Coverage evaluation of 7–15 GHz bands from existing sites

White paper

Spectrum within the upper-mid range from 7 to 15 GHz is regarded as the "Golden Bands" for 6G due to the potential availability of wider spectrum than that in FR1 for high throughput, as well as the more favorable propagation characteristics of the frequencies as compared to millimeter waves in FR2 (24-51.2 GHz). Critical to the attractiveness of new spectrum for mobile broadband is the ability to re-use the existing site grid on which the current network is deployed. Any need for further site densification causes an undue cost burden as well as extended lead time for deployment. The recently concluded World Radiocommunications Conference (WRC) 2023 agreed on a new IMT/6G study item for WRC-27 including new frequency bands in the 7–15 GHz range. It will conduct further study on technical challenges and solutions to build economically viable and high-performing networks in this spectrum [2].

We provide an analysis comparing the cell edge coverage at 3.5, 7 and 13 GHz bands from existing urban macro cell sites. System level simulation parameters are selected to strike a balance between required transmit power, antenna array size, performance and EMF exposure conditions. Our evaluation shows that the lower part of these Golden Bands (cf. 7 GHz) shares many similarities with the 3.5 GHz spectrum band. Using the same maximum transmit power but two times the bandwidth and four times the number of antenna elements and transceivers chains, future 6G extreme MIMO can provide comparable cell edge throughput as 5G deployed in the 3.5 GHz spectrum band to indoor UEs at 500m ISD. For denser ISD of 350m or for indoor CPE, cell edge rates at 7 GHz could be up to 2.8 times higher relative to edge rates in the 3.5 GHz band. The upper part of the Golden Bands, such as 13 GHz, could provide higher DL edge rates (up to 1.6 times relative to 5G at 3.5 GHz) with some level of densification (e.g., 350m ISD instead of 500m) using effective isotropic radiated power (EIRP) of 85 dBm/100MHz. However, if the FCC's current EIRP proposal of 75 dBm/100MHz is applied, much denser deployments (e.g., 200m ISD) will be required to provide reasonable downlink edge rates.

Contents

Introduction

The World Radiocommunication Conference 2023 (WRC-23) has set the stage for the continued development and deployment of 5G as well as the planning for 6G [1][2] by:

1. Identifying the upper 6 GHz band (6.425-7.125 GHz) for International Mobile Telecommunications (IMT) in Europe, Middle East and Africa, as well as in some countries in the Americas and Asia Pacific
2. Defining an Agenda Item for WRC-27 with new bands to be studied for 6G, including 7.1-8.4 GHz (excluding 7.25-7.75 GHz in Europe used by NATO) and 14.8-15.35 GHz.

There is also a US spectrum pipeline [3] outside the WRC process concerning the 12.7 GHz band (12.7–13.25 GHz), which will be exclusively used for licensed mobile broadband.

While new spectrum is always welcome to improve mobile broadband service, all spectrum bands are not equally attractive. In general, the higher the frequency, the more challenging the band is for wide area coverage. A part of the shortcomings can be overcome with advanced technologies such as higher order antenna arrays and sophisticated beam forming, but the basic propagation characteristics are governed by the universal, fundamental rules of physics. Also, operating requirements for coexistence in the same band or in adjacent bands may lead to some limitations for products and deployments. For example, one has to address co-existence with incumbents like satellites in the upper 6 GHz band and various federal allocations like space research, fixed and mobile satellites, as well as meteorological and earth exploration satellites in the 7.125–8.4 GHz range [4].

A key property of the radio propagation channel is the path loss, usually decomposed into “basic” outdoor loss, representing losses suffered between the outdoor base antenna and outdoor locations near the terminal, and building penetration loss. Compared to the C-band (center frequency assumed at 3.5 GHz), the Golden Bands have two basic issues, namely, higher path loss and higher building penetration loss.

For example, 7 GHz and 13 GHz, which represent the lower and upper parts of the Golden Bands, have respectively 6 and 11.4 dB higher free space path loss as well as 4.5 and 6.5 dB higher building penetration loss (depending upon the composition of construction materials) compared to 3.5 GHz, according to the 3GPP TR 38.901 [5] high-loss model.

There are two closely related advanced techniques that could be leveraged to overcome some of the limitations:

1. Larger antenna arrays achieve higher nominal directivity gain, for example, up to 11.4 dB higher at 13 GHz if maintaining the same aperture.
2. Advanced beamforming enabled by higher numbers of transceiver (TRX) chains, to reduce gain degradation induced by channel angular spread, especially for edge users.

