Wi-Fi 7
In Depth

Your guide to mastering Wi-Fi 7, the 802.11be protocol, and their deployment

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General Power Rules

802.11 operations in the 6 GHz band come with interesting new power rules. In the 2.4 GHz and 5 GHz bands, the rules about maximum allowed power are built on the concept of effective isotropic radiated power (EIRP), a measure of the total quantity of energy radiated by the antenna of the transmitter (non-AP STA or AP STA). The maximum EIRP is fixed for 2.4 GHz and each sub-band of 5 GHz. This limitation means that an 802.11 STA transmitting a signal over an 80 MHz channel cannot transmit more energy overall than the same STA transmitting over a 20 MHz channel in the same band. As a result of this rule, the energy transmitted over each megahertz of a 80 MHz transmission is lower than the energy transmitted over each megahertz of a 20 MHz transmission. This idea might sound strange, but it is similar to the idea of the output of a water hose. Suppose your hose is allowed to deliver 1.5 liters of water per second. It will spray less water per unit of surface (square inches or square centimeters) if you spread the jet over a 5-meter-wide circular area than if you focus the jet, power-washer style, over a small (e.g., 1 square centimeter or 0.5 square inch) surface.

A consequence of the EIRP rule is that the functional area of an 80 MHz BSS is smaller than that of a 20 MHz BSS. In both cases, the beacons are transmitted over 20 MHz, so they can be transmitted at similar power and reach the same area. However, an 80 MHz data frame will contain less energy per megahertz than a 20 MHz data frame, with the consequence that the 20 MHz frame can still be properly received and decoded at a distance from the transmitter where the 80 MHz frame is no longer understandable. Another way to express this phenomenon is to note that the signal-to-noise (SNR) ratio over each megahertz of frequency decreases as the channel width increases.

This constraint was taken into consideration during the debate over the authorization of 802.11 in the 6 GHz band. The regulatory bodies that have authorized operations in the 6 GHz band have so far adopted another method for computing power, the maximum power spectral density (PSD). In this system, the maximum amount of energy that a transmitter can emit is regulated on a per unit of spectrum basis (i.e., per hertz). In the water hose analogy, the regulation would limit the amount of water spread per unit of surface, rather than the total amount of water sent by the hose. Practically, this rule means that a transmitter can send the same amount of energy over each megahertz irrespective of the channel width. As such, the 20 MHz transmission has the same useful range as the 80 MHz transmission. A natural consequence is that the total amount of energy sent over a 80 MHz transmission is larger than the total amount of energy sent over a 20 MHz transmission, at least for a frame of the same duration.

Standard, Low, or Very Low Power

One key factor driving the various 6 GHz adoption decisions of the different regulatory bodies is that the different segments of the band were already used by existing entities (the incumbents). In some cases, these entities had stopped using the band for historical reasons. In other cases, the entities were still actively using the band, and authorizing 802.11 meant ensuring a peaceful coexistence with these incumbents, by regulating the power that 802.11 entities could use.

LPI, VLP, and SP in Outdoor and Indoor Scenarios

The general power rules (based on PSD) apply to all segments of the 6 GHz band, but with different PSD maximums depending on the scenario and the segment of the band. Most regulatory domains distinguish indoor from outdoor scenarios. Most incumbents are outdoor systems, either fixed or mobile point-to-point and point-to-multipoint communication systems. An 802.11 radio operating at low power indoors presents limited interference risks for an outdoor incumbent. Therefore, many regulatory domains allow 802.11 to function with no restrictions indoors, as long as they use a power setting called Low Power Indoor (LPI). In the FCC domain, APs can operate in LPI mode in all four segments: U-NII-5, U-NII-6, U-NII-7, and U-NII-8. The AP must then not exceed 5 dBm/MHz. For a 20 MHz channel, this limit represents an AP set at 18 dBm. With the PSD rule, this limit also represents an AP set to 21 dBm for a 40 MHz channel, 24 dBm for an 80 MHz channel, and 27 dBm for a 160 MHz channel. In addition, the FCC rule clarifies that the AP maximum power in LPI mode is 30 dBm, alluding to the fact that the AP cannot be set to more than 320 MHz without reducing its power per megahertz. The ETSI also recognizes LPI, but allows this mode only in U-NII-5 and U-NII-6, and with a limit of 10 dBm/MHz, resulting in an AP power maximum of 23 dBm for a 20 MHz channel. However, the ETSI also sets 23 dBm as the AP maximum power. Therefore, the AP should also be set at 23 dBm maximum for a 40 MHz, 80 MHz, or 160 MHz channel. Practically, this means that the PSD rule finds its limit in the ETSI domain at 23 dBm EIRP.

