Insights on Spectrum for 6G

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February 2025

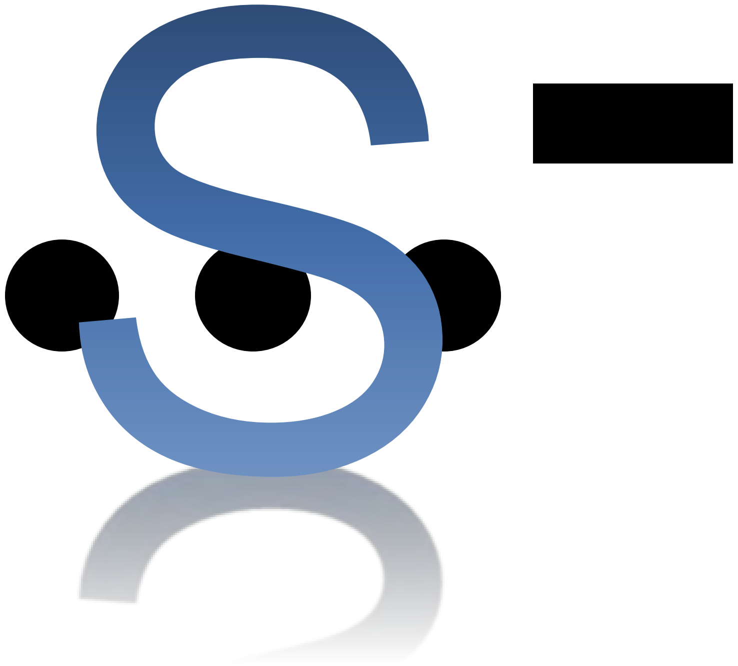
Today's Topics

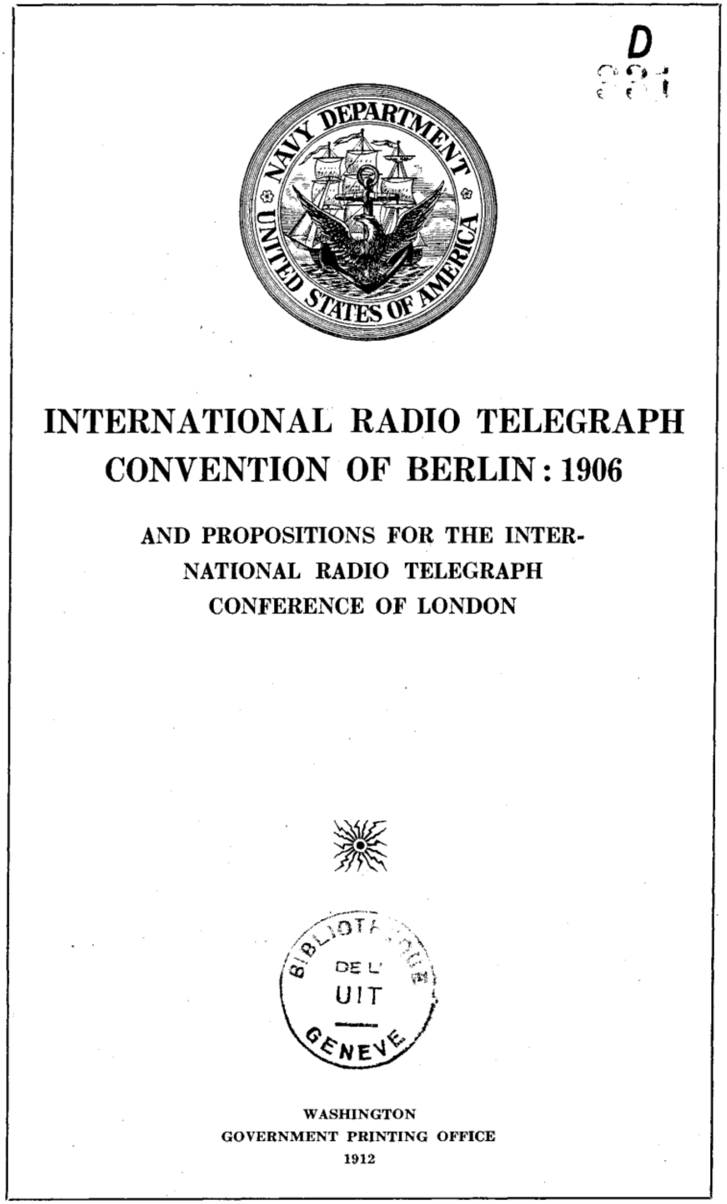
- Foundations of Spectrum for Radio
- History of Spectrum use in Cellular
- 6G Specifics by Frequency Range
- Conclusions

Audience Quiz: You will be graded.

Policies and Standards

Who knows what this means?



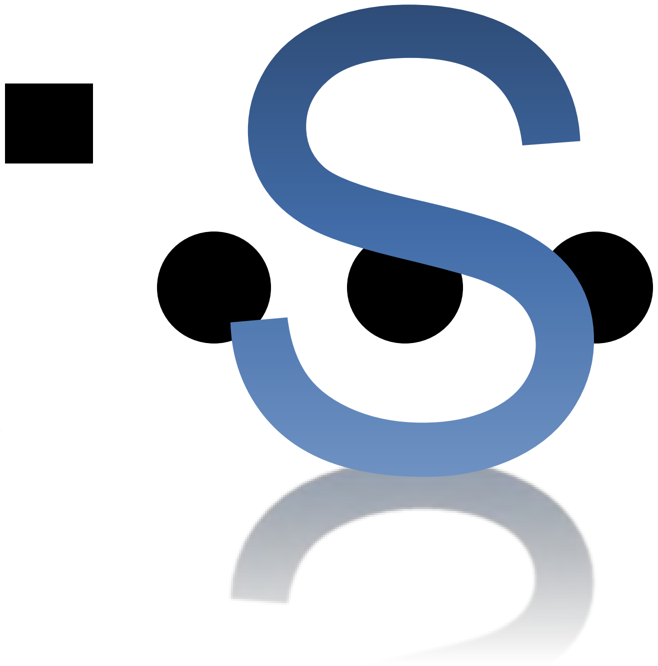


NAVY DEPARTMENT UNITED STATES OF AMERICA

INTERNATIONAL RADIO TELEGRAPH
CONVENTION OF BERLIN: 1906

AND PROPOSITIONS FOR THE INTER-
NATIONAL RADIO TELEGRAPH
CONFERENCE OF LONDON

WASHINGTON
GOVERNMENT PRINTING OFFICE
1912



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What has happened since the Titanic?

A sea change of Spectrum Policy and Allocation

	1920	1945	1970	1995	2020
Spectrum Policy	Command and Control: block allocation and licensing	Restriction of Chain Broadcasting		Market-based spectrum approach: “owned” or “common”	Licensed Shared Spectrum: behaves like “Common”
Technical & Business Impact	Filters, bands, oversight	NBC becomes NBC + ABC		Investment levels drive performance requirements	“Real-time” spectrum brokerage (e.g. CBRS)

Audience Quiz: You will be graded.

Which frequencies does 3GPP stipulate for use in mobile cellular communications?

NR operating band	Uplink (UL) operating band BS receive / UE transmit F_{UL_low} – F_{UL_high}	Downlink (DL) operating band BS transmit / UE receive F_{DL_low} – F_{DL_high}	Duplex Mode
n1	1920 MHz – 1980 MHz	2110 MHz – 2170 MHz	FDD
n2	1850 MHz – 1910 MHz	1930 MHz – 1990 MHz	FDD
n3	1710 MHz – 1785 MHz	1805 MHz – 1880 MHz	FDD
n5	824 MHz – 849 MHz	869 MHz – 894 MHz	FDD
n7	2500 MHz – 2570 MHz	2620 MHz – 2690 MHz	FDD
n8	880 MHz – 915 MHz	925 MHz – 960 MHz	FDD
n12	699 MHz – 716 MHz	729 MHz – 746 MHz	FDD
n13	777 MHz – 787 MHz	746 MHz – 756 MHz	FDD
n14	788 MHz – 798 MHz	758 MHz – 768 MHz	FDD
n18	815 MHz – 830 MHz	860 MHz – 875 MHz	FDD
n20	832 MHz – 862 MHz	791 MHz – 821 MHz	FDD
n24[16]	1626.5 MHz – 1660.5 MHz	1525 MHz – 1559 MHz	FDD
n25	1850 MHz – 1915 MHz	1930 MHz – 1995 MHz	FDD
n26	814 MHz – 849 MHz	859 MHz – 894 MHz	FDD
n28	703 MHz – 748 MHz	758 MHz – 803 MHz	FDD
n29	N/A	717 MHz – 728 MHz	SDL[19]
n30[3]	2305 MHz – 2315 MHz	2350 MHz – 2360 MHz	FDD
n31	452.5 MHz – 457.5 MHz	462.5 MHz – 467.5 MHz	FDD
n34	2010 MHz – 2025 MHz	2010 MHz – 2025 MHz	TDD
n38[10]	2570 MHz – 2620 MHz	2570 MHz – 2620 MHz	TDD
n39	1880 MHz – 1920 MHz	1880 MHz – 1920 MHz	TDD
n40	2300 MHz – 2400 MHz	2300 MHz – 2400 MHz	TDD
n41	2496 MHz – 2690 MHz	2496 MHz – 2690 MHz	TDD
n46	5150 MHz – 5925 MHz	5150 MHz – 5925 MHz	TDD[13]
n47[11]	5855 MHz – 5925 MHz	5855 MHz – 5925 MHz	TDD
n48	3550 MHz – 3700 MHz	3550 MHz – 3700 MHz	TDD
n50	1432 MHz – 1517 MHz	1432 MHz – 1517 MHz	TDD[1]
n51	1427 MHz – 1432 MHz	1427 MHz – 1432 MHz	TDD
n53	2483.5 MHz – 2495 MHz	2483.5 MHz – 2495 MHz	TDD
n54	1670 MHz – 1675 MHz	1670 MHz – 1675 MHz	TDD
n65	1920 MHz – 2010 MHz	2110 MHz – 2200 MHz	FDD[4]
n66	1710 MHz – 1780 MHz	2110 MHz – 2200 MHz	FDD
n67	N/A	738 MHz – 758 MHz	SDL[19]
n70	1695 MHz – 1710 MHz	1995 MHz – 2020 MHz	FDD
n71	663 MHz – 698 MHz	617 MHz – 652 MHz	FDD
n74	1427 MHz – 1470 MHz	1475 MHz – 1518 MHz	FDD
n72	451 MHz – 456 MHz	461 MHz – 466 MHz	FDD
n75	N/A	1432 MHz – 1517 MHz	SDL[19]
n76	N/A	1427 MHz – 1432 MHz	SDL[19]
n77[12]	3300 MHz – 4200 MHz	3300 MHz – 4200 MHz	TDD
n78	3300 MHz – 3800 MHz	3300 MHz – 3800 MHz	TDD
n79[17]	4400 MHz – 5000 MHz	4400 MHz – 5000 MHz	TDD
n80	1710 MHz – 1785 MHz	N/A	SUL
n81	880 MHz – 915 MHz	N/A	SUL
n82	832 MHz – 862 MHz	N/A	SUL
n83	703 MHz – 748 MHz	N/A	SUL
n84	1920 MHz – 1980 MHz	N/A	SUL
n85	698 MHz – 716 MHz	728 MHz – 746 MHz	FDD
n86	1710 MHz – 1780 MHz	N/A	SUL
n89	824 MHz – 849 MHz	N/A	SUL
n90	2496 MHz – 2690 MHz	2496 MHz – 2690 MHz	TDD[5]
n91	832 MHz – 862 MHz	1427 MHz – 1432 MHz	FDD[9]
n92	832 MHz – 862 MHz	1432 MHz – 1517 MHz	FDD[9]
n93	880 MHz – 915 MHz	1427 MHz – 1432 MHz	FDD[9]
n94	880 MHz – 915 MHz	1432 MHz – 1517 MHz	FDD[9]
n95[8]	2010 MHz – 2025 MHz	N/A	SUL
n96[14]	5925 MHz – 7125 MHz	5925 MHz – 7125 MHz	TDD[13]
n97[15]	2300 MHz – 2400 MHz	N/A	SUL
n98[15]	1880 MHz – 1920 MHz	N/A	SUL
n99[16]	1626.5 MHz – 1660.5 MHz	N/A	SUL
n100	874.4 MHz – 880 MHz	919.4 MHz – 925 MHz	FDD
n101	1900 MHz – 1910 MHz	1900 MHz – 1910 MHz	TDD
n102[14]	5925 MHz – 6425 MHz	5925 MHz – 6425 MHz	TDD[13]
n104[17, 18]	6425 MHz – 7125 MHz	6425 MHz – 7125 MHz	TDD
n105	663 MHz – 703 MHz	612 MHz – 652 MHz	FDD
n106	896 MHz – 901 MHz	935 MHz – 940 MHz	FDD
n109	703 MHz – 733 MHz	1432 MHz – 1517 MHz	FDD[9]

5G NR FR1 Bands

3GPP 38.101-1

3GPP does NOT…

…define the spectrum for IMT operations.

…regulate radio behavior.

…set policy on which bands are for IMT and which are not.

3GPP DOES…

…define the functional, performance, and testing standards *by specific frequency range*.

…sometimes defines performance and tests redundant to regulatory constraints.

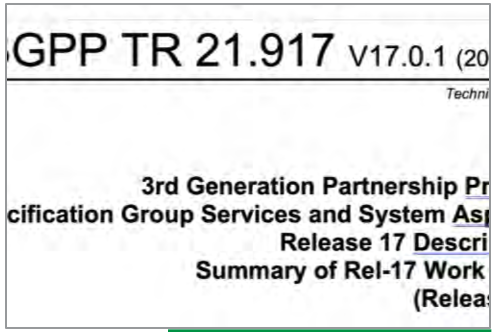
4G LTE Bands

3GPP 36.101

E-UTRA Operating Band	Uplink (UL) operating band BS receive UE transmit F_{UL_low} – F_{UL_high}			Downlink (DL) operating band BS transmit UE receive F_{DL_low} – F_{DL_high}			Duplex Mode
1	1920 MHz	–	1980 MHz	2110 MHz	–	2170 MHz	FDD
2	1850 MHz	–	1910 MHz	1930 MHz	–	1990 MHz	FDD
3	1710 MHz	–	1785 MHz	1805 MHz	–	1880 MHz	FDD
4	1710 MHz	–	1755 MHz	2110 MHz	–	2155 MHz	FDD
5	824 MHz	–	849 MHz	869 MHz	–	894MHz	FDD
6[1]	830 MHz	–	840 MHz	875 MHz	–	885 MHz	FDD
7	2500 MHz	–	2570 MHz	2620 MHz	–	2690 MHz	FDD
8	880 MHz	–	915 MHz	925 MHz	–	960 MHz	FDD
9	1749.9 MHz	–	1784.9 MHz	1844.9 MHz	–	1879.9 MHz	FDD
10	1710 MHz	–	1770 MHz	2110 MHz	–	2170 MHz	FDD
11	1427.9 MHz	–	1447.9 MHz	1475.9 MHz	–	1495.9 MHz	FDD
12	699 MHz	–	716 MHz	729 MHz	–	746 MHz	FDD
13	777 MHz	–	787 MHz	746 MHz	–	756 MHz	FDD
14	788 MHz	–	798 MHz	758 MHz	–	768 MHz	FDD
15	Reserved			Reserved			FDD
16	Reserved			Reserved			FDD
17	704 MHz	–	716 MHz	734 MHz	–	746 MHz	FDD
18	815 MHz	–	830 MHz	860 MHz	–	875 MHz	FDD
19	830 MHz	–	845 MHz	875 MHz	–	890 MHz	FDD
20	832 MHz	–	862 MHz	791 MHz	–	821 MHz	FDD
21	1447.9 MHz	–	1462.9 MHz	1495.9 MHz	–	1510.9 MHz	FDD
22	3410 MHz	–	3490 MHz	3510 MHz	–	3590 MHz	FDD
23[1]	2000 MHz	–	2020 MHz	2180 MHz	–	2200 MHz	FDD
24[17]	1626.5 MHz	–	1660.5 MHz	1525 MHz	–	1559 MHz	FDD
25	1850 MHz	–	1915 MHz	1930 MHz	–	1995 MHz	FDD
26	814 MHz	–	849 MHz	859 MHz	–	894 MHz	FDD
27	807 MHz	–	824 MHz	852 MHz	–	869 MHz	FDD
28	703 MHz	–	748 MHz	758 MHz	–	803 MHz	FDD
29	N/A			717 MHz	–	728 MHz	FDD[2]
30[15]	2305 MHz	–	2315 MHz	2350 MHz	–	2360 MHz	FDD
31	452.5 MHz	–	457.5 MHz	462.5 MHz	–	467.5 MHz	FDD
32		N/A		1452 MHz	–	1496 MHz	FDD[2]
33	1900 MHz	–	1920 MHz	1900 MHz	–	1920 MHz	TDD
34	2010 MHz	–	2025 MHz	2010 MHz	–	2025 MHz	TDD
35	1850 MHz	–	1910 MHz	1850 MHz	–	1910 MHz	TDD
36	1930 MHz	–	1990 MHz	1930 MHz	–	1990 MHz	TDD
37	1910 MHz	–	1930 MHz	1910 MHz	–	1930 MHz	TDD
38	2570 MHz	–	2620 MHz	2570 MHz	–	2620 MHz	TDD
39	1880 MHz	–	1920 MHz	1880 MHz	–	1920 MHz	TDD
40	2300 MHz	–	2400 MHz	2300 MHz	–	2400 MHz	TDD
41	2496 MHz		2690 MHz	2496 MHz		2690 MHz	TDD
42	3400 MHz	–	3600 MHz	3400 MHz	–	3600 MHz	TDD
43	3600 MHz	–	3800 MHz	3600 MHz	–	3800 MHz	TDD
44	703 MHz	–	803 MHz	703 MHz	–	803 MHz	TDD
45	1447 MHz	–	1467 MHz	1447 MHz	–	1467 MHz	TDD
46	5150 MHz	–	5925 MHz	5150 MHz	–	5925 MHz	TDD[8]
47	5855 MHz	–	5925 MHz	5855 MHz	–	5925 MHz	TDD[11]
48	3550 MHz	–	3700 MHz	3550 MHz	–	3700 MHz	TDD
49	3550 MHz	–	3700 MHz	3550 MHz	–	3700 MHz	TDD[16]
50	1432 MHz	-	1517 MHz	1432 MHz	-	1517 MHz	TDD[13]
51	1427 MHz	-	1432 MHz	1427 MHz	-	1432 MHz	TDD[13]
52	3300 MHz	-	3400 MHz	3300 MHz	-	3400 MHz	TDD
53	2483.5 MHz	-	2495 MHz	2483.5 MHz	-	2495 MHz	TDD
54	1670 MHz	-	1675 MHz	1670 MHz	-	1675 MHz	TDD
…							
64	Reserved						
65	1920 MHz	–	2010 MHz	2110 MHz	–	2200 MHz	FDD
66	1710 MHz	–	1780 MHz	2110 MHz	–	2200 MHz	FDD[4]
67		N/A		738 MHz	–	758 MHz	FDD[2]
68	698 MHz	–	728 MHz	753 MHz	–	783 MHz	FDD
69	N/A			2570 MHz	–	2620 MHz	FDD[2]
70	1695 MHz	–	1710 MHz	1995 MHz	–	2020 MHz	FDD[10]
71	663 MHz	–	698 MHz	617 MHz	–	652 MHz	FDD
72	451 MHz	–	456 MHz	461 MHz	–	466 MHz	FDD
73	450 MHz	–	455 MHz	460 MHz	–	465 MHz	FDD
74	1427 MHz	–	1470 MHz	1475 MHz	–	1518 MHz	FDD
75		N/A		1432 MHz	–	1517 MHz	FDD[2]
76		N/A		1427 MHz	–	1432 MHz	FDD[2]
85	698 MHz	–	716 MHz	728 MHz	–	746 MHz	FDD
87	410 MHz	–	415 MHz	420 MHz	–	425 MHz	FDD
88	412 MHz	–	417 MHz	422 MHz	–	427 MHz	FDD
103[18]	787 MHz	–	788 MHz	757 MHz	–	758 MHz	FDD
106	896 MHz	–	901 MHz	935 MHz	–	940 MHz	FDD

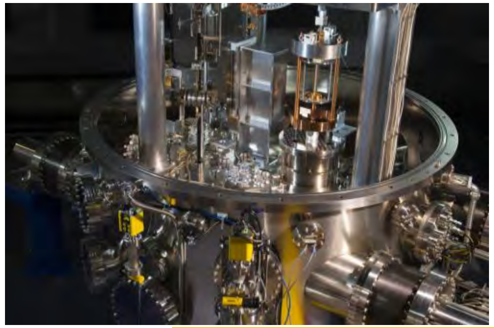
Important Distinctions

These terms are often confused and conflated



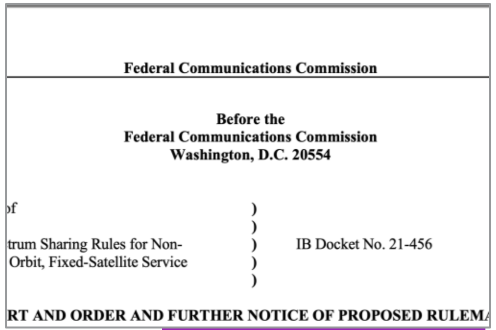
1 **Specification**

Technical **Specification**: A document defining desired behavior of a system.