It may be noted that the effective analog beamforming gain is often degraded by angular spread, especially for cell-edge users (including indoor users and users in non-line of sight channels).

This analysis captures all the above key aspects and estimates network performance under a diverse set of operating conditions by also taking into consideration the impact of EIRP limit and EMF exposure condition.

Modeling framework

The three aspects of pathloss, as described in 3GPP TR 38.901 channel models [5] (applicable to 0.7-100 GHz) are covered in the following subsections.

Path loss

In line with the relevant theoretical models, path loss scales proportionally to frequency squared, which means doubling the frequency induces 6 dB extra loss. Compared to the 3.5 GHz band, the 7 GHz band experiences 6 dB higher free space path loss, whereas the 13 GHz band gets hit by a 11.4 dB loss.

In order to compensate for the path loss and make 7 GHz (resp. 13 GHz) propagation loss comparable to that of 3.5 GHz, four times (resp. over 13 times) more antenna elements (AEs) could be packed into the same aperture. In this study [1], four times more antenna elements are used, leading to 6 dB higher nominal gain for 7 and 13 GHz:

1. 3.5 GHz (64 TRX, 256 AE, 29 dBi nominal gain with 8 dBi patches)
   - AE 8 rows x 16 columns x 2 pol; each TRX support a column of 4 AEs
2. 7 and 13 GHz (256 TRX, 1024 AE, 35 dBi nominal gain with 8 dBi patches)
   - AE 16 rows x 32 columns x 2 pol; each TRX support a column of 4 AEs

Delay/angular spread

In theoretical models and 3GPP TR 38.901 [5], delay and angular spreads are only weakly dependent on frequency. While delay spread poses similar challenges for different frequency bands, angular spread has a larger impact for higher frequency bands due to the narrower directional beams generated by larger arrays.

It has been observed that the narrow directional beams of an array such as grid-of-beam analog beamforming will be “widened” by the channel angular spread, resulting in degradation of effective beamforming gain, especially for edge users either indoors or in non-line-of-sight propagation (NLOS). In Figure 1, the measured effective beamforming gain in the NLOS channel is shown to be 10 dBi as compared to its nominal gain of 14.5 dBi when measured in an anechoic chamber. Figure 2 shows the statistics of measured effective gain in a typical indoor environment [6], where at least 7.2 dB gain degradation (out of 14.5 dBi nominal gain) was observed for 10% of users. Higher frequency bands usually use a larger array with higher nominal beamforming gain (i.e., narrower beam width), which makes it more susceptible to directional gain degradation induced by channel angular spread.

1 The base station and antenna characteristics used in the analysis (e.g., number of TRXs and number of antenna elements) do not reflect or anticipate product characteristics but serve to the purpose of evaluating coverage and performance trends across different frequency bands.

Figure 1. Measured effective beamforming gain in NLOS vs. nominal gain in an anechoic chamber

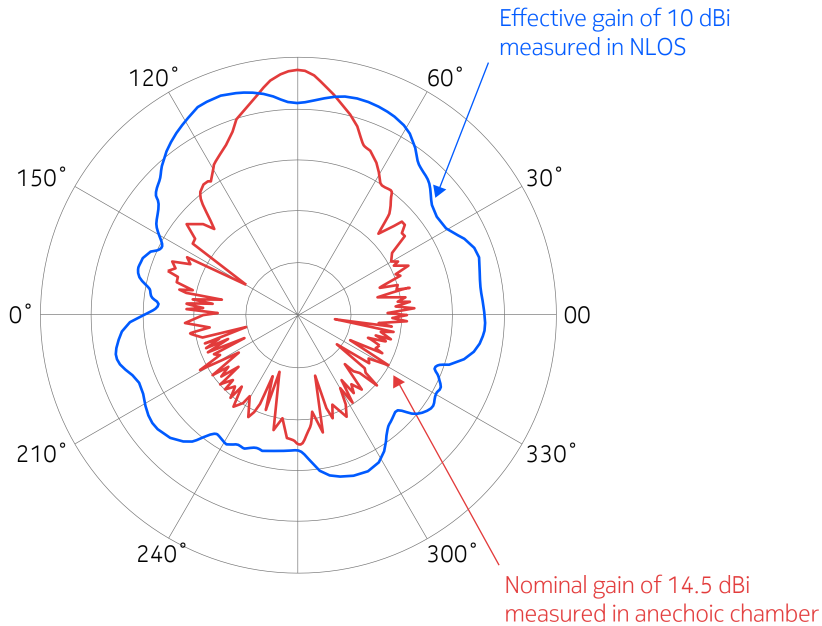
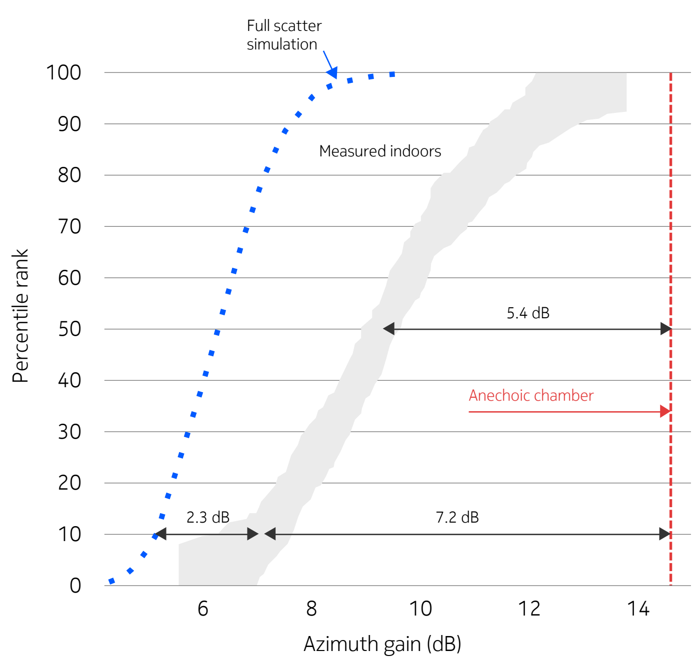


