per-symbol resolution for 256QAM used with Wi-Fi 5.



3. 1024QAM is one of the features implemented in Wi-Fi 6 for increased data speed and capdacity. This diagram shows a QAM constellation diagram with 64 symbols. (Courtesy of MathWorks)

On the downside, the 1024QAM data mapping that takes place at a Wi-Fi 6 transmitter, to achieve the conversion of digital bits to I/Q symbols, places great demands on the linearity of power amplifiers (PAs) used for transmissions in a 1024QAM system—more so than in

256QAM systems. If power amplification is not linear and the ratio of the energy per bit to the noise level (Eb/N0) is not properly controlled, data errors can be readily introduced into higher-order QAM systems such as 1024QAM.

Evolving to Meet Demand

Whether it's called IEEE 802.11 or Wi-Fi, wireless networks have become an increasingly important part of many lives worldwide, whether in fixed environments such as homes or factories or in large public domains like convention centers, museums, or even in a sporting stadium. Demand for increased capacity and throughput speeds grows as users add more wireless devices to each network and expect faster response times as they download large files or even stream their favorite video programming.

Wi-Fi 6, the former IEEE 802.11ax, builds on the technology legacies of earlier Wi-Fi generations to maintain compatibility with older wireless devices at 2.4 GHz. Simultaneously, it provides increased capacity and enhanced data rates within the 5-GHz channels of newer Wi-Fi generations.

It's a wireless standard that's also poised for evolution, with special features to help save power when networking requirements are minimal or when hordes of new IoT sensors are added in range of a wireless network and must be periodically monitored for their contributions—without "breaking the bank" in power consumption.

And, for the large amounts of new data expected from the next generation of wireless cellular communications systems, namely 5G, Wi-Fi 6 promises something that no earlier Wi-Fi generation can offer: Access for growth into some of the new bandwidth being made available within the 6- to 7-GHz range. If used wisely, this combination of new features and bandwidth should make Wi-Fi 6 a capable companion technology for 5G for many years to come.

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CHAPTER 3:

Wi-Fi 6E is Reshaping RF Security Requirements

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Even as it promises a less-congested Wi-Fi spectrum, the advent of Wi-Fi 6E poses new challenges to RF security professionals. Here's a look at how an SDR-based approach to spectrum analysis can help get the job done.

Fixed and mobile internet usage is growing rapidly as our world depends more on the wireless spectrum, thanks in large part to the great migration to working from home. A May 2020 report found that overall internet traffic grew by more than 40% between February and April, with video streaming accounting for 58% of all traffic.[1] Much of this traffic is being driven away from mobile back to fixed Wi-Fi access points.

The arrival of Wi-Fi 6E will help to alleviate the congestion on existing Wi-Fi networks. In response to the need for greater reliability, access, and performance, the Federal Communications Commission (FCC) voted in April 2020 to open up the 6-GHz band (5.925 to 7.125 GHz) for unlicensed use.[2] Adding more than 1.2 GHz of high-frequency spectrum, the announcement represents the largest addition to Wi-Fi since the original 802.11b standard of the late 1990s and paves the way for the Internet of Things (IoT), virtual and augmented reality (VR/AR), and other high-bandwidth, low-latency applications.

However, the move to the 6- to 7-GHz band and beyond presents a new challenge to RF security and technical surveillance countermeasures (TSCM) professionals. With most previous devices using signals in the 2.4- or 5-GHz bands, spectrum-analysis equipment also was designed to cover up to a maximum of 6 GHz. As a result, many users will need to increase the frequency range of their RF measurement equipment to get a complete view of the spectrum environment in their facility.

This article will introduce the Wi-Fi 6E standard and provide an overview of the new specifications, improvements over previous standards, and potential applications and uses. It will then explore how these new signals will impact RF security professionals before showing how a software-defined approach to spectrum analysis allows for greater performance at a lower cost than traditional hardware.

RF security will always play an important role in corporate offices, government facilities, sensitive compartmented information facilities (SCIFs), and other environments where sensitive information must be protected. By understanding the new standard, security professionals can ensure they have the equipment and performance needed to maintain control of the wireless spectrum.

Understanding Wi-Fi 6E

A recent Cisco report estimates that 5.6 billion people will use the internet by 2023. The number of connected devices is expected to grow from 18.4 billion in 2018 to more than 29 billion by 2023.[3] In addition to this rapid rise in the number of connected devices, high-definition video streams and other high-bandwidth applications have dramatically increased the amount of data flowing at a given time.

Low-latency applications such as gaming, VR/AR, and autonomous vehicles also require high levels of performance and reliability, whereas IoT applications often have wide networks of low-powered sensors all sharing data in real-time.

In response to these changing requirements, the FCC has authorized a new band of spectrum for unlicensed use. This section will explore the differences and benefits of the new Wi-Fi 6E standard and the 6- to 7-GHz band.

