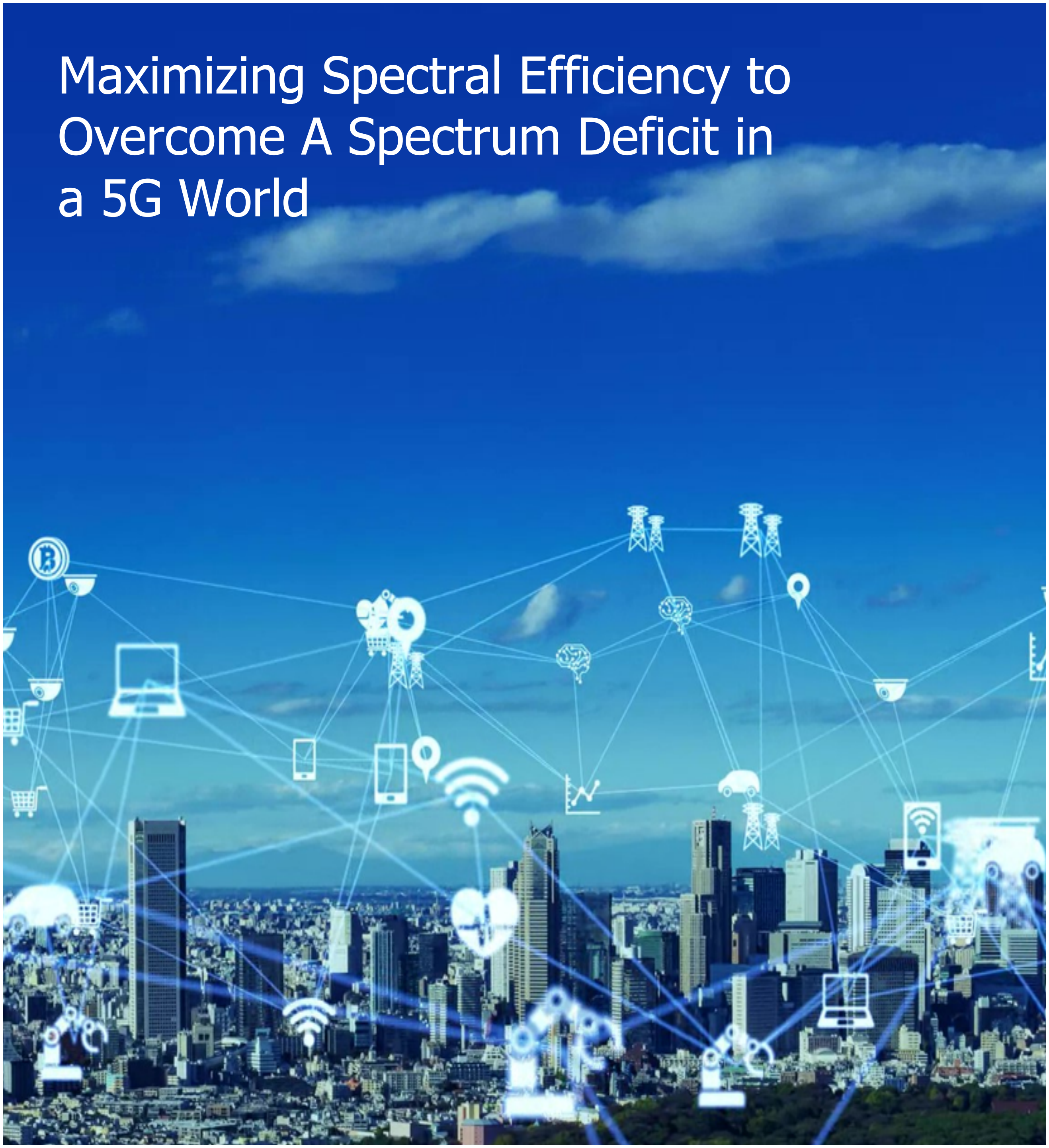
Maximizing Spectral Efficiency to Overcome A Spectrum Deficit in a 5G World



WHITE PAPER

Maximizing Spectral Efficiency to Overcome A Spectrum Deficit in a 5G World

RESONANT®

Introduction

Radio frequency spectrum is the lifeblood of the wireless industry, but there's a significant potential for a deficit in the amount of spectrum available for growing mobile data services.

