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Qualcomm

Engaging 60 GHz and Beyond in 5G

Evolution of 5G

From Rel-16 to Rel-17

- 3GPP Rel-16 achieved the following milestones:
  - Expansion of cellular to new verticals
    - Automotive, industry/factory automation, broadcasters, cable operators, satellite comm, etc
  - eMBB enhancements
    - UE power savings, eMIMO, RIM/CLI, IAB, etc.
  - Explore expansion to new spectrum (7-24GHz, unlicensed)
  - Continue LPWA / 5G Massive MTC evolution with NBIOT/eMTC

Principles of Release 17:

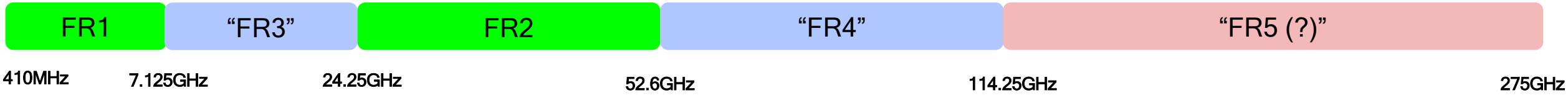
- Leverage the flexibility of 5G to
  - continue to expand the scope of cellular

  AND
  - Evolve stability & maturity of 5G further

Spectrum Expansion

“FR3”, “FR4” & beyond

- NR Rel-15 defined FR1 (“sub7”) and FR2 (“mmW”)
- “FR3” is subject of RAN4 study
  - Increased ranges of currently defined FR1 (410MHz-7.125GHz) & FR2 (24.25GHz-52.6GHz)
- >52.6 GHz (“FR4”) went through a round of RAN study
  - Rel-17 to define NR in the frequency range from 52.6GHz to 114.25GHz
  - Specific bands:
    - 57-71 GHz: Unlicensed spectrum in most countries
    - 71-76, 81-86, 92-95 GHz: Licensed spectrum in most countries
- Discussions on >114.25GHz (“FR5?”) are occurring in some regulatory circles
  - Possible future evolution of the 5G NR framework