Figure 2. Statistics of measured effective beamforming gain in an indoor environment where high gain degradation (induced by large angular spread) is observed



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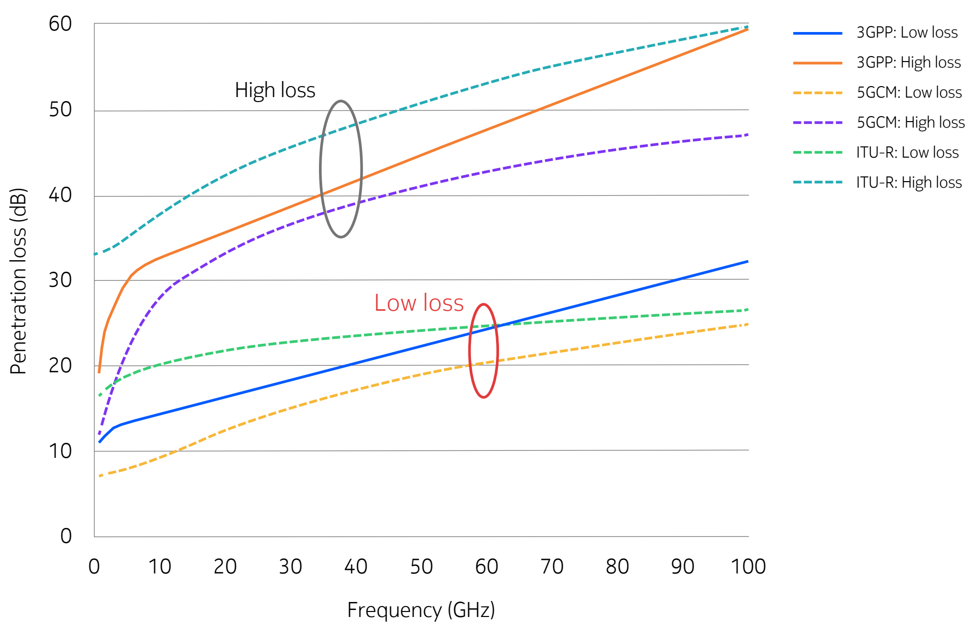
Building penetration loss

Building penetration loss is frequency dependent and varies from building to building depending on the composition of construction materials. 3GPP, ITU-R [7] and 5GCM [8] also provide recommendations for building penetration loss up to 100 GHz, as shown in Figure 3, where their loss values are a function of frequency. All three recommendations classify penetration loss using categories that exhibit high or low penetration loss depending on the thermal insulation in the building design. The following reference values from 3GPP TR 38.901 [5] are well established for modeling.

1. 3GPP high loss model (30% concrete +70% IRR glass)
   -- 26.9 dB / 31.4 dB / 33.5 dB @ 3.5 / 7 / 13 GHz
2. 3GPP low loss model (70% concrete + 30% plain glass)
   -- 12.7 dB / 13.6 dB / 14.8 dB @ 3.5 / 7 / 13 GHz

The following chart highlights frequency dependent material penetration loss as well as two reference building penetration loss models from 3GPP (Figure 3).