Operation in LPI mode is allowed only indoors. Practically, this means that an AP leveraging LPI cannot be weatherized. The AP also cannot have an external antenna, a restriction meant to ensure that the gain of the antenna will not cause the AP to exceed the EIRP limits.

A 20 MHz channel set to 18 dBm (FCC) or 23 dBm (ETSI) in 6 GHz is called “low power,” but keep in mind that the power envelope allowed in 5 GHz depends on the sub-band and can also be seen as “low.” In U-NII-1, the maximum EIRP indoors is also 18 dBm in the FCC domain and 23 dBm in the ETSI domain. Other segments of the band allow for higher power—for example, 30 dBm EIRP in the FCC domain and the ETSI domain with U-NII-2c, with DFS and TPC (dynamic frequency selection and transmit power control, to avoid interference with airport radar systems). Therefore, 6 GHz LPI is not necessarily very “low.” However, the propagation characteristics of the 6 GHz band (compared to the 5 GHz band) may result in a practically usable smaller cell in 6 GHz. (For Wi-Fi 6 and Wi-Fi 7 deployments, see Chapter 8, “Wi-Fi 7 Network Planning.”)

Ultimately, proponents of 802.11 in 6 GHz requested the possibility for higher power, modestly called Standard Power (SP). The FCC granted this request, for operation both indoors and outdoors, but only in U-NII-5 and U-NII 7, and with the conditions detailed in the next section, “AFC Rules.” SP enables the AP to operate at up to 23 dBm/MHz, but with a maximum EIRP of 36 dBm.

As you might expect, if the AP power is regulated, the non-AP STA power is regulated as well. One difficulty is that the non-AP STA cannot know if it is indoors or outdoors; by contrast, an AP is fixed, and an admin deploying the AP knows if the AP is deployed indoors or outdoors. Therefore, the non-AP STA is always designated as a client *under the control of an access point*. The non-AP STA must contact an AP first, before knowing if it can operate at the SP or LPI level. In both cases, the non-AP STA power limit is 6 dB below the AP maximum in the FCC domain, but the same level as the

AP in the ETSI domain. If the AP is not at maximum power in the FCC domain, it might be possible that the STA happens to operate at the same power as the AP. Even if it is at maximum power, the AP typically has highly sensitive antennas. As a result, the 6 dB difference might not cause dramatic asymmetry issues between DL and UL transmissions.

The ETSI has allowed, and the FCC is considering, a Very Low Power (VLP) mode, indoors and outdoors, with a PSD of –8 dBm/MHz and a maximum EIRP, for the AP and the non-AP STA, of 14 dBm. This mode is primarily intended for client-to-client communications (e.g., a smartphone to a smartwatch) or small mobile systems (e.g., a phone acting as an AP to connect a Wi-Fi laptop to the phone cellular network).

Table 3-5 summarizes these various power limits.

TABLE 3-5 6 GHz Power Limits

Mode	Domain	Max Tx Power EIRP		Max PSD EIRP	
		AP (dBm)	Client (dBm)	AP (dBm)	Client (dBm)
SP	FCC	36	30	11	5
LPI	FCC	30	24	5	–1
	ETSI	23	23	10	10
VLP	FCC, ETSI (under consideration)	14	14	–8	–8

AFC Rules

LPI is authorized indoors. Allowing an SP mode triggered a vigorous debate, because the notion of "indoors" itself is always ambiguous. An AP may be deployed indoors, yet close to a window with low RF absorption characteristics. Increasing the power beyond LPI meant increasing the risks that APs would interfere with incumbents, even if the AP is indoors. In the end, there may not be many differences in the interference risk if the AP is indoors (but close to the outdoors, from an RF propagation perspective) or directly outdoors.