How Wi-Fi 6E Differs from Previous Standards

Early Wi-Fi standards, such as 802.11b, were first deployed in the late 1990s. They operated in a tiny sliver of the unlicensed 2.4-GHz ISM band from 2.400 to 2.495 GHz. With a narrow range and overlapping channels, the ISM band eventually became too crowded to cope with the increasing density of devices and growing bandwidth requirements.[4]

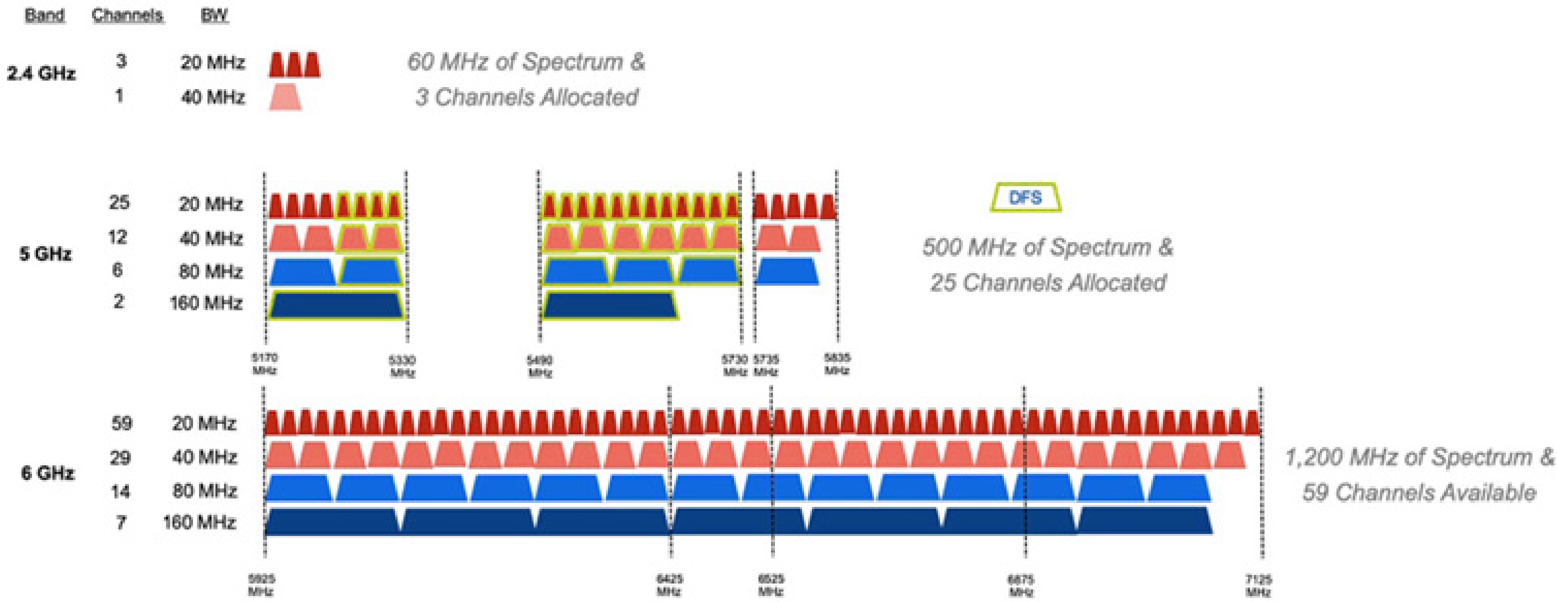
Though the first 5-GHz standards go back to the same period, widespread use became more common with the introduction of 802.11n, known today as Wi-Fi 4.[5] Operating from 5.170 to 5.835 GHz, this higher-frequency standard reduced the strain on the overcrowded 2.4-GHz band and improved speed, reliability, capacity, and bandwidth. Further performance improvements were realized as technology advanced and new standards were launched, specifically 802.11ac (Wi-Fi 5) in 2013 and the more recent 802.11ax (Wi-Fi 6) in 2018.

With its approval from the FCC, Wi-Fi 6E represents one of the largest and most significant additions to Wi-Fi in its history. It has the potential to dramatically boost speed, bandwidth, capacity, and reliability while reducing congestion, latency, and power requirements. Put simply, it will increase the amount of spectrum available for routers and other devices by nearly a factor of five, resulting in more bandwidth and less interference.[6]

The biggest and more important change for RF security professionals is that Wi-Fi 6E will use the 6- to 7-GHz band ranging from 5.925 to 7.125 GHz. Previously used to support utilities, public safety, and wireless backhaul, unlicensed devices will now be allowed to share this spectrum through a regulatory framework that protects existing users while allowing for more efficient use of the wireless spectrum.

Wi-Fi 6E will support 14 additional non-overlapping 80-MHz channels and 7 non-overlapping 160-MHz channels, a dramatic improvement from the 20-MHz non-overlapping channels currently available in Wi-Fi 5 (**Fig. 1**). Combined with advanced channel-allocation technology, this will greatly reduce congestion and interference for users in high-density environments such as office buildings, apartment complexes, or large public venues.

In addition, Wi-Fi 6E will dramatically improve speed and latency. One industry report suggested that the average fixed-broadband download speed would increase to 280 Mb/s



1. Wi-Fi 6E supports 14 non-overlapping 80-MHz channels and seven non-overlapping 160-MHz channels, a significant improvement over previous 2.4- and 5-GHz standards.

by 2022, more than double the current U.S. average of 137 Mb/s.[7] Tests have demonstrated latency levels as low as 2 to 5 ms.[8]

Of course, the tradeoff when dealing with higher-frequency signals is a decrease in propagation and range. Compared to 2.4- and 5-GHz signals, 6-GHz signals will travel shorter distances and be more susceptible to physical barriers such as buildings, walls, trees, and other obstacles. In larger spaces, multiple access points will be required to ensure coverage and maintain reliability.