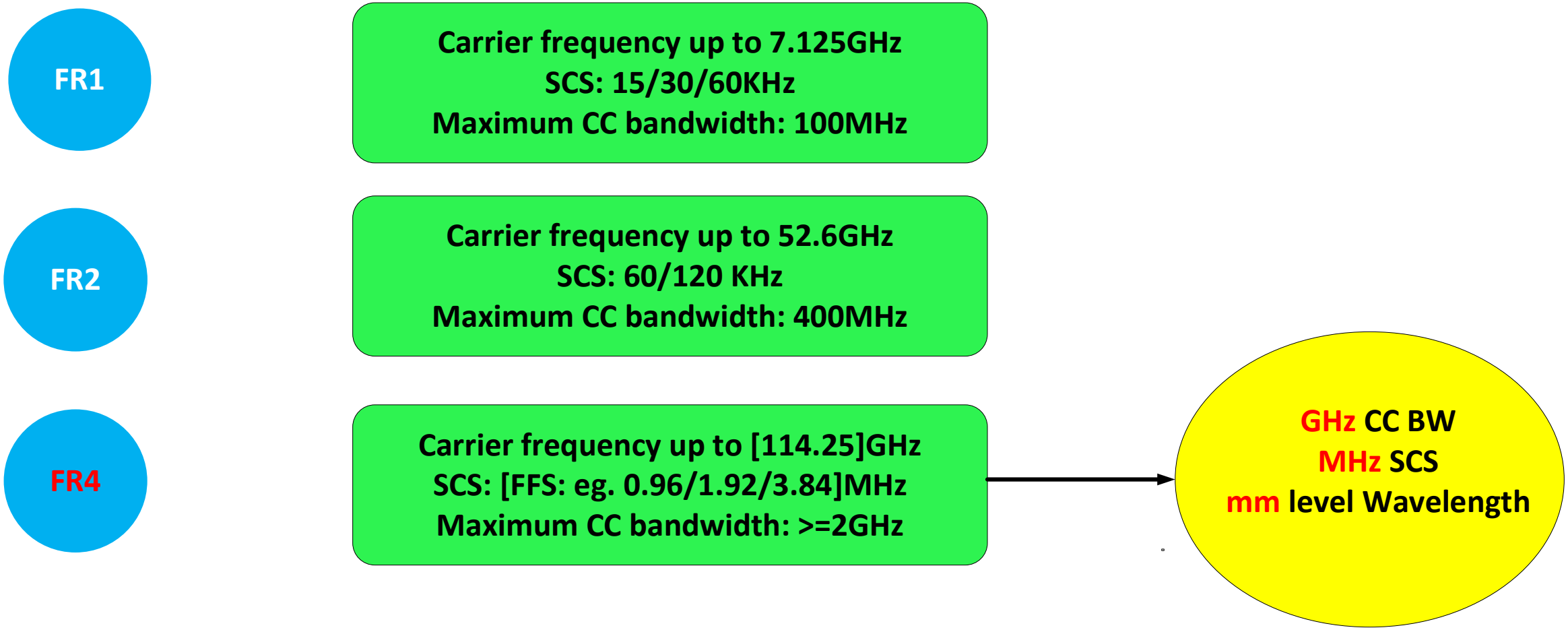


Frequency diagram not at scale

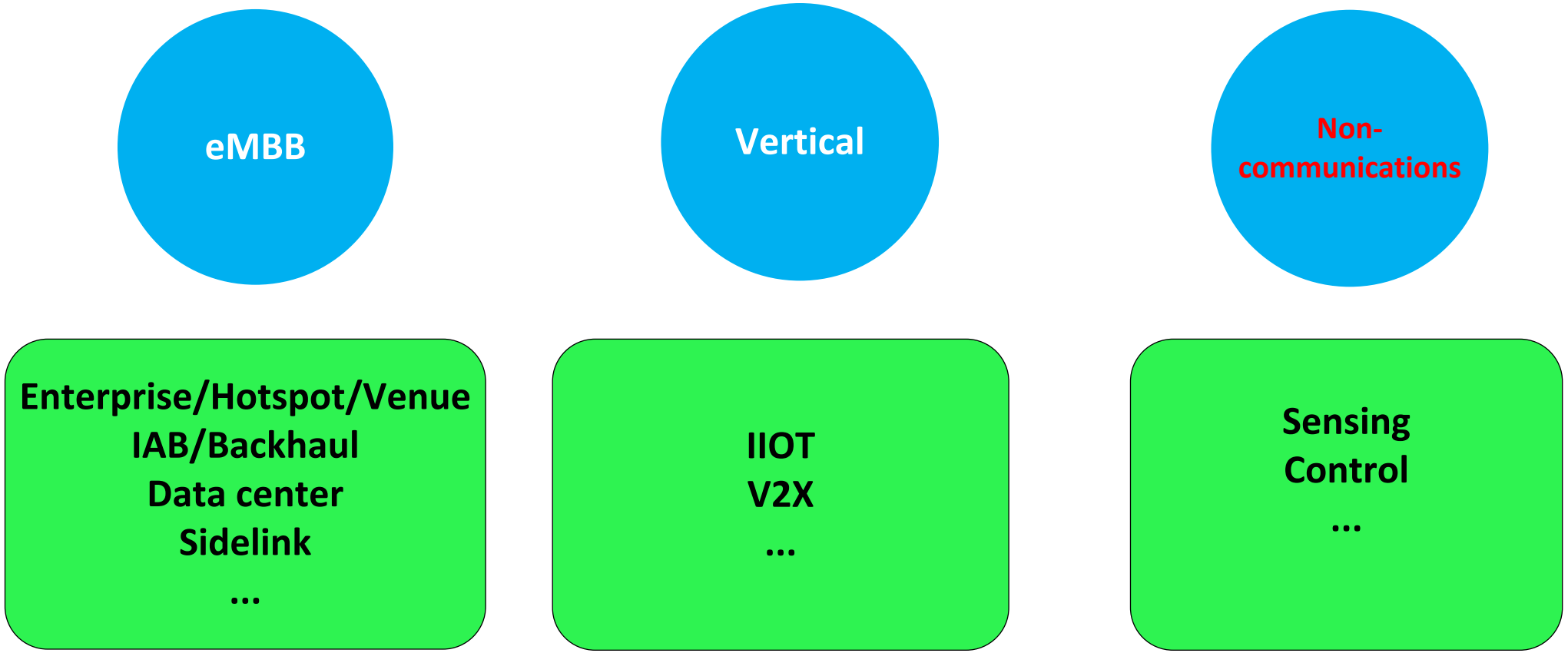
Spectrum availability and regulation in FR4

Country	Spectrum (GHz)	EIRP limit with unlicensed mobile use case	EIRP limit with Unlicensed fixed link use case	Spectrum	EIRP limit with licensed fixed link use case	Licensed mobile use case
Europe/CEPT	57-66, 66-71 TBD	40dBm (mean)		71-76, 81-86 92-114.25 TBD	85dBm	TBD
South Africa	57-66	40dBm	55dBm	71-76, 81-86	85dBm	TBD
USA	57-71	40dBm (avg.) 43dBm (peak)	82dBm (avg.) 85dBm (peak)	71-76, 81-86, 92-95 95-114.25 TBD	85dBm	Open for mobile use case, details TBD
Canada	57-71	40dBm (avg.) 43dBm (peak)	82dBm	71-76, 81-86	85dBm	TBD
Brazil	57-64	*peak power <= 27dBm		71-76, 81-86	85dBm	TBD
Mexico	57-64	40dBm (avg.) 43dBm (peak)	85dBm	71-76, 81-86	85dBm	TBD
China	59-64	44dBm (mean), 47dBm (peak)		TBD	TBD	TBD
Japan	57-66	*power below 250mW		71-76, 81-86	*peak power below 1W	TBD
South Korea	57-66	43dBm (peak)	57dBm	71-76, 81-86	85dBm	TBD
Singapore	57-66	40dBm		71-76, 81-86	available till Dec 2019	TBD
Australia	57-66	43dBm (peak)	52dBm	TBD	TBD	TBD
Israel, India, Taiwan	TBD		TBD	TBD	TBD	TBD

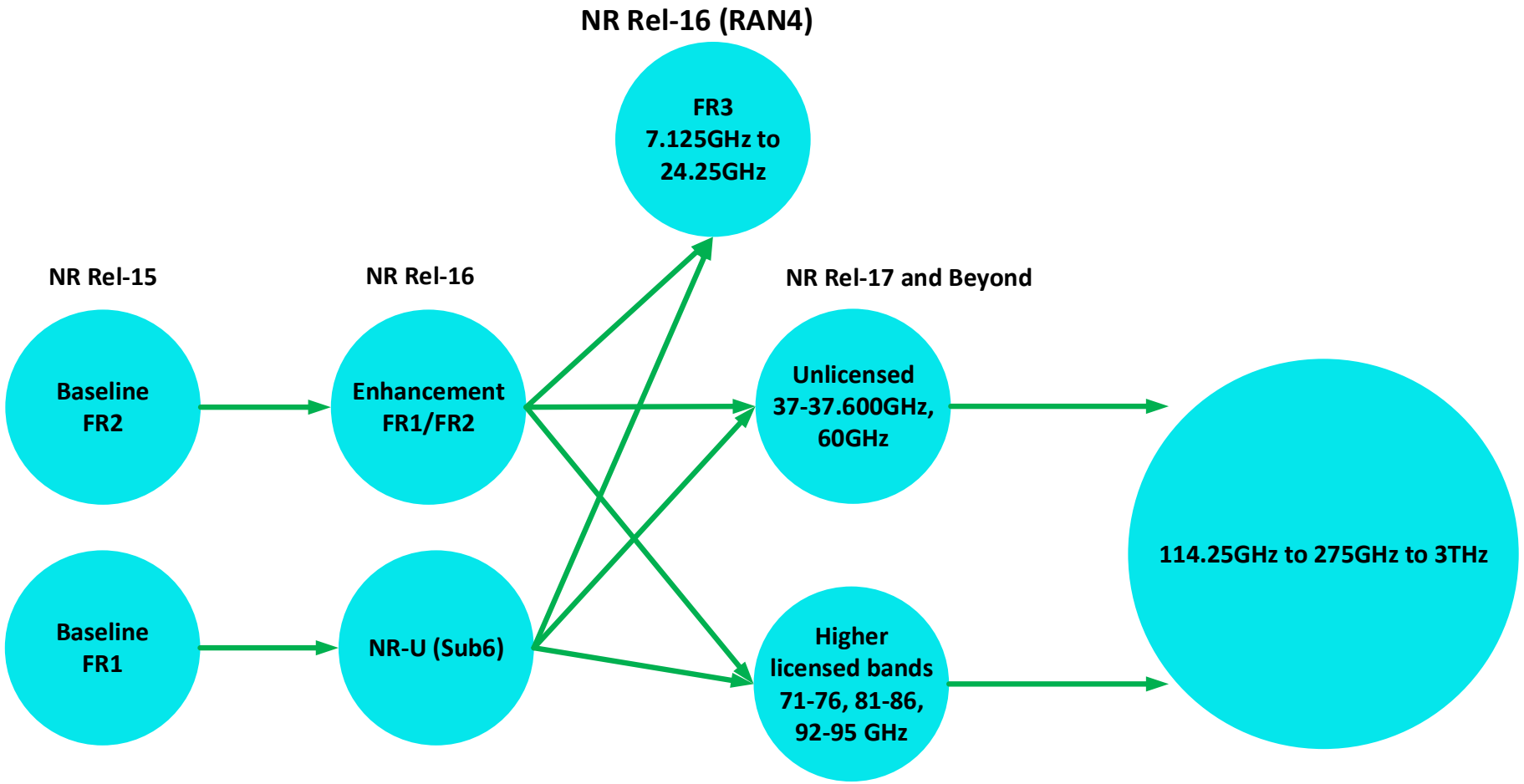
First order properties of FR1/2/4



Use cases


eMBB
Vertical
Non-communications
Enterprise/Hotspot/Venue
IAB/Backhaul
Data center
Sidelink
...
IIOT
V2X
...
Sensing
Control
...