Figure 3. Building penetration loss at different frequencies

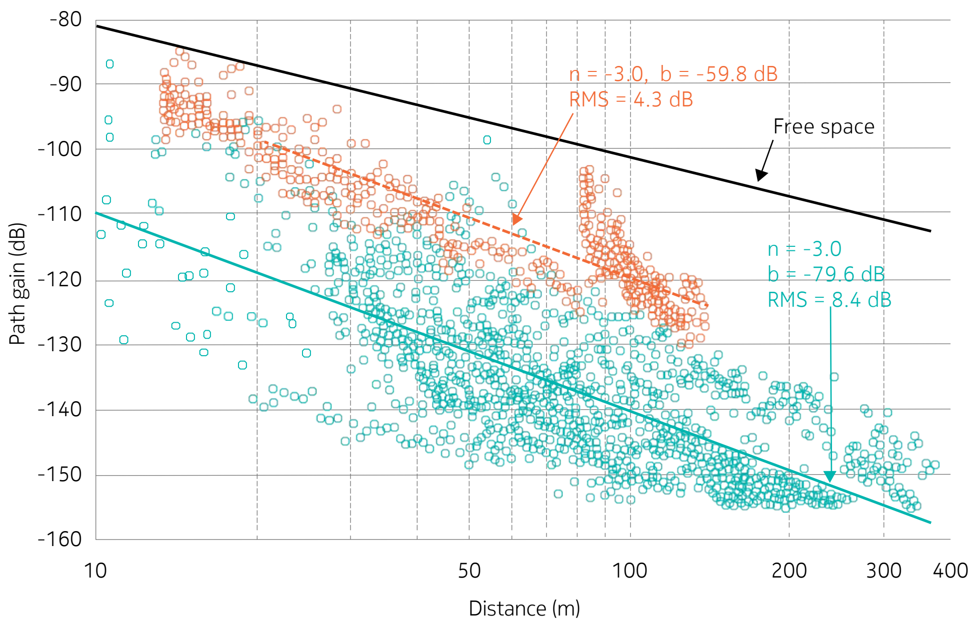


TR 38.901 - V14.3.0 - 5G; Study on channel model for frequencies from 0.5 to 100 GHz.

		Carrier frequency						
Material	**Penetration loss (dB)**	**2**	**2.6**	**3.5**	**7**	**10**	**13**	**28**
Standard multi-plane glass	L glass = 2 + 0.2 f	2.4	2.5	2.7	3.4	4.0	4.6	7.6
IRR glass	L IRRglass = 23 + 0.3 f	23.6	23.8	24.05	25.1	26.0	26.9	31.4
Concrete	L concrete = 5 + 4 f	13.0	15.4	19.0	33.0	45.0	57.0	117.0
Wood	L wood = 4.85 + 0.12 f	5.1	5.2	5.3	5.7	6.1	6.4	8.2
(30% glass + 70% concrete								
UMa/UNi: Low-loss (70% IRR + 30% concrete		11.8	12.3	**12.7**	13.6	14.2	**14.8**	17.8
UMa/UNi: High loss		22.4	24.4	**26.85**	31.4	32.5	**33.45**	37.9

To further illustrate the typical building penetration loss seen in field measurements, Figure 4 is a plot of propagation loss (including building penetration loss) measured in the Upper West Side of Manhattan using 28 GHz spectrum. The data [9] was collected using seven buildings from 38 runs, totaling over 2,000 links (distinct transmit-receiver pairs). The dataset is labeled by window glass types (low-e vs. plain/traditional), where a 20 dB gap in outdoor to indoor building penetration loss was observed, consistent with the large gap between high-loss and low-loss models. New measurements in 7–15 GHz are currently being performed to validate the applicability of the 38.901 model.

Figure 4. 20 dB outdoor to indoor loss gap between buildings with low-E windows and with plain glass windows, observed from 28 GHz measurements conducted in the Upper West Side of Manhattan



Simulation model setup

Detailed system level simulations were carried out using the configuration parameters specified in Table 1. The 3GPP TR 38.901 [5] building penetration loss recommendation (50% high-loss, 50% low-loss) model was used in the system level simulations performed using a UMa (urban macrocell) channel model with 80% indoor users and 20% outdoor users. Two max EIRP levels are used for 7 and 13 GHz simulations to evaluate their impact on DL coverage. Two Inter-Site Distances (ISD) are evaluated, where a 500m ISD corresponds to typical dense urban deployment scenarios and a 350m ISD represents ultra-dense deployment in some EU, Japanese or Korean cities.

