A study of CBRS and licensed spectrum for dedicated networks.

White paper

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The intent of this study is to discuss the specificities of the Citizens Broadband Radio Service (CBRS) band and licensed bands such as the C-Band, compare their respective performance, and provide some perspectives for each as it relates to dedicated networks.

1. Background

A "dedicated network" here may refer to either a private network (PN), a neutral-host network (NHN), or a combination of both. An "enterprise" refers to a private corporation or a government entity looking to deploy a dedicated network for their specific needs. As we review different spectrum options for deploying dedicated networks, the geographic scope is limited to the United States – other parts of the world use different licensed spectrum bands, and may have specific spectrum bands assigned for industrial private networks.

Multiple factors should be considered when an enterprise chooses the spectrum for a dedicated cellular network. Those include the ease and cost of accessing that spectrum, whether the spectrum is shared with other enterprises or telcos, the available aggregate bandwidth, the regulations on maximum allowable transmit power, the expected availability or reliability of the network, the spectrum controlling paradigm (e.g., owned licensed, leased, shared, or governed by a spectrum coordination system), and the device ecosystem. Furthermore, network performance aspects – including throughput, latency, and coverage – are other key considerations having dependencies on some of the above factors.

Different enterprises have different needs depending on their industry vertical, the targeted applications, and where they are in their communications infrastructure modernization journey. Most will however try to strike a balance between ease of installation and operation, performance, and cost when deploying a new, dedicated cellular-type network.

2. Spectrum availability to enterprises

The CBRS band (3.55–3.70 GHz) in the U.S. is governed by FCC rules to offer a shared spectrum paradigm, where the fifteen defined 10 MHz Time Division Duplex (TDD) channels are coordinated between different cellular-type users and non-cellular incumbents. This is accomplished via a three-tiered scheme managed by the CBRS Spectrum Access System (SAS). See [1] and [2] for background on the CBRS band and corresponding spectrum sharing scheme. CBRS is of interest for enterprises, since its unlicensed characteristic technically allows it to be used by any entity without requiring the purchase of a license. In other words, as far as spectrum rights are concerned, any enterprise can access CBRS General Authorized Access (GAA, also known as Tier-3) spectrum with no dependency on another spectrum owning entity. The ecosystem of base station radios, devices, and private network solution vendors is also growing around CBRS, providing options to an enterprise including lower-cost, turnkey solutions. This is especially true as of today for LTE CBRS (B48 band), while the ecosystem for 5G NR CBRS (n48 band) still needs to mature.

Accessing licensed cellular bands such as LTE low-band, 5G NR mid-band, and 5G NR mmWave on the other hand – which entails a number of advantages as discussed below – requires the enterprise to partner with another entity who won parts of that spectrum at an auction (the spectrum licensee). One exception to this is a rarer case when the enterprise itself owns some licensed spectrum that they intend to use for their dedicated network, such as CBRS Prioritized Access Licenses (PAL).

One aspect of the CBRS band and technology worth pointing out is that, similarly to Wi-Fi, the use of GAA channels offers no guarantee of being the sole operator on certain radio frequency channels. When operating in the GAA or unlicensed tier of CBRS spectrum (Tier-3), a deployer is not only competing for spectrum with other entities trying to use GAA channels in the area, but also vulnerable to channel preemption and transmit power limitations due to Department of Defense (DoD) or Fixed Satellite Service (FSS) incumbents (Tier-1) and

PAL license owners (Tier-2), in accordance to the FCC's Part 96 rules for CBRS [3]. Geographically speaking, the risk associated with Tier-1 users is higher for network deployments close to off-shore Dynamic Protection Areas (environmental sensing capability-based DPAs or E-DPAs), zones surrounding inland Portal-controlled DPAs (P-DPAs), or near FSS earth stations; see [4] for related maps. In practice, an operator of CBRS GAA spectrum may only be able to use a limited number of channels, and their base stations may be required to transmit at a reduced power, compared to what they had originally planned. This is due to interference management by the SAS and its enforcement via channel "grants", as illustrated via a real example in Table 2-1 below. Service outages have also been experienced from time to time with CBRS installations, as illustrated via the recorded events in Table 2-2.