Looking at the different segments of the 6 GHz band, the FCC concluded that there would be two key types of incumbents: some static (non-mobile) systems (e.g., person-to-person [P2P] radio links, from public safety dispatch to cell tower backhaul, but also satellite links) in U-NII-5 and U-NII-7 and some mobile systems (e.g., a TV news truck sending feeds back to the main station) in U-NII-6 and U-NII-8. Limiting interferences to mobile systems is very difficult, because these systems can appear anywhere, at any point in time. Therefore, the FCC decided to forbid 802.11 outdoors, as well as indoors operations at power beyond LPI, in U-NII-6 and U-NII-8. In U-NII-5 and U-NII-7, coexistence with non-mobile systems might be possible. Thus, the FCC allowed outdoors and indoors operations at the SP level, but with the conditions that an AP would not radiate energy upward (beyond 21 degrees above the horizon, to avoid disrupting satellite services) and that it would not use SP power on a particular channel before making sure that no incumbent (operating on that channel) would be in range.

The verification process operates through a query to a management system called the Automated Frequency Coordinator (AFC). Any incumbent can register its system, transmitter and receiver locations, frequencies, bandwidths, polarizations, transmitter EIRP, and antenna height, plus the make and model of the antenna and equipment used, with the FCC's Universal Licensing System (ULS). The incumbent is expected to register any new system, or any existing system whose transmission characteristics change. The incumbent must also update the ULS when any equipment is decommissioned.

Private entities can then set up an AFC system, which is a query/response service. An expected business model is that the AFC service will be offered to entities deploying APs for a nominal fee. Then, each time an AP is deployed and is configured to use SP in the 6 GHz band, the AP must first query an AFC, providing the AP location to some level of accuracy agreed upon by the FCC. (Typically, this level is within 100 m of the ground truth, with an uncertainty factor provided either as an ellipse with a specified center point and major and minor axis lengths, a polygon with specified vertices, or a polygon identified by its center and array of vectors.[31]) The AFC can then use this location information, along with the ULS information and the RF propagation models approved by the FCC (described in documents called the *6 GHz Report and Order*[32]), to compute the predicted interference of the AP with any incumbent nearby. The AFC then returns to the AP a list of channels in U-NII-5 and U-NII-7 that the AP can use without causing interference to an incumbent receiver of more than –6 dB, along with the possible EIRPs (from 21 dBm to 36 dBm). The AP must wait for this response before adopting SP in U-NII-5 or U-NII-7.

The AP can then operate normally at SP. The nonmobile systems are not expected to move. However, it is possible that new systems might be deployed, and these incumbents have spectrum access priority over 802.11. Therefore, at least every 24 hours (and each time it reboots), the AP needs to query the AFC again.

This system ensures peaceful coexistence between incumbents and 802.11 systems, while providing 850 MHz (500 MHz in U-NII-5 and 350 MHz in U-NII-7) of the spectrum to 802.11 where SP is allowed. This space represents forty-two 20 MHz channels, but only four 160 MHz channels (see Figure 3-13). In some areas of the FCC domain, it is likely that most channels in U-NII-5 or U-NII-7 will be available all the time, that an AP will operate in SP mode all the time, and that the only reason why an AP would change channels is because of some RRM decision. However, in other areas, such as dense urban environments, or in deployments where wide channels are in use, the number of SP-enabled available channels could potentially be very limited. In this scenario, some APs in a deployment might be allowed to operate at SP level, while neighboring APs on the same floor would be allowed to operate only in LPI mode. In such a case, a design decision needs to be made: allow neighboring APs to operate at 6 dB power differences, or design all BSSs to operate at LPI power level only.

31 See AFC System to AFC Device Interface Specification, www.wi-fi.org/discover-wi-fi/6-ghz-afc-resources.

32 See these FCC documents: FCC 20–51; 35 FCC Rcd 3852 (2020); 85 FR 31390 (May 26, 2020).

6 GHz Discovery and Special Features

Beyond the power complexity, a great advantage of the 6 GHz band for 802.11 is that it constitutes a greenfield. As no previous version of Wi-Fi was deployed in this band, there is no need for constraining backward-compatibility. Therefore, optimizations are possible that would not be allowed in other bands.

Short Beacons for AP Discovery

One element that had been bothering 802.11 designers for a long time is the issue of AP discovery. APs send beacons at regular intervals (typically every 102.4 ms or 100 TUs) to signal the BSS characteristics. The beacons contain a lot of information, so a beacon is considered as a frame that occupies a lot of airtime. Meanwhile, when a STA tunes onto a channel to discover APs, having to wait more than 100 ms to make sure that it hears all the beacons[33] is not desirable. A delay of 100 ms is a long time, especially if the STA has to scan more than 20 channels (in the 5 GHz band) or close to 60 channels (in the 6 GHz band in the FCC domain). A one-pass-per-channel scan operated at that scale will consume close to 10 seconds—an unacceptable delay. In the traditional spectrum (2.4 GHz and 5 GHz), there is no easy solution to this problem. Increasing the frequency of beacons would mean increasing the overhead on the channel.