In mid-January 2021, a big step was taken for 5G networks in the U.S. as mobile network operators (MNOs) spent over $80 billion dollars to acquire the spectrum upon which their network services will be built. But according to a model of spectral demand created by Resonant, an updated version of a model developed by the FCC (reference: "MOBILE BROADBAND: THE BENEFITS OF ADDITIONAL SPECTRUM, OCTOBER 2010" FCC Staff Technical Paper), growing demand for data services threatens to result in a situation where data demand will overwhelm the available spectrum starting in 2021 and continuing to get worse through 2025 (see Figure 1).

This analysis is based on 4G data services and doesn't factor in growing 5G services that will require ever larger swaths of spectrum to fuel high-bandwidth applications. Given the amount of money spent on spectrum, ensuring that it is not wasted is an important consideration. In our model, we estimate that more than $1B of spectrum in the US alone could be wasted due to interference degrading spectral efficiency by as little as 1%.

There are a number of techniques and technologies available to better manage network capacity and improve on the problem by increasing spectral efficiency. Spectral efficiency is a measure of how effective the usable bandwidth, derived from a given frequency band, is consumed. Improving spectral efficiency is a function of the wireless protocol and several RF technologies including the RF filter. This whitepaper explores how to improve

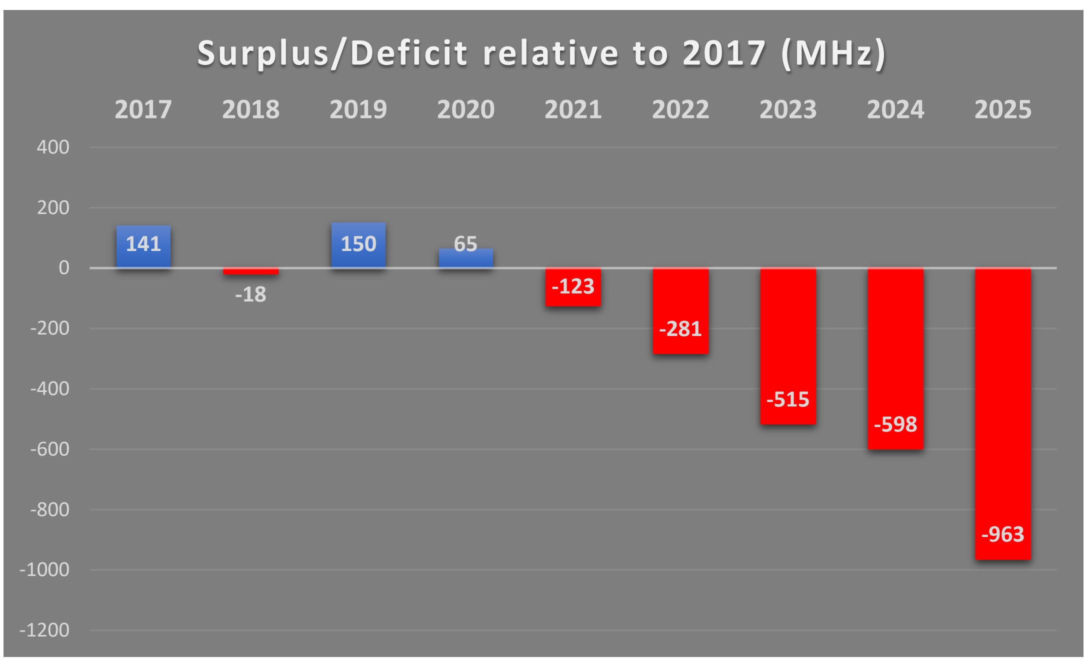


Figure 1. Spectrum situation (surplus and deficit) based upon the Resonant Spectrum Usage Model.

spectral efficiency to help MNOs meet their need for spectrum.

The Importance of Spectrum
All wireless communication signals travel over the air via radio frequency (RF) bands, or spectrum. The most tangible way to understand what spectrum is and how it works is to consider a car radio. When the radio is tuned to 95.5 FM, what is happening is that the radio is picking up the signal from a station broadcasting at the 95.5 megahertz frequency.