Table 1. Configuration parameters for system level simulation

System level simulation configuration parameters	5G (NR, mMIMO)	6G (eMIMO)
	Configuration 1: DL GoB (P1 or P2 or CRI) --> UE or CRI-specific CSI-RS --> Type-I CSI --> DL TX	
BS		
Antenna geometry	8x16x2 (256 radiators) (radiator antenna gain = 8 dBi)	16x32x2 (1024 radiators) (radiator antenna gain = 8 dBi)
TRXU geometry	2x16x2 4:1 aggregation of radiators in elevation 10˚ electrical downtilt	4x32x2 4:1 aggregation of radiators in elevation 10˚ electrical downtilt
Max TX power Max Array gain Max EIRP	Max Tx Power: 53 dBm Max Array gain: 29 dBi 82 dBm EIRP (@rank=1) for 100 MHz BW	Max Tx Power: 53 dBm Max Array gain: 35 dBi 88 dBm EIRP (@rank=1) for 200 MHz BW
Carrier frequency	3.5 GHz	7 GHz, 13 GHz
Duplex mode	TDD DSUDD (no data on ‘S’)	
CSI acquisition	MU Configuration 1; Max rank = 1 (5G), Max rank = 2 (6G): top L beams per UE (L=1,2,4, or 8) Rank=1: 2-port PMI feedback; Rank=2: 4-port PMI feedback	
Scheduler	Wideband “greedy” MU scheduler; UE priority determined by PF scheduler	
Link adaptation	OLLA with 10% BLER target; Max MCS = 256 QAM; MU CQI derived from SU CQI	
Precoding I BF method	MU: Wideband regularized ZF I SU: Wideband single stream	
Impairments Limitations	Configuration 1: P2 BM, non-ideal CSI-RS, non-ideal DMRS Receiver EVM: 28 dB, Transmitter SINR: 22dB	
UE/CPE		
Antenna geometry	4RX (1x2x2) 2TX (1x1x2) Radiators: isotropic (0 dBi)	8RX (1x4x2, UE) 7 GHz: 4TX (1x2x2, UE) and 8TX (1x4x2, CPE) 13 GHz: 8TX (1x4x2, UE/CPE) Radiators: isotropic (0 dBi); directional (8 dBi)
SRS Max TX power	SRS max UL TX power (mobile hand-held form factor) is based on achieving: • 23 dBm max average EIRP for UE • 37 dBm max average EIRP For CPE	
RX modeling	Non-ideal MMSE 12 orthogonal DMRS ports per sector 2-symbol non-ideal DMRS model	
Network		
Cell I UE placement	21 cells, wrap-around I outdoor UE height (1.5m), indoor UE height (per UMa/UMi)	
W load I Modulation I T-put	10 UEs/cell, full buffer I maximum MPR = 7.44 (8 x 0.93) I TDD DL T-put: 3/5 x SE for DSUDD (no data on ‘S’) TDD UL T-put: 1/5 x SE for DSUDD (no data on ‘S’)	
UE speed / Path loss / Penetration Loss Model	3 kmph / 3GPP TR 38.901 / High penetration/Low penetration models chosen 50%/50% randomly. UMa - 80% indoor / 20% outdoor; grid is 350 m or 500 m ISD	
CSI-RS & UE feedback		
CSI-RS type Number of ports per CSI-RS resource	Configuration 1,2 (UE specific); Configuration 4 (NA) 2 ports per UE (total number of ports = 32 per PRB per CSI-RS subframe)	
CSI-RS periodicity	20 ms per UE	
CSI-RS based channel est. at the UE	Link-level abstraction model	
UE feedback type	Type-I CSI WB; MU: Max rank = 1 (5G), Max rank = 2 (6G)	

Key results

Key results that are obtained from detailed system-level simulations using the configurations from Table 1 are summarized in Figure 5 for DL and UL in terms of cell edge throughput (Tput) and in Table 2 and 3 for relative gains.