FR4 Design: Built on top of FR1/FR2 and NR-U



EIRP and Antenna Arrays

Ballpark Characterization

	16 ant. elements	32 ant. elements	64 ant. elements	128 ant elements	256 ant elements	512 ant elements
Total ant. gain (dB)	17	20	23	26	29	32
Power per ant. element	EIRP (Assume: 5 dBi antenna element gain)					
0 dBm	29	35	41	47	53	59
3	32	38	44	50	56	62
6	35	41	47	53	59	65

- Observations:
  - Licensed bands have a higher EIRP limit → Hence, coverage is likely to be determined by implementation capabilities

- Observations:
  - Unlicensed band (57-71 GHz) has a low EIRP limit → Hence, EIRP is more likely to be determined by regulatory limits

ETSI Regulations in 60 GHz

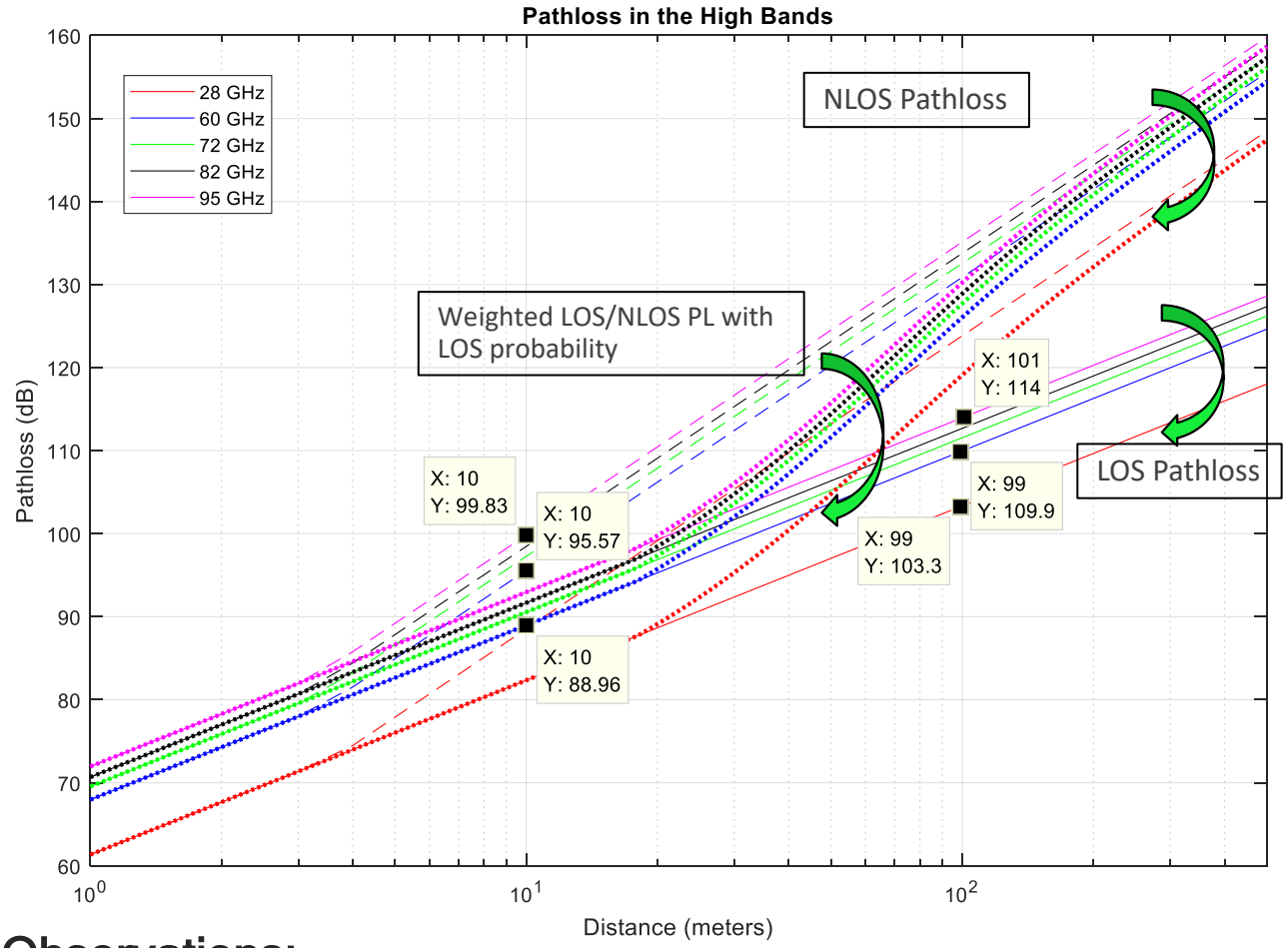
Mode	Power / Magnetic Field	Notes
c1	40 dBm e.i.r.p., 23 dBm/MHz e.i.r.p. density	Fixed outdoor installations are not allowed.
c2	40 dBm e.i.r.p., 23 dBm/MHz e.i.r.p. density and maximum transmit power of 27 dBm at the antenna port or ports	
c3	55 dBm e.i.r.p., 38 dBm/MHz e.i.r.p. density and transmit antenna gain ≥ 30 dBi	Applies only to fixed outdoor installations

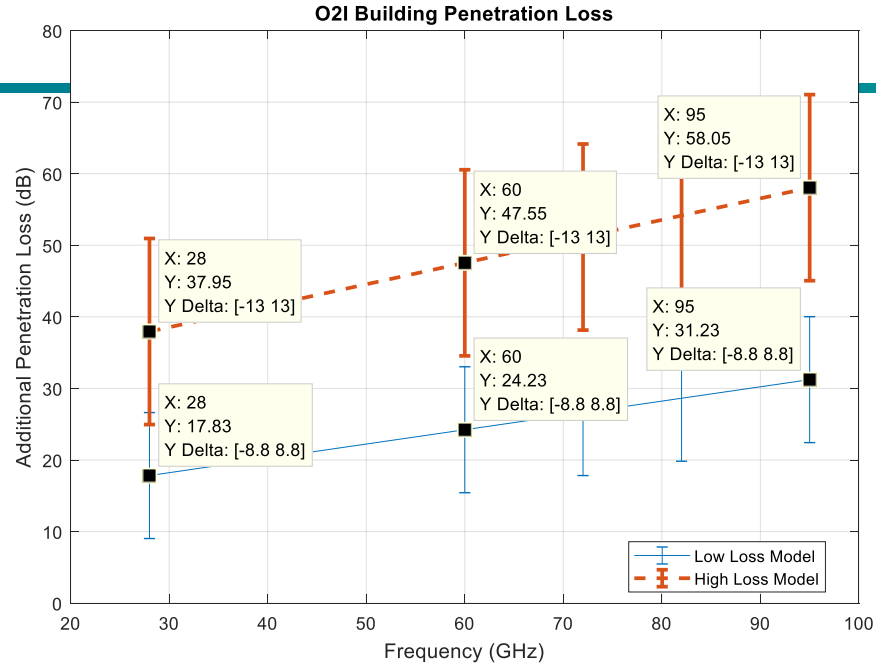
Frequency diagram not at scale

System Studies

- **System Studies**
  - Capacity / Coverage for InH and UMi deployments
  - Spectrum Sharing: The unregulated / uncoordinated version
  - IIoT Capacity: A preview