One solution was to allow APs to send, between regular beacons, shorter beacons containing the minimum information that a STA needs to determine whether it wants to wait for the full beacon or move on to another channel. (See the "Scanning Procedures" section in Chapter 1, "Wi-Fi Fundamentals.") Another solution was to allow active scanning. In this approach, a STA sends a probe request, instead of waiting for the next beacon. The probe response includes the same information (in the context of AP discovery) as the beacon. However, many STAs performing probe exchanges end up adding to the channel overhead, ultimately consuming as much time as it would take if the AP were to send more beacons. In the 6 GHz spectrum, with 59 potential channels, the 802.11ax designers decided to implement new and more efficient discovery mechanisms.

Out-of-Band Discovery

One such mechanism relies on the idea that many AP devices operating in the 6 GHz band will be multi-radio, and also operate in another band (2.4 GHz or 5 GHz). A STA discovering APs will also scan the 2.4 GHz and 5 GHz bands—and will likely scan these bands first for the foreseeable future, as the STA has today more chances to find an AP in 2.4 GHz or 5 GHz than in 6 GHz. Therefore, Wi-Fi 6E mandates that multi-radio AP devices operating in 6 GHz and at least one other band must advertise their 6 GHz BSS in the other band(s). This advertisement uses an element of the beacon or the probe response called the Reduced Neighbor Report (RNR) element.[34] In its initial intent, this element informs the STA about neighbor APs in a compact form in a field called TBTT Information

33 In practice, the STA may even need to wait for two beacon intervals, to make sure to get the second-time beacons it may have missed the first time.

34 See 802.11-2020, clause 9.4.2.170; 802.11ax-2021 clause 11.49

Set. This field identifies each channel where the STA can find other APs, the TBTT offset that indicates the neighbor AP's beacon period offset with that of the local AP, and some optional information like the neighbors' SSIDs or BSSIDs.

Note

In the RNR, the SSID is the short SSID, a 4-octet hash of the SSID. Using the hash instead of the full SSID (which can be up to 32 octets long) makes the field shorter while still carrying relevant information the same way.

In Wi-Fi 6E, the RNR element is used by the 2.4 or 5 GHz AP to inform STAs about the 6 GHz AP. In that version of the RNR, the TBTT Information Set field still includes the TBTT offset (allowing the STA to know when to jump to the other channel with a minimum wait time before hearing the other AP beacon) and the optional BSSID/SSID fields. However, it adds a new BSS Parameters field (shown in Figure 3-11), with the following additional elements:

- **OCT Recommended:** Specifies whether the AP device recommends that the STA use on-channel tunneling (OCT) to communicate with the 6 GHz AP. OCT allows the STA to send a management frame (e.g., a probe) intended for a STA (and an AP in this case) through another STA (or AP) co-located on the same physical device. In other words, OCT allows the STA to use the 2.4 GHz or 5 GHz AP to communicate with the 6 GHz AP present in the same AP device.
- **Same SSID:** Indicates whether the 6 GHz AP supports the same SSID as the local AP.
- **Multiple BSSID and Transmitted BSSID:** Indicates whether the 6 GHz AP is part of a multiple BSSID set. The transmitted BSSID indicates whether the BSSID is that of the AP itself or that of the multiple BSSID set.
- **Member of ESS with 2.45 GHz Co-Located AP:** Indicates whether the other APs of the ESS are also multi-band. A value of 1 indicates that the ESS does not include 6 GHz-only APs, meaning that all 6 GHz APs in the ESS can be discovered while scanning 2.4/5 GHz.
- **Unsolicited Probe Response Active:** Indicates whether all the APs in the ESS also send unsolicited probe response frames every 20 TUs (or less). These probes allow the STA to discover the APs by just listening on a channel for 20 TUs. In such a case, there is no need to send probe requests and no need to wait 100 TUs.
- **Co-Located APs**: Indicates whether the 6 GHz AP described in this report is co-located with the reporting AP (i.e., the 6 GHz AP is in the same AP device as this 2.4/5 GHz AP).