To listen to a different station requires re-tuning the radio to a different frequency, such as 99.9 FM. No two stations transmit over the same spectrum in the same geographic area, because this would cause interference between the two. In addition, wireless signal strength is reduced as the radio gets further from the transmitter until, ultimately, the station can no longer be heard.

Mobile phones work in a similar way. Wireless operators license the right to transmit wireless signals over certain frequencies and to keep other operators or businesses from using those frequencies in a particular geographic area.

In the case of licensed frequency, the Federal Communications Commission (FCC) is the U.S. government agency that licenses and monitors who is using which slices of spectrum. Licenses are allocated in an auction process generating billions of dollars in revenue for the government.

The US has led the world in allocation of commercial wireless spectrum prior to 5G, but had fallen behind other countries in the allocation of "mid-band" spectrum (3GHz – 6GHz). This despite recognizing its significance for advancing new applications and an enhanced user experience, not to mention the generation of significant government revenue. China in particular has taken a lead in allocating sub-6GHz spectrum for 5G and aggressively deploying its network.

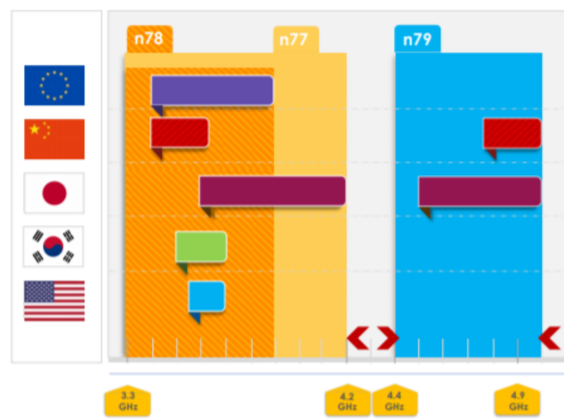


Figure 2. Current regional 5G sub-6GHz frequency bands, n77, n78 and n79 spanning 3.3GHz to 5GHz.

However, FCC auction 105, which closed in July 2020 (the so-called Citizens Broadband Radio Service (CBRS) Auction), made available the first sub-6GHz spectrum (3550-3650 MHz) in the US. CBRS is RF spectrum from 3.5GHz to 3.7GHz that the FCC has repurposed from exclusive military use to allow shared use of the spectrum for businesses and consumers, with certain stipulations that the spectrum be shared with the U.S. military and other priority licensees such as local governments.

The auction generated $4.6 billion in licensing fees for the FCC. It was followed by Auction 107 (so-called C-band auction) starting in in December 2020 for licenses covering 280MHz of spectrum in frequency bands below 4GHz. That auction raised

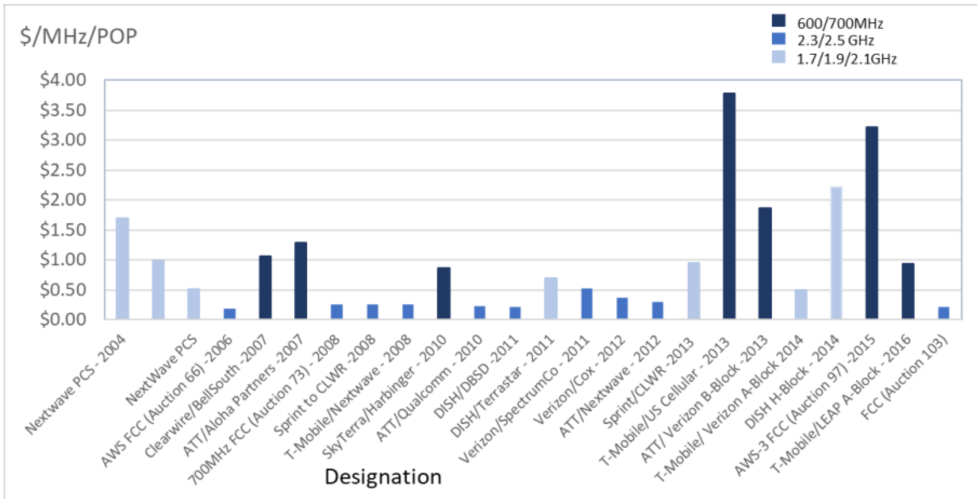


Figure 3. Cost of acquiring licensed spectrum from auctions and acquisition.

