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ANALYSIS OF WI-FI 6E AND 5G SPECTRUM EFFICIENCY AT 6 GHZ

Findings

This note examines the spectrum efficiency of licence-exempt Wi-Fi 6E (i.e., Wi-Fi 6 operating at 6 GHz) versus licensed IMT. In particular, it considers a presentation given by Nokia, together with other IMT vendors, in November 2021 about the relative spectrum efficiencies of the two technologies. In this paper, IMT is assumed to be 5G New Radio (5G NR), as standardised by 3GPP[1].

In the November 2021 presentation, Nokia claimed that "5G delivers 3x greater spectral efficiency than Wi-Fi 6 in meeting more challenging latency requirements". This note explores the spectrum efficiency (SE) of 5G NR and Wi-Fi 6 generally and the particular issue of latency and SE as raised by Nokia and others. The Nokia analysis of low latency requirements appears to have focused on indoor 5G networks for specialised industrial applications and not on general wide area public networks.

As shown in Annex 1 of this paper, both Wi-Fi 6 and 5G NR have a similar peak spectrum efficiency. The actual performance of Wi-Fi and 5G NR depends mostly on network configurations, network topology and functions at ISO layer 3 and above, rather than the underlying technology.

The Nokia presentation focuses on services/scenarios requiring latencies of 200, 10, 4, and 1 ms or less. However, latencies of 1 ms (or less) are unlikely to be generally available in public 5G networks. Non standalone 5G networks will rely on 4G core networks, which will not likely meet the 10 ms user plane latency. Whilst standalone 5G networks will be able to meet the lower latency requirements, it seems unlikely that many public networks will be standalone in the medium term. This is discussed in more detail below.

Nokia's November 2021 presentation appears to draw on an IEEE Nokia paper[2]. In that paper, the "DL radio performance" of the two systems is compared. That is (we assume) the time from when a source sends a packet to when the destination receives it. This is the IMT user plane latency defined in M.2410 (which specifies 4 ms for enhanced mobile broadband and 1 ms for ultra-reliable low latency communications). The more common metric for network performance is the round-trip delay, i.e. the time from sending a packet to receiving a reply. It is this round-trip delay that is an important Quality of Service (QoS) for offering services – hence the use of ping test for Internet services.

The scenario explored by Nokia is for an indoor factory of 50 metres x 120 metres with twelve indoor 5G base stations. There are 12 co-channel access points and base stations sharing 80 MHz TDD spectrum, with no external interference. Such a scenario may be relevant for advanced private local networks deployed by industry, e.g., in the 3800-4200 MHz band. But for public networks, 5G base stations will not be deployed indoors at 20 metre intervals, unless they are using millimetre wave spectrum. Most public 5G networks leverage a topology based on macrocell base stations that cannot easily deliver the traffic density nor the low latency considered by Nokia.

The characteristics of 5G deployments used in the ITU sharing and compatibility studies for WRC-23 state that *"it is expected that the same BS infrastructure will typically be used for networks in both 3-6 GHz and 6-8 GHz"* with outdoor urban macro base stations with about 20 metre antenna height (see document 5D/716 Annex 4.4).

The assumption in this paper is that the 6 GHz band would be used for TDD services (as only unpaired spectrum is likely to be available). In general, 5G TDD networks may be unable to offer very low latencies because of the way they are configured. This is because (as the Nokia IEEE paper notes – see below) there is an additional delay in a TDD network, as some packets will need to wait for the next DL transmission opportunity. This does not apply to FDD networks. The effect is most pronounced at low latency (see table 10 of Nokia paper). At 1 ms latency, 5G FDD can offer nearly 2x the spectrum efficiency of 5G TDD.

[1] https://www.3gpp.org/release-15

[3] https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=9446078

For public wide area networks, the requirement to synchronise TDD networks makes it difficult to both avoid interference and have flexible networks. This is to avoid a BTS transmitting in one cell when another is receiving nearby at the same time. In an isolated 5G cell (such as in a remote factory) this may not be an issue. But in a city centre with contiguous 5G coverage in 6 GHz there will need to be coordination on the TDD frame structure in terms of when UL and DL slots occur (i.e. synchronisation). A frame structure optimised for low latency may not be the best one for asymmetric traffic.

An operator that attempts to offer very low latency could create interference to other operators, or to its own network, unless every network nationally operates at very low latency, which may not be efficient for macro-cells. The configuration of a nationwide network is the result of compromises between coverage, capacity, latency and the cost of the network. As a result, it may not be realistic to expect public wide area 5G networks to deliver low latency.