Figure 5. Summary of DL and UL simulation results

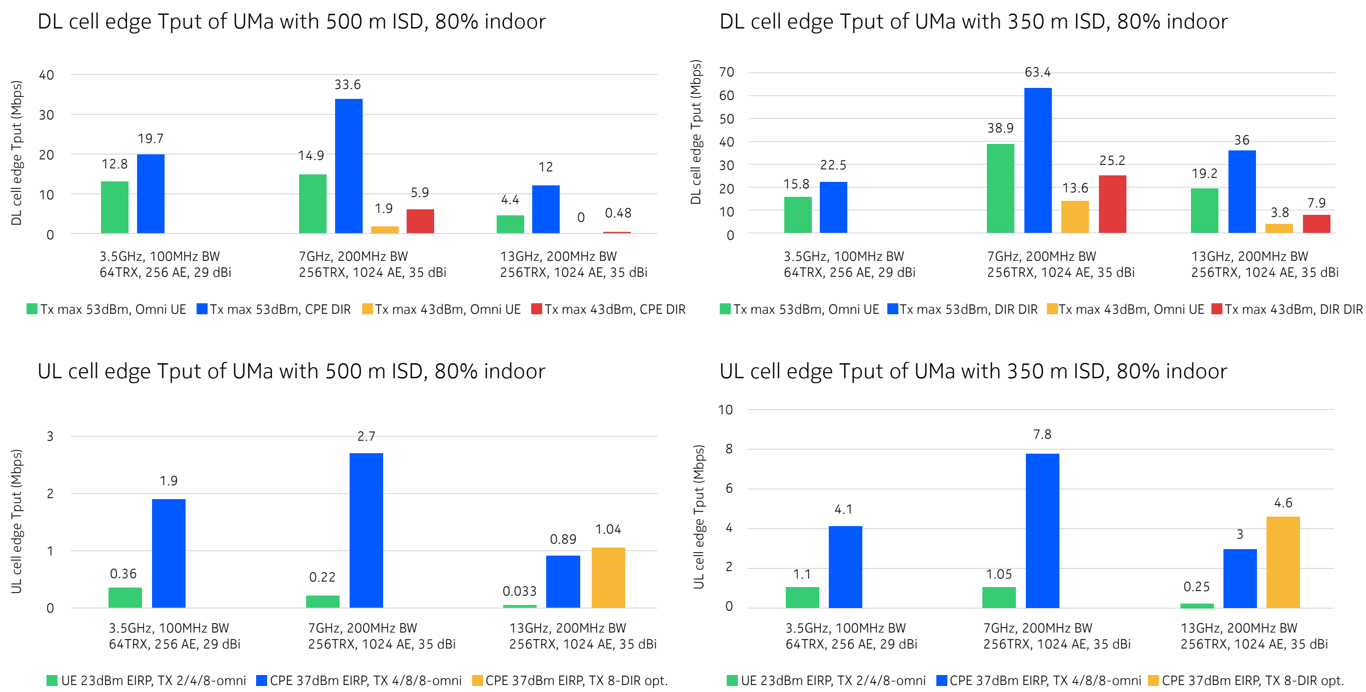


Table 2. DL Cell Edge Throughput of eMIMO deployed at 7 and 13 GHz relative to 5G in 3.5 GHz band

DL Cell Edge Tput relative to 3.5 GHz*	**500m ISD**		**350m ISD**	
	UE	CPE	UE	CPE
7 GHz** vs. 3.5 GHz	1.2x	1.7x	2.5x	2.8x
13 GHz** vs. 3.5 GHz	0.35x	0.61x	1.2x	1.6x

*82 dBm/100MHz DL EIRP, 100MHz BW; UE 4RX omni and CPE 4RX DIR antennas.
**85 dBm/100MHz DL EIRP, 200MHz BW; UE 8RX omni and CPE 8RX DIR antennas.

Table 3. Comparison of Cell Edge Throughput of 7 GHz and 13 GHz

7 GHz vs. 13 GHz* (same BS antenna conf.)	**500m ISD**		**350m ISD**	
	UE	CPE	UE	CPE
UL (Omni UE, Omni CPE)	6.7x	3.0x	4.2x	2.6x
DL (Omni UE, DIR CPE)	3.4x	2.8x	2.0x	1.8x

*8RX UE/CPE at DL. For UL, 4TX UE and 8TX CPE at 7GHz, whereas 8TX UE and 8TX CPE at 13GHz.