2 **Standard**

Standard: *a Specification* adopted by an industry group or government to drive consistent implementation, functionality and performance.



3 **Policy**

Spectrum **Policy**: a *Standard* that defines legal limits on physical and system behavior within a specified jurisdiction.

4 **Physical Behavior**

How it really works

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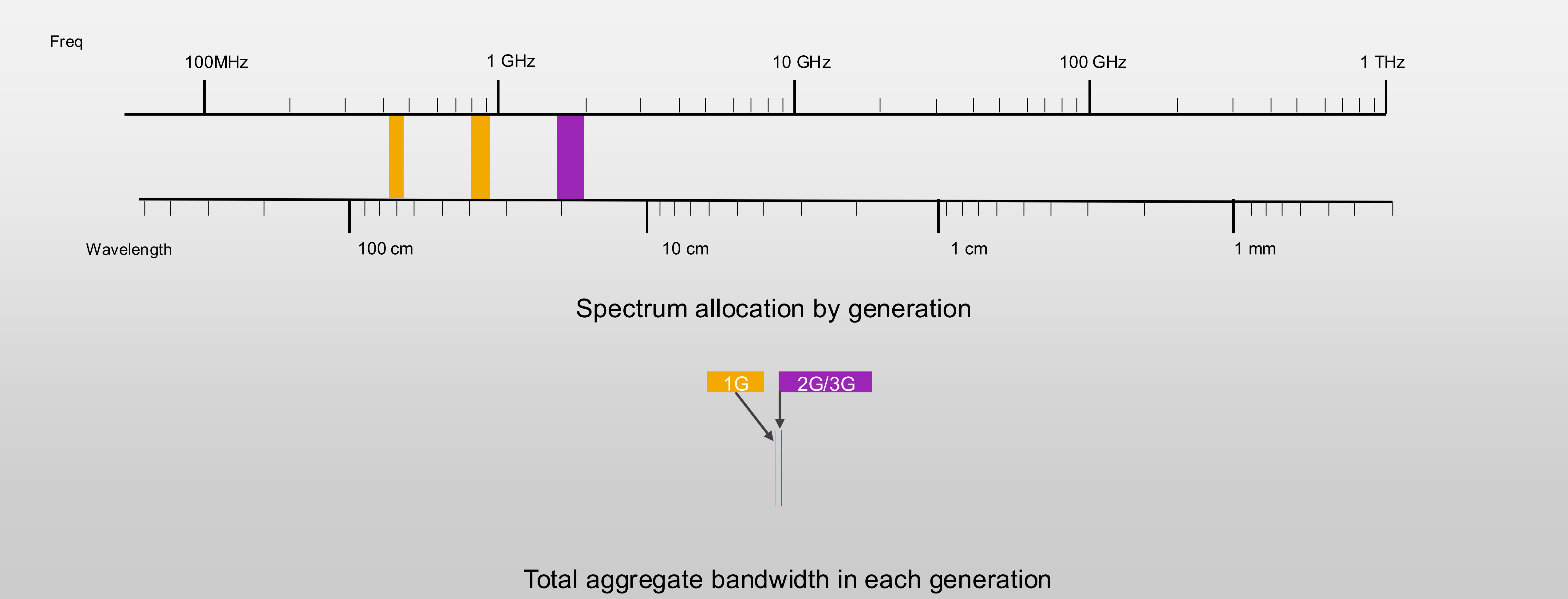
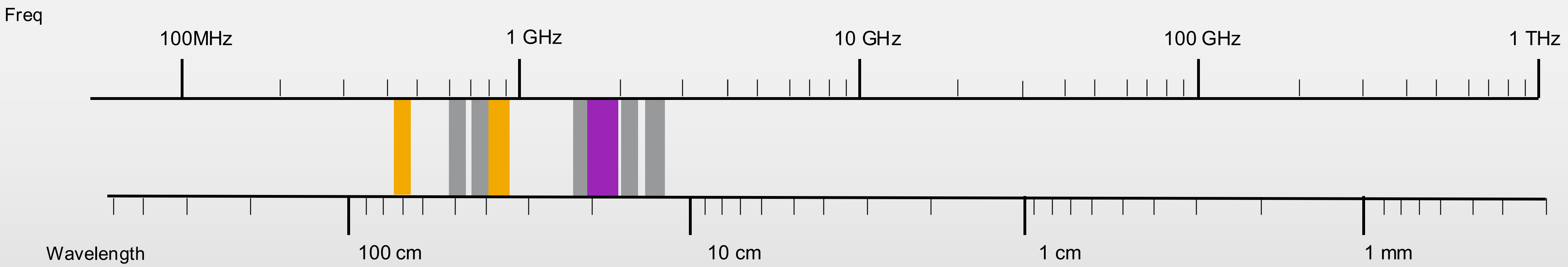
6G Will Use New Spectrum

Unprecedented bandwidth expansion

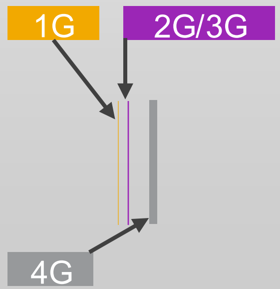


6G Will Use New Spectrum

Unprecedented bandwidth expansion



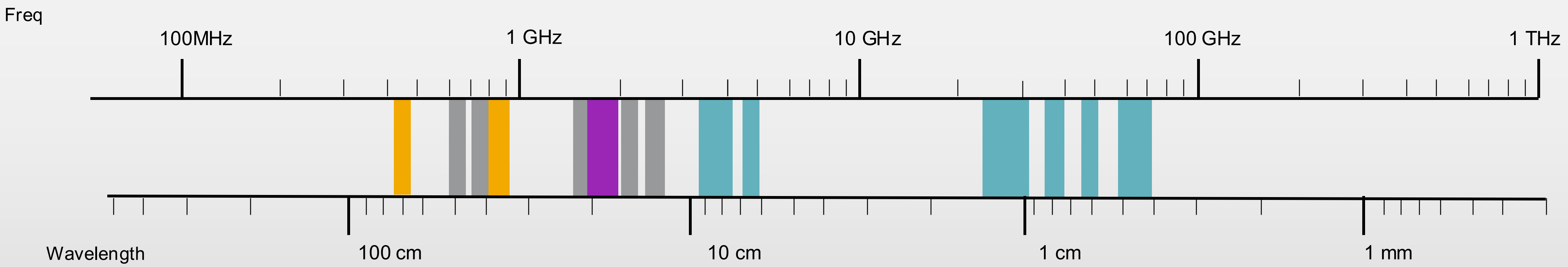
Spectrum allocation by generation



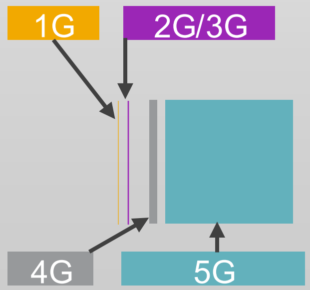
Total aggregate bandwidth in each generation

6G Will Use New Spectrum

Unprecedented bandwidth expansion



Spectrum allocation by generation



Total aggregate bandwidth in each generation

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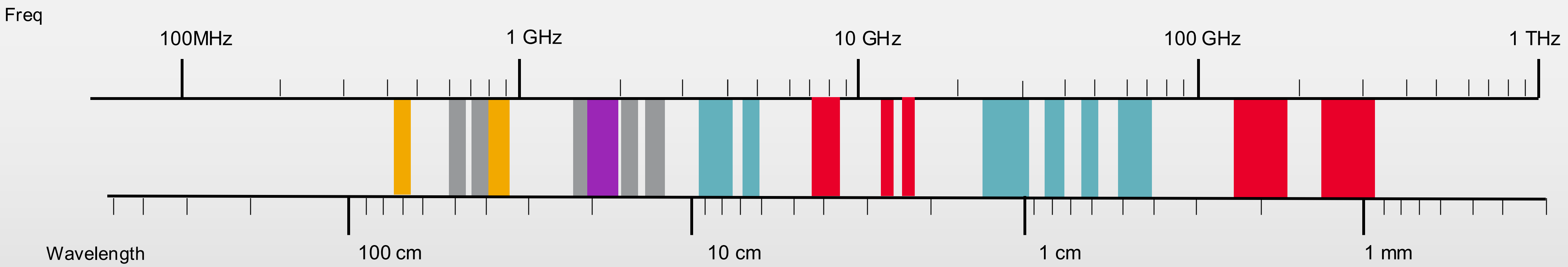
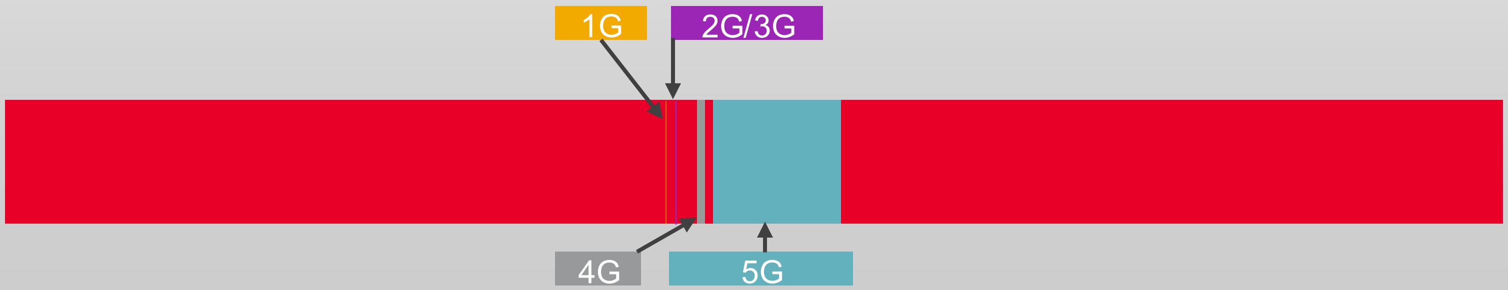


Spectrum allocation by generation



Total aggregate bandwidth in each generation

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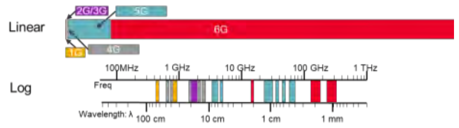
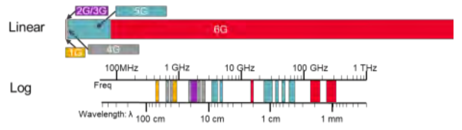
6G Candidate Spectrum: Specifics



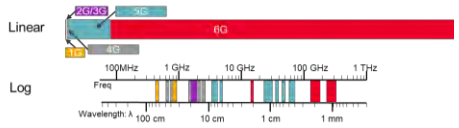
	6G Research Topics: NOMA	Waveforms	Channel Coding	Unlicensed/ WiFi	Advacned MIMO	Satellite	Mobility/Coverage	ISAC	PA & LNA	Antennae	Mobile Regulatory Situation	Technical Challenges
<7 GHz	✓	✓	✓	✓	✓	✓			✓	✓	• Minor changes ongoing e.g. 3.4-3.8 GHz and 6-7 GHz Most allocations/auctions complete.	• Coverage • Spectral Efficiency
7-16 GHz		✓	✓		✓	✓	✓	✓	✓	✓	• Entire band has co-primary use • Heavy Federal/DoD Allocation • Most EU states ambivalent at best • Passive (EES) Satellite & Radio Astronomy co-existence	• Co-existence • Coverage & Cell Density
16-24 GHz						✓			✓			• “FR2-like” (more challenging than <16GHz)
24-71 GHz			✓	✓			✓	✓	✓	✓	• 24-52 GHz Allocated or will be allocated to Mobile use • 57-71 GHz Unlicensed	• Coverage • Energy Efficiency • Mobility
71-110 GHz		✓	✓					✓	✓	✓	• Point-To-Point & Automotive Radar • Inadequate contiguous sub-bands. • Heavy constraints 90 GHz - 110 GHz	• Coverage • Energy Efficiency • Noise BW • Mobility
110-170 GHz		✓	✓		✓	✓	✓	✓	✓	✓	• Lightly regulated • ITU RR-5.340 Constraints: Radio Astronomy/EES • WRC-27 Proposed Agenda	• Coverage • Energy Efficiency • Link Budget • Noise BW • Mobility • Co-Existence
>170 GHz		✓					✓	✓	✓	✓	• Lightly regulated • ITU RR-5.340 Constraints: Radio Astronomy/EES • ITU-R WRC-27 Proposed Agenda • ITU Decisions post WRC-27	



6G Candidate Spectrum: Specifics

	6G Research Topics: NOMA	Waveforms	Channel Coding	Unlicensed/ WiFi	Advacned MIMO	Satellite	Mobility/Coverage	ISAC	PA & LNA	Antennae	Mobile Regulatory Situation	Technical Challenges
<7 GHz	✓	✓	✓	✓	✓	✓			✓	✓	• Minor changes ongoing e.g. 3.4-3.8 GHz and 6-7 GHz Most allocations/auctions complete.	• Coverage • Spectral Efficiency
7-16 GHz		✓	✓		✓	✓	✓	✓	✓	✓	• Entire band has co-primary use • Heavy Federal/DoD Allocation • Most EU states ambivalent at best • Passive (EES) Satellite & Radio Astronomy co-existence	• Co-existence • Coverage & Cell Density
16-24 GHz						✓			✓			• "FR2-like" (more challenging than <16GHz)
24-71 GHz			✓	✓			✓	✓	✓	✓	• 24-52 GHz Allocated or will be allocated to Mobile use • 57-71 GHz Unlicensed	• Coverage • Energy Efficiency • Mobility
71-110 GHz		✓	✓					✓	✓	✓	• Point-To-Point & Automotive Radar • Inadequate contiguous sub-bands. • Heavy constraints 90 GHz - 110 GHz	• Coverage • Energy Efficiency • Noise BW • Mobility
SubTHz: 110-170 GHz		✓	✓		✓	✓	✓	✓	✓	✓	• Lightly regulated • ITU RR-5.340 Constraints: Radio Astronomy/EES • WRC-27 Proposed Agenda	• Coverage • Energy Efficiency • Link Budget • Noise BW • Mobility • Co-Existence
SubTHz: >170 GHz		✓					✓	✓	✓	✓	• Lightly regulated • ITU RR-5.340 Constraints: Radio Astronomy/EES • ITU-R WRC-27 Proposed Agenda • ITU Decisions post WRC-27	

6G Candidate Spectrum: Specifics

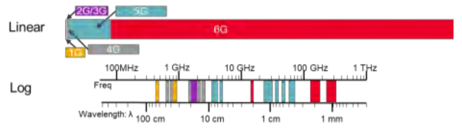


FR1

	NOMA	Waveforms	Channel Coding	Unlicensed/ WiFi	Advacned MIMO	Satellite	Mobility/Coverage	ISAC	PA & LNA	Antennae	Mobile Regulatory Situation	Technical Challenges
<7 GHz	✓	✓	✓	✓	✓	✓			✓	✓	• Minor changes ongoing e.g. 3.4-3.8 GHz and 6-7 GHz Most allocations/auctions complete.	• Coverage • Spectral Efficiency
7-16 GHz		✓	✓		✓	✓	✓	✓	✓	✓	• Entire band has co-primary use • Heavy Federal/DoD Allocation • Most EU states ambivalent at best • Passive (EES) Satellite & Radio Astronomy co-existence	• Co-existence • Coverage & Cell Density
16-24 GHz						✓			✓			• "FR2-like" (more challenging than <16GHz)
24-71 GHz			✓	✓			✓	✓	✓	✓	• 24-52 GHz Allocated or will be allocated to Mobile use • 57-71 GHz Unlicensed	• Coverage • Energy Efficiency • Mobility
71-110 GHz		✓	✓					✓	✓	✓	• Point-To-Point & Automotive Radar • Inadequate contiguous sub-bands. • Heavy constraints 90 GHz - 110 GHz	• Coverage • Energy Efficiency • Noise BW • Mobility
110-170 GHz		✓	✓		✓	✓	✓	✓	✓	✓	• Lightly regulated • ITU RR-5.340 Constraints: Radio Astronomy/EES • WRC-27 Proposed Agenda	• Coverage • Energy Efficiency • Link Budget • Noise BW • Mobility • Co-Existence
>170 GHz		✓					✓	✓	✓	✓	• Lightly regulated • ITU RR-5.340 Constraints: Radio Astronomy/EES • ITU-R WRC-27 Proposed Agenda • ITU Decisions post WRC-27	

6G Research Topics

6G Candidate Spectrum: Specifics



"FR3" (7-16 GHz and 16-24 GHz)