Table 2-1:
eNB Tx power in a CBRS GAA private network at a sports event in 2023

eNB / sector	RF Output per port [dBm]	Reference Signals EIRP per port [dBm]	UL Traffic Volume (3 days) [MB]
eNB 4 / sector 1	26	7	17,225
eNB 2 / sector 2	36	17	7,285
eNB 1 / sector 1	36	17	5,210
eNB 4 / sector 2	26	7	4,629
eNB 2 / sector 1	36	17	4,078
eNB 1 / sector 2	26	7	1,977
eNB 5 / sector 1	33	14	174
eNB 6 / sector 1	33	14	145
eNB 3 / sector 1	26	7	99
eNB 3 / sector 2	26	7	4

Table 2-2:
Examples of CBRS outage events from 2022 into Q1 2023 (non-exhaustive list)

Date	Outage description	Impacted area	Outage duration
2022	30% of the CBSDs managed by one OAM instance out of service, following an OAM software upgrade.	Multiple markets	
2022	A number of CBSDs managed by one OAM instance out of service, following an OAM software upgrade (time zone issue).	Multiple markets	
2022	98% of the CBSDs managed by one OAM instance out of service, following an OAM software upgrade (load balancing issue).	Multiple markets	
1/3/2023	900 CBSDs from one SAS provider out of service nationwide (authentication issue following SAS upgrade).	Nationwide	2 hours 50 min.
1/4/2023	1800 CBSDs from one SAS provider out of service nationwide (SAS database issue).	Nationwide	3 hours 3 min.
3/13/2023	A number of CBSDs nationwide blocked by one SAS provider, after an influx of traffic in Illinois market.	Nationwide	Several hours

As can be seen in Table 2-1, only three out of the ten radios were transmitting close to their maximum specified RF Output of 37dBm. Other radios had their transmit power reduced by 3 or 10 dB by the SAS, impacting some of the high-traffic sectors in this private network.

The information in Table 2-2 was sourced from Verizon maintenance engineering teams based on customer-impacting outages in their markets.

In addition, and as seen from Table 2-2, CBRS installations may experience service availability outages for varying reasons, including but not limited to the SASs.

As an alternative where it is desired to deploy in protected spectrum, telecommunication companies (telco), such as Verizon, have an established offering where they allow prospective enterprises to leverage the telco's licensed spectrum (possibly including CBRS PAL) when deploying a dedicated network. Depending on the location of the said network and the chosen band(s), the telco may like to use a RAN sharing scheme such as Multi-Operator Core Network (MOCN) or Multi-Operator Radio Access Network (MORAN) to allow their own subscribers to use the dedicated network's RAN nodes. MOCN can be used in situations where the system has a single spectrum band or where a single entity owns spectrum rights to all the bands and frequency channels configured on the system; MORAN can be used in cases where multiple entities (e.g., different Mobile Network Operators) own spectrum rights to different bands or channels yet agree to share parts of the RAN infrastructure.

While RAN sharing may in some cases reduce the available capacity for the enterprise's private devices such as manufacturing robots, it also benefits the enterprise since their employees on a regular cellular plan will now see extended carrier coverage at the facility. If needed, the RAN may be configured to limit the amount of radio resources that public subscribers are allowed to use on the dedicated network, thus protecting the enterprise's private devices.

While the FCC enforces rules for each spectrum band in the U.S., licensed bands are generally not subject to the same low-power restrictions or geographic limitations as seen with CBRS, owing to the unique three-tiered spectrum sharing scheme in place for CBRS. The use of conventional licensed spectrum thus allows for predictable network performance; that predictability also means the ability to design a right-sized network, as well as to avoid degradations over time due to increased spectrum utilization by other entities. Licensed bands can possibly be used in conjunction with unlicensed ones such as CBRS GAA.

3. Bandwidth, transmit power, and other RF parameters

Below we listed some of the key RF parameters influencing the performance of cellular-type systems, along with their definition. When comparing the performance of different systems, as done in section 4, it is useful to understand the underlying RF parameters and their values.