The IEEE paper makes it clear that Wi-Fi 6 can also support reliable sub-ms latencies, with a lower offered load. As the latency performance of a network gets better, the throughput drops dramatically. According to Nokia, 5G at 200 ms latency can support a throughput of nearly 800 Mb/s/80 MHz. When that latency is reduced to 1 ms, then throughput drops to 65 Mb/s/80 MHz – which is more than a factor of 10. This issue (we believe) is more related to Erlang and trunking efficiency, rather than spectrum efficiency.

If a user has a choice between connecting to an indoor Wi-Fi access point, or a nearby 5G base station outdoors, they will experience a significant loss to the 5G link budget compared to Wi-Fi. 5G will need to contend with perhaps an extra 30 dB power loss, for the signal to penetrate the building's external walls[3]. Shannon's Law suggests a loss in capacity of 10x to meet this 30 dB loss[4]. This would easily offset the 3.3x spectral efficiency claimed for low latency (1 ms) services in the Nokia presentation.

Most users of Wi-Fi are home-based or in offices/ public spaces. Their main requirement is to have access to affordable high-performance equipment that is straightforward to deploy. Both Wi-Fi and 5G NR-U equipment can provide a very high QoS, both in terms of data rates and latency, if sufficient licence-exempt spectrum is available. Should access to 6 GHz spectrum require a licence, licence-exempt services would be excluded from the market, thereby limiting the usage of the spectrum. A lack of licence-exempt spectrum may also impact competitive dynamics, as users must rely more on 5G licensed services instead of Wi-Fi.

Discussion

The issue of spectrum efficiency is important, but also complex and nuanced. It can be measured using a number of different metrics. For example, Report ITU-R M.2410 (minimum performance requirements for 5G) specifies peak, average, and 5th percentile spectral efficiencies in bits per second per Hertz (bits/s/Hz).

These spectral efficiencies can also be defined for various test environments, such as indoor, outdoor, and rural. Report ITU-R M.2410 also specifies different user plane latency requirements: 4 ms for enhanced mobile broadband services (eMBB), and 1 ms for ultra-reliable low latency services (URLCC)[5]. However, this is not included as a specific 5G spectrum efficiency (SE) target.

Within the ITU, there are specific SE metrics considered for various systems. For a land mobile radio system this can also be thought of as Erlangs (data or bps) / (bandwidth x area)[6]. The inclusion of area takes into account the area served or the *area denied to other users*. This area component is not explicitly accounted for in the Nokia IEEE paper. It has used bps/Hz for a fixed area of a factory (50 metres x 120 metres). Other metrics might include power efficiency or energy used per bps/ (Hz x area).

The inclusion of area is potentially important as low power RLANs/Wi-Fi can share with existing services, such as fixed wireless links (FS) or fixed satellite services (FSS), because they operate within a defined area. Whilst WP5D is still studying the sharing issue in the 6 GHz band, some regulators have already expressed their view that, based on their national assessment, 5G cannot share with incumbent services. That is unless the 5G deployments are restricted to very low power base stations.

[3] ITU-R P.2109-1 provides a method for estimating building entry loss at frequencies between about 80 MHz and 100 GHz. Fig. 1 reports more than 16 dB attenuation for traditional building in the 6 GHz band, and more than 32 dB for thermally efficient buildings.

[4] see Annex 1, Table 3

[5] https://www.itu.int/pub/R-REP-M.2410

[6] https://www.itu.int/dms_pubrec/itu-r/rec/sm/R-REC-SM.1046-3-201709-I!!PDF-E.pdf – Annex 2

Two sharing studies submitted[7] to the WP5D process (that show 5G sharing is feasible) assume very limited deployment of 5G, with an average of one tri-sector outdoor base station every 500 to 600 km^2. If that is a correct assumption (on the level of deployment needed to protect FSS), then the spectral efficiency of outdoor 5G, using the area metric, will be very low.

In general, Wi-Fi carries far more traffic than cellular networks, according to figures and forecasts published by Cisco and Analysys Mason. Figures released by some regulators suggest Wi-Fi's overall share may be rising. For example, UK regulator, Ofcom's analysis[8] of crowdsourced data from Android smartphones found that 73% of the traffic they generated travelled over Wi-Fi and 27% over mobile networks between January and March 2021 – the latest figures available. That compares with 65% on Wi-Fi and 35% on mobile networks in the same period of 2020 (pre-pandemic).