Band	NOMA	Waveforms	Channel Coding	Unlicensed/ WiFi	Advacned MIMO	Satellite	Mobility/Coverage	ISAC	PA & LNA	Antennae	Mobile Regulatory Situation	Technical Challenges
<7 GHz	✓	✓	✓	✓	✓	✓			✓	✓	• Minor changes ongoing e.g. 3.4-3.8 GHz and 6-7 GHz Most allocations/auctions complete.	• Coverage • Spectral Efficiency
7-16 GHz		✓	✓		✓	✓	✓	✓	✓	✓	• Entire band has co-primary use • Heavy Federal/DoD Allocation • Most EU states ambivalent at best • Passive (EES) Satellite & Radio Astronomy co-existence	• Co-existence • Coverage & Cell Density
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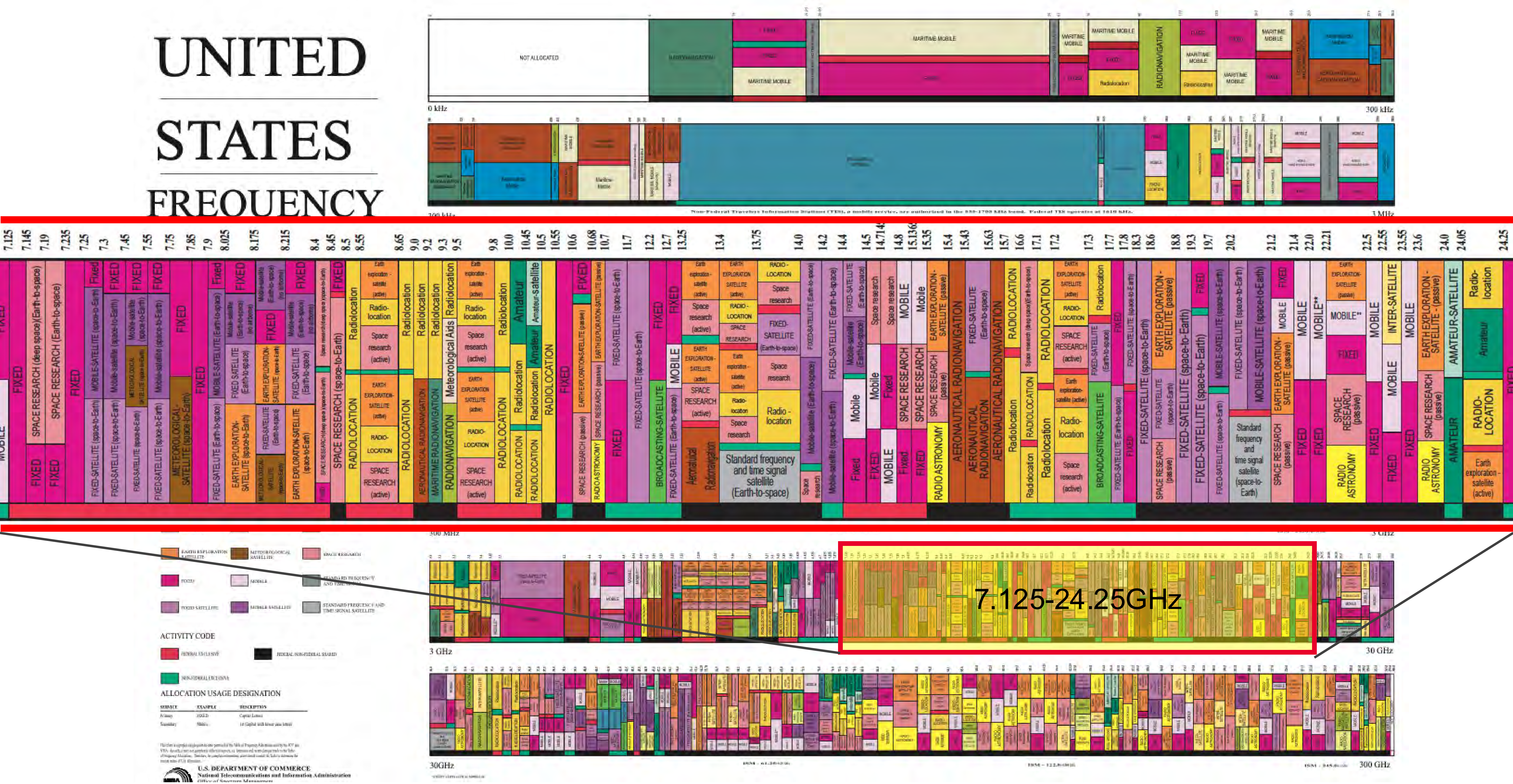
71-110 GHz		✓	✓					✓	✓	✓	• Point-To-Point & Automotive Radar • Inadequate contiguous sub-bands. • Heavy constraints 90 GHz - 110 GHz	• Coverage • Energy Efficiency • Noise BW • Mobility
110-170 GHz		✓	✓		✓	✓	✓	✓	✓	✓	• Lightly regulated • ITU RR-5.340 Constraints: Radio Astronomy/EES • WRC-27 Proposed Agenda	• Coverage • Energy Efficiency • Link Budget • Noise BW • Mobility • Co-Existence
>170 GHz		✓					✓	✓	✓	✓	• Lightly regulated • ITU RR-5.340 Constraints: Radio Astronomy/EES • ITU-R WRC-27 Proposed Agenda • ITU Decisions post WRC-27	

Latest in Spectrum: Focus 7-24 GHz

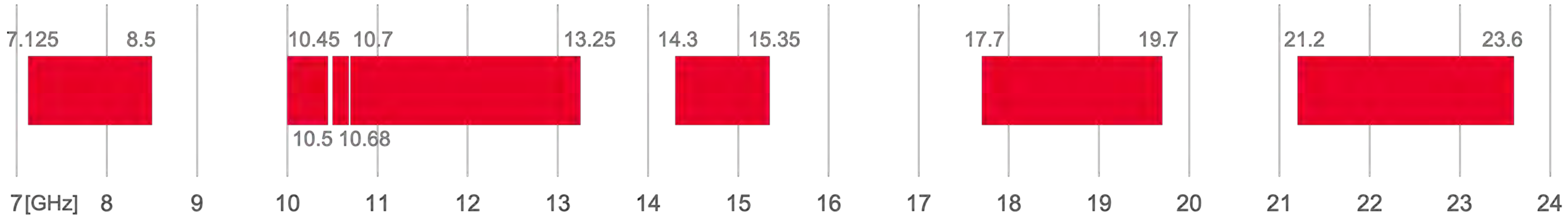
ITU and WRC-23

USA FCC and NTIA


UNITED
STATES
FREQUENCY
0 kHz
300 kHz
3 MHz
300 MHz
3 GHz
30 GHz
30GHz
300 GHz
7.125-24.25GHz
EARTH EXPLORATION SATELLITE
METEOROLOGICAL SATELLITE
SPACE RESEARCH
FIXED
MOBILE
STANDARD FREQUENCY AND TIME SIGNAL
FIXED SATELLITE
MOBILE SATELLITE
STANDARD FREQUENCY AND TIME SIGNAL SATELLITE
ACTIVITY CODE
FEDERAL EXCLUSIVE
FEDERAL/NON-FEDERAL SHARED
NON-FEDERAL EXCLUSIVE
ALLOCATION USAGE DESIGNATION
U.S. DEPARTMENT OF COMMERCE
National Telecommunications and Information Administration

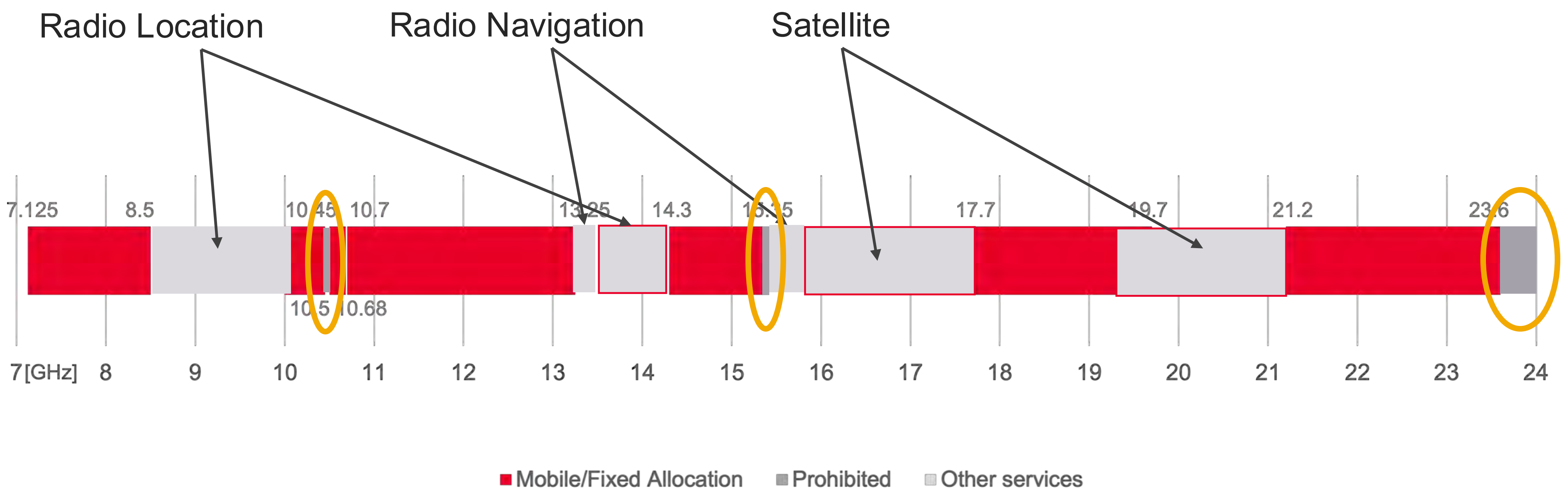
6G: New Spectrum Candidates

7-24 GHz



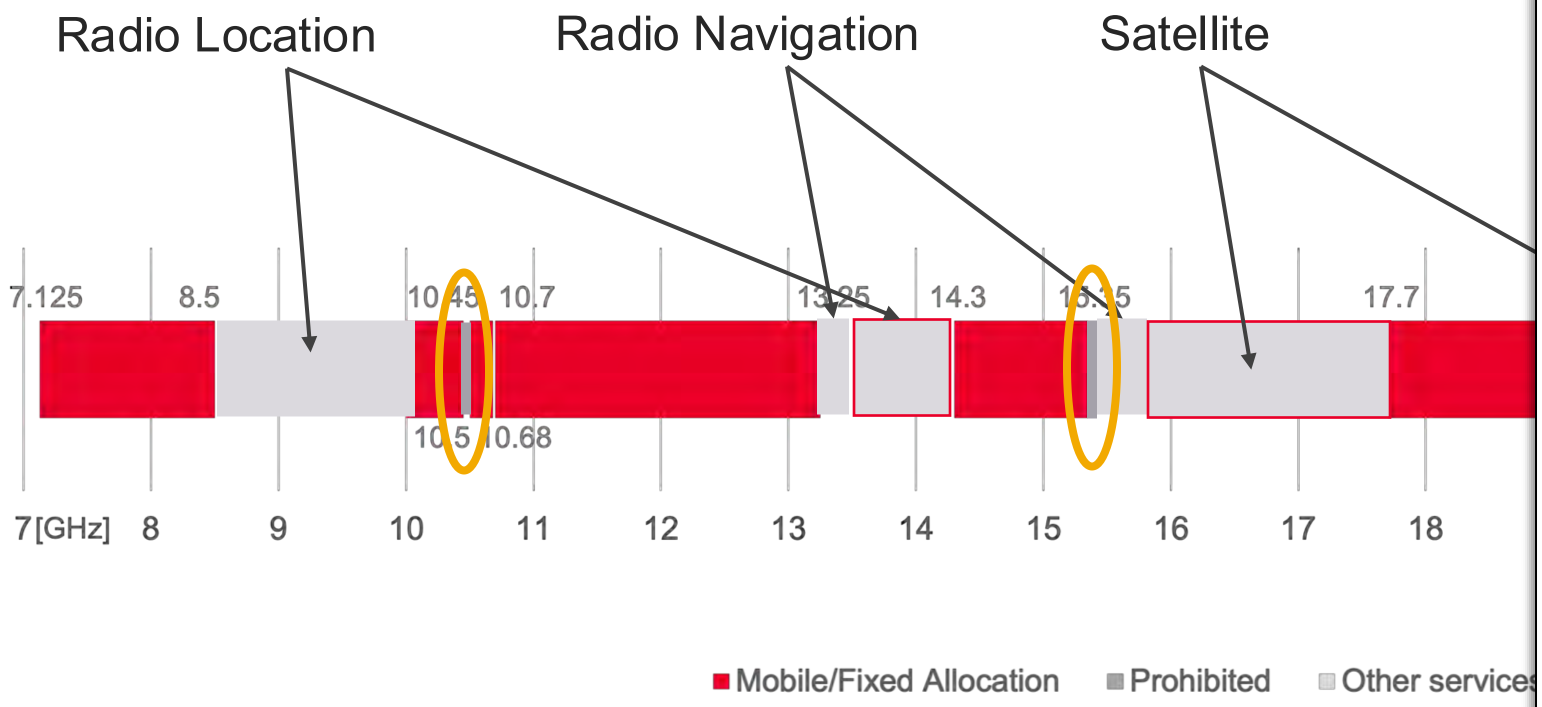
6G Spectrum Candidates

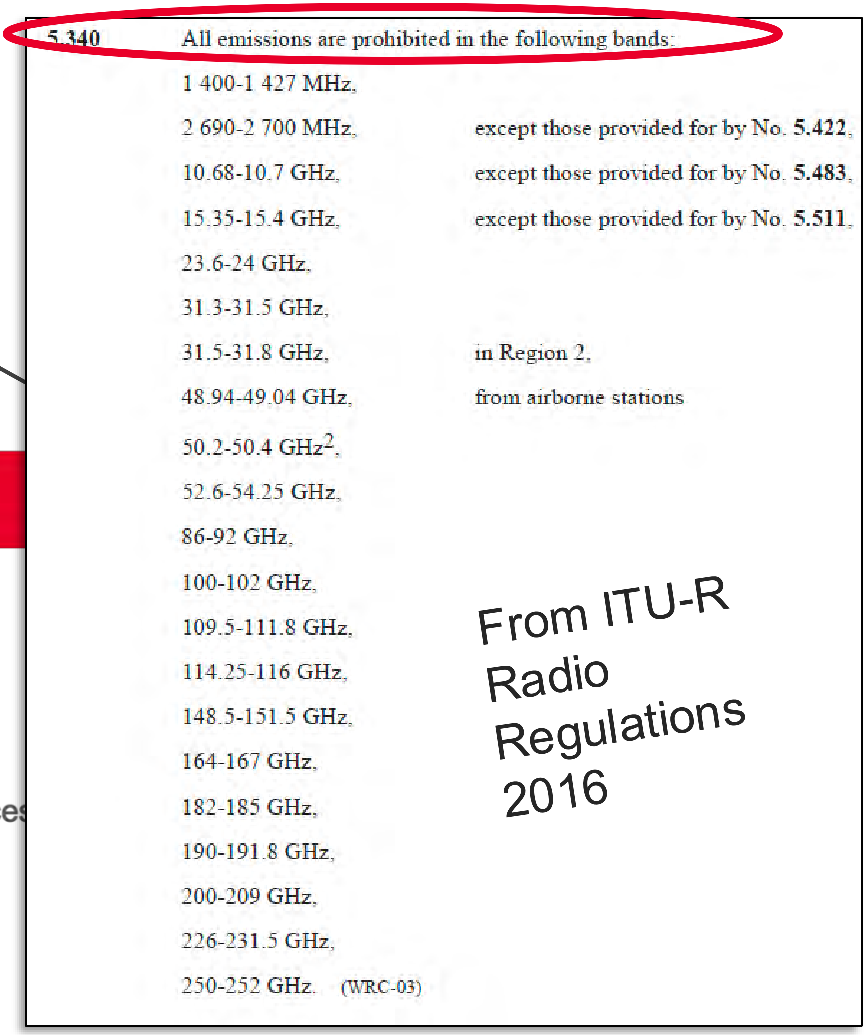
7-24 GHz: USA Allocations



6G Spectrum Candidates

7-24 GHz: USA Allocations





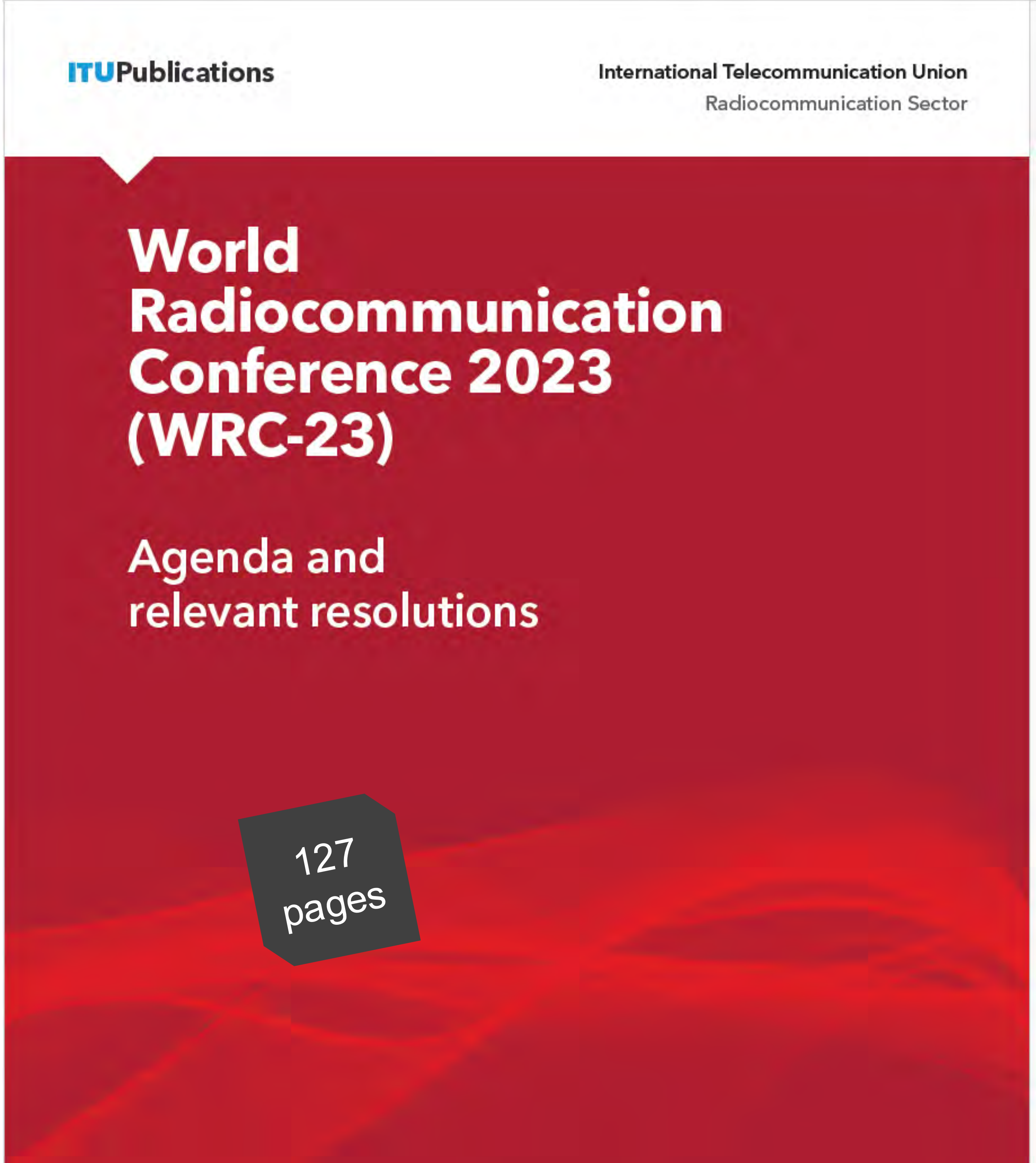
5.340 All emissions are prohibited in the following bands:

1 400-1 427 MHz,	
2 690-2 700 MHz,	except those provided for by No. **5.422**,
10.68-10.7 GHz,	except those provided for by No. **5.483**,
15.35-15.4 GHz,	except those provided for by No. **5.511**,
23.6-24 GHz,	
31.3-31.5 GHz,	
31.5-31.8 GHz,	in Region 2,
48.94-49.04 GHz,	from airborne stations
50.2-50.4 GHz²,	
52.6-54.25 GHz,	
86-92 GHz,	
100-102 GHz,	
109.5-111.8 GHz,	
114.25-116 GHz,	
148.5-151.5 GHz,	
164-167 GHz,	
182-185 GHz,	
190-191.8 GHz,	
200-209 GHz,	
226-231.5 GHz,	
250-252 GHz. (WRC-03)	