Summary of results

- For UE (max average EIRP of 23 dBm) equipped with 2/4/8 TX and omni-antenna elements at 3.5/7/13 GHz bands, respectively, at 500m ISD, the cell edge UL rate at 7 GHz is about two-thirds of the edge rate at 3.5 GHz, whereas 13 GHz could only provide about 9% of the edge rate at 3.5 GHz. For denser deployments with 350m ISD, UL edge rates are more than tripled at all frequencies and the gaps also become smaller: the UL edge rate at 7 and 13 GHz is about 95% and 23%, respectively, of that at 3.5 GHz.
- Cell edge UL rate by a 4TX UE at 7 GHz is about seven times the rate of an 8TX UE at 13 GHz at 500m ISD. At 350m ISD, the gap is about four times, as shown in Table 3.
- For CPE with max average EIRP of 37 dBm, where 4/8/8/ TX are used at 3.5/7/13 GHz respectively, UL edge rates at 7 GHz are up to two times higher than 3.5 GHz at 350m ISD. Adopting directional antennas at 13 GHz would help increase its UL edge rate to comparable levels at 3.5 GHz.
- 75 dBm/100MHz DL max EIRP at 13 GHz, as proposed by FCC [3], corresponds to max 43dBm transmit power over 200MHz BW. This would lead to outage at the cell edge for urban macro sites with ISD of 500m, preventing efficient spectrum use.
- 85 dBm/100MHz max EIRP at 13 GHz improves cell edge DL performance (supporting basic mobile use cases but still up to three times lower than edge rates at 3.5 GHz for 500m ISD). Edge DL rates for 7 GHz are better than 3.5 GHz (up to 2.5x higher rate at 350 m ISD).
- Under the same configurations (Tx power, TRX chains, number of antenna elements, antenna type), the cell edge DL rates at 7 GHz are about three times the rate at 13 GHz at 500 m ISD. The gap reduces to two times at 350 m ISD.

EMF exposure mitigation

Various countries around the world follow different guidelines on EMF exposure as shown below in Figure 6.

Note that most of the countries, including the US, have adopted the EMF exposure limit of 10 W/m2 specified in FCC 47CFR 1.1310 [10] for the general public for frequencies between 2 and 100 GHz. For a compliance distance of d [m], the maximum EIRP is upper bound by EIRPmax =10W/m2 x 4pd2.

Extra power reduction factor (FPR) together with a TDD duty cycle of 0.75 could introduce -6 dB margin to reduce the EMF exposure (averaged over 30 min) following the actual maximum approach as specified in IEC 62232 ED3 [11]. With a TDD duty cycle of 3/5 (due to not having data on the 'S' symbol of DSUDD) would result in a margin FPR =-7 dB.

Max EIRP of 88 dBm (if 200MHz bandwidth is used with an 85dBm/100MHz limit) implies a compliance distance of 36 m if a -6 dB power reduction factor is applied, and the compliance reduces to 32 m for a -7 dB power reduction factor, which corresponds to the duty cycle of 3/5 (as modeled in the DL system-level simulation).

- EMF exposure mitigation measures would be needed for some specific sites if sufficient compliance distance, as shown in Table 4, cannot be maintained.

Figure 6. EMF exposure limits for different frequencies

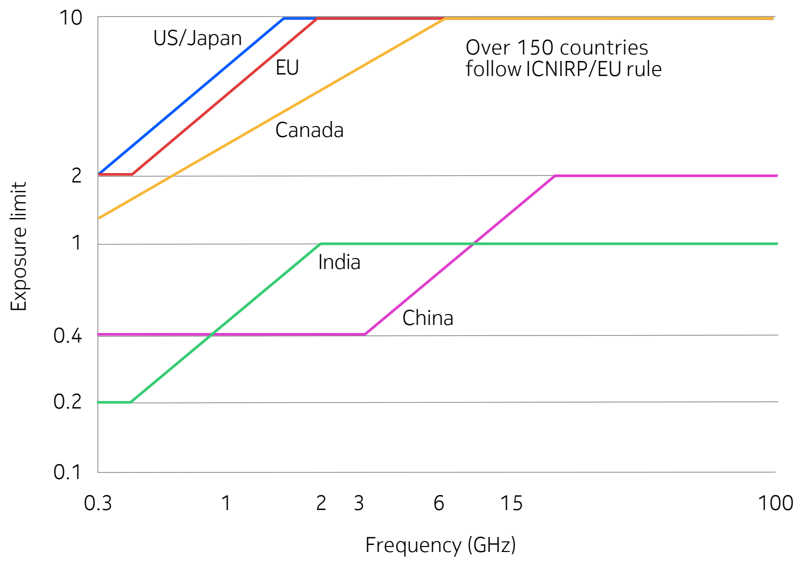


Table 4. EMF exposure compliance distance as a function of max EIRP

Max EIRP	Compliance distance after mitigation	
	-6 dB margin	**-8 dB margin**
82 dBm	18 m	14 m
85 dBm	25 m	20 m
88 dBm	36 m	28 m
92 dBm	56 m	45 m