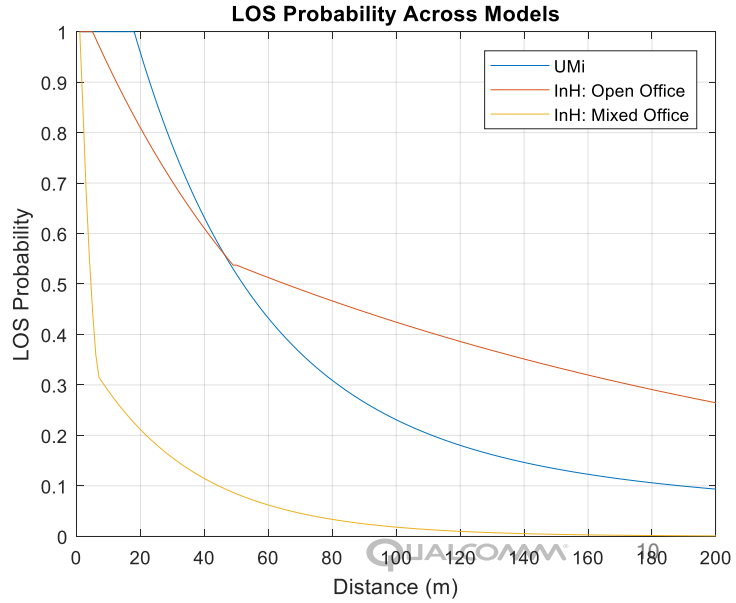
Propagation Comparison





Out-To-In Loss as a function of frequency

LOS probability is frequency Independent from the 38.901 model

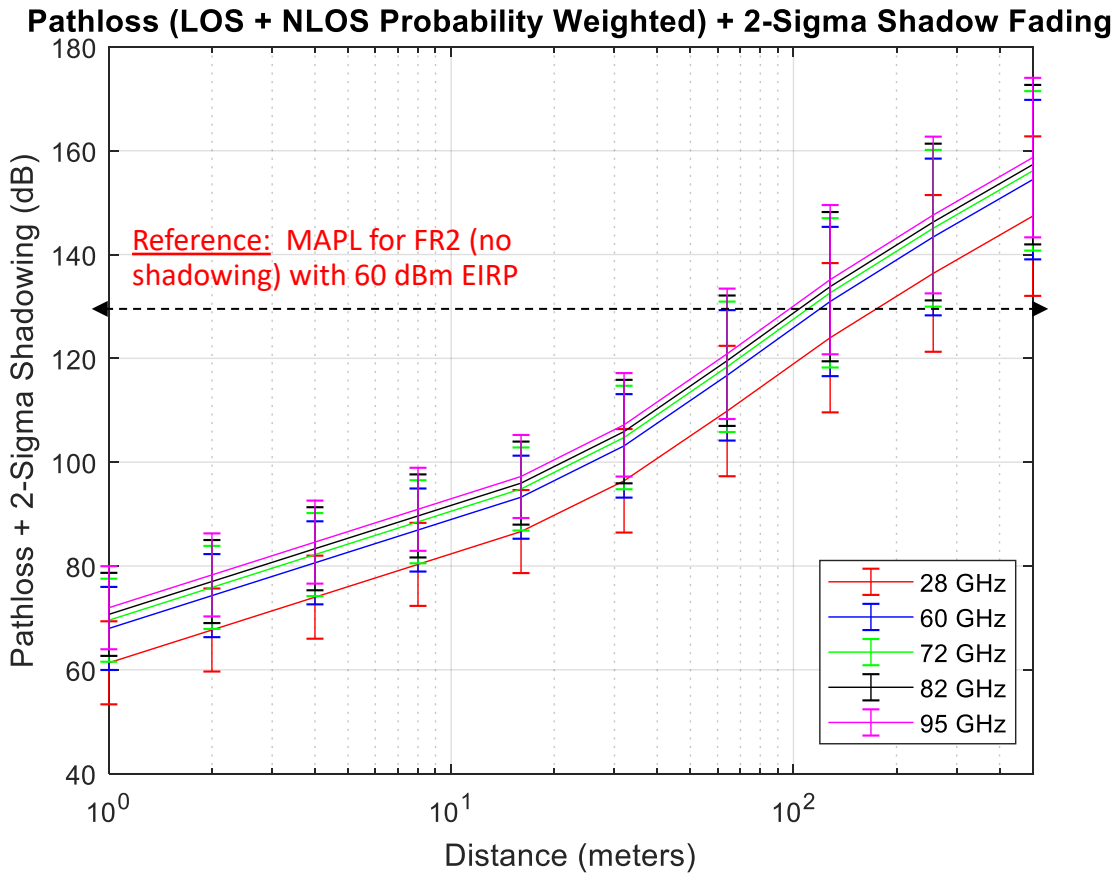


- **Observations:**
  - Propagation at 60 GHz is about 6.6 dB worse compared to FR2
  - Propagation at 95 GHz is about 11 dB worse compared to FR2
  - Note: Beamforming can be increased for FR4, due to smaller wavelengths (larger antenna arrays)

Source: 3GPP TR 38.901 Study on Channel Model for Frequencies from 0.5 to 100 GHz

Propagation Comparison

Assume licensed FR4, similar to licensed FR2 has a high (>= 73 dBm) EIRP limit



Compared to FR2....	FR4 (60 GHz)	FR4 (95 GHz)
Propagation loss	-6.6 dB	-11.0 dB
EIRP (assuming 60 dBm for FR2 deployments)	-20 dB	--
Out-to-in loss (Low loss model)	-6.4 dB	-14.4 dB
Beamforming	+3-6 dB (Rx only) (No gain on Tx if system is EIRP limited)	6-16 dB (3-8 dB on Tx, 3-8 dB on Rx) **Assuming 2-6x more antenna elements*
Total without Out-to-In loss	***--20 to 23 dB***	***- 5 dB to 5 dB***
With Out-to-In (low loss model)	*-30 dB*	*-15.4 dB*