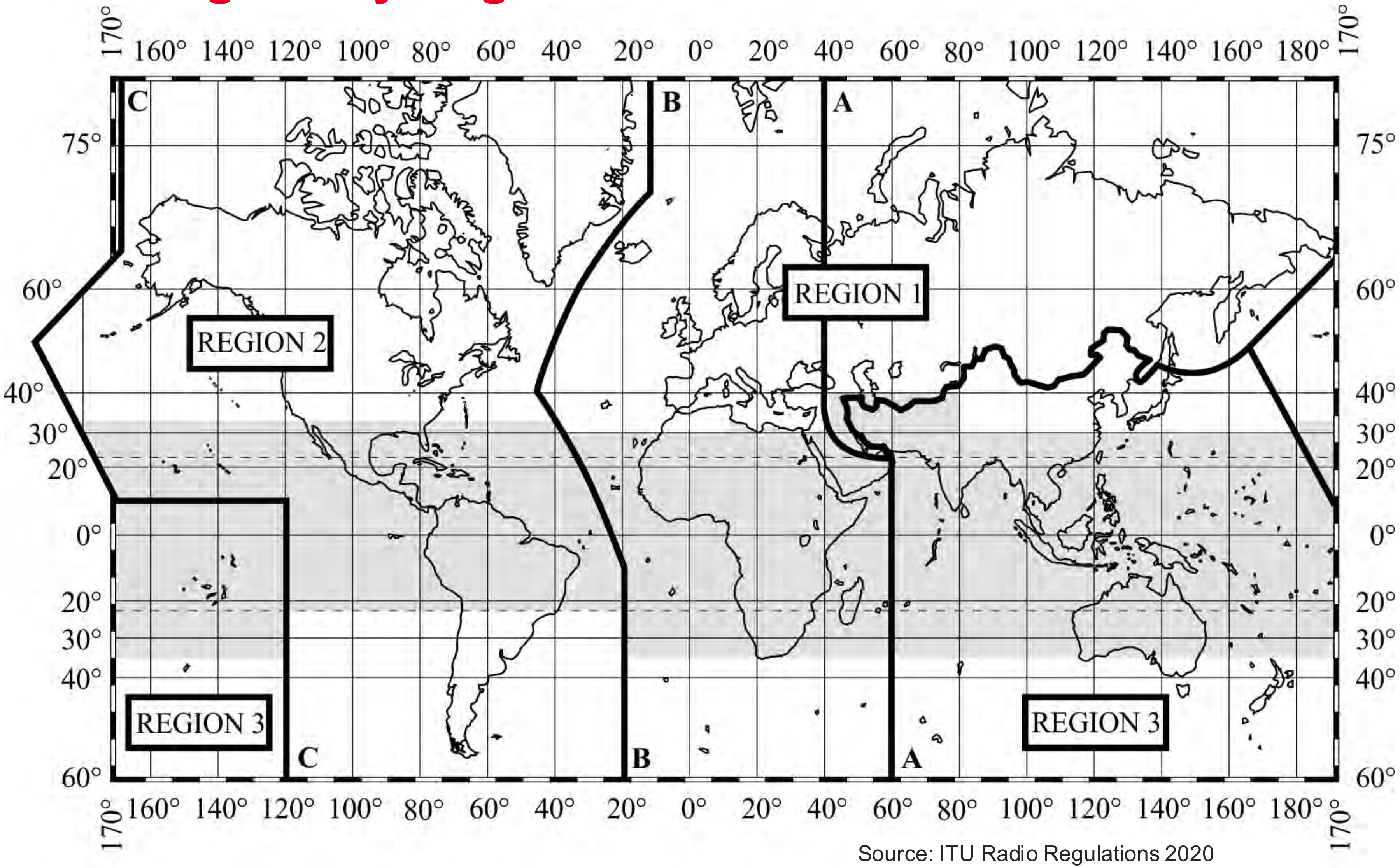
ITU-R: World Radio Conferences

…First, a Primer…

- ITU: Part of UN: Resulting "Radio Regulations" are a matter of international treaty
- 5-week long ITU-R World Radio Conferences every 4 years with agenda set 2 years in advance
- Decisions from WRC's either update Radio Regulations, set up decision frameworks, or to initiate/continue technical study
- Scope includes all facets of radio spectrum. *Most of the time is spent on satellite topics*
- IMT (Cellular) occupies much of the remainder



ITU-R Radio Regulatory Regions



Source: ITU Radio Regulations 2020

So What DID Happen at WRC-23?

Now Incorporated into 2024 Radio Regulations

- 691 Pages of Decisions (Final Acts)
- Not intuitive
- Use Table of Contents
- Look through the 101 resolutions (linked in ToC (start on P241)—majority (>60) are satellite-related

Keysight WRC-23 Summary: IMT Focus

WRC-23 Agenda Items
New Spectrum • 10.0-10.5 GHz Region 2 (but not USA?) • 6.425-7.125 GHz Region 1 (Not USA!) **New Applications** • High-Altitude IMT Base Stations (HIBS: 20-50km) (bands below 2.7 GHz) • Managing existing IMT “Mobile” Allocations and Fixed-Wireless Access (add ”Fixed” allocations?)

Keysight WRC-23 Summary: IMT Focus

WRC-23 Agenda Items

New Spectrum

- 10.0-10.5 GHz Region 2 (but not USA?)
- 6.425-7.125 GHz Region 1 (Not USA!)

New Applications

- High-Altitude IMT Base Stations (HIBS: 20-50km) (bands below 2.7 GHz)
- Managing existing IMT “Mobile” Allocations and Fixed-Wireless Access (add ”Fixed” allocations?)

Future WRC (2027 and 2031)

New Spectrum

- 7.125-8.4 GHz
- 14.8-15.35 GHz
- 102-275 GHz

Studies!

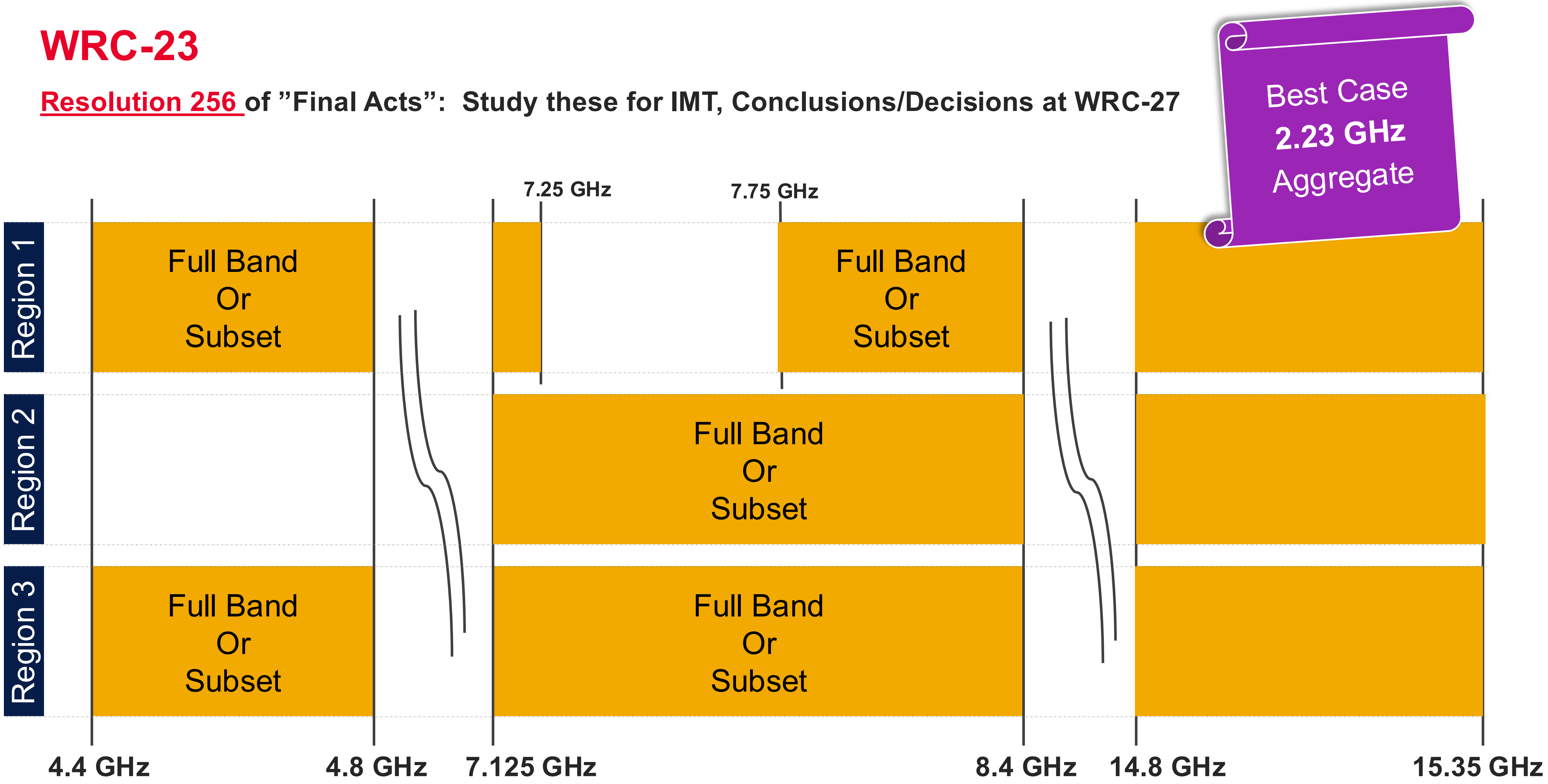
New Applications

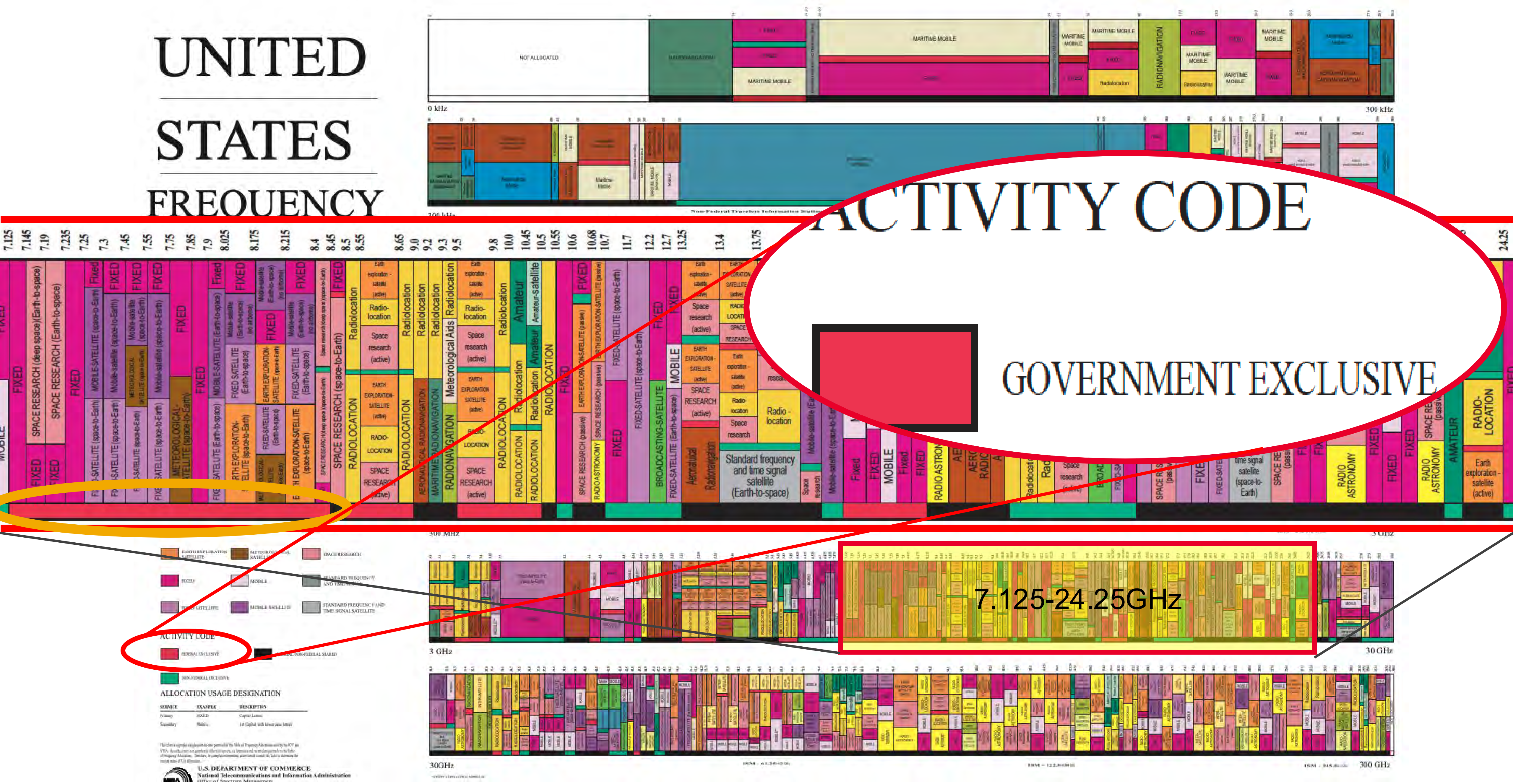
- Mobile satellite direct connect to IMT UE’s (4.4-4.8 GHz)
- IMT UE’s in Aeronautical applications (694-960 MHz (R1), 890-942 MHz (R2), 3.4-3.7 GHz (R3))

Explaining The Appearance of Apparent Industry ←→ ITU mismatch Overall rule: ITU is not the final regulatory say on much of what is used for IMT (e.g. FCC NPRM for 12.7-13.25 GHz)	
10-10.5GHz was the only “FR3” band in WRC-23. 4.4-4.8, 7.125-8.4, 14.8-15.35 (as well as SubTHz) will not get decisions until 2027 or 2031.	1) ITU time dominated by satellite topics and satellite industry. Band has heavy primary allocation to satellite; 2) WRC-23 Agenda has been frozen for 2 years; 3) Complexity of regional and national policy issues means “FR3” gets handled piecemeal for international harmonization; 4) US/FCC made 5.95-7.125GHz all unlicensed, next possible 500MHz was at 10GHz—but US opted out.
HIBS (e.g. Loon) are small applications compared to Satellite or UAV?	1) See #1 above (IMT represents a threat in some ways); 2) NTN topics are points of disagreement between Europe+USA and Russia/China/Iran. Aligning on agenda topics is fraught—thus decisions get spread over time.
IMT “mobile” vs. FWA: FWA has blurred the lines between “Mobile” and ”Fixed” Allocations	Resolution 175 (From WRC-19) was recommended for deletion—apparently this did not get enough support.

WRC-23

Resolution 256 of "Final Acts": Study these for IMT, Conclusions/Decisions at WRC-27




UNITED
STATES
FREQUENCY
ACTIVITY CODE
GOVERNMENT EXCLUSIVE
7.125-24.25GHz
0 kHz
300 kHz
300 MHz
3 GHz
30 GHz
30GHz
300 GHz
ACTIVITY CODE
ALLOCATION USAGE DESIGNATION
U.S. DEPARTMENT OF COMMERCE

7-24 GHz: Why Is This Such a Target and What Is At Stake

Why is "FR3" So Popular?

Incremental Spectrum for IMT

- Capacity demand: Studies suggest demand for additional 2GHz by end of next decade (USA example)
- < 7.125 GHz: mostly has inadequate contiguous available bandwidths

Incremental Revenue For Vendors

- Semiconductor, network equipment, device, (and test equipment! ☺) vendors want a driver for incremental revenue

Perception of Accessible Technology

- Technology/cost compromise:
  - "easier" to deploy than > 24GHz
  - >24GHz: Systems deemed too expensive

Why is 7-24 GHz so Difficult?

Regulatory Limitations

- Co-Primary Use
- "Interrupted" bands: No MOBILE Allocations (yet). ITU:
  - 8.5-10.0 GHz
  - 13.4-14.0 GHz
  - 15.4-17.7 GHz

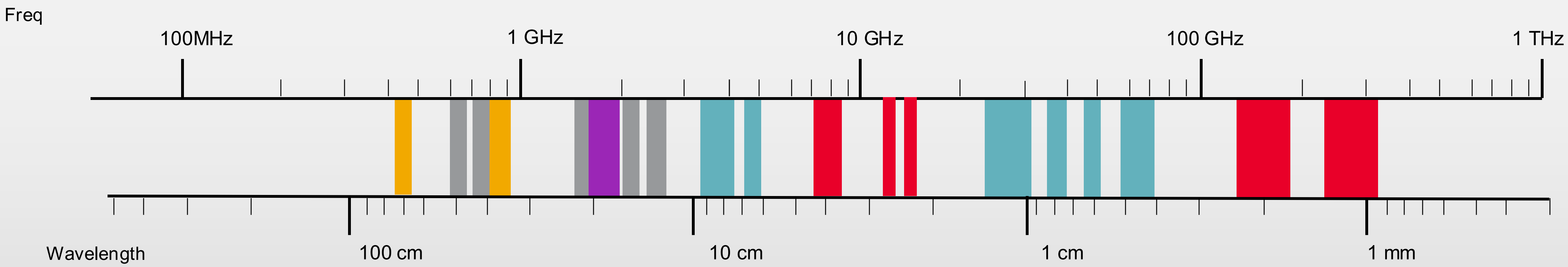
  Specific Countries: more limitations
- Federal-Exclusive use varies by country

Technology: Link Budget

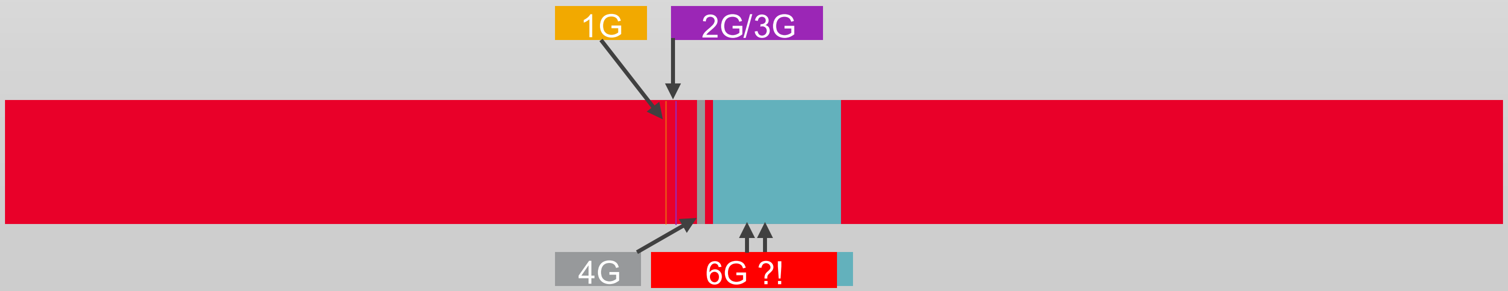
- 5G move to 3.5GHz degraded Uplink Link-Budget by as much as 18dB. One to three more octaves aggravates this problem
- Minimum cell-size (inverse of cell-site density) is at an economic limit—backhaul + site acquisition $$
- Impacts PA efficiency: network power consumption and UE battery-life/heat management