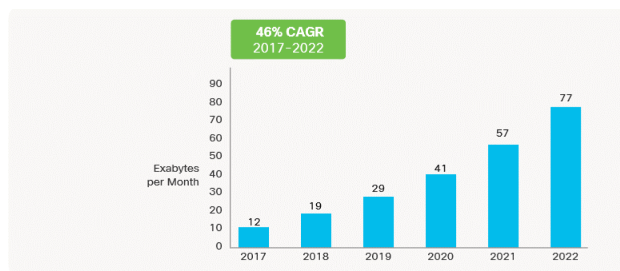
more than $80B, far exceeding even the most optimistic of estimates.

Considering the results from US FCC Auction 105, which raised a total of $4.6B for 70MHz of spectrum, this values spectrum at more than $65 million per MHz. Figure 3 breaks down this cost from previous auctions by dividing the cost per MHz by the population density covered.

These extremely high costs mean the lost opportunity cost of a 1% degradation in spectral efficiency caused by poor filtering and increased interference, would waste bandwidth costing over $1 billion.

The Resonant Model: Predicting a Spectrum Deficit

Future spectrum requirements and trends can be understood as a function of current / past spectrum used for mobile broadband. Resonant developed a model (see Figure 5) predicting net spectrum availability based on the growth of global wireless data as forecast in the Cisco Annual Internet Report[1]. This report predicts rapidly climbing wireless data consumption that will total 77 Exabytes per month by 2022.



Source: Cisco VNI Mobile, 2019

Figure 4. Mobile data growth.

The model is adjusted to account for projected additional network density via cell site growth and improvements in technology resulting in increased spectral efficiency.

However, this is a macro view of spectrum needs that vary significantly by location, network density, data speed and time of the day. In this model we assume the same

1 https://www.cisco.com/c/en/us/solutions/executive-perspectives/annual-internet-report/index.html

annual level of performance (data speed) is maintained, which is very conservative, since a fundamental premise of 5G is increased data speed. Nor does this demand take into account the pull-forward in wireless data usage from "stay-at-home" change in routine due to COVID-19.

However, this model does clearly show the dramatic increase in spectrum needs driven by the growth in wireless data. mmWave spectrum will absolutely help in critical pinch points associated with dense urban environments, but the extreme coverage limitations at these high frequencies will limit widespread deployments.

resources and services from consumers versus the available network capacity and the capital investment needed to meet customer requirements.

The model topline is the data growth as reported in the Cisco Annual Internet Report, and from that data we calculated the proportional data growth from the baseline year of 2017. From a demand perspective, it is clear that the continual move to wireless for data applications, and in particular for video, is driving the increase in mobile data. And as new generations of wireless technology with more advanced devices are launched then more use of broadband applications will follow – so long as the network can also support them.

	2017	2018	2019	2020	2021	2022	2023	2024	2025
Data Growth (Exabytes/month)	12	19	29	41	57	77	102	135	175
Data Growth (Proportional)	100%	158%	242%	342%	475%	642%	853%	1122%	1459%
Cell Sites (US)	323,448	349,344	395,562	416,762	436,762	456,762	476,762	496,762	516,762
Traffic per site growth	100%	147%	198%	265%	352%	454%	579%	731%	913%
Average Spectral Efficiency (bps/Hz/sector)	1.89	1.87	2.04	2.39	2.49	2.55	2.68	2.83	2.88
Adjusted Growth	100%	99%	108%	127%	132%	135%	142%	150%	153%
Spectral Efficiency Adjusted Traffic per site	100%	148%	183%	209%	267%	336%	407%	487%	599%
Cellular Spectrum Required (2017 start)	328.3	487	602	687	875	1103	1337	1600	1965
Licensed Spectrum Available (excl mmWave)	469	469	752	752	752	822	822	1002	1002
Surplus/Deficit relative to 2017 (MHz)	**141**	**-18**	**150**	**65**	**-123**	**-281**	**-515**	**-598**	**-963**

Figure 5. Resonant model of bandwidth availability through 2025.

Because network capacity varies by location and daily usage, making absolute numbers difficult, our model is based upon relative changes to demand and capacity from a baseline year (2017), assuming the network is dimensioned for 30% surge capacity. All calculations (table rows) are relative to this baseline year.