Finally, Wi-Fi 6E will only be accessible to new devices that support the standard and will have no backward compatibility. Early entrants should encounter a nearly clear playing field, away from the congestion and interference of the 2.4- and 5-GHz bands.

With so many advantages and the potential for substantial performance improvements, it's no surprise that Wi-Fi 6E devices are expected to become prevalent in 2021. One IDC research director estimates there will be more than 338 million devices entering the market by the end of the year, and nearly 20% of all Wi-Fi 6 device shipments will support the 6-GHz band by 2022.[9]

The resulting increase in broadband speeds, combined with the accelerated deployment of IoT and other advanced technologies, is expected to generate more than US$180 billion in revenue over the next five years.[10] So how does this affect RF security, and how will equipment requirements shift as new Wi-Fi 6E-enabled devices enter the market?

The Changing Nature of RF Security

RF security has evolved over the years as devices, hackers, and covert surveillance products became more sophisticated. For as long as there has been sensitive information, surveillance, and countersurveillance, operators have found new ways to evade and outsmart the other.

The widespread proliferation of low-cost, easy-to-use, and powerful wireless communications technology has made it relatively simple for governments, rival corporations, or even individuals to deploy surveillance devices, transmit sensitive information, and disrupt the wireless signal environment.

The following section shows how the new Wi-Fi 6E standard will change performance requirements for spectrum-analysis equipment used for TSCM and RF security applications.

What the New Standards Mean for Spectrum-Analysis Hardware

As mentioned earlier, the new standard operates in the range of 5.925 to 7.125 GHz, significantly higher than previous standards. Until now, most users were only concerned with signals below 6 GHz. Spectrum-analysis equipment, in turn, also was limited to these ranges. The result is that most existing TSCM and spectrum-analysis hardware deployed and used in the field today will be unable to detect and analyze these new 6- to 7-GHz signals.

This is an obvious issue for RF security professionals because they will basically be blind to these new devices, which presents a serious security vulnerability. It not only limits how users can detect and remove unauthorized devices, but it also prevents them from getting a complete view of the signal environment in their facility.

A second challenge is the width of the new band and channels. With 1.2 GHz of spectrum divided into 80/160-MHz channels, equipment with low instantaneous bandwidth (IBW) and sweep rates may miss out on sporadic and short-duration signals of interest.

Finally, as the requirements for TSCM and RF security rise in complexity and operators become more sophisticated, traditional sweeping techniques must be augmented with continuous, 24/7 coverage. Modern surveillance devices can store information and transmit it in short bursts outside of regular office hours to avoid detection by sweeps. Many also use frequency hopping or low-powered signals to further reduce the likelihood of detection.

Another consideration is that threats to RF security aren't necessarily malicious. For example, an employee may be unsatisfied with the connectivity in their office and decide to bring in a router from home to boost their connection. Similarly, an employee may forget to check their device before entering a SCIF or other restricted facility.

In such cases, the threat to RF security is the result of an honest mistake or accident rather than an intentional event. Continuous monitoring of the facility would allow security professionals to detect the transmitter and then take steps to remove or secure the device.

A Continuous, Software-Defined Approach to RF Security Applications

With much of the existing equipment currently deployed in the field unable to detect and analyze signals in the 6- to 7-GHz band, RF security and TSCM professionals will need to upgrade their capabilities. The question then becomes: What is needed to get the best coverage and ensure effective monitoring of the wireless spectrum?

Traditional, hardware-based spectrum-analysis equipment does provide the frequency range and bandwidth required for Wi-Fi 6E devices, but they are otherwise poorly suited for TSCM and security applications. Large, complex, and expensive, these solutions are designed for lab or manufacturing environments that require extremely high performance. On the other hand, existing handheld and low-cost analyzers do not generally cover the frequency ranges and bandwidths needed. Instead, users should consider the benefits of a software-defined approach to spectrum monitoring.

Real-Time Spectrum Analyzers and Surveillance Systems

In a software-defined spectrum analyzer, the software runs over a hardware layer. The hardware components tend to perform only the RF-to-digital conversion, allowing a standard PC or laptop to provide the necessary computing power.

2. The Surveillance System developed by thinkRF includes real-time spectrum analyzers, a laptop, IP networks for multi-sensor deployments, Kestrel’s TSCM Professional Software, omnidirectional antennas, and a carrying case for field deployments.

An example of such an instrument is thinkRF's R5550-408 real-time spectrum analyzer, which provides a frequency range of 9 kHz to 8 GHz, 100 MHz of IBW, and a 28-GHz/s sweep rate. It enables users to monitor, detect, and analyze W-Fi 6E signals. It can be used either as an RF analyzer or as an RF downconverter for existing equipment.

This type of instrument can be integrated with specialized TSCM software such as Kestrel TSCM Professional Software from the Professional Development TSCM Group (PDTG). When combined with directional antennas and other equipment, users gain a complete surveillance system that allows them to conduct full-spectrum scans up to 8 GHz without additional upgrades (**Fig. 2**). Users can distinguish between friendly and unauthorized signals, demodulate the signal if required, and locate the source for removal.