6G Will Use New Spectrum

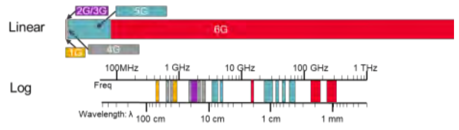
Unprecedented bandwidth expansion



Spectrum allocation by generation



Total aggregate bandwidth in each generation

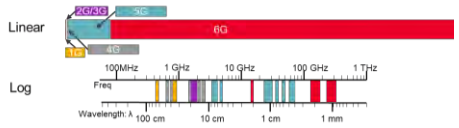


6G Candidate Spectrum: Specifics

Band	6G Research Topics: NOMA	Waveforms	Channel Coding	Unlicensed/ WiFi	Advacned MIMO	Satellite	Mobility/Cov erage	ISAC	PA & LNA	Antennae	Mobile Regulatory Situation	Technical Challenges
<7 GHz	✓	✓	✓	✓	✓	✓			✓	✓	• Minor changes ongoing e.g. 3.4-3.8 GHz and 6-7 GHz Most allocations/auctions complete.	• Coverage • Spectral Efficiency
7-16 GHz		✓	✓		✓	✓	✓	✓	✓	✓	• Entire band has co-primary use • Heavy Federal/DoD Allocation • Most EU states ambivalent at best • Passive (EES) Satellite & Radio Astronomy co-existence	• Co-existence • Coverage & Cell Density
16-24 GHz						✓			✓			• "FR2-like" (more challenging than <16GHz)
24-71 GHz			✓	✓			✓	✓	✓	✓	• 24-52 GHz Allocated or will be allocated to Mobile use • 57-71 GHz Unlicensed	• Coverage • Energy Efficiency • Mobility
71-110 GHz		✓	✓					✓	✓	✓	• Point-To-Point & Automotive Radar • Inadequate contiguous sub-bands. • Heavy constraints 90 GHz - 110 GHz	• Coverage • Energy Efficiency • Noise BW • Mobility
110-170 GHz		✓	✓		✓	✓	✓	✓	✓	✓	• Lightly regulated • ITU RR-5.340 Constraints: Radio Astronomy/EES • WRC-27 Proposed Agenda	• Coverage • Energy Efficiency • Link Budget • Noise BW • Mobility • Co-Existence
>170 GHz		✓					✓	✓	✓	✓	• Lightly regulated • ITU RR-5.340 Constraints: Radio Astronomy/EES • ITU-R WRC-27 Proposed Agenda • ITU Decisions post WRC-27	

KEYSIGHT

6G Candidate Spectrum: Specifics



Band	NOMA	Waveforms	Channel Coding	Unlicensed/ WiFi	Advacned MIMO	Satellite	Mobility/ Coverage	ISAC	PA & LNA	Antennae	Mobile Regulatory Situation	Technical Challenges
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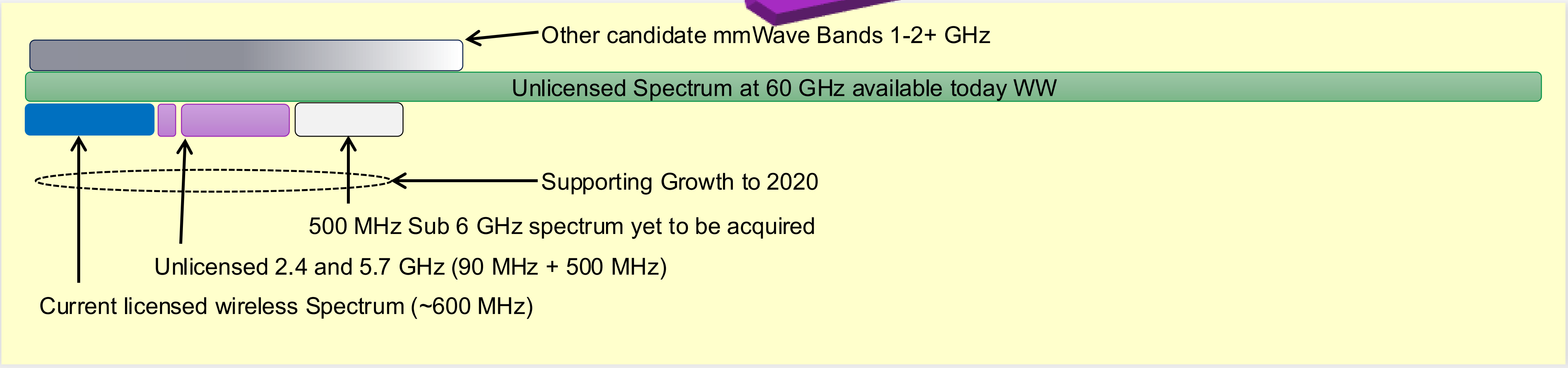
7-16 GHz		✓	✓		✓	✓	✓	✓	✓	✓	• Entire band has co-primary use • Heavy Federal/DoD Allocation • Most EU states ambivalent at best • Passive (EES) Satellite & Radio Astronomy co-existence	• Co-existence • Coverage & Cell Density
16-24 GHz						✓			✓			• "FR2-like" (more challenging than <16GHz)
FR2-1 24-52 GHz			✓	✓		✓	✓	✓	✓	✓	• Allocated or will be allocated to Mobile use	• Coverage • Energy Efficiency
54-71 GHz			✓	✓			✓	✓	✓	✓	• Unlicensed	• Mobility
71-110 GHz		✓	✓					✓	✓	✓	• Point-To-Point & Automotive Radar • Inadequate contiguous sub-bands. • Heavy constraints 90 GHz - 110 GHz	• Coverage • Energy Efficiency • Noise BW • Mobility
110-170 GHz		✓	✓		✓	✓	✓	✓	✓	✓	• Lightly regulated • ITU RR-5.340 Constraints: Radio Astronomy/EES • WRC-27 Proposed Agenda	• Coverage • Energy Efficiency • Link Budget • Noise BW • Mobility • Co-Existence
>170 GHz		✓					✓	✓	✓	✓	• Lightly regulated • ITU RR-5.340 Constraints: Radio Astronomy/EES • ITU-R WRC-27 Proposed Agenda • ITU Decisions post WRC-27	

5G Why millimeter-Wave?

Keysight's 1st mmWave slide from 2014
Over TEN YEARS AGO!!!

It's all about bandwidth: Give me more data!



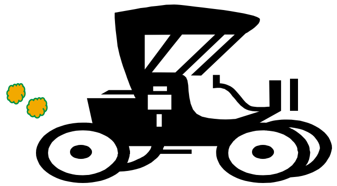
Claude Shannon Channel Capacity

$$C=B[\log_2(1+S/N)]$$

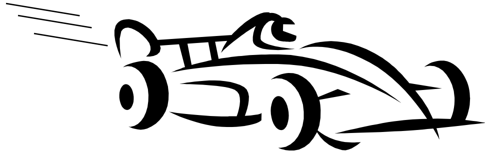
- C ≡ Channel Capacity in Bits/Sec
- B ≡ Channel Bandwidth
- S/N ≡ Signal to Noise Ratio

Assume S/N=10:1 (10dB)

- B=20MHz: C=~70MB/s



- B=2GHz: C=~7000MB/s



The FR2 “Uphill Battle”

Fast-Forward to 2024:
FR2 is Challenging

- Cost
- No ”Killer App”
- Reliable Link Management

But some of us remember other “Firsts” that had a difficult start:

- Packet Radio:
  - 1G (“analog”) CDPD
  - Early 3G HSPA vs. EGPRS
- Early SMS
- First photos we took on mobile phones

What is Driving Another Generati

Three Focus Areas For Technology

1 **Subscription Growth**

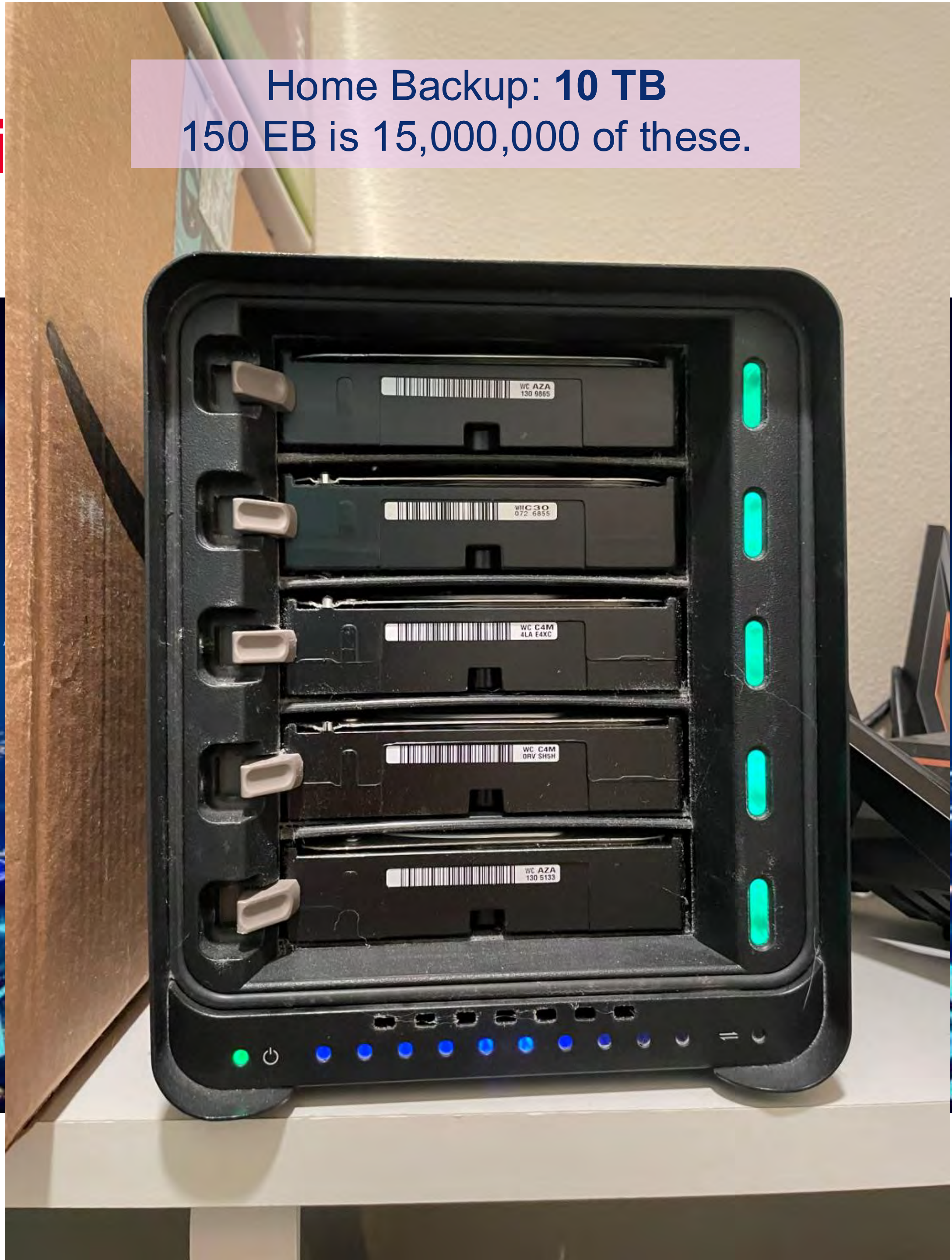
2015: 7.3 Billion
2022: 8.3 Billion
2028: 9.1 Billion

2 **Mobile Data Consumption**

2015: 6 EB/Month
2022: 95 EB/Month
2024: 150 EB/Month
2030: 473 EB/Month

3

Source: Ericsson Mobility Reports 2016 and 2024



Spectrum Challenge

Data needs bandwidth which comes from incremental spectrum

Spectrum Demand

+ 2GHz Incremental

+

Spectrum Constraint

Multiple Competing Demands

+

FR3 Challenge

Not as easy as it looks

CTIA Commissioned Study April '23

- **Capacity Deficit:** Expected to be >10 EB/month by end '27 and >17EB/month by '32
- **Spectrum Deficit:** 400MHz by '27, 1400MHz by '32

Government, Commercial, Scientific, Satellite All Need More

- **WRC-23 for IMT:** Study <1800MHz* for WRC-27
- **EU States:** Not considering adding spectrum for IMT
- **USA:** 6-7GHz Unlicensed, rejected 12.2-12.7 GHz & 10-10.5GHz Proposals

Technology Challenges

- Uplink Budget: 3.5GHz required >15dB improvements
- muMIMO: gNB Complexity, Cost, Mass, Energy consumption
- Spectrum Sharing may be required by policy

* Except Region 3

FR2 Deserves a Closer Look

>3GHz Already Allocated in Many Countries

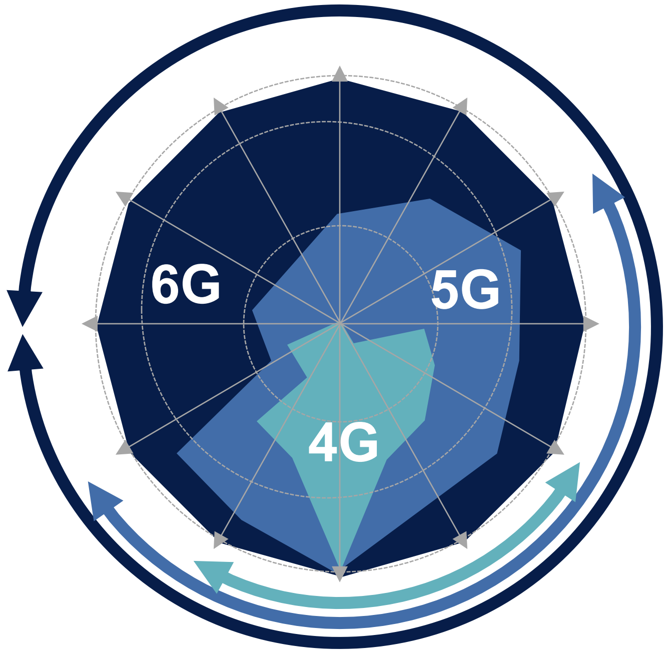
+>2GHz Potential Additions

+14GHz Unlicensed

Improving Performance of FR2

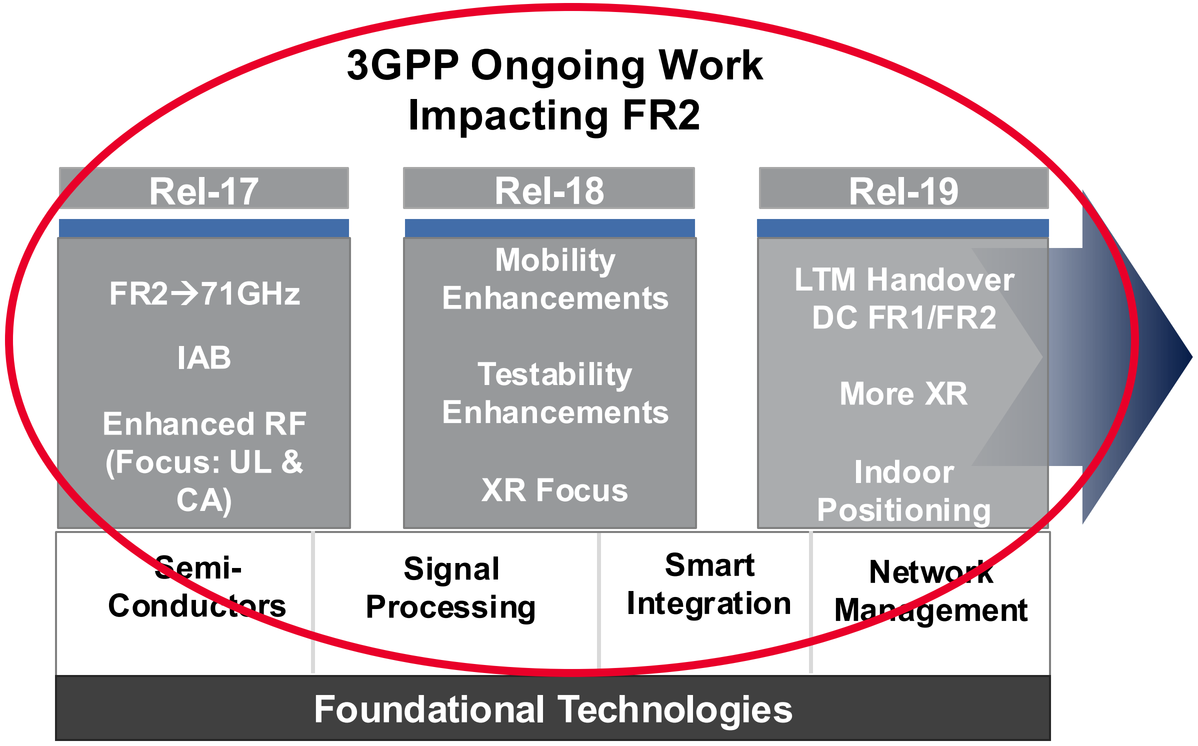
Roger's View: Our industry innovates best under these conditions:

Demand Exceeds Current Performance + **Specification in Standards: Economy of Scale** = **Technology Enables Market Demand**



KPIs for each generation:

- Data rates, bandwidth
- Frequency bands
- Spatial multiplexing
- Coverage
- Virtualization
- Latency & QoS
- Location
- 3D connectivity
- Energy efficiency
- Digital twin
- Network sensing
- AI/ML
- Security



Applications' Increasing Demand: High Bandwidth, Short Wavelength

FR2 Enables

Sporting

All 30 USA NFL Stadiums + Plans for NHL

XR

Gaming
Training
Troubleshooting
Medical

Industrial

CoBots
Visual Inspection
High-Speed Video

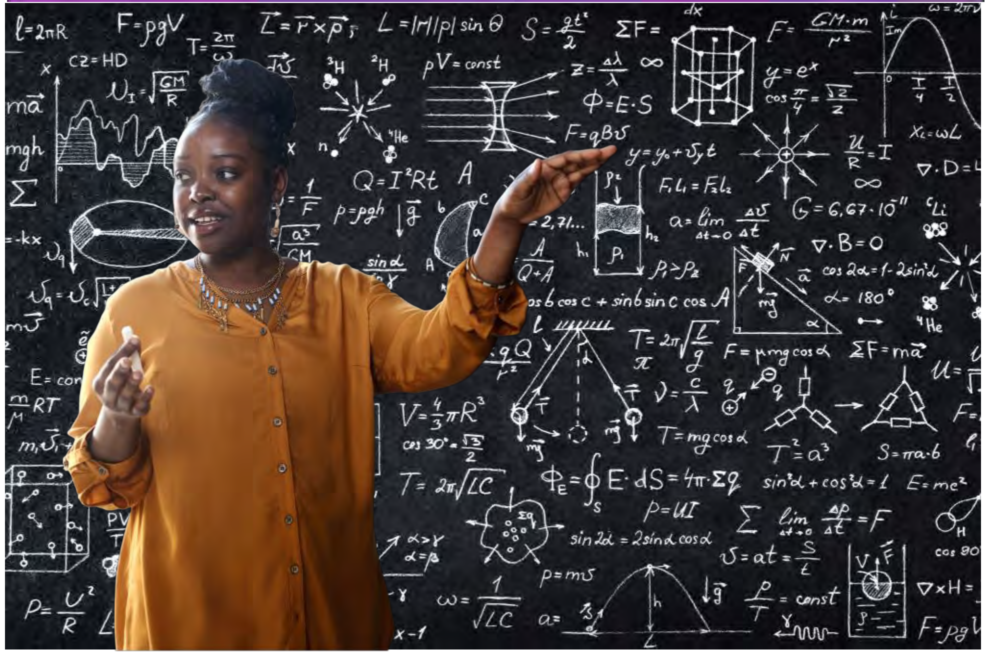
Other Inherent Technology Benefits

- Short Wavelength & High Bandwidth = Sensing: Physical and Time Resolution
- Directional Tx/Rx: Security, Capacity (Spatial Multiplexing)
- Antenna Size: Compact Implementation

Learnings From The Past 24 Months

If we build it, they may not come….

”Lessons Learned”



6G Vision Calibration: ’23-’24

- Evolution more than revolution
- **Engage earlier with the verticals**

Service Awareness

When is the last time you *knew* you had FR2 coverage and performance?

Today's Topics

- Foundations of Spectrum for Radio
- History of Spectrum use in Cellular
- 6G Specifics by Frequency Range
- Conclusions

Summary: Observations & Commentary

New Spectrum Considerations for 6G: Late Summer 2024

6-24 GHz

Regulators:

ITU WRC-23 Focus Areas

- 6.425-7.025 & 7.025-7.125 GHz
- 10-10.5 GHz (Region 1 & 3)
- Will set the stage for further 6G recommendations

ITU WRC-27 Draft Agenda:

- Includes various bands 7-16 GHz, but many EU regulators oppose this.