- **Channel bandwidth [MHz]**
  This is the bandwidth of one frequency channel, sometimes also referred to as component carrier (CC). Within a given cellular frequency band, a UE may be able to aggregate multiple channels or CCs. LTE CBRS supports channel bandwidths of up to 20MHz, as other LTE bands. NR CBRS, on the other hand, supports channel bandwidths of 20, 30 and 40MHz (typical) and above. The C-Band (3.70–3.89GHz), a licensed NR TDD band also part of the mid-band spectrum, supports channel bandwidths of up to 100MHz.
- **User aggregate bandwidth [MHz]**
  This is the sum of all CCs' bandwidth across all the frequency bands aggregated by a User Equipment (UE) when connected to one or more base stations (e.g., eNB or gNB) at a given time. Different aggregation techniques are available to a UE, such as Carrier Aggregation (CA) and Dual Connectivity (DC), and a combination of both is also possible. The user aggregate bandwidth not only depends on the UE capabilities discussed next, but also on the radio resources assigned by the base station depending on factors including cell load and user throughput needs.
- **CA and DC capabilities of UEs**
  Depending on the type, release year, make, or model of a UE, the CA and DC capabilities vary. Also, the CA & DC capabilities are typically less in the uplink (UL) compared to the downlink (DL), due to device hardware constraints. For instance, as of today in the LTE CBRS band (B48), only select device models are capable of aggregating two channels in uplink, and those must be contiguous (Uplink 48C combination). On the other hand, some device models are capable of aggregating up to four channels in downlink. The CA and DC capabilities of a UE are communicated to the network via RRC UE Capability Information procedure, based on which the network may assign only a band combination that is supported by the particular UE.
- **Base station Tx power [dBm, mW or W]**
  This is the total transmit power of the eNB or gNB for the sector of concern. Common measures include the RF Output (used e.g., for a standalone radio module) and Equivalent Isotropic Radiated Power (EIRP) (used e.g., for a radio module with integrated antenna, such as an indoor small cell). A perhaps more practical measure for performance comparison purposes is the base station transmit power normalized per bandwidth (e.g., [dBm per MHz]), focusing on the bands and CCs used by a given UE. The base station Tx power is dependent on the product specifications of the considered radio module (sometimes simply referred to as radio), and the network topology and corresponding RF planning. Specifically for the CBRS band, the CBRS base station (also referred to as CBSD) Tx power is capped by the FCC's Part 96 regulations depending on the type of CBSD (47 dBm / 10MHz channel for Category B CBSDs, 30 dBm / 10MHz channel for Category A CBSDs), and may also be dynamically adjusted (reduced) on a per-sector basis based on channel grants issued by the SAS. As mentioned earlier, the main goal of this SAS scheme is to protect higher-tier CBRS users (e.g., Navy ships, DoD portal activations, earth

stations of incumbent FSS satellite operators, PAL licensees, etc.). CBSDs Tx power in the CBRS band is also limited near the Canadian border. On the other hand, conventional licensed spectrum tends to have less stringent base station Tx power restrictions.