Networked for remote deployment, multiple units can be deployed throughout a facility for continuous, 24/7 coverage. Information from static and roaming units is able to be sent to a centralized location for analysis, while real-time alerts and triggers can be configured to notify security professionals of an unauthorized or unknown signal. Users also can create a signal library, record data for post analysis, and generate reports.

This approach offers numerous benefits when used in addition to regular sweeps by TSCM professionals. Not only does it provide greater coverage, but it also ensures that users maintain a full view of the spectrum environment and can identify unknown signals from new Wi-Fi 6E-enabled devices operating above 6 GHz.

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CHAPTER 4:

The Wireless Standard Shuffle from 1G to Wi-Fi 6

JACK BROWNE, Technical Contributor

Wireless standards set the guidelines and limits for equipment manufacturers seeking to comply with the requirements of the latest wireless-communications networks.

Much is being written and imagined about the many capabilities of future wireless-communications systems and reaching into higher frequency ranges. But current wireless systems are based on well-conceived standards, which have worked for many applications, from simple radio-frequency identification (RFID) tags for tracking goods in warehouses to more elaborate 4G Long Term Evolution (4G LTE) cellular wireless systems. 5G cellular technology may be coming, but existing standards define quite a bit of wireless-communications technology that already works quite well.

Wireless standards organize radio waves into separate spaces, from the shortest-distance personal area networks (PANs) to longer-distance satellite-communications (satcom) systems, so that those radio waves coexist with minimal interference. Scientific organizations like the IEEE and the International Telecommunications Union (ITU) develop wireless standards for different technologies and applications, for compatibility and efficiency.

Many different working groups may exist within one organization. These include the many IEEE 802.11 wireless local-area-network (WLAN) working groups for different forms of short-range WLAN communications systems, including at mmWave frequencies (the IEEE 802.11ad working group).

The IEEE's working groups lend tremendous support to the continuing development of wireless standards for many different applications. For example, the IEEE 802.11 working group is focused on the enhancement of WLAN technologies and systems, while the IEEE 802.15 working group is devoted to wireless specialty networks. Standards developed by this latter working group include IEEE 802.15.4-2015 for low-power, low-data-rate WPANs and IEEE 802.15.3e.2017 for high-data-rate, multimedia wireless networks, including close-proximity point-to-point communications. For higher frequencies, IEEE 802.15.3c-2009 defines wireless networks capable of data rates in excess of 5 Gb/s using the 60-GHz band.

In many cases, wireless-communications standards are managed by industry groups or forums, such as Bluetooth short-range wireless devices from 2.400 to 2.485 GHz. Initially developed as part of an IEEE standard (IEEE 802.15.1), it's managed by the Bluetooth Special Interest Group (SIG), which boasts more than 30,000 companies as members. Bluetooth is among the most popular short-range wireless standards, replacing cables in many applications.

Similarly, Worldwide Interoperability for Microwave Access (WiMAX) is a family of wireless standards developed by the WiMAX Forum. Based on IEEE 802.16 wide-area-network (WAN) communications standards, WiMAX is one of the most popular wireless WAN standards for various "last-mile" wireless applications, including wireless sensor networks.

By now, all wireless standards are digital, and a common trend is for higher data rates for fixed or mobile communications in whatever bandwidth is available. This need of bandwidth in support of higher data rates has pushed operating frequencies higher, where bandwidths are available. Wireless cellular systems provide a good example of this trend, moving from the sub-1-GHz frequencies of the first-generation analog advanced mobile phone service (AMPS) wireless systems to the multiple-frequency bands of 5G cellular wireless networks, including at millimeter-wave (mmWave) frequencies.

Wireless Evolution

Early wireless standards such as AMPS were relatively inefficient in their use of bandwidth, employing 30-kHz-wide channels in the 800-MHz band. One of the first wireless mobile telephone standards, the Nordic Mobile Telephone (NMT) service developed for Norway, Sweden, and Denmark, made use of two different frequency bands in its 450-MHz NMT-450 and 900-MHz NMT-900 variants. Many industry and standards organizations have grown throughout the years in support of different wireless cellular telephone standards, such as the Third Generation Partnership Project (3GPP) and its work in aiding the growth of 3G and 4G wireless telephone standards.

Early mobile cellular telephones used analog transmission techniques in 1G systems, switching to digital switching in the following generation. (Courtesy of Wikipedia)

As the number of carriers and subscribers expanded, the need for bandwidth would increase. This, in turn, required enhancements in modulation, multiple-access schemes, and digital switching in subsequent generations of cellular communications standards through current 4G Long Term Evolution Advanced (LTE-A) systems. The steady rise to the now billions of worldwide wireless mobile telephone subscribers has led to the somewhat accelerated development of high-speed, high-frequency 5G wireless systems.

Advances in mobile wireless telephone hardware have followed the evolution of cellular standards and their base stations, from large and power-hungry to much smaller, more energy-efficient units with increased computer processing power. Early briefcase-sized mobile telephones (**see figure**) were designed more for use in automobiles than to be

TABLE 1: COMPARING CELLULAR RADIO STANDARDS		
Generation	Technologies	Data rates
1G	AMPS, NMT, TACS	2.4 to 14.4 kb/s
2G	GSM, cdmaOne	14.4 kb/s
2.5G	GPRS, EDGE, DECT	144 kb/s
3G	W-CDMA, TD-CDMA, UMTS, 3GPP	3 Mb/s
4G	LTE LTE Advanced	100 Mb/s 300 Mb/s

carried, and the aggressive power consumption led to extremely short battery recharge cycles.