FCC proposed rulemaking to add 12.5-13.25 GHz for IMT

US NTIA Spectrum Strategy: 7.125-8.4 GHZ

Industry & Academia:

7-15 GHz popular for next significant addition for 6G

Work focused on extreme MIMO and amplifier performance.

24-71 GHz

Regulators

- Most regions allocated. Eyes on are India & China potential
- Do not expect major changes in the next two years

Industry & Academia

- Operators not profitable in this band. Some have abandoned their spectrum position
- Economies of scale not yet obvious—no “killer app”
- Focus: Decrease cost, increase performance, drive applications
- <u>Remains a good choice for 6G expansion</u>

>100 GHz

Regulators

- Early experimental licensing established (esp. in USA)
- Strict and large “no fly zones” in some bands due to passive satellite and radio-astronomy concerns

Industry & Academia

- Industry: FR2 challenges driving less favor for mainstream adoption
- Academia: Still a favorite for research (novel territory) and niche applications

Audience Quiz

Only Two Questions; Just like in school: 50% grade = Fail

1. What does “FR3” Mean?

2. What is the 500KHz radio spectrum used for?

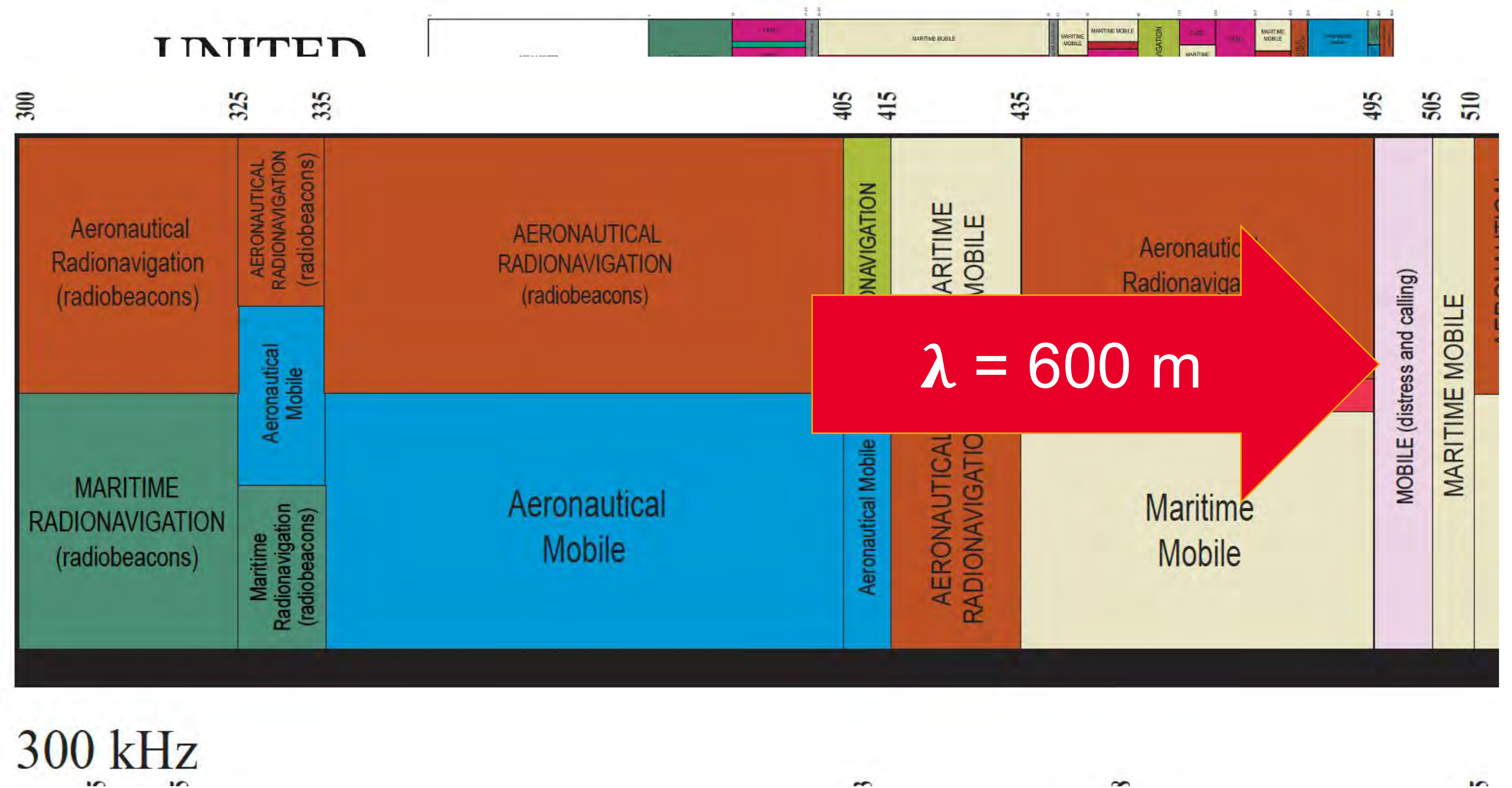
Audience Quiz

Only two questions; 50% grade = Fail

1. What does “FR3” Mean?

- Nothing
- FR1: 3GPP Frequency Range 1 from 450 MHz→7.125 GHz
- FR2-1: 3GPP Frequency Range 2-1 from 24.25→52.6 GHz
- FR2-2: 3GPP Frequency Range 2-2 from 52.6→71 GHz
- FR3 has become common parlance for 7.125-24.25 GHz, but *not used in any 3GPP specifications as of end 2024*

2. What is the 500kHz radio spectrum used for?


300
325
335
405
415
435
495
505
510
Aeronautical Radionavigation (radiobeacons)
AERONAUTICAL RADIONAVIGATION (radiobeacons)
AERONAUTICAL RADIONAVIGATION (radiobeacons)
Aeronautical Mobile
MARITIME RADIONAVIGATION (radiobeacons)
Maritime Radionavigation (radiobeacons)
Aeronautical Mobile
Aeronautical Mobile
AERONAUTICAL RADIONAVIGATIO
Maritime Mobile
MOBILE (distress and calling)
MARITIME MOBILE
λ = 600 m
300 kHz

What to Look For*:

6-24 GHz

- 6G novel spectrum focus: 7-16 GHz. 6-7 will be established as 5G and UL offload by 2030
- Links will be terrestrial *and* non-terrestrial. Satellite today is big business despite unclear MNO NTN business model
- >7GHz terrestrial use will require next-generation advanced MIMO with active antenna systems
- CC Bandwidths likely 200MHz max. Inter-and intra-band carrier aggregation will continue to proliferate

24-71 GHz

- FR2 is *not* dead—will be leveraged for 5GA & 6G
- Industry will continue to evolve functionality and capability
- Watch FWA & XR (esp. mobile gaming) for a volume and cost driver
- 5G Investments will be leveraged. Focus on cost, mobility, reliability

>100 GHz

- Academic *and* commercial research continues
- Commercial 6G: Mobile *access* links will not use this band until after 2035
- Industrial links, backhaul, and other PTP for niche applications
- D-Band (WR 6.5: 110-170 GHz) is getting the most attention

*Subject to change without notice

KEYSIGHT

KEYSIGHT

Channel Modelling for FR3

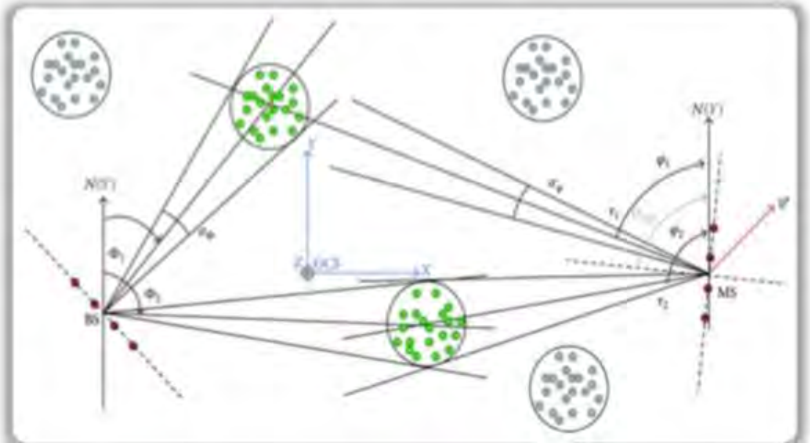
Randy Becker
Winter 2025

6G Requirements: A drive towards deterministic channel models

4G and 5G channel modeling requirements

- MIMO and beamforming with limited resolution for environment awareness and adaptation
- Time, frequency and spatial domain statistical characteristics

Stochastic geometry-based channel models



6G use cases and channel modeling requirements

- Smaller cells and short-range communications
- Accurate location-based services
- Specular propagation at sub-THz
- Enhanced environment awareness and adaptation
  - Integrated sensing and communications (ISAC)
  - Extreme MIMO

Deterministic modeling

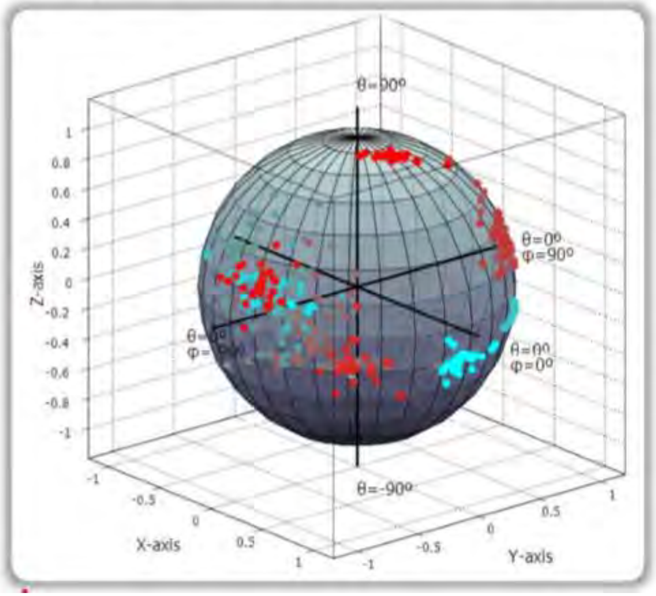
- Environment-aligned RF propagation model "digital twin"
- Spatial consistency
  - Multiple users and BSs
  - Time evolution of channel characteristics
  - Direction & delay & phase

Keysight Vision of Channel Modeling Options for 6G

Stochastic Models → (Realistic environment / Spatial consistency) → **Semideterministic** → (Accurate environment / Digital twin) → **Deterministic**

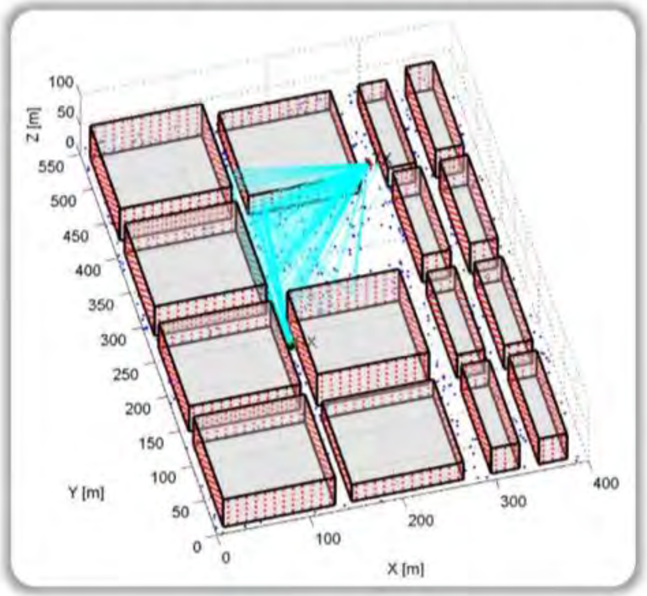
Enhanced stochastic GSCM modeling concept

- Specular path parameterization
- Distribution of rays
- More accurate polarization model
- Location based clusters for near-field effect and spatial consistency improvements



Semi-deterministic map-based hybrid model

- Simplified map/layout
- Combination of stochastic and deterministic model
- Include randomness for example to introduce random/configurable objects for blockage



Raytracing modeling

- Sub-wavelength sampling of deterministic path calculation
- Accurate map/layout environment model
- Site specific environment aligned propagation model "digital twin"

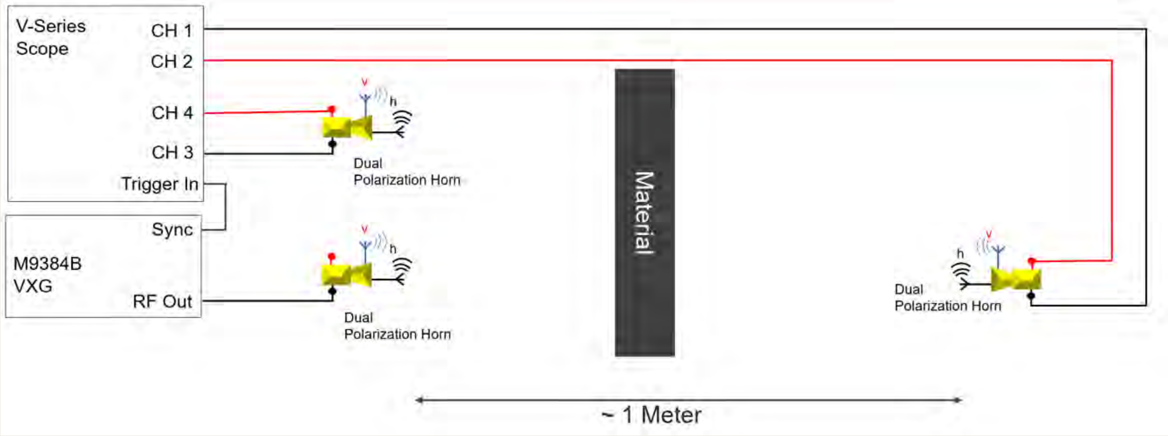
Channel and Materials Measurements

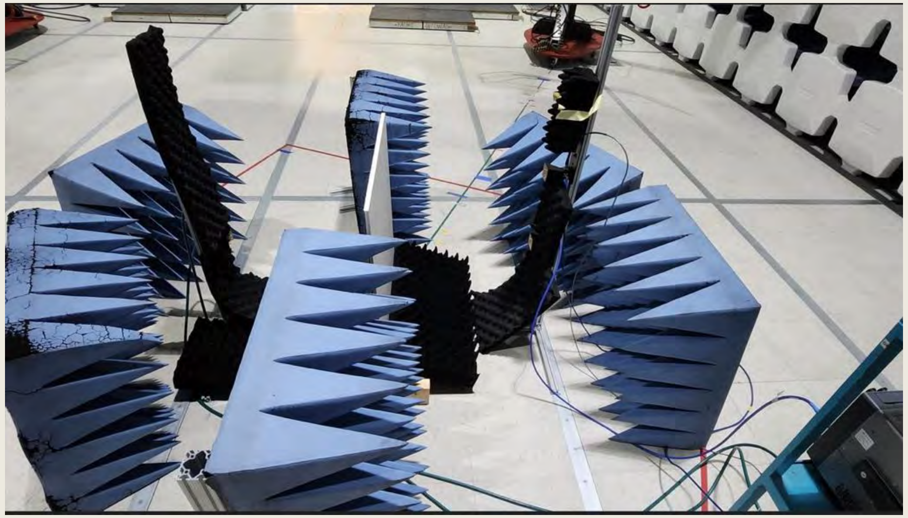
Keysight Measurement Summary

- Material Measurements
- Indoor Scenarios:
  - Conference Room
  - Café
  - Factory Floor
- Outdoor Measurements
  - LOS and non-LOS measurements in open courtyard with elevated transmit antenna
- Measurement system based on Keysight 89600 VSA Software
- Measurements performed at 7.0, 10.25 and 13 GHz

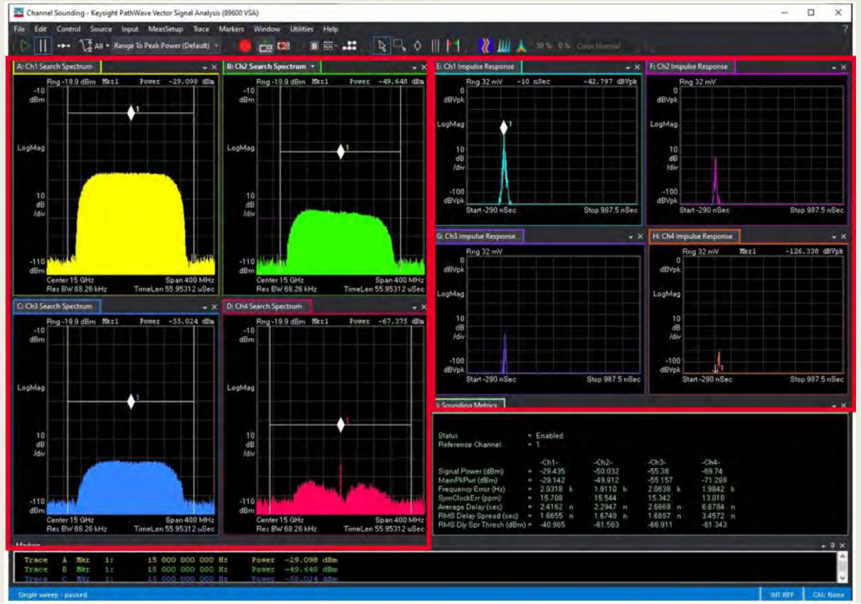
5

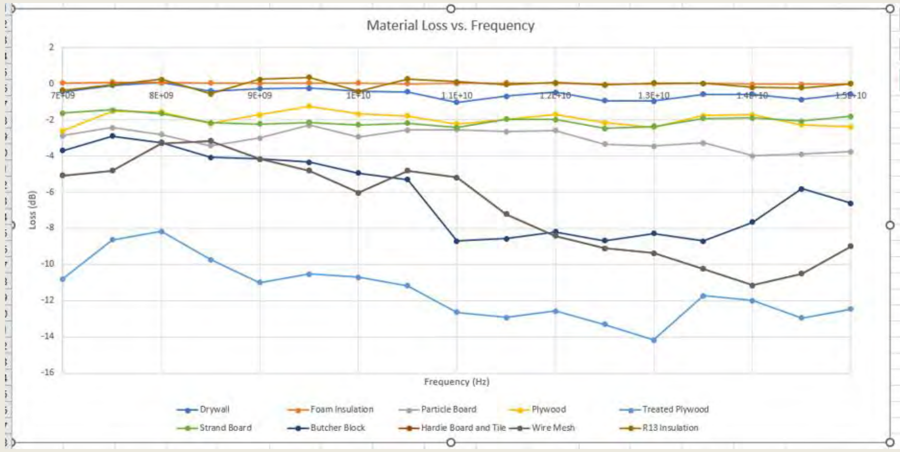
Material Measurements





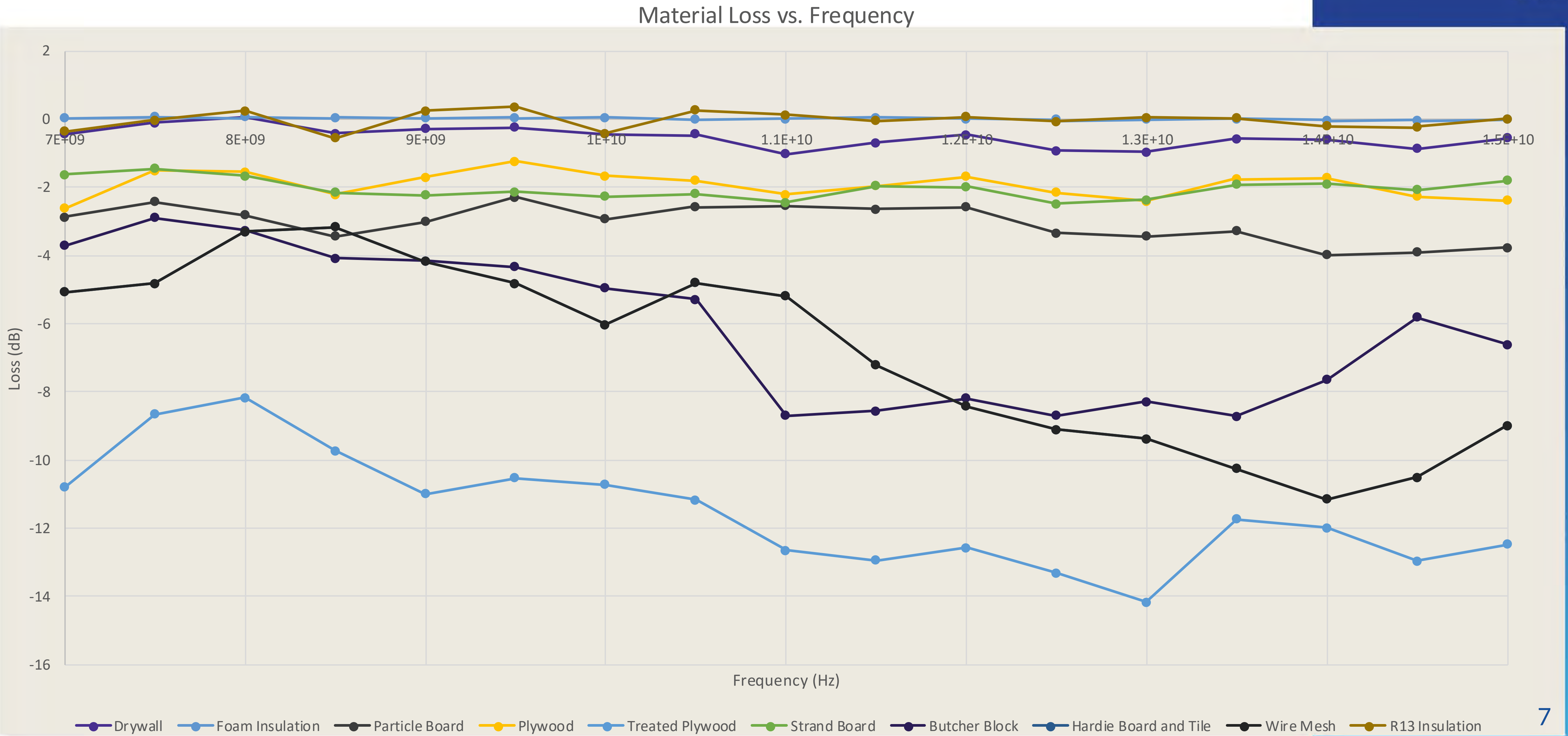
Transmission and reflection measured for co-polarization and cross-polarization