Data Growth: The critical equation that network operators balance both in near and long term, is the demand for network

Cell Site Growth: The number of cell sites is a key factor in the overall network capacity. A traditional 4G macrocell has a transmission range up to 40 km and can support more than 200 users per sector, but this is highly dependent on the terrain and the nature of the network service. The volume of data that can be processed at each cell site is determined by the spectral

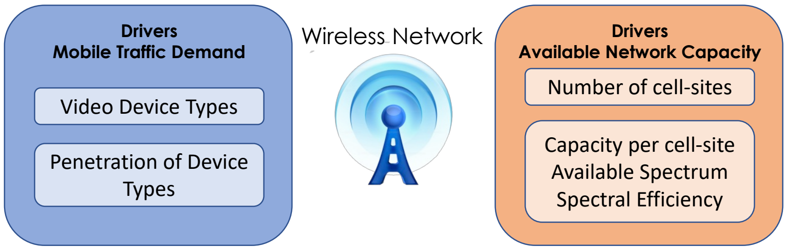


Figure 6. Mobile demand and capacity drivers for the wireless network.

efficiency and total bandwidth processed as shown in Figure 6.

Spectral reuse can be improved via the densification of the network, such as the use of small cells, allowing the same spectrum to be utilized in progressively smaller areas. Ultimately there are diminishing capacity returns as interference between neighboring sites will increase as footprint decreases.

Spectral Efficiency: Network capacity depends on the spectral efficiency of wireless technologies, which, as expressed in the formula below, is dependent upon new radio technologies.

$$\text{Network Capacity} = \frac{\text{Spectral Efficiency Multiplier}}{\text{New Radio technologies eg massive MIMO, coding schemes}} + \frac{\text{Spectral Capacity Multiplier}}{\text{More spectrum: Licensed, Unlicensed, Shared}} + \frac{\text{Spectral Reuse Multiplier}}{\text{Densification, including small cells}}$$

with,

$$Spectral\ Efficiency = \frac{Throughput, bps}{Channel\ (Band)Bandwidth, Hz}$$

With the inputs in Figure 5, we were able to determine the spectrum required for US data services and compare that to the spectrum that is expected to be available and from there understand how and when a spectrum surplus turns to a spectrum deficit.

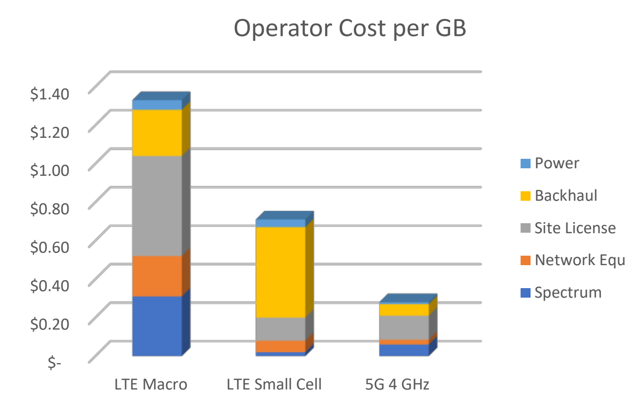
What the model shows (see Figure 1) is that despite efforts to open up new spectrum in the 3.5-4GHz range, by 2025 the spectrum deficit relative to 2017 is more than 963MHz.

Consequently, it becomes an imperative for mobile operators to find other means to increase the total wireless data capacity, such as increased capital spend to accelerate basestation and small cell deployments, offloading data traffic to unlicensed spectrum, and utilizing technologies that boost spectral efficiency such as massive MIMO (mMIMO) and unlicensed 5G RF bands (5G NR-U), while at the same time, improving RF filtering to protect from increasing potential for interference.

Importance of Spectral Efficiency

One point that is quite evident from the model is that with the significant cost of acquiring spectrum and the expected growth in data consumption, it is critical that spectrum is used as efficiently as possible. One key reason is the cost of acquiring spectrum. As seen in in Figure 7, the cost of acquiring licensed spectrum has increased dramatically in recent years.