Those early wireless-communications devices have evolved along with the wireless standards and networks, to the current, microprocessor-managed "smart" wireless systems that double as memory banks and portable computers for many users. A brief comparison of cellular telephone standards shows how data rates have increased even as the size of mobile telephones continues to shrink (**Table 1**). The most drastic development when moving to the second generation was the change from analog to digital transmission/reception techniques, which also gave rise to the availability of the short-message-service (SMS) function in 2G cellular systems.

The transition from 1G AMPS to 2G cellular systems became known for its change from analog to digital transmission protocols, including code-division multiple access (CDMA) and Global System for Mobile Communications (GSM), a time-division multiple-access (TDMA) scheme in which radio transmissions are broken into different time slots. Techniques such as TDMA and frequency-division multiple access (FDMA) in 2G cellular standards sought more-efficient use of spectrum than in analog AMPS systems.

Searching for Spectrum

Bandwidth is a precious commodity for any wireless network and available bandwidth tends to be fragmented. Thus, many wireless carriers wind up with "collections" of frequency spectrum that's scattered depending on geography.

The fragmented radio spectrum and continuing quest for higher data rates in wireless standards has encouraged the development of innovative transmission protocols over the years, such as FDMA and TDMA. In addition, wireless network infrastructure has made use of novel design approaches. For example, multiple-input, multiple-output (MIMO) antenna architectures enable the use of beamforming techniques to achieve signal connections even in noise environments, serving simultaneous wireless users without sacrificing data rates.

Later cellular communications standards, such as 4G LTE-A, have also made use of carrier aggregation to combine radio channels and create wider effective bandwidths from the bits and pieces of spectrum, even if they are not continuous. Newer cellular standards such as 3G and 4G have incorporated smaller, closely spaced cells as well. Equipped with smart signal switching, they compensate for growing demands for faster data communications even with limited frequency spectrum resources.

As part of the development of worldwide 5G wireless standards, the IEEE 5G Initiative is

TABLE 2: A BRIEF LOOK AT WLAN STANDARDS			
Standard	Data rate (Mb/s)	Frequency (GHz)	Approximate range (distance from router, ft)
802.11a	54	5.0	50
802.11b	11	2.4	150
802.11g	54	2.4	50
802.11n	300	2.4/5.0	175

compiling a massive database related to 5G technology and applicable standards that will be available via internet access at the IEEE website. In addition, the organization is inviting online feedback at www.5gandbeyonddb@ieee.org for those wishing to contribute to the development of 5G wireless standards.

Wireless standards differ in terms of communications distance and power, from far-reaching cell- and satellite-based systems to lower-power wireless standards such as single-building WLANs. The IEEE's set of 802.11 WLAN standards are probably the world's most widely followed wireless computer networking guidelines. They're supported by additional nonprofit organizations such as the Wi-Fi Alliance, which helps certify the compliance of new electronic products to IEEE 802.11 standards.

The latest generation of consumer and commercial Wi-Fi products claimed to meet IEEE 802.11ax requirements have been branded as Wi-Fi 6—the sixth generation of Wi-Fi (**Table 2**). Prior to Wi-Fi 6, previous generations of Wi-Fi technology have been Wi-Fi 5, which embodied IEEE 802.11ac technology, and Wi-Fi 4, aided by IEEE 802.11n technology.

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CHAPTER 5:

5-GHz Wi-Fi Coexistence with 5G Cellular Improves the User Experience

ANAND RAGHAVAN, JUSTIN LEE, TANUJ KHURANA, JIN CHO

Combined with 5G's high speeds, efficient use of both Wi-Fi and 5G spectrums could offer substantially increased data rates with negligible latency. Wi-Fi thus must remain an integral part of smartphones, complementing 5G to optimize user experience.

The ever-increasing demand for higher data rates and reduced buffering times continues to drive the evolution of cellular communication and transmission. 5G promises to take performance to levels never seen before, with mounting pressure to deploy 5G handsets faster than any previous cellular standard.