6

Conclusion and Observations

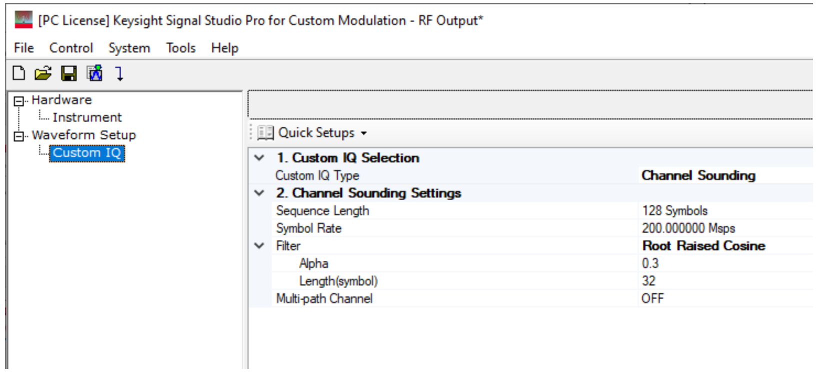


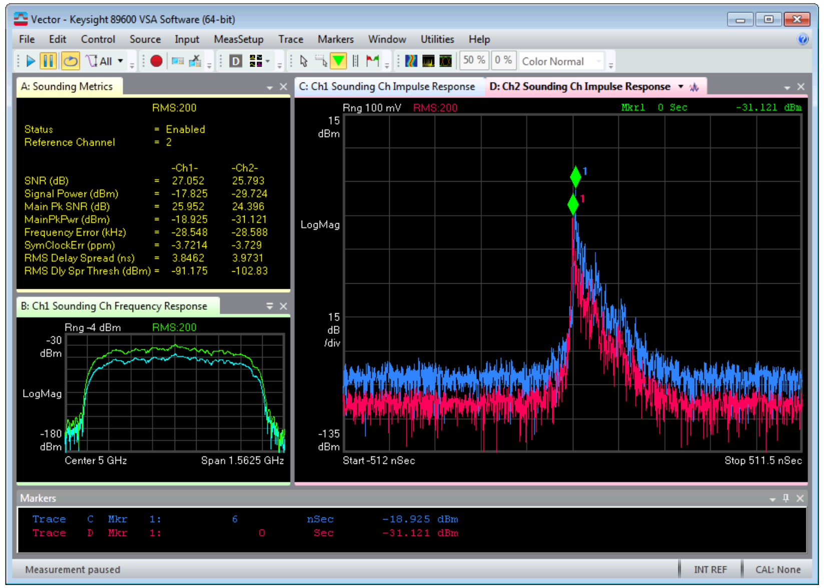
Indoor/Outdoor Measurement System

- Omni-directional transmit antenna
- Directional horn antenna mounted on azimuth/elevation rotator
- M9484B Vector Signal Generator
  - 44 GHz Frequency Range
  - 2 GHz Modulation Bandwidth
- 89600 VSA Channel Sounding Measurement Software
- UXR0252A Oscilloscope
  - 2 Channels
  - 256 Gs/s Sample Rate
  - 100 GHz Bandwidth

Key Benefits of Keysight Channel Sounding Software

- Measurement operates with a wide variety of Keysight test equipment:
  - Vector Signal Generators (VXG) for Signal Generation with bandwidths up to 2.5 GHz and carrier frequencies up to 54 GHz
  - Arbitrary Waveform Generators (AWG) for bandwidths up to more than 30 GHz and up conversion to sub-THz carrier frequency
  - Signal Analyzers (PXA, UXA) for bandwidths to 4 GHz and carrier frequencies up to 50 GHz
  - Oscilloscopes (UXR):
    - Bandwidths up to more than 30 GHz and down conversion from sub-THz
    - Multiple Channels

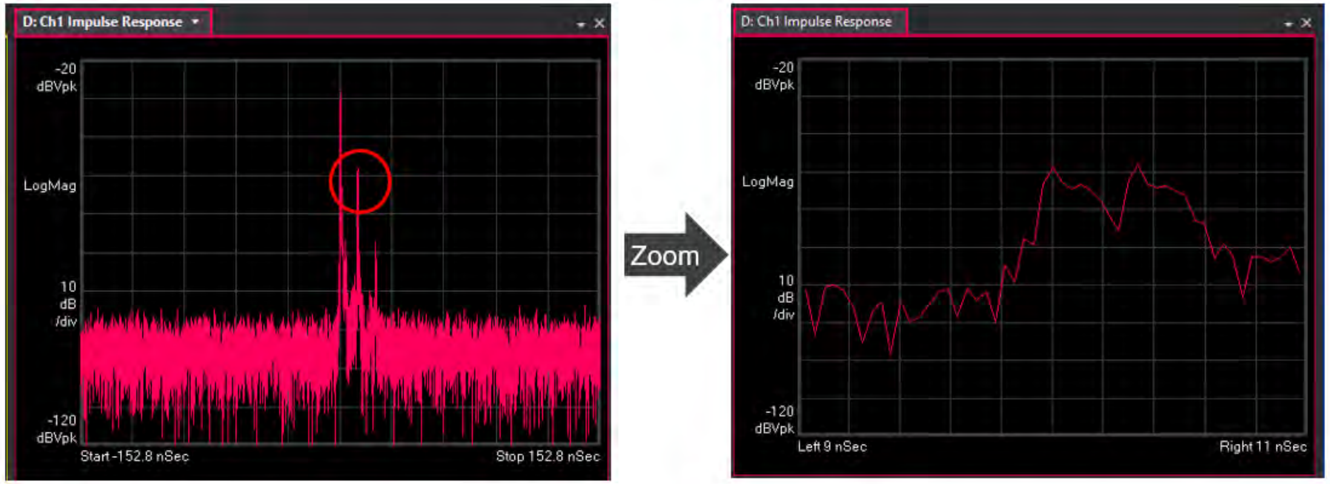


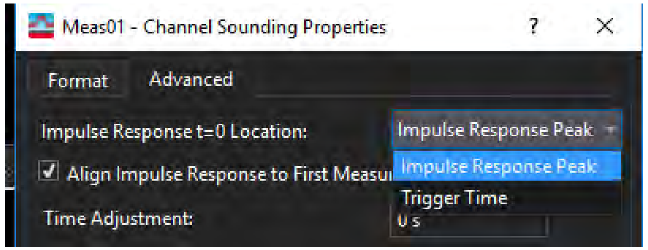


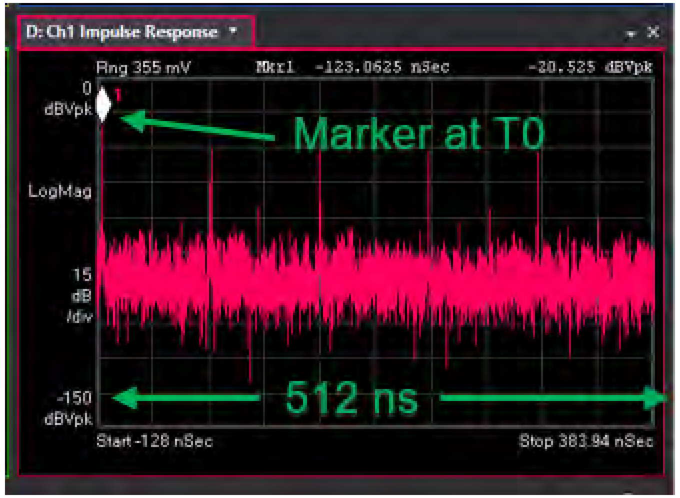
Key Parameters of Channel Sounding Waveform

Time Based Parameters

- Resolution:
  - Time difference between two paths can be measured
  - ~ 1/Signal Bandwidth
- Range:
  - Time difference between first and last paths that can be measured
  - ~ Sequence Length * Resolution

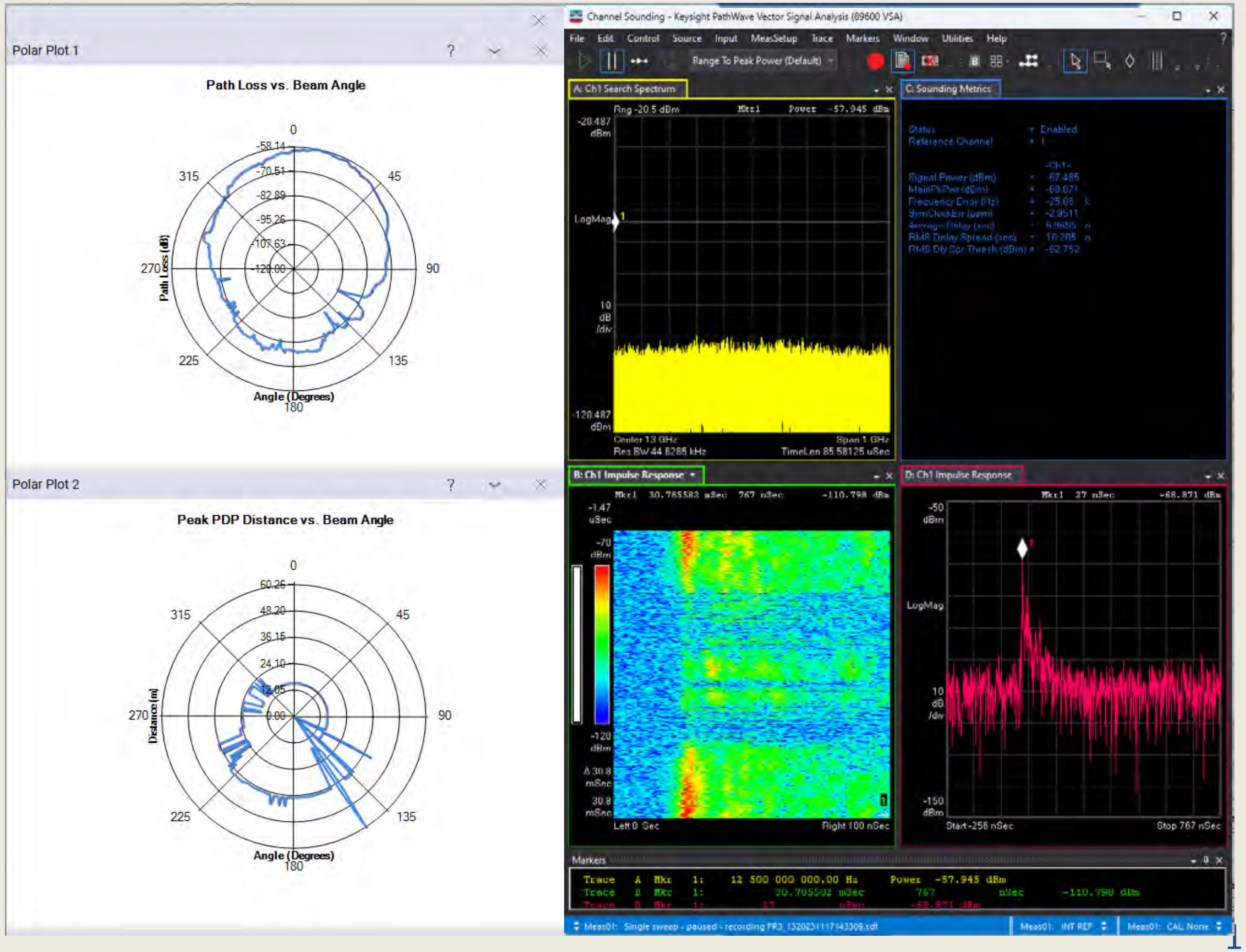






Indoor/Outdoor Measurement Process

- 89600 VSA recording file generated for each rotation of the RX antenna
  - Data is measured in one-degree steps, triggered to provide absolute propagation time measurements
  - RX elevation angles from -30 to +30 in ten-degree steps
- 89600 recording file post processed to generate CIR at each measurement point
- Data generated:
  - CIR data: CSV file for all measurements in one recording file
  - VSA Spectrogram trace file containing all points in one file (shown in trace B at right)
  - Plots of peak impulse power vs RX azimuth angle and distance to peak impulse power vs RX Azimuth
- CIR data shared with Next G Alliance.
  - Recording files and other data files retained by Keysight but not shared as they require Keysight software to use



Indoor Measurements

Abhinav Mahadevan

Michael Millhaem

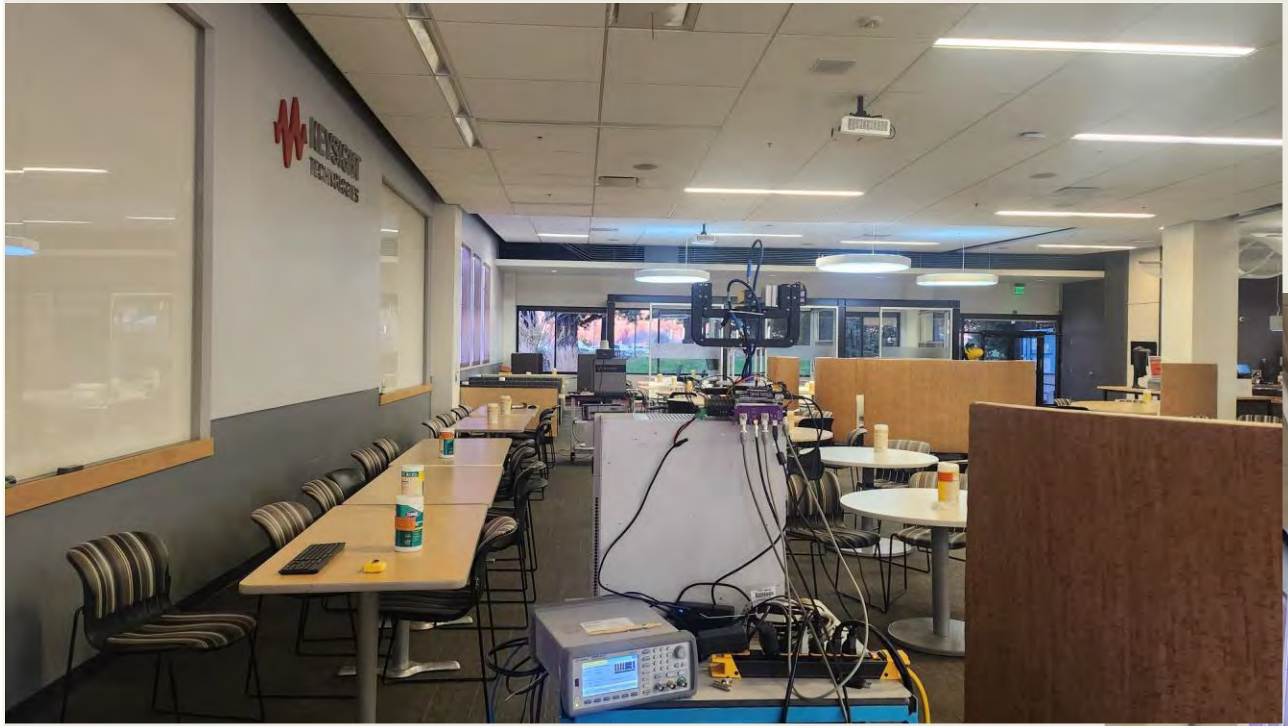
Measurement Details

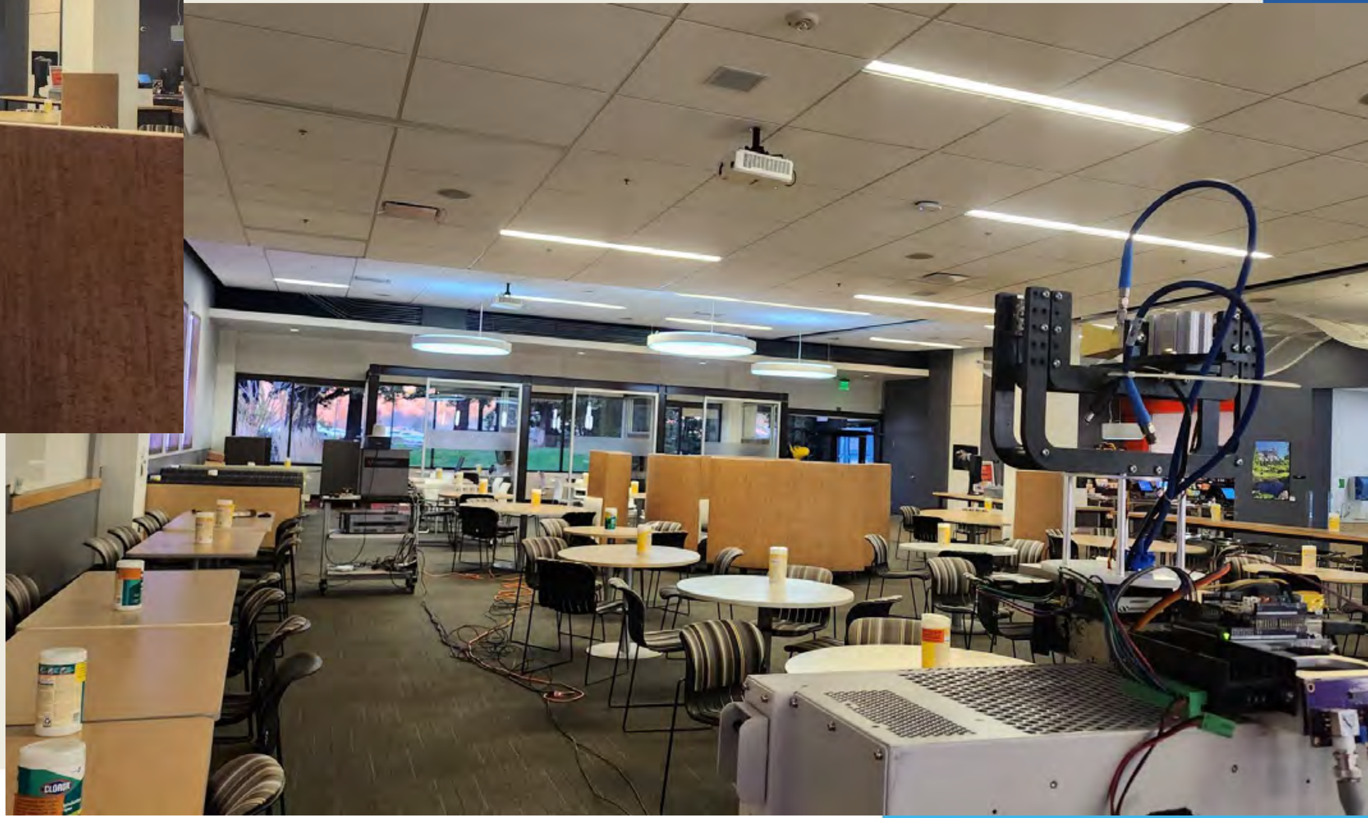
> FCC Licenses: 6.75-7.25 GHz, 10-10.5 GHz, 12.75-13.25 GHz
> Measurement of Conference Room, Keysight Cafeteria, Factory Floor
> Calibration was done by normalizing loss at 1m distance
> TX Antenna frequency range: 300 MHz-40 GHz Omni Directional
> RX Antenna Frequency range: 6-53 GHz