Larger arrays become possible at smaller wavelengths for same array dimensions

- **Summary:**
  - *Licensed FR4 operation can achieve similar coverage as FR2* for Out-to-Out and In-to-In scenarios. Out-to-In is expected to be very challenging (may use other ways to overcome this limit similar to methods considered for FR2)
  - Unlicensed FR4 coverage is not limited to very short ranges → Approx. 70m for LOS links, 20m for NLOS links whereas 802.11ad typically advertises a 1-10m range

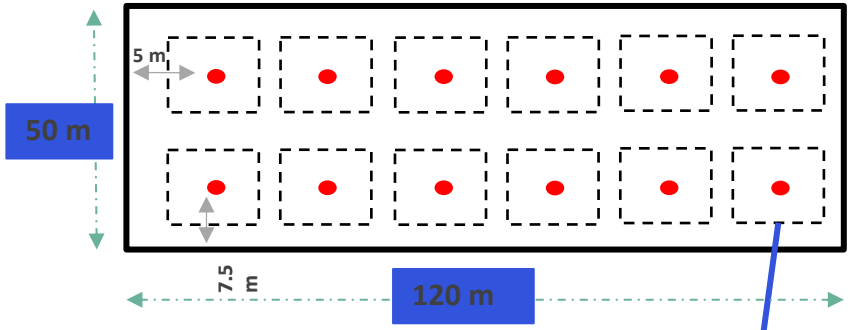
System Study Assumptions

- This section explores system level performance for
  - Single operator, 28/60/72/82/95 GHz
  - DL Only, UL Only, Mixed DL / UL: Full buffer traffic
  - Spectrum sharing: Multi-operator performance without special mechanisms

Parameters	
Carrier freq.	28 / 60 / 72 / 82 / 95 GHz
BW	*As in previous slide*
EIRP	*As in previous slide*
gNB ant array	128/256/512 antenna elements
UE ant array	4/16 antenna elements
Traffic	DL only, Full buffer traffic
Codebook	L3-only codebook at gNB and UE

InH Deployment

- Single sector pointing down
- 12 gNB over 120 m x 50 m
- 10 UE per gNB

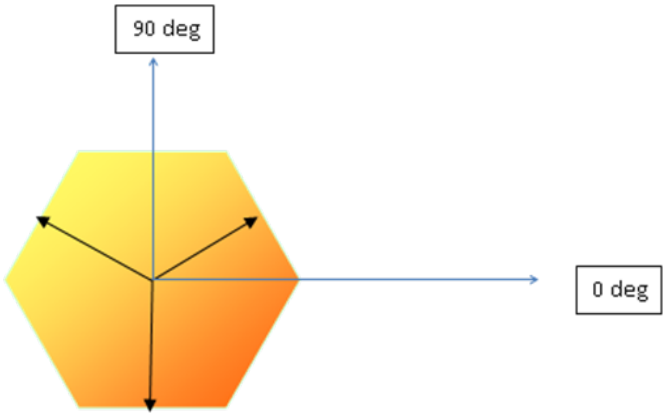


5 m x 5 m box – No Walls

- Nodes are slot synchronized

UMi Deployment

- Three sector pointing vertical
- 19 gNB, with three sectors each
- 10 UE per sector
- ISD: 20/50/100/200m



InH, Open Office: Comparison of DL Spectral Efficiencies

28 GHz (Cfg 1,3,5 are typical)

	Cfg 1	Cfg 2	Cfg 3	Cfg 4	Cfg 5	Cfg 6
BW (MHz)	100	100	400	400	800	800
EIRP (dBm)	52	40	52	40	52	40
gNB (M,N,P)	128 per pol (16,8,2)					
UE ant (M,N,P)	Two panels at UE: 16 per pol (4,4,2) 1 (max. RSRP) panel is chosen at association					

20 ms ISD {Config, Tilt} 78.57% FS eff 90% BW eff	5th Percentile UE SE (bps/Hz)	Median UE SE (bps/Hz)	Mean Cell SE (bps/Hz)
	(128, 16)	(128, 16)	(128, 16)
Cfg 1	0.45	0.95	8.83
Cfg 2	0.46	0.95	8.75
Cfg 3	0.47	0.95	8.82
Cfg 4	0.39	0.92	8.40
Cfg 5	0.44	0.96	8.80
Cfg 6	0.35	0.88	8.06

60 GHz (Cfg 2,4,6 are Regulatory compliant)

	Cfg 1	Cfg 2	Cfg 3	Cfg 4	Cfg 5	Cfg 6
BW (MHz)	50	50	500	500	2160	2160
EIRP (dBm)	52	40	52	40	52	40
gNB ant (M,N,P)	128 per pol (16,8,2)					
UE ant (M,N,P)	Two panels at UE: 16 per pol (4,4,2) 1 (max. RSRP) panel is chosen at association					

20 ms ISD {Config, Tilt} 78.57% FS eff 90% BW eff	5th Percentile UE SE (bps/Hz)	Median UE SE (bps/Hz)	Mean Cell SE (bps/Hz)
	(128, 16)	(128, 16)	(128, 16)
Cfg 1	0.49	0.92	8.51
Cfg 2	0.44	0.89	8.24
Cfg 3	0.46	0.93	8.58
Cfg 4	0.28	0.79	7.14
Cfg 5	0.40	0.91	8.15
Cfg 6	0.15	0.54	5.59

82 GHz (Cfg 1,3,5 estimated to be achievable)

	Cfg 1	Cfg 2	Cfg 3	Cfg 4	Cfg 5	Cfg 6
BW (MHz)	100	100	625	625	1250	1250
EIRP (dBm)	52	40	52	40	52	40
gNB ant (M,N,P)	128 per pol (16,8,2)					
UE ant (M,N,P)	Two panels at UE: 16 per pol (4,4,2) 1 (max. RSRP) panel is chosen at association					

20 ms ISD {Config, Tilt} 78.57% FS eff 90% BW eff	5th Percentile UE SE (bps/Hz)	Median UE SE (bps/Hz)	Mean Cell SE (bps/Hz)
	(128, 16)	(128, 16)	(128, 16)
Cfg 1	0.45	0.92	8.42
Cfg 2	0.36	0.86	7.67
Cfg 3	0.45	0.93	8.24
Cfg 4	0.19	0.63	6.17
Cfg 5	0.37	0.91	8.03
Cfg 6	0.13	0.53	5.46

- **Summary:**
  - FR4 can support indoor use cases, as in FR2
  - 60 GHz: 5th PC UE data rates: 324 Mbps (10 UE / cell) Mean cell throughput: 12.07 Gbps
  - 82 GHz: 5th PC UE data rates: 462 Mbps (10 UE / cell) Mean cell throughput: 10.04 Gbps