Conclusion

The lower part of the Golden Bands (cf. 7 GHz), when both base station and user terminals are equipped with more antenna elements, can provide comparable (for UE) or higher (for CPE) cell edge throughput than 5G deployed at 3.5 GHz spectrum. The upper part of the Golden Bands, such as 13 GHz, could provide reasonable cell edge coverage by using a higher number of TRX chains and directional antennas on the UE/CPE side. Under the same configurations (Tx power, TRX chains, number of antenna elements, antenna type), the cell edge DL rates at 7 GHz are about three times the rate at 13 GHz at 500m ISD. The gap reduces to two times at 350m ISD. For UL, the cell edge rate of a 4TX UE at 7 GHz is about seven times the rate of an 8TX UE at 13 GHz at 500m ISD, and the gap is about four times at 350m ISD, as summarized in Table 3.

Our coverage analysis comparing the cell edge throughput at 3.5, 7 and 13 GHz bands from existing urban macro cell sites indicates that +75 dBm/100 MHz EIRP in 13GHz band — with deployment scenarios considering ISD values that are typical of currently deployed 5G bands — would result in very poor cell-edge performance or even service outage. For example, for common user equipment with omni-directional antennas, a +75 dBm/100 MHz EIRP for base stations in the 13 GHz band would lead to a cell-edge throughput that is only 24% of the edge rate for C-band at 350m ISD. This EIRP would lead to service outages for a 500m ISD.

By increasing the EIRP limit to +85 dBm/100 MHz for 13 GHz, it could provide higher DL edge rates than 5G in 3.5 GHz band (1.2 times for UE and 1.6 times for CPE) with 350m ISD. Cell-edge DL throughput in the 13 GHz band would be lower than that of 5G in C-band (35% for UE and 61% for CPE) with 500m ISD, as summarized in Table 2. However, this is still a major improvement over the EIRP of +75dBm/100 MHz, as mentioned before.

With respect to EMF exposure, the limit of 10 W/m2 is considered, as per FCC rules, and necessary distances from the base station for compliance with this requirement are assessed following standard approaches.

Assuming +85 dBm/100 MHz as EIRP limit, a 200 MHz operating bandwidth at Golden Bands would lead to an 88 dBm maximum EIRP, whose compliance distance is 36 m if a -6 dB power reduction factor is applied (see Table 4). Note that EMF exposure mitigation measures can be employed in specific sites to reduce the required compliance distance, if needed.

Further improvements in coverage are needed to make the Golden Bands more valuable for 6G deployments. For example, UL power control parameters can be fine-tuned to increase UL cell edge spectral efficiency (SE). More TRX chains with directional antenna have been shown beneficial for coverage enhancement, and further improvement on CSI acquisition, beam management and MU-MIMO precoding could also be very helpful.

More disruptive innovations that require standardization are another venue for active research.

Abbreviations

3GPP	Third-generation partnership program
BLER	Block error rate
BM	Beam management
BS	Base station
BW	Bandwidth
CPE	Customer premises equipment
CQI	Channel quality indicator
CRI	CSI-RS resource indicator
CSI	Channel state information
DL	Downlink
DMRS	De-modulation reference signal
EIRP	Effective isotropic radiated power
EMF	Electro-magnetic field
eMIMO	Enhance MIMO
EVM	Error vector magnitude
GoB	Grid of beams
ICNRP	International Commission on Non-Ionizing Radiation Protection
ISD	Inter-site distance
IRR	Infrared reflecting
MCS	Modulation and coding scheme
MPR	Maximum power reduction
MIMO	Multiple-input, multiple-output
mMIMO	Massive MIMO
MMSE	Minimum mean square error
MU	Multi-user
NSA	Non-standalone
NLOS	Non-line-of-sight propagation
NR	New radio (5G)
OLLA	Outer loop link adaptation
P1/2	Priority 1/Priority 2
PF	Proportional fairness

PMI	Pre-coded matrix indicator
PRB	Physical resource block
QAM	Quadrature amplitude modulation
RS	Reference signal
RX	Receive
SE	Spectral efficiency
SINR	Signal-to-interference-plus-noise ratio
SRS	Sounding reference signal
SU	Single user
TDD	Time division duplex
Tput	Throughput
TRX	Transceiver
TX	Transmission
UMa	Urban macrocells
UMi	Urban microcells
UE	User equipment
WB	Wideband
ZF	Zero forcing

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Document code: CID213702 (April)