Spectral efficiency is essential for mobile operators to make the most cost-effective use of their spectrum. Spectral efficiency defines how effective a given frequency carries a packet of data (bits per second per Hertz) and is dependent upon new radio technologies as defined by 3GPP and other standards bodies. The technology innovations for improved spectral efficiency of 5G include better RF filters, mMIMO and a more scalable frequency structure to optimize “packing” into the available spectrum. These technologies improve spectral efficiency by enabling the processing of significantly wider bandwidths through the same infrastructure, reducing the cost for deployment by the MNO.



Source: Mobile Experts

Figure 7. Cost of deploying wireless networks, expressed as cost/GB.

Spectral Efficiency Technologies: RF Filters

As described above, critical to realizing the capacity and speed gains promised by 5G and Enhanced Mobile Broadband (eMBB) services is to fully utilize all of the spectrum available to the wireless operator at maximum spectral efficiency. RF filters provide spectrum protection for the full frequency bandwidth from potential interfering signals. However, for 5G, filter requirements are quite different from 4G.

These new filter requirements include:

- Wide bandwidth (>500MHz and up to 2000MHz)
- High frequency (>3GHz)
- High power (to compensate for poor propagation at high frequency). It will be important for filters to demonstrate very high power handling – more than 30 dBm (1 Watt) at the edge of the band
- Low loss (to maximize the signal efficiency)

And with increasing use of the 5G and Wi-Fi bands, filters will need to mitigate a very real interference problem that will degrade the user experience.

Spectral Efficiency Technologies: mMIMO

mMIMO is an antenna system with many antennas at a basestation – from dozens up to 100 antennas. mMIMO offers improved coverage and capacity because multiple antennas can be combined forming multiple directed beams enabling high data rates. mMIMO improves spectral efficiency by using space division multiple access to simultaneously serve many users in a cell using the same bandwidth.

Licensed vs Unlicensed Spectrum

While not a spectrum efficiency technology, unlicensed spectrum expands the spectrum available to MNOs. Currently, unlicensed spectrum is the foundation for a number of wireless local area networks (LAN) , scientific and short-range consumer use (Wi-Fi, Bluetooth, Ultra Wideband, etc.). It has the advantage (see Figure 8) that it is free for all to use, but has limited range when compared to licensed technologies to minimize interference issues. The relative lack of regulation also means there are no guarantees for quality of service and security.

Unlicensed Spectrum		Licensed Spectrum	
Pros	Cons	Pros	Cons
Easy and quick to deploy	Others can use same frequency	Ability to manage quality of service	Limited spectrum for each operator
Low cost hardware	Difficult to provide wide-scale coverage	Scalable for nationwide coverage	Expensive infrastructure

Figure 8. Pros and cons of unlicensed spectrum and licensed spectrum.

Mobile operators can offload data traffic from their licensed spectrum to unlicensed Wi-Fi networks as seen in Figure 9. Initially operators were resistant to moving users onto Wi-Fi networks because of the negative revenue implications and relatively unmanaged frequency situation. However, the widespread availability of Wi-Fi functionality on smart devices, the potential for an overall improved quality of service, availability of streaming video to smartphones in dense environments, was driving customer retention.

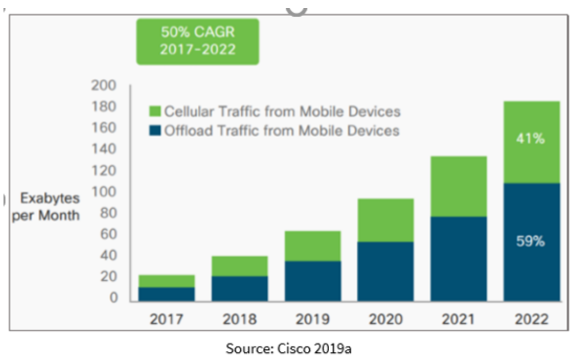


Figure 9. Global mobile traffic offload to Wi-Fi.

5G New Radio – Unlicensed (5G NR-U) is one way that mobile operators can utilize unlicensed spectrum. 3GPP Release 16 introduced 5G NR-U which enables the implementation of 5G on unlicensed spectrum, opening up access to significantly more spectrum both in the US and other parts of the world.