60 GHz in UMi Deployment

- Common Assumptions: Up to rank 2, up to 256 QAM are used

Config, ISD, 78.57% FS efficiency 90% BW efficiency	SU / MU Order	5th Percentile UE SE (bps/Hz)	Median UE SE (bps/Hz)	Mean Cell SE (bps/Hz)
		(256, 16)	(256, 16)	(256, 16)
Config 1, 200	SU	0	0.06	1.08
Config 2, 200	SU	0.06	0.52	5.28
Config 3, 200	SU	0	0.006	0.25
Config 4, 200	SU	0.009	0.26	3.16
Config 5, 200	SU	0	0.001	0.08
Config 6, 200	SU	0.002	0.12	1.76
Config 1, 100	SU	0.02	0.23	2.78
Config 2, 100	SU	0.27	0.70	7.76
Config 3, 100	SU	0.002	0.05	0.86
Config 4, 100	SU	0.12	0.56	6.00
Config 5, 100	SU	0	0.01	0.27
Config 6, 100	SU	0.06	0.36	4.17
Config 1, 50	SU	0.06	0.33	3.93
Config 2, 50	SU	0.30	0.80	8.22
Config 3, 50	SU	0.006	0.10	1.48
Config 4, 50	SU	0.21	0.67	6.96
Config 5, 50	SU	0.001	0.03	0.55
Config 6, 50	SU	0.11	0.48	5.38
Config 1, 20	SU	0.07	0.31	3.80
Config 2, 20	SU	0.19	0.59	7.08
Config 3, 20	SU	0.01	0.11	1.49
Config 4, 20	SU	0.16	0.53	6.34
Config 5, 20	SU	0.002	0.03	0.58
Config 6, 20	SU	0.11	0.42	5.03

	Config 1	Config 2	Config 3	Config 4	Config 5	Config 6
Bandwidth (MHz)	50	50	500	500	2160	2160
	Reduce BW to increase PSD density					
EIRP (dBm)	40	60	40	60	40	60
gNB ant (M,N,P)	256 per pol (32,8,2)					
UE ant (M,N,P)	Two panels at UE: **16 per pol (4,4,2)** 1 (max. RSRP) panel is chosen at association					

- Given low EIRP, increasing PSD density (i.e., lowering bandwidth) helps 60 GHz increase coverage → See 50 MHz, 500 MHz results vs. 2.16 GHz
- Many NR supported techniques can increase coverage
- Summary: 60 GHz can support dense urban use cases for a few 10s of meters
  - R-15 / R-16 NR techniques can be used to optimize coverage

60 GHz (Cfg 1,3,5 are Regulatory compliant)

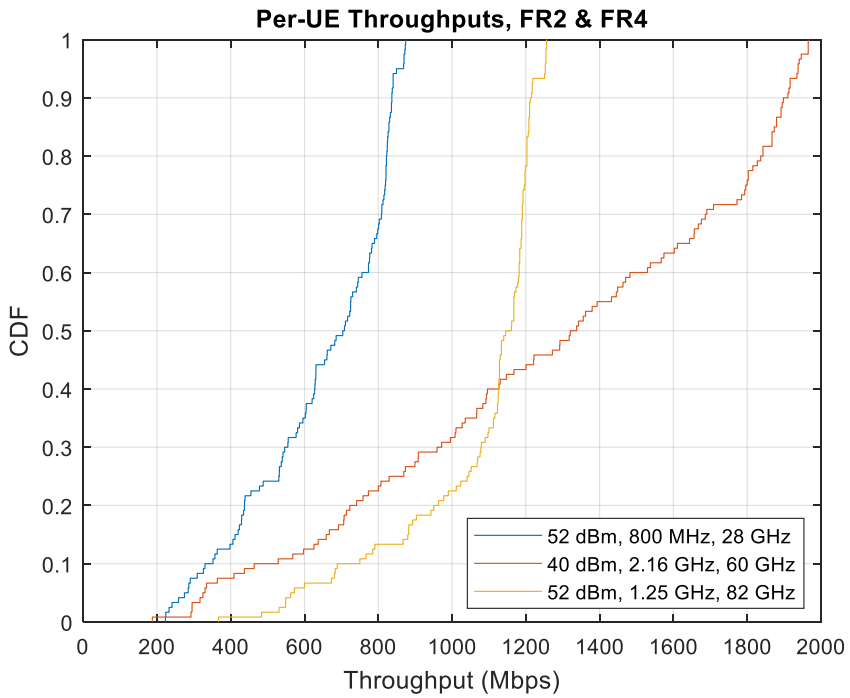
60 GHz (Cfg 2,4,6 are with hypothetical higher EIRP)

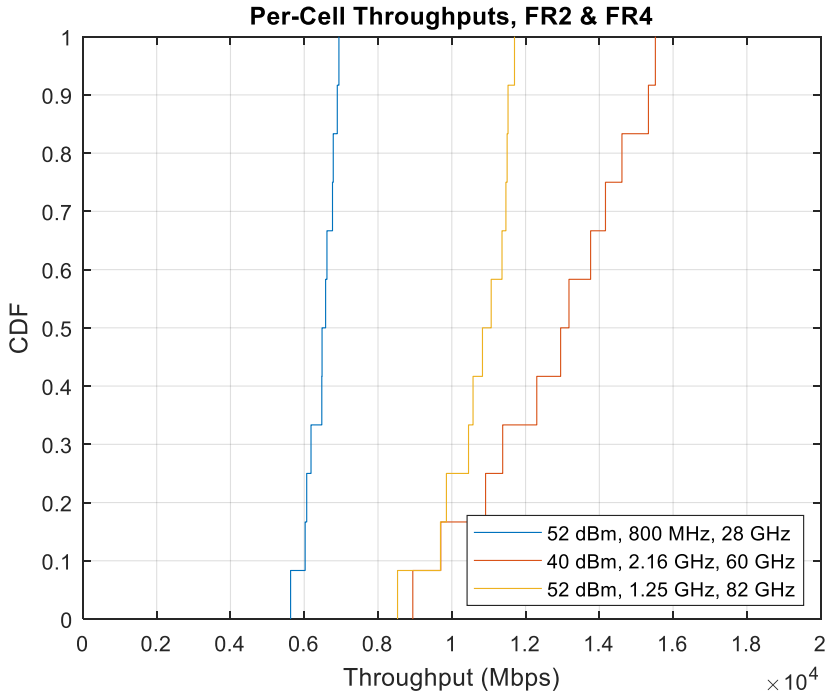
Comparison Across Bands: With “Typical” Parameters

Operating Parameters:

- 28 GHz: 52 dBm, 800 MHz, 128 gNB el per pol, 4 UE el. per pol
- 60 GHz: 40 dBm, 2.16 GHz, 512 gNB el per pol, 16 UE el. per pol
- 82 GHz: 52 dBm, 1.25 GHz, 512 gNB el per pol, 16 UE el. per pol