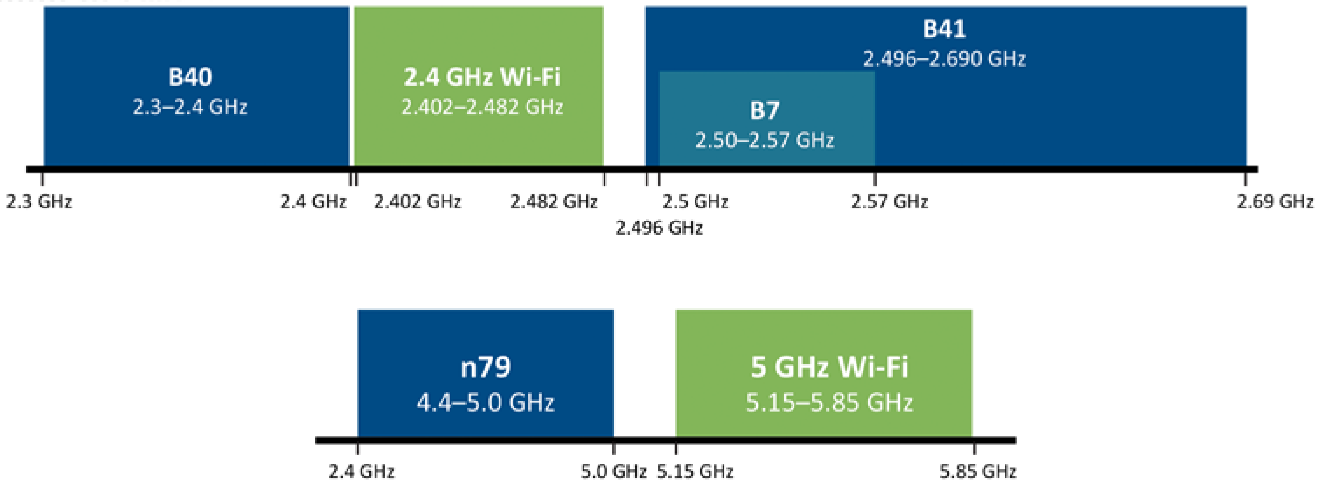
With this urgency to release 5G smartphones, potential Wi-Fi coexistence issues have largely been ignored, even though Wi-Fi and 5G cellular are complementary technologies. Effective coexistence of the two technologies would greatly enhance the end-user experience. In fact, Wi-Fi data usage can reach as high as 92% of total smartphone data usage according to various analytics reports.

Furthermore, the 5-GHz Wi-Fi channel (802.11a/n/ac/ax) is being widely implemented in user equipment (UE) across the world, offering additional range beyond the traditional 2.4-GHz spectrum. Combined with the high speeds available in 5G, the efficient utilization of both Wi-Fi and 5G spectrums has the potential to offer substantially increased data rates with negligible latency. Therefore, it's important that Wi-Fi remain an integral part of smartphones and complement 5G to provide the optimal user experience.

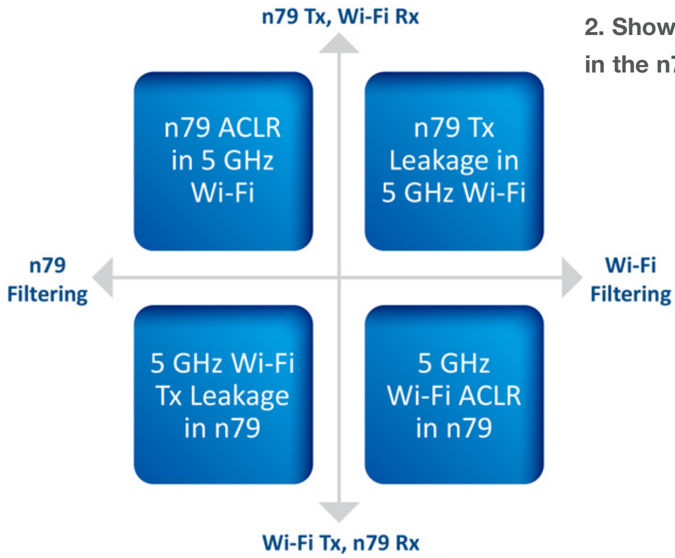
Interference Issues

Due to the proximity of cellular and Wi-Fi channels in 2.4- and 5-GHz spectrums, utilizing both Wi-Fi and New Radio (NR) spectrums can cause interference during operation. The 2.4-GHz Wi-Fi channel is adjacent to the n41, n40, and n7 spectrum, while the n79 band is adjacent to the 5-GHz Wi-Fi channel (**Fig. 1**).

This poses serious interference threats due to transmit (Tx) leakage and adjacent channel



1. The 2.4-GHz Wi-Fi channel is adjacent to the n41, n40, and n7 spectrum, while the n79 band is adjacent to the 5-GHz Wi-Fi channel.

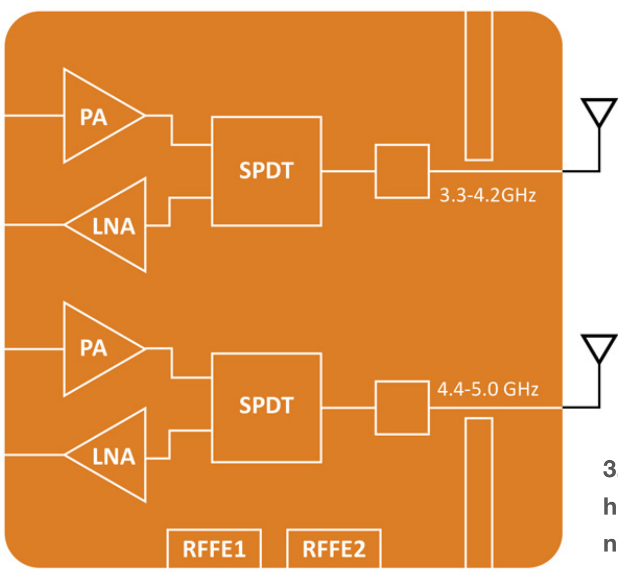


2. Shown is a simple illustration of interferences in the n79 and Wi-Fi coexistence cases.

leakage ratio (ACLR) in respective bands, which can greatly impact data rates if appropriate filtering isn't used. In addition, there is the potential risk of hardware damage due to high power signals reaching receive (Rx) paths. **Figure 2** shows a simple illustration of interferences in the n79 and Wi-Fi coexistence cases.