Vertical Expansion		Capacity and Operational Efficiency Enhancement	
• IIoT (Industrial IoT) • URLLC • 2-Step RACH	• NR Positioning • NR Unlicensed • V2X	• MIMO Enhancements • MR-DC • Integrated Access and Backhaul (IAB)	• Mobility Enhancements • cross link interference (CLI)/remote interference management (RIM) • UE Power Savings

5G NR-U can be deployed as a stand-alone configuration, or it can be "anchored" using licensed spectrum, where the lower frequency "anchor" provides a coverage backstop, especially for essential overhead signaling.

Additional Spectrum Technology for 5G Deployments

In addition to the spectral efficiency technologies there are other techniques available to help carriers bring services to users and to manage their valuable spectrum assets.

Carrier Aggregation: Because the total spectrum determines the user data speed, pieces of spectrum from different bands (see Figure 10) can be aggregated or combined to increase data speed.

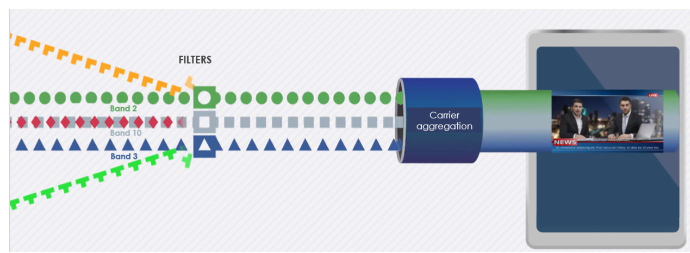


Figure 10. Aggregation of multiple frequency bands to increase data speeds.

This technique has been used extensively in 4G in order to increase data speeds, and the expectation is that for 5G this will be utilized even more significantly, with over 10,000 carrier combinations predicted for early 5G

Dynamic Spectrum Sharing (DSS): DSS is a transitional technology that does not increase capacity but addresses the issue of enabling 5G coverage using low frequency spectrum, even though the spectrum is also used for 4G, accelerating early nationwide deployment of 5G. Traditionally, new-generation radio access technologies are deployed on separate spectrum blocks – as was the case with 2G, 3G and 4G. This would require operators to buy new spectrum or re-farm the existing spectrum to allocate the new generation. This is a very slow and costly process. Spectrum re-farming could take a decade, but with DSS it can be done overnight. DSS allows the deployment of both 4G and 5G in the same band and dynamically allocates spectrum resources between 4G and 5G based on user demand.

Time Division Duplexing (TDD)

To increase flexibility as well as make spectrum usage more efficient, TDD is used in 5G. TDD uses the same frequency for communication in both directions (to and from the mobile device), unlike the alternative frequency division duplexing (FDD) technology that uses entirely different frequencies for each channel. By changing the time slot duration, network performance can be tailored to meet different needs and use cases. However, using the same frequencies has implications for interference management between neighboring sites. Consequently, to utilize the spectrum most efficiently, TDD networks, operating in the same frequency range have to be synchronized. Base stations need to transmit at the same fixed time periods and all devices should only transmit in dedicated time periods.

High Frequency, Wide Bandwidth Filters

5G and Wi-Fi will have a co-existence challenge unlike any other in the history of wireless technology. 5G bands n77 and n79 and the 5GHz and now 6GHz Wi-Fi band are adjacent in frequency with little guard band to separate them. The co-existence problem has been summarized in a report by industry analyst firm Navian (and seen in Figure 11): "5GHz band for Wi-Fi, which is essential for smartphones, sits between the 4.5GHz and 6-7GHz bands. If these frequencies are to be fully utilized, each bandwidth would need a steep filter. Also with n77 and n79, high-performance filters for each of these bands would be needed at the same time, since band gap of 200MHz is too narrow to be utilized fully."