} Larger array size for similar dimensions at FR4

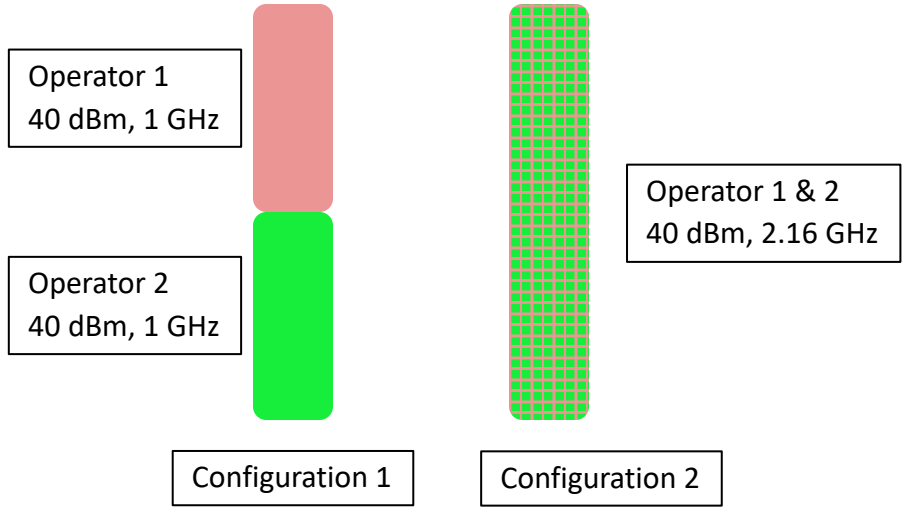


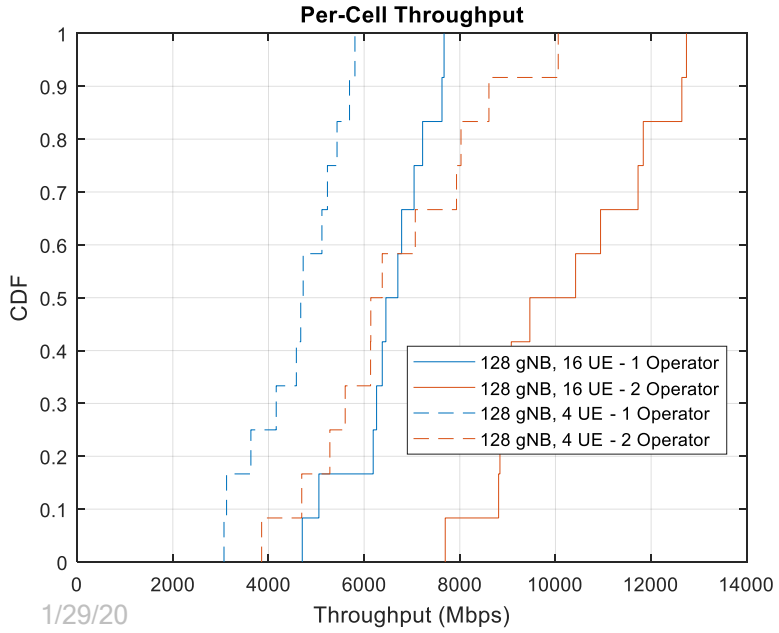


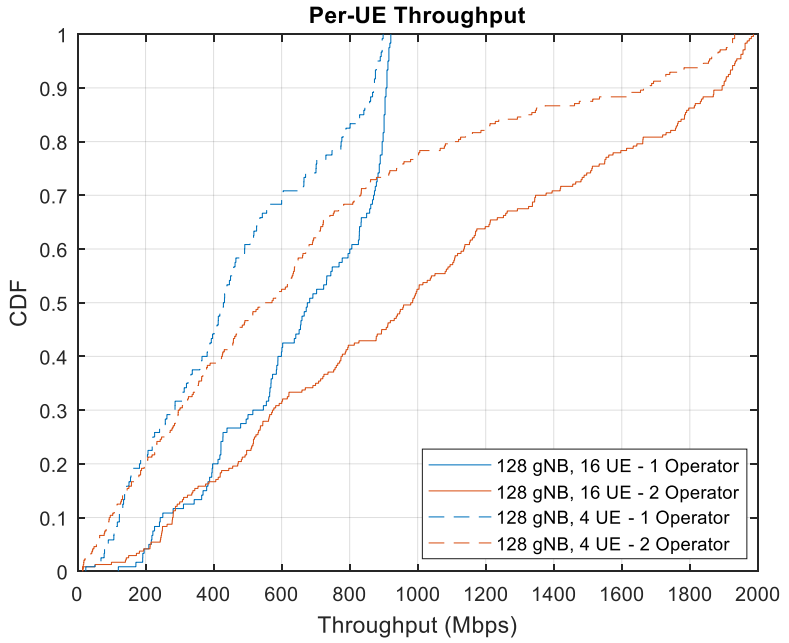
- **Conclusion:**
  - With GHz of bandwidth available in FR4, multi-Gbps data rates are achieved in both licensed and unlicensed spectrum

60 GHz: Uncoordinated Spectrum Sharing

- Comparison Exercise
  - FR4 includes licensed and unlicensed spectra
  - We compare performance between shared co-channel operation and FDM operation in 60 GHz among two operators **given**:
    - Uncoordinated sharing (i.e, no LBT or sharing rules)
    - gNB antenna elements: {512, 128, 32} per polarization
    - UE antenna elements: {16, 4} per polarization
    - EIRP levels: 40 dBm → the FCC limit, and 60 dBm → Increased EIRP level for study purpose
  - Metrics:
    - Per-UE / Per-cell throughput for 1 operator over 1 GHz each (versus)
    - Per-UE / Per-cell throughput for 2 operators over 2.16 GHz total