- **UE Tx power [dBm or mW]**
  This is the allowed maximum transmit power of an end-device, or UE. Common measures include the RF Output (used e.g., for FR1), the Total Radiated Power (TRP) and EIRP (used e.g., for FR2). The 3GPP standards specify maximum RF Output, TRP and EIRP, among other RF transmission metrics, for different categories of UEs. Specifically for the CBRS band, the FCC also specifies additional limitations on the Tx power of mobile CBRS End User Devices (EUD), such as a maximum TRP of 23dBm for most EUDs (this limitation is exceptionally relaxed for CPE-CBSDs, which are Customer Premise Equipment stationary end-devices typically mounted outdoors). On the other hand, in licensed spectrum there are options for UEs to transmit at RF Outputs or TRPs higher than 23dBm, even for some mobility devices. For instance, Class 2 UEs are allowed to transmit at an RF Output of 26dBm in the C-Band, instead of 23dBm for Class 3 UEs.
- **LTE TDD slot pattern**
  For cellular bands operated in a Time Division Duplex (TDD) fashion, the TDD slot pattern, also sometimes referred to as UE duty cycle, determines the radio resources available for the uplink relative to the downlink radio resources, and vice versa. For example, as of today, the LTE CBRS band (B48) is typically operated with LTE TDD configuration 2 by most operators, which roughly corresponds to a UL:DL ratio of 1:3 and thus favors the downlink. Certain Private Network (PN) and Neutral Host Network (NHN) deployments are exploring the use of LTE TDD configuration 1, which roughly corresponds to a UL:DL ratio of 1:1, to increase the UL throughput which may otherwise be quite limited in LTE CBRS. There are however technical barriers in doing so in practice, notably because of the TDD cross-link interference phenomenon (i.e., mutual interference of two cellular systems operating with different TDD slot patterns in same or adjacent bands).
- **NR TDD slot pattern**
  As of today the NR C-Band (n77) is typically operated with TDD slot pattern DDDSUUDDDD, which roughly corresponds to a UL:DL ratio of 1:3 (in 5G NR, note the standards do not specify predefined TDD configurations as they did in LTE). Some development and interoperability work is under way to have the RAN and UE ecosystem officially support a TDD slot pattern DDDSUUUUDD in NR mid-band spectrum, which roughly corresponds to a UL:DL ratio of 1:1. In general, 5G NR is expected to provide more flexibility to manage the TDD slot patterns compared to LTE, such as the ability to adjust the slot pattern for a UE or group of UEs differently from the broader population of UEs within the same cell.
- **MIMO layers**
  MIMO stands for Multiple Input Multiple Output, and refers to a capability of smart array antennas in cellular networks to leverage the spatial characteristics of the RF channel between a transmitter and a receiver to transmit multiple data streams over the same frequency band and channels. When used effectively, MIMO can significantly improve the spectral efficiency thus the throughput (e.g., doubling it for 2-layer MIMO). Here again, similarly to the CA and DC capabilities of UEs, the MIMO capabilities are typically less in the uplink compared to the downlink. In that regard, one known limitation in LTE CBRS is the lack of support for UL MIMO (i.e., only one spatial layer is supported in uplink). The limited uplink CA and MIMO capabilities of UEs partly explain the relatively low UL user throughput performance seen in LTE CBRS (see section 4). On the other hand, in NR CBRS or in NR licensed bands such as the C-Band, some UE models support 2-layer UL MIMO.
- **Numerology**
  While in LTE all supported frequency bands use the same subcarrier spacing (SCS) of 15kHz / Transmit Time Interval (TTI) of 1ms, 5G NR introduces the concept of numerology (μ), which allows for flexibility in the SCS and slot duration (TTI). This was adopted in particular due to the much wider range of frequency bands supported in NR, resulting in very different propagation delays and phase synchronization requirements. LTE CBRS operates at the same SCS of 15kHz and TTI of 1ms as other LTE bands (corresponds to μ=1), despite being part of the mid-band spectrum. NR CBRS, on the other hand, typically operates at an SCS of 30kHz and slot duration of 0.5ms (corresponds to μ=2). The SCS and slot duration are inversely proportional. The shorter slot duration (TTI) for NR CBRS compared to LTE CBRS may give it a slight latency advantage, everything else being equal.

4. Performance comparison

Tables 4-1 and 4-2 below show the assumed RF parameters and simulation-estimated throughput, for 3 hypothetical cellular systems – LTE CBRS with 3x20MHz channels, NR CBRS with 1x40MHz + 1x20MHz channels, NR C-Band with 1x60MHz channel. In these simulations, we have deliberately chosen an aggregate bandwidth of 60MHz for all cases to allow for easier comparison. The two NR cases are for 5G Standalone (5G SA) mode of operation. The simulations used a system-level LTE and NR performance estimation tool developed by Verizon and consumed by internal teams f or studies including spectrum use or network slicing. Here, the tool assumed a typical indoor small cell, with one user in the cell dropped randomly at different locations – thus experiencing different RF conditions – over multiple simulation runs.