Scenario 1: Indoor Conference Room

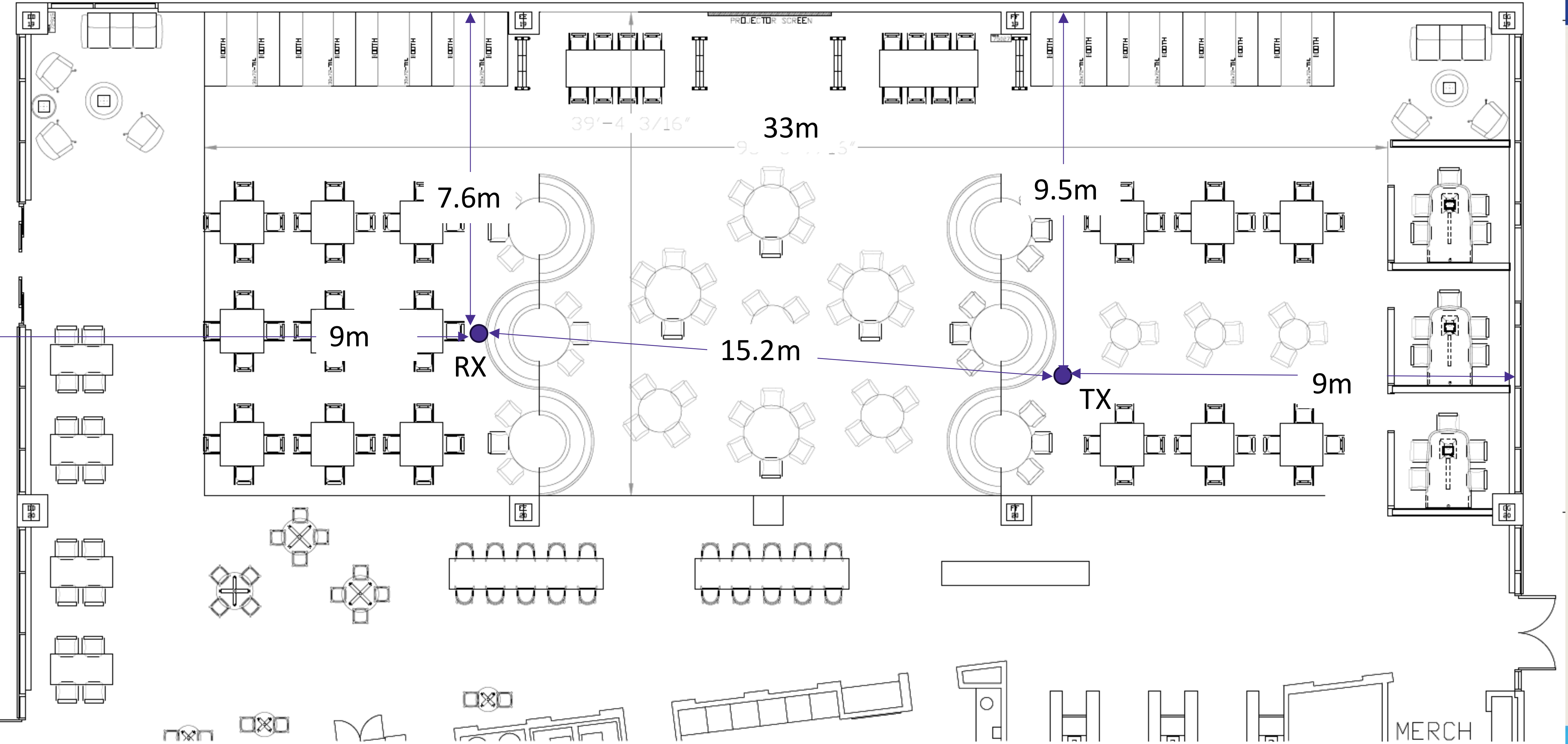
NEXT G ALLIANCE
An ATIS Initiative

Scenario 2: Keysight Cafeteria

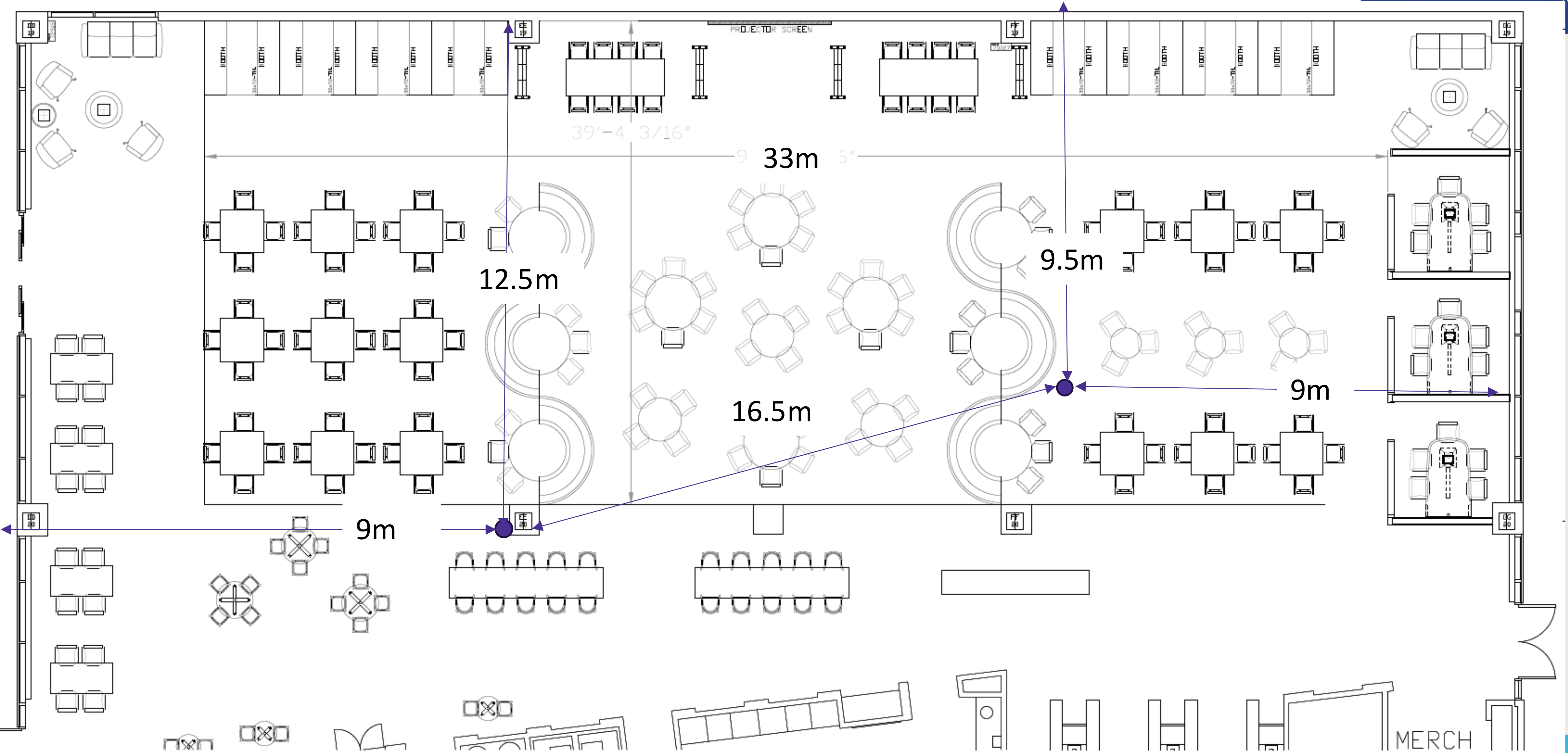




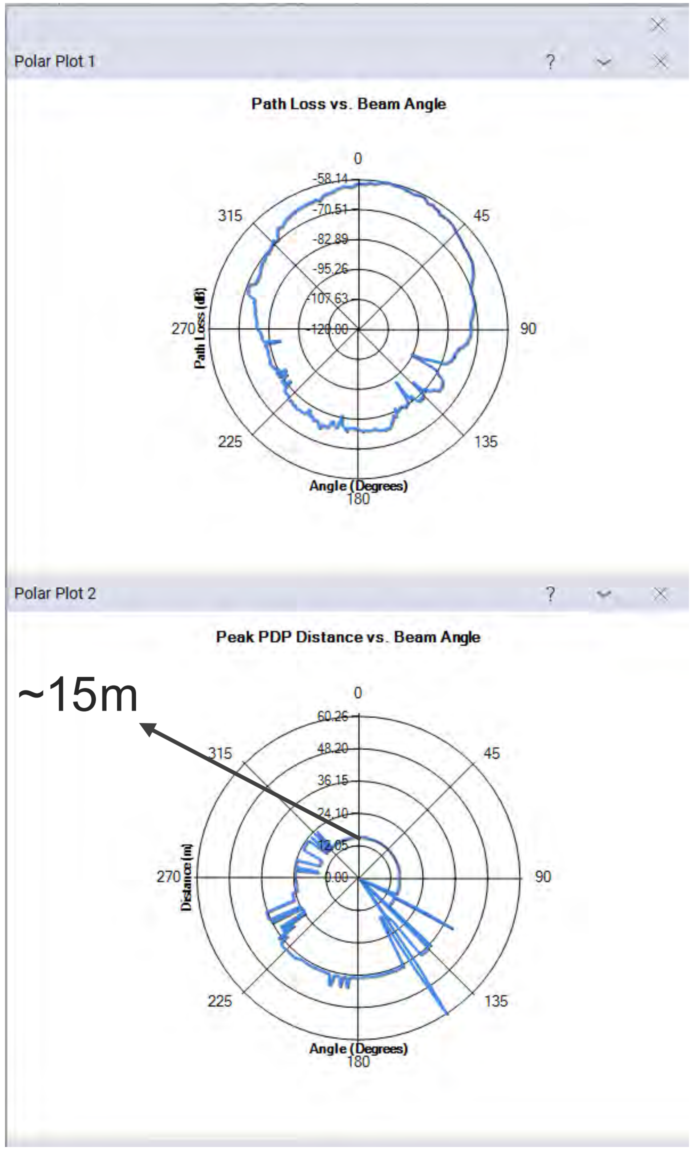
Cafeteria Scenario

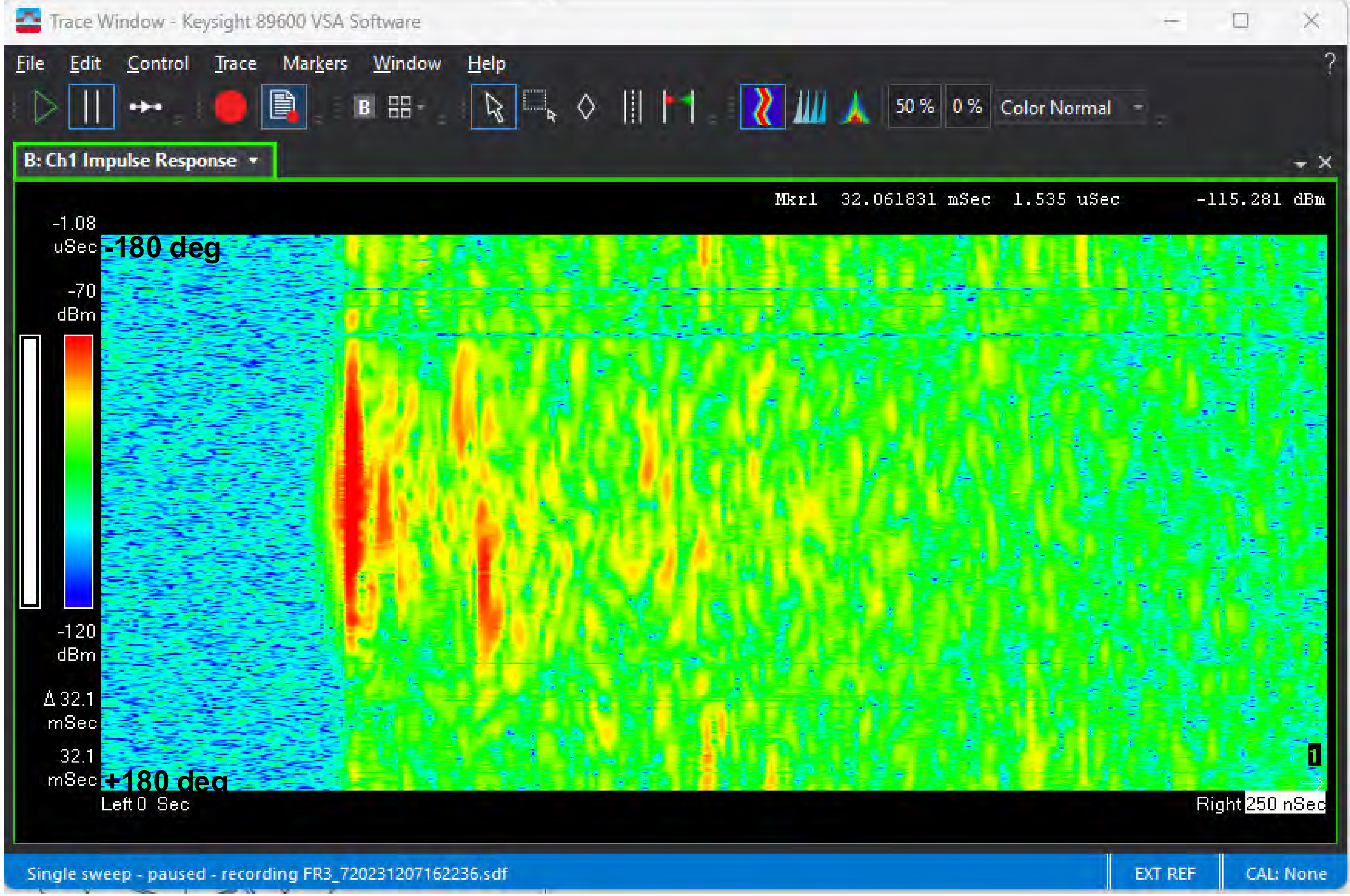


Cafeteria Scenario

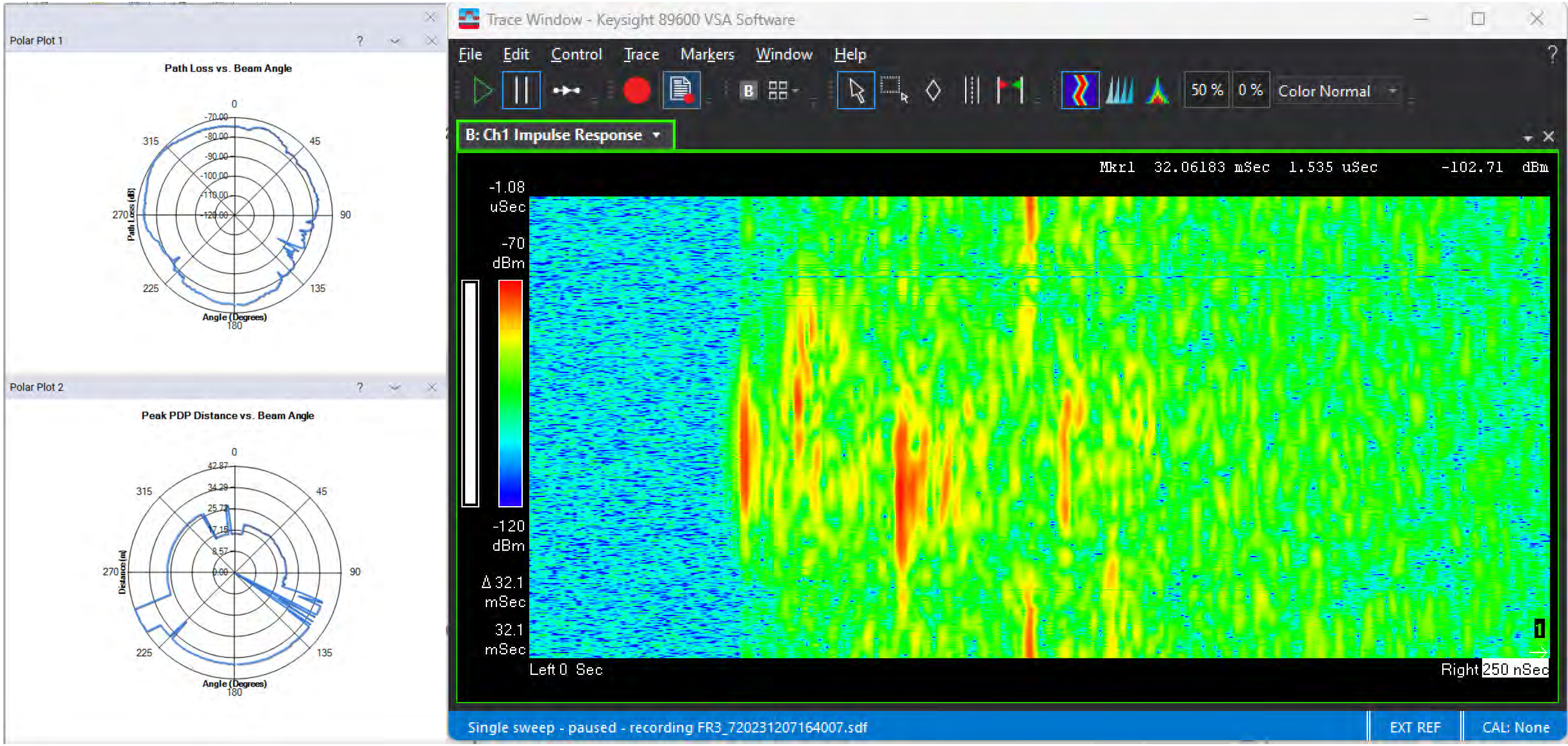


LOS