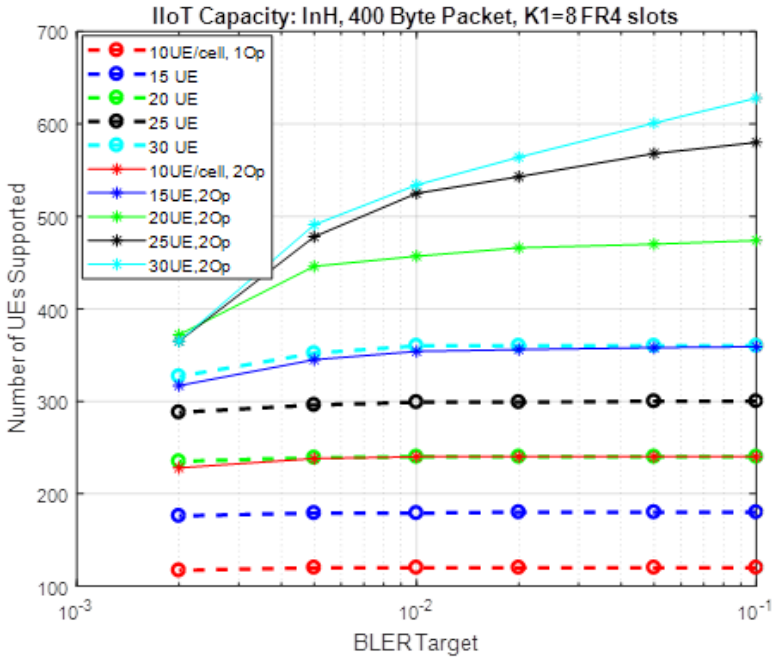


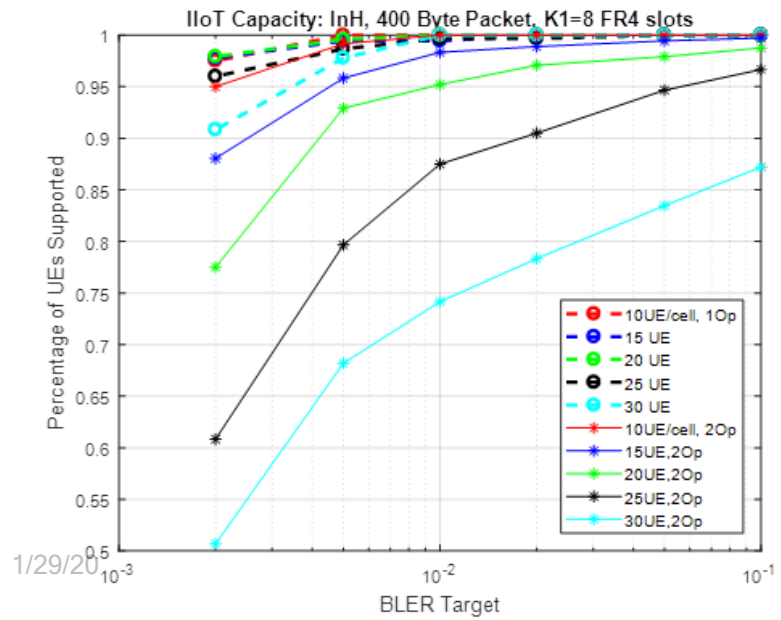


Observations:

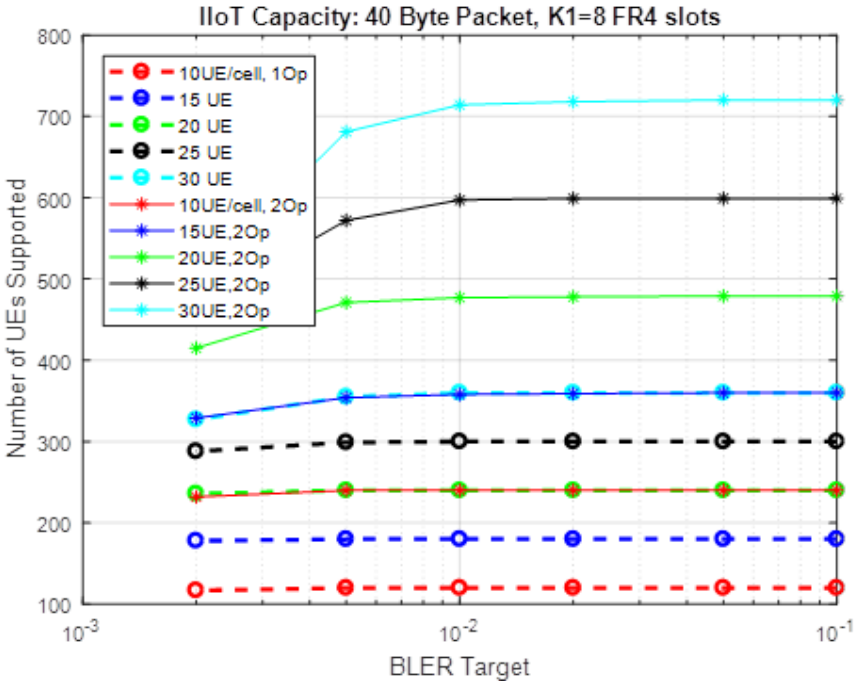
- Spectrum sharing largely outperforms FDM operation
- Peak throughput is limited by maximum available bandwidth for FDM

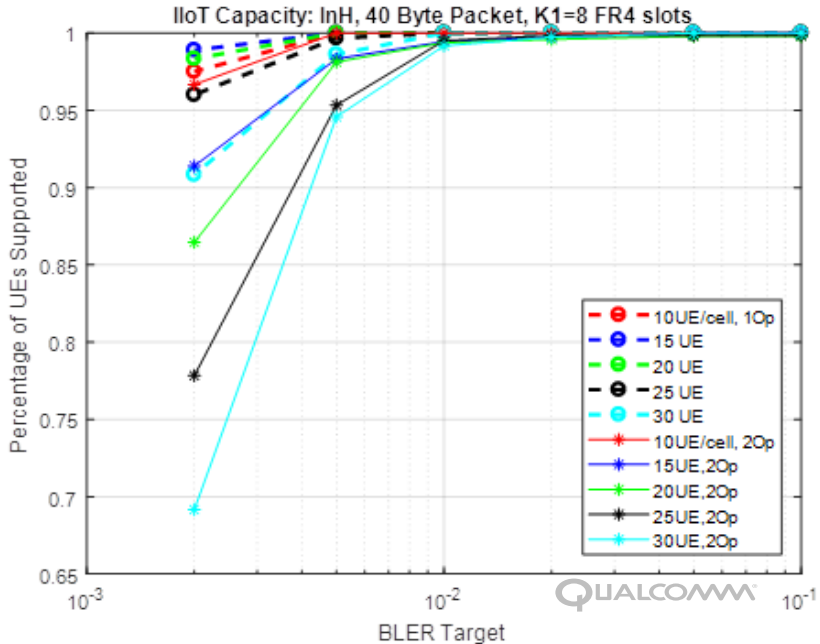
IIoT Capacity with 60 GHz: A Preview





- **Initial Observation:**
  - A high fraction of UEs can support IIoT traffic with at least 1e-3 reliability for 25 UE per cell
    - Several optimizations not used here
  - Although spectrum sharing impacts IIoT capacity noticeably, IIoT is unlikely to be a fully shared spectrum operation





Conclusions from System Study

- Capacity / Coverage with 60 GHz
  - In InH deployments (20 m ISD), mean cell throughputs of approx. 10 Gbps can be achieved with approx. 300 Mbps for the tail UE assuming 10 UE per cell (assuming 2.16 GHz channel)
  - In UMi deployments (out-to-out only), a range of 50-100 m can be achieved with a suite of NR supported techniques

- Spectrum sharing
  - Even uncoordinated spectrum sharing largely outperforms FDM operation → Light regulations may be enough
  - Room for intra-technology interference management is explored further

- IIoT Capacity
  - Even with a basic 500 MHz configuration without optimizations, > 95% of UEs meet the 1 msec latency requirement even with 25 UE per cell in 60 GHz
  - FR4 is a promising spectrum for IIoT use cases