Table 4-1:
RF parameters for 3 hypothetical cellular systems

	LTE CBRS with 3x20MHz channels	NR CBRS with 40MHz + 20MHz channels	NR C-Band with 60MHz channel
Channel bandwidth [MHz]	20	40 or 20	60
Intra-band CA capabilities of UE	UL 1-CC / DL 4-CC	UL 1-CC / DL 3-CC	N/A
User aggregate bandwidth [MHz]	UL 20 / DL 60	UL 40 / DL 60	UL 60 / DL 60
eNB/gNB max. RF Output per port and per channel [dBm]	27	27	27
UE Tx power [dBm]	23	23	26
TDD slot pattern	LTE TDD Config. 2 (DSUDDDSUDD)	DDDSUUDDDD	DDDSUUDDDD
MIMO layers	UL 1-layer / DL 2-layer	UL 1-layer / DL 4-layer	UL 1-layer / DL 4-layer
Numerology	1 (SCS=15kHz)	2 (SCS=30kHz)	2 (SCS=30kHz)

Table 4-2:
Simulated user throughput

Date	LTE CBRS with 3x20MHz channels	NR CBRS with 40MHz + 20MHz channels	NR C-Band with 60MHz channel
UL Throughput [Mbps]	14	36	56
DL Throughput [Mbps]	339	485	597

NOTE: To ensure consistency with the subsequent testbed-measured results, the above simulations assume a UE with similar capabilities as the one used in our actual tests, including a limitation to UL 1-CC in the CBRS band.

Tables 4-3 and 4-4 below show the used RF parameters and testbed-measured throughput and round-trip time (RTT) latency results, for 3 private network systems – LTE CBRS with 4x20MHz channels, NR CBRS with 1x40MHz, NR C-Band with 1x100MHz channel. The total bandwidth is different for the 3 cases and reflects the actual configurations at the time of these tests; one may thus want to scale the throughput numbers as appropriate for spectral efficiency comparison. These results were measured at Verizon indoor private network testbeds, for a single user in near-cell RF condition. The two NR cases are for 5G SA mode of operation.

Table 4-3:
RF parameters for 3 private network systems

	LTE CBRS with 4x20MHz channels	NR CBRS with 40MHz channel	NR C-Band with 100MHz channel
Channel bandwidth [MHz]	20	40	60
Intra-band CA capabilities of UE	UL 1-CC / DL 4-CC	N/A	N/A
User aggregate bandwidth [MHz]	UL 20 / DL 80	UL 40 / DL 40	UL 100 / DL 100
eNB/gNB max. RF Output per port and per channel [dBm]	17	37	27
UE Tx power [dBm]	23	23	23
TDD slot pattern	LTE TDD Config. 2 (DSUDDDSUDD)	DDDSUUDDDD	DDDSUUDDDD
MIMO layers	UL 1-layer / DL 2-layer	UL 1-layer / DL 4-layer	UL 1-layer / DL 4-layer
Numerology	1 (SCS=15kHz)	2 (SCS=30kHz)	2 (SCS=30kHz)

Table 4-4:
Measured user throughput and latency in private network testbeds

	LTE CBRS with 4x20MHz channels	NR CBRS with 40MHz channel	NR C-Band with 100MHz channel
UL Throughput [Mbps]	12	39	105
DL Throughput [Mbps]	471	550	1260
Avg RTT Latency [ms]	17	Not measured	14

NOTE: The 3GPP standards currently impose a maximum user aggregate bandwidth of 40MHz in uplink in the CBRS band, in consideration of out-of-band emissions (OOBE) limitations by the FCC. Accordingly, even if we were to increase the total bandwidth for the NR CBRS case, the resulting UL throughput would be similar to our measurement with 1x40MHz.

As can be seen in Table 4-4, NR CBRS offered substantial throughput gains in both uplink and downlink compared to LTE CBRS. This is worth noting, considering that the total bandwidth of 40MHz used in the NR CBRS test is lower than the total bandwidth of 80Mhz in the LTE CBRS case. Furthermore, NR C-Band with a total bandwidth of 100MHz offered significant UL and DL throughput gains compared to both LTE CBRS and NR CBRS. The downlink performance on C-Band is expected to further increase with the aggregation of a second channel – a configuration that was not yet supported by the private network system at the time of these tests.

The trends are overall consistent with the simulated throughput results shown earlier in Table 4-2; with some of the differences between simulated and testbed-measured results attributed to the former assuming a wide range of RF conditions whereas the latter were conducted in near-cell RF condition.

Table 4-5 below shows field-measured throughput results for an NR C-Band macro network system, with 1x100MHz + 1x40MHz channels. The primary cell (PCell) carrying the signaling and uplink data was configured with 100MHz, and the secondary cell (SCell) with 40MHz. The aggregate bandwidth of 140MHz corresponds to Verizon's minimum C-Band spectrum holding in each of the FCC's Primary Economic Areas (PEAs) in the contiguous U.S. These results were measured on a Verizon commercial gNB, for a single user in near-cell RF condition. This case is for 5G SA mode of operation.