To date, neither carriers nor OEMs have required n79 coexistence with 5-GHz Wi-Fi channels. Therefore, current RF front-end (RFFE) implementations don't take this into account. A significant desensitization (desense) in 5-GHz Wi-Fi channels may result if no additional measures are taken.

For example, Skyworks' SKY58255 module (**Fig. 3**) is an ultra-high band Tx/Rx module supporting bands n77 to n79. This module is currently being designed into multiple



3. Skyworks' SKY58255 module is an ultra-high band Tx/Rx module supporting bands n77 to n79.

Table 1: Current n79 LPAMID/DRX rejection without use of external high rejection filtering

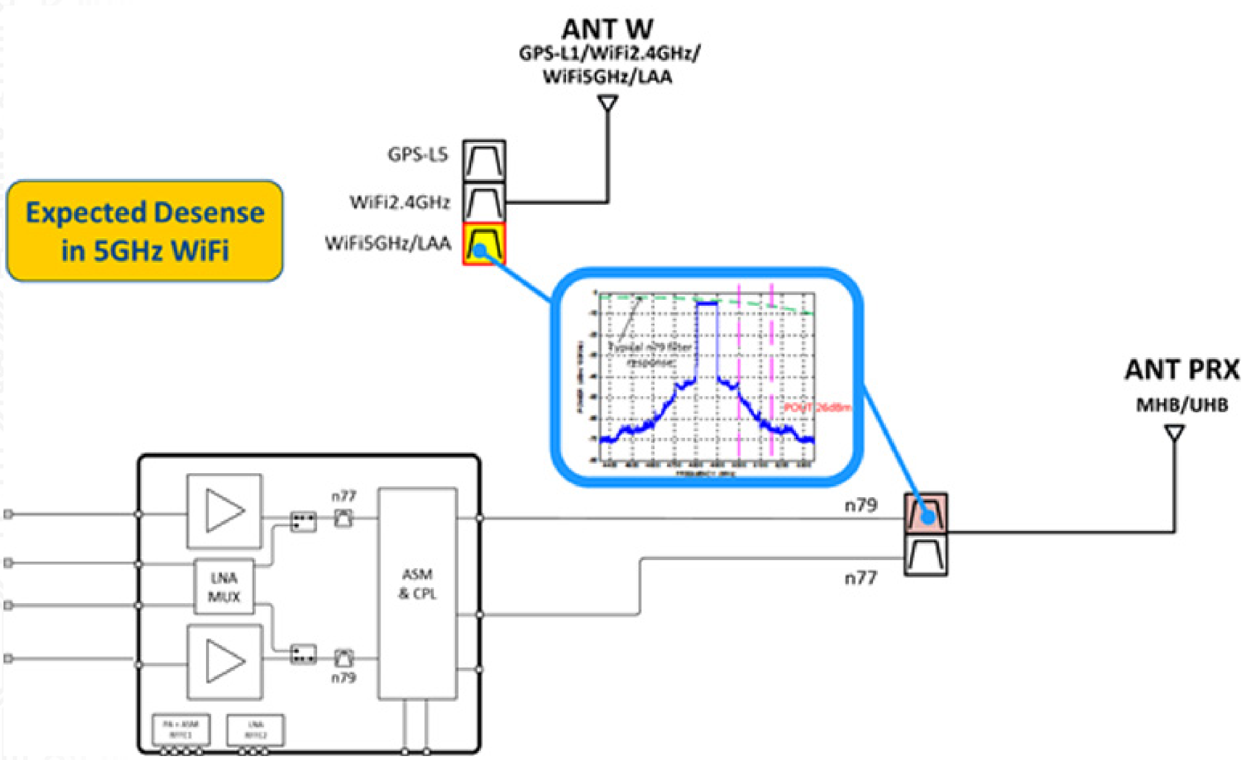
Rejection / Freq. (MHz)	5150	5350	5550	5750	5850
5 GHz Wi-Fi Rejection from LPAMiF	-2	-3.2	-5.3	-8.2	-9.9
Expected Desense in 5 GHz Wi-Fi	36.4	30.5	18.8	13.7	11.6

phones in China and other markets. Because n79 with 5 GHz Wi-Fi isn't considered a design target, this module is optimized for best-in-class insertion loss and noise figure, which may result in less-than-ideal Wi-Fi coexistence performance (**Table 1**).

The use of external high-rejection filters and antennaplexers (**Fig. 4**) can help remedy this issue. With rejection up to 25 to 35 dB, utilizing one of Skyworks' antennaplexers can greatly improve the desense and enable the end-user device to achieve the coexistence needed for proper utilization of both spectrums. **Table 2** demonstrates the enhancement.