Importance of 5G core networks in latency performance

5G requires not only 5G NR (air interface), but also a 5G core network to offer the full range of potential service offerings (such as network slicing and virtualised cloud elements etc). There are a number of deployment options for 5G known broadly as 5G standalone (SA) and 5G non-standalone (NSA). A major difference between SA and NSA, is that NSA uses the 4G core network (evolved packet core or EPC). This choice (NSA/EPC) severely limits the range of service options that can be offered by 5G. Hence when considering the use cases suggested by Nokia the availability of SA versus NSA is important. Most 5G networks in most countries use NSA – and that may well be the case for many years. Among the many telcos that have recently deployed 4G, there may not be the appetite or funds available to change to 5G SA.

NSA 5G networks are very unlikely to meet tight latency requirements. The round-trip (ping) latency is probably closer to 20 ms for an idealised 4G core network[9]. According to a recent survey in the UK[10], the (round-trip) latency of 4G was 36 ms and for 5G it was 29 ms. This suggests the round trip latency on 4G and 5G is very similar (perhaps due to the EPC). More importantly it suggests the downlink radio latency measured in the Nokia paper (1 ms) is not a significant issue in the total delay budget currently achievable in deployed commercial 5G networks. If the radio access delay is 1 ms, but it takes 30 ms to send a packet and receive a reply, the latter would seem to be the limiting factor on potential applications, such as the remote control of vehicles.

Spectrum Efficiency (SE)

It is important to have a full and rounded view on spectrum efficiency measures and not rely on overly narrow definitions that perhaps focus on a very specific feature/market set/deployment scenario. It is also important to compare like with like as far as possible.

All other things being equal, a spectrum band that is used exclusively by a single network operator (i.e., licensed 5G) will have an advantage in controlling interference, compared to a spectrum band that is shared, such as the licence-exempt bands used for RLANs/Wi-Fi/Bluetooth. This is because extra interference from other uncoordinated users will tend to raise the noise floor, and hence reduce the spectrum capacity (Shannon's Law). It may also be the case that 5G indoor base stations can use higher transmission power than Wi-Fi because they are licensed. This allows a higher signal-to-noise ratio for 5G (effectively) and hence allows greater throughput.

However, cellular networks are designed to deliver coverage, whereas Wi-Fi is designed to deliver capacity/density. While spectrum efficiency may be higher for specialised professional local networks, achieving high levels of spectrum usage typically depends on opening the band to as many users as possible. **Local spectrum efficiency does not necessarily lead to efficient spectrum usage**.

RLANs – in particular Wi-Fi – have by far the largest number of access points deployed and therefore the highest frequency reuse. While a licence-exempt mechanism is designed to reuse the whole spectrum available in every location, a licensed regime is designed to exclude some users from part of the spectrum in a specific place. This significantly reduces the overall spectrum use and therefore the efficient use of spectrum.

It is also the case that low power, mainly indoor, RLAN services can share spectrum more easily (than outdoor 5G can) with existing services, such as satellite earth-to-space connections, in the case of 6 GHz. Sharing a

[7] PT1(22) 67 by Ericsson & PT1(22)22 by Russia – see FSS sharing paper for more detail.

[8] https://www.ofcom.org.uk/research-and-data/telecoms-research/mobile-smartphones/mobile-matters

[9] LTE for UMTS book by Holma, page 289.

[10] https://5g.co.uk/guides/how-fast-is-5g/#5G_latency_explained

band between several services increases the efficient use of spectrum. In addition to the higher allowable maximum transmit power, systems for operation in licensed spectrum, including 5G NR, do not have to follow other co-existence restrictions that are usually in place for licence-exempt operation. More specifically, even in the case of the indoor operation considered in the Nokia paper, Wi-Fi and other license exempt technologies, including 5G NR-U, are designed to follow restrictions, such as limited transmit power and duty cycles to co-exist with the incumbents. In other words, a true spectrum efficiency measure should also factor in the spectrum utilization by incumbents, in the case of licence exempt.

There are other important metrics with regard to the efficient use of spectrum – such as economic, or environmental impact, as well as pro-competitive benefits. The ITU-R Radio Regulations (Section 0.3) states that spectrum *"must be used rationally, efficiently and economically"*.

There is little point in deploying a technology that is theoretically more spectrally efficient (perhaps in very few situations) if that technology cannot be used, or its use is severely limited. For example, if there is not sufficient market scale to develop mass market consumer devices (the 5G deployment densities assumed in some sharing studies are very small), or if it cannot share with incumbent services that are protected under ITU regulations and registered in other countries. Licence-exempt services are hugely popular with consumers who can choose how to connect to broadband in their homes or public spaces.