Table 4-5:
Measured user throughput in outdoor on-air testbed

	NR C-Band with 100MHz channel (PCell)	NR C-Band with 40MHz channel (SCell)	NR C-Band with 100MHz + 40MHz channel
UL Throughput [Mbps]	90	N/A	90
DL Throughput [Mbps]	810	266	1076

NOTE: As for the CBRS band results presented earlier, the UE used in these C-Band field tests has a limitation to UL 1-CC, resulting in no uplink throughput gain from adding an SCell on top of the PCell.

5. CBRS Prioritized Access Licenses (PAL)

As explained earlier, the unlicensed or GAA channels of the CBRS band, also known as Tier-3, are particularly vulnerable to both channel preemption/reshuffling and Tx power reduction by the SAS due to the mandate to prioritize Tier-1 and Tier-2 CBRS users, and also vulnerable to channel crowding from other nearby GAA deployers using the same 10MHz TDD channels. The SASs are not authorized to give any one GAA deployer exclusive access to a GAA channel. For an enterprise looking for more predictable network availability and reliability, using PAL licensed channels within the CBRS band could be an alternative or an intermediate option to using conventional, non-shared licensed bands. CBRS channels operating as PAL provide protection against crowding from GAA users and other PAL licensees, via exclusive PAL channel grants from the SAS. However, the use of PALs does not provide protection against Tier-1 incumbents from requisitioning channels, nor does the use of PALs remove FCC requirements on CBRS operations such as low power transmission and periodic "heartbeats" between CBSDs and the managing SAS.

At the FCC auction 105 in September 2020, seven PAL licenses (each being a right to a 10MHz TDD channel) were put for sale in the contiguous U.S., with any bidding entity allowed to purchase up to four 10 MHz PALs per county. Note a PAL license in a given county is not tied to a particular frequency; rather, the SAS may assign any 10MHz channel within the lower 100MHz portion of the CBRS band (i.e., 3.55–3.65 GHz), based on the standard SAS channel granting procedure. An eNB/gNB or a UE may aggregate CBRS channels operated in both GAA and PAL modes.

Verizon typically owns three or four PAL licenses (i.e., rights to 30 to 40MHz of CBRS licensed spectrum) in 157 counties in densely populated areas, corresponding to 46% of the U.S. population as of September 2020. Some non-telco enterprises also own PAL licenses in certain areas.

6. Conclusion

In this study we reviewed some of the characteristics of the CBRS band for enterprises looking at a lower-cost approach to private and neutral-host networks mainly for coverage, while pointing out the inherent limitations of this band in terms of reliability and performance. We proposed ways to enhance the reliability and performance of CBRS to a certain extent, such as by using PAL licenses or migrating from LTE to NR CBRS. We shared some simulation and actual test results comparing the performance of LTE and NR CBRS with that of premium licensed spectrum – specifically the C-Band, which falls in the same frequency range but offers larger aggregate bandwidths and is less subject to regulatory restrictions. These results evidence the higher performance of the C-Band, including for uplink throughput which is of importance in many private network use cases. See [5] for examples of 5G private network use cases, and [6] and [7] for typical network requirements.

The added benefits of using conventional licensed spectrum in dedicated networks (e.g., private or neutral-host networks) include the ability to handle some advanced use cases such as industrial, medical and other enterprise applications, and doing so while targeting certain service level objectives such as service availability, network reliability, user latency and throughput. This potential can be unlocked by partnering with an experienced telco such as Verizon, who may not only facilitate access to the spectrum but also support the enterprise in the design, deployment and post-launch management of the networks [8].

The enterprise's anticipated needs for a private or neutral-host network, as well as its familiarity with cellular technologies, may help it make decisions around spectrum and other aspects of the network design. When the choice is not obvious, one possible approach may consist in deploying a CBRS system first to get hands-on with a dedicated network at a relatively low upfront cost, and later upgrade it with licensed spectrum. With such a deployment scenario, the enterprise may want to check upgradability options when acquiring the initial system.

7. References

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