Hardware Filtering

While some techniques are available to help improve coexistence performance, the use of hardware filtering for coexistence can offer multiple advantages, including higher throughput, which translates directly into faster data rates. Hardware filtering is also



4. Antennaplexers, such as those offered by Skyworks, deliver improved coexistence.

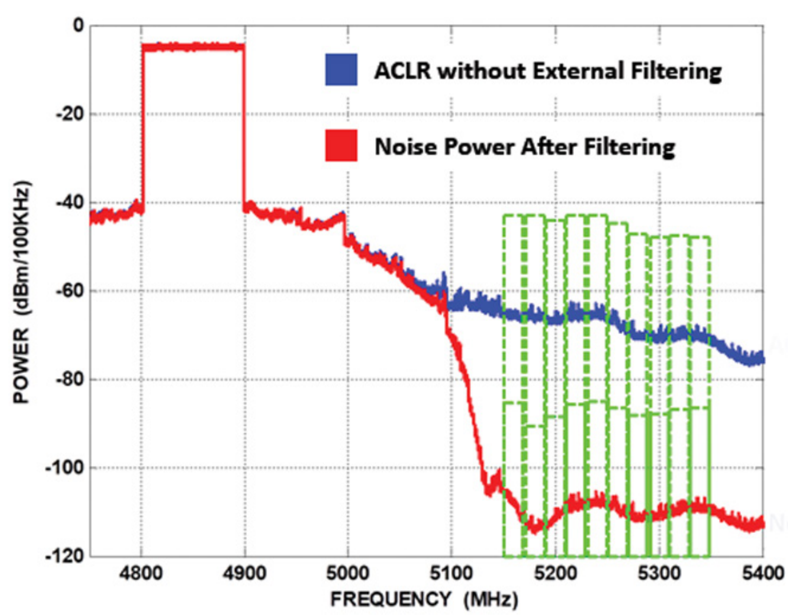
Table 2: Improved Desense Performance with Skyworks' Antennaplexers

Rejection / Freq. (MHz)	5150	5350	5550	5750	5850
Wi-Fi 5 rejection from LPAMiF n79 Tx	-2.1	-3.2	-5.3	-8.2	-9.9
Rejection with High Rejection AntennaPlexer	-22	-22.2	-23.5	-30.8	-25.8
Combined Rejection	-24.1	-25.4	-28.8	-39	-35.7
Expected Desense in Wi-Fi 5 with Combined Rejection	14.6	8.9	1.3	0.1	0.2

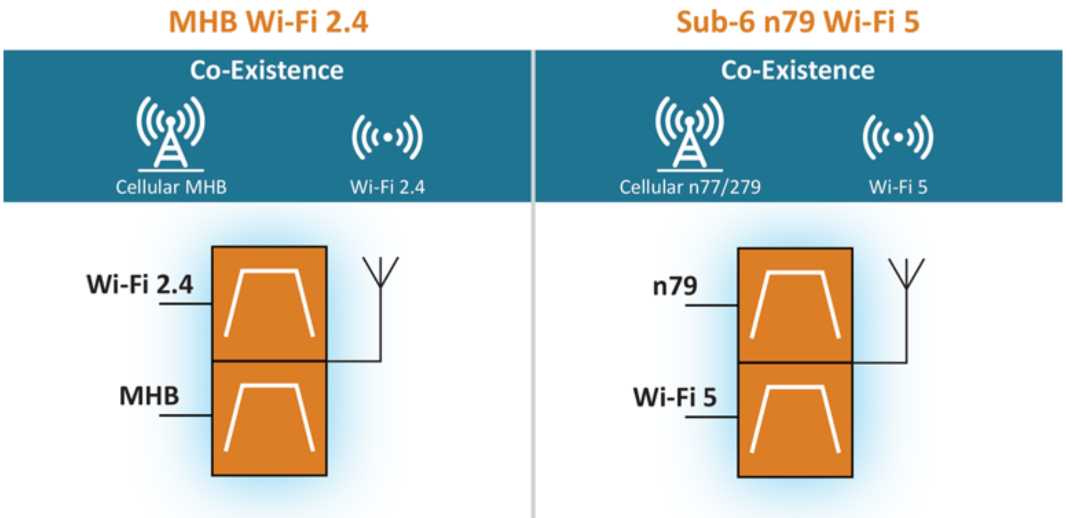
platform-agnostic, offering OEMs the flexibility to use the transceiver platform of their choice. In addition, it removes any restriction on Wi-Fi and the end-user benefits from hotspot or external-AP modes. Most importantly, hardware filtering is future-proof, so any additional band combinations would not affect the filtering, particularly as 5G continues to evolve and new bands are allocated.

An example of hardware filtering can be found in Skyworks' n77 to n79 antennaplexer, which offers rejection of greater than 25 dB with low insertion loss and enables coexistence between Wi-Fi and n79 frequencies (**Fig. 5**).

A similar concept can be extended to the mid-high band 2.4-GHz Wi-Fi filtering to enable n7 and n41 to 2.4-GHz Wi-Fi and n40 to 2.4-GHz Wi-Fi n79 coexistence (**Fig. 6**). External implementation of the filter also allows flexibility in some SKUs where certain bands may



5. This plot demonstrates high-rejection filtering with an n77/79 antennaplexer (not to scale).



6. Antennaplexers enable happy coexistence for 2.4-GHz Wi-Fi and 5-GHz Wi-Fi.

not be required.

In addition, potential application scenarios exist in NR/LAN interworking and NR/WLAN dual connectivity, which have been discussed in 3GPP as a working item. Having a hardware-based solution will enable UE to take advantage of this advanced capability.

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