Nokia's spectrum efficiency (SE) figures

Dated 11 November 21, Nokia's presentation *Licensed 6 GHz for IMT: an opportunity for society* discusses (amongst other things) the relative spectrum efficiency of 5G NR and Wi-Fi 6 downlink. The data is based on a simulation for an indoor factory type environment of 50 metres x 120 metres using 80 MHz and 12 co-channel access points or 5G nodes. However, no further information on assumptions of powers etc. or reference to a paper is given.

The Nokia presentation gives the following data for 5G NR-TDD and Wi-Fi 6:

TABLE 1

Max delay	5G	Wi-Fi 6	5G SE	Wi-Fi 6 SE	Ratio SE *
ms	*Mb/s/80 MHz*	*Mb/s/80 MHz*	*b/s/Hz*	*b/s/Hz*	
	4x4	4x4	per stream	per stream	
200 ms	770	540	2.41	1.69	1.4
10 ms	440	200	1.38	0.63	2.2
4 ms	360	150	1.13	0.47	2.4
1 ms	65	20	0.20	0.06	3.3

**Spectrum Efficiency*

Table 1 clearly shows that the SE of both 5G and Wi-Fi falls dramatically as the maximum delay tolerance is tightened. For example, SE drops for 5G from 2.41 b/s/Hz for 200 ms latency to 0.2 b/s/Hz for 1 ms. Similarly, for Wi-Fi it drops from 1.69 to 0.06 b/s/Hz.

This shows the latency requirement has a very large impact on the throughput of both 5G and Wi-Fi 6 and is probably more to do with trunking efficiency than anything else. Part of the difference between 5G and Wi-Fi may be due to the lack of coordination between access points – the data in the Nokia presentation shows the 12 access points are co-channel.

Trunking Efficiency and Grade of Service

In a traditional voice circuit analogue phone system, the impact of the required grade of service on the capacity of a network is understood by using Erlang equations, which introduces the concept of trunking. This concept is well understood, for example, in PMR where a pool of channels is shared by many users and depending on the statistical nature of the calls (how long they last and how often they are made) a calculation can be made of the probability that the call is blocked because other users are making a call. This probability for blocking is known as the grade of service.

Tables can be derived (see https://www.itu.int/rec/T-REC-E.800SerSup1-198811-I/en) to show the Erlang E loss based on the traffic offered and the number of circuits, and the GOS blocking probability. It can be seen from the table that, as the GOS (loss probability) increases, the maximum offered traffic reduces. So, for 1 channel at 1% blocking probability the maximum offered traffic is 0.01 E. That is only 1/100 E can be carried or 1% efficiency. However, at 100 channels the same 1% GOS can carry 84.04 E. That is an efficiency of 84.04%. In the case of the Nokia data, it seems likely that the drop in overall efficiency can be explained by the need to hold back more network resources to ensure that no "user" waits more than the set amount of time (i.e. 1 ms latency).

As you increase the QoS requirement (lower latency in an IP world), the throughput drops and there is less trunking efficiency.

Although the IP world isn't dealing with Erlangs, the principle of traffic queuing would seem to be the same.

Assumptions

Nokia's numbers rely on many assumptions that may or may not apply to specific deployment cases. It is not clear whether the 5G access points are coordinated, and if so, are the Wi-Fi access points also coordinated? Many vendors offer Wi-Fi access point controllers that optimise the network efficiency in a similar way to a 5G access point controller.

Nokia doesn't say explicitly that the 5G is using licensed spectrum, but that is likely to be the case. Licensing the spectrum excludes most users and therefore undoubtedly reduces spectrum efficiency. Should 5G (like Wi-Fi) operate over licence-exempt spectrum, it would also have to respect the channel access mechanism[11], which would bring its performance much closer to the reported Wi-Fi performance.

Moreover, Nokia's usage scenario (5G base stations indoors every 20 metres) seems a very specific one. For most scenarios, 5G base stations are likely to be outdoors and Wi-Fi 6 access points indoors. As a result, the 5G network will need to contend with an average building penetration loss of around 30 dB for modern thermally-efficient buildings. The received power will likely be a factor of 1,000 times less for 5G penetrating a building than assumed in the Nokia presentation – and may be more (deep within buildings). That is one of the reasons most people prefer to be connected to a Wi-Fi network when indoors – they receive a higher QoS and generally at lower cost.

The paper submitted to the IEEE Access by Nokia[12] seems to be the source of the November presentation and it gives much more detail. It presents similar results for spectrum efficiency (if allowance is made for the IEEE paper assuming 2x2 MIMO, and the presentation assuming 4x4 MIMO). Another difference is the IEEE paper uses a delay condition of only 100 ms for the surveillance camera/application IV, whereas the presentation uses 200 ms (see Table 2 below). The other delay conditions are the same.

The key parameters in the IEEE paper assume different transmit powers for Wi-Fi 6 and 5G, with 23 dBm and 27 dBm (both omni antennas). Without the 4 dB difference in power, the spectrum efficiency difference would be reduced by around half[13]. That would effectively mean that for 200, 100 and 10 ms latencies, the spectrum efficiencies would be almost the same for 5G NR and Wi-Fi 6.

TABLE 2

delay	SE per stream*	SE per stream*	ratio
	5G TDD	Wi-Fi 6	
100 ms	2.00	1.25	**1.60****
10 ms	1.85	1.13	**1.64**
4 ms	1.85	0.56	**3.29**
1 ms	0.25	0.08	**3.13**

**Bits/s/Hz*
*** Slides assume 200 ms*
Spectrum Efficiency (SE) vs Delay

[11] In many regions, including the EU
[12] https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=9446078
[13] See Annex 1, Table 3

Conclusions

Spectrum efficiency can be defined in a number of ways. Perhaps the most straightforward is bits/s/Hz for a given percentage of users (as mentioned in ITU-R M.2412). The inclusion of area takes account of the area served *or the area denied to other users*, as discussed in SM.1046. Latency performance is not widely used as a metric for spectrum efficiency. We believe that latency performance is more closely related/correlated to network topology.

In the case of the 6 GHz band, the inclusion of area is particularly important, given low power RLANS/Wi-Fi can share with existing services, such as fixed or fixed satellite services. Whilst WP5D is still studying this sharing issue, some regulators have already expressed their view that, based on their national assessment, 5G cannot share with incumbent services – unless the 5G deployments are restricted to very low power base stations.

Two sharing studies submitted to the WP5D process assume (as far as we can tell) very limited deployment of 5G – perhaps one tri-sector outdoor base station every 500 to 600 km. If that is a correct assumption, and used in other studies, then the spectral efficiency of 5G using the area metric will be very small.

Other SE metrics might include power efficiency or energy used per bps/(Hz x area). If energy efficiency is used, then an indoor-to-indoor service has a 30 dBm (1,000x) better performance than an outdoor-to-indoor service. This is because building attenuation adds 30 dB to the link budget.

As most modern wireless systems converge towards the same underlying radio technologies (e.g. OFDMA and MIMO), the spectrum efficiency of a network is not typically the product of the technology deployed. It has much more to do with the network topology and potentially the regulatory regime (exclusive spectrum or shared spectrum).

Network operators will select a technology and a regulatory framework that best meets their requirements. They may, for example, obtain a much higher QoS by deploying many affordable access points, rather than a selected few, very expensive ones.

For regulators, local spectrum efficiency does not translate into overall efficient use of spectrum. Network topology (e.g. indoor deployment), affordability of equipment and ease of deployment are some of the aspects that improve the efficient use of spectrum, much more significantly than the local peak spectrum efficiency of a given technology.

EU regulators should ensure that there is spectrum available to support public wide area networks (e.g., in 3400-3800 MHz), local licensed private networks (e.g. in 3800-4200 MHz) and licence-exempt radio local area networks (e.g. in the 5925-7125 MHz), as all three topologies correspond to different market needs.

When considering efficient spectrum use, it is worth keeping in mind that RLANs deliver the vast majority of the wireless traffic and will continue to be the main Internet access technology for the foreseeable future.

Annex 1: Peak Spectrum Efficiency (downlink)

The peak spectrum efficiency possible for a radio system is the:

maximum symbol rate x maximum bits per symbol

The maximum symbol rate from Nyquist or Hartley is 2 symbols per second. For both Wi-Fi 6 and 5G NR (release 15) the maximum modulation level is 1024 QAM. For 1024 QAM each symbol can carry 10 bits of information (which would need to include signalling overheads etc., as well as user data). Therefore, not all 10 bits are available as user data.

Thus, for both Wi-Fi 6 and 5G NR the maximum theoretical spectral efficiency is 2 x 10 = **20 bits/s/Hz**

As QAM is not a single side band modulation scheme, this reduces the maximum spectral efficiency to **10 bits/s/Hz**. However, with MIMO it is possible to have a number of spatial streams or layers, which effectively make use of a multipath propagation environment. Both Wi-Fi 6 and 5G NR can support 8 layers/streams, **theoretically allowing 80 bits/s/Hz**.

The likelihood of the propagation environment indoors (where Wi-Fi is most used) supporting 8 layers (for either technology) is probably very small. **This might suggest a more likely limit of around 20 bits/s/Hz with multiple layers**.

Wi-Fi 6E

According to one source[14] the spectral efficiency (SE) of Wi-Fi 6 (AKA 801.11 ax) is over 60 bits/s/Hz assuming 8 spatial streams etc.

That gives an SE of 60/8 = 7.5 bits/s/Hz.

The Nokia presentation from November 21 shows 9.6 Gb/s per 160 MHz (assuming 8 streams) is 1.2 Gb/s per stream. That is about 7.5 Mb/s per MHz. This suggests an SE of about 7.5 bits/s/Hz.

Suggests single stream SE would be about 7 bits/s/Hz for Wi-Fi 6E.

EXAMPLE CALCULATION – SINGLE LAYER WI-FI 6 (78.125 KHZ) SUB-CARRIER SPACING

scs kHz	bw MHz	sub carriers	symbols /s**	Mb/s	spect effncy b/s/Hz	actual SE b/s/Hz*
78.125	80	1,024	75,294,118	752.9	9.4	7.06

**Max code rate 0.83 and overhead 10%.*
*** Symbol duration 13.6 µs. – assume 10 bits per symbol 1024 QAM.*

5G NR

Submissions from https://5g-ppp.eu/5g-ppp-imt-2020-evaluation-group/ give a peak spectral efficiency of just under 50 kb/s/Hz (table 12 December 19 submission) for 5G NR TDD downlink – assuming 8 layers in this band. For a single layer/stream that is an SE of about 6 bits/s/Hz.

For comparison, Coleago's spectrum demand report for the GSMA (exhibit 10)[15] used an average spectral efficiency of **3.7/2.6** bits/s/Hz (DL/UL) for small cells in this band and **6.0/4.1** for macro cells.

For a single layer this suggests a peak spectral efficiency of 6.25 bits/s/Hz for 5G NR.

EXAMPLE CALCULATION – SINGLE LAYER 30 KHZ SUB-CARRIER SPACING

SCS kHz	bw MHz	sub carriers	symbols /ms	bits/ms 1024 QAM	Mb/s	Max SE b/s/Hz	actual SE b/s/Hz*
30	100	3,333	93,333.3	933,333.3	933.3	9.3	5.95

**Coding rate (0.93 max), signalling overhead (14%) and TDD frame structure (0.8).*
*** Assume 14 symbols per slot (per carrier), and 2 slots per ms (scs 30 kHz). 1024 QAM is 10 bits per symbol.*

[14] https://www.draytek.co.uk/information/blog/how-does-802-11ax-wi-fi-6-work
[15] https://www.gsma.com/spectrum/wp-content/uploads/2021/07/Estimating-Mid-Band-Spectrum-Needs.pdf

Conclusion on Peak SE calculations

The peak spectral efficiencies of Wi-Fi 6 and 5G NR are broadly similar, and for a single stream/layer they approach the Shannon Limit. **That is a peak spectral efficiency of around 6-7 bits/s/Hz (single stream/layer)**.

How the two technologies work when actually deployed will depend on the deployment scenario and how the bandwidth is divided between the access points/base stations: how well the interference between devices is controlled and the signal-to-noise ratio that is available. All other things being equal a licensed network will tend to be able to offer a lower signal-to-noise ratio.

The ability to reach the high spectrum efficiencies quoted of 50 bits/s/Hz is highly dependent on the availability of multiple paths from transmitter to receiver to effectively "multiply the Shannon Limit".

TABLE 3: IMPACT OF POWER ON SNR AND CAPACITY[16]

linear SNR	dB SNR	Shannon capacity change
2x	3.0	1.6x
2.5x	4.0	1.8x
4x	6.0	2.3x
10x	10.0	3.5x
100x	20.0	6.7x
1000x	30.0	10.0x

The table above suggests that with a 30 dB building penetration loss, which effectively reduces the signal-to-noise ratio, there is a reduction in capacity by a factor of **10** using Shannon's Law, i.e.:

Capacity = BW x Log_2 (1 + S/N) – *where S/N is linear*

[16] https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=9446078