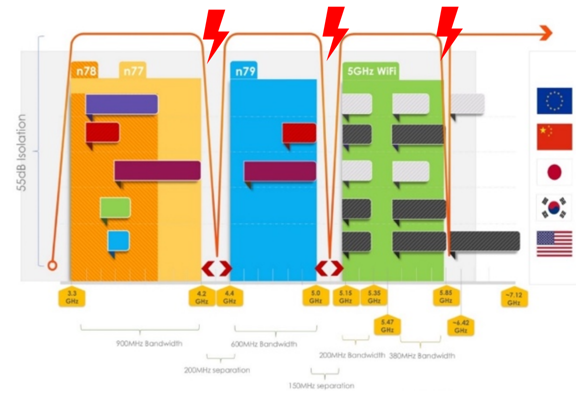


Figure 11. Depiction of current regional 5G and Wi-Fi spectrum allocations in 3.3GHz to 7.12GHz frequency range. Showing the potential for co-existence interference issues. *Denotes potential co-existence problem areas.*

RF filters designed for 4G requirements are not suited to these new filtering challenges. And hence a new filter design is required. Resonant's XBAR filters provide the full, wide bandwidth, high frequency operation, low loss and high power capability necessary for 5G and Wi-Fi to coexist with maximum performance.

Resonant XBAR RF Filter

X-BAR is a bulk acoustic wave (BAW)-based resonator technology that can be used to create filters that deliver performance for 5G networks; offering best-in-class performance for ultra-wideband applications. Other resonator technologies, developed for 4G, sacrifice performance in order to achieve the wide bandwidths in particular, degrading spectral efficiency relative to XBAR.

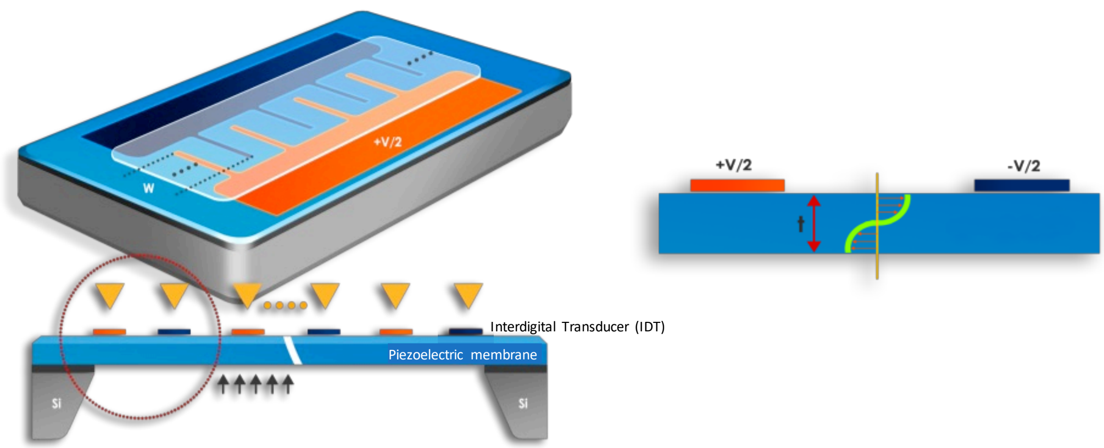


Figure 12. Filters required to prevent interference and allow co-existence/operation for these bands

XBAR resonators consist of a single crystal, piezoelectric layer, with a metal interdigital transducer (IDT) on the top surface. The metal traces excite a bulk acoustic wave within the piezoelectric, the primary frequency and coupling characteristics being determined by the physical dimensions and properties of the piezoelectric.

Summary

Just as the top three success factors in real estate are location, location, and location; success in wireless services hinges on spectrum, spectrum, and spectrum. Without the spectrum needed for wide bandwidth, a wireless carrier is at a significant disadvantage to its competitors. The importance of spectrum can be seen in the $81 billion paid for spectrum during the FCC's Auction 107.

But data demand is also growing which means there is a significant potential for a spectrum deficit that could grow to be more than 900 MHz by 2025 according to our model. This situation puts pressure on operators to ensure they are maximizing their complete spectrum holdings using technologies optimized for spectrum efficiency. Maximizing spectral efficiency will take a new breed of RF filter that can minimize signal loss, mMIMO antennas that provide improved coverage, and access to unlicensed spectrum (via 5GNR-U) that can mitigate some of the growth in data consumption through the use of unlicensed spectrum. mMIMO and 5G NR-U will also increase the demand for wideband filters.

Resonant's Infinite Synthesized Networks (ISN®) filter design and XBAR technologies are combined to create the highest performance filters for both FR1 and FR2. These filters have very wide bandwidths, support frequencies up to 40GHz, manage high powers for these frequency bands and offer very low loss.

For more details on Resonant's ISN and XBAR technologies, visit www.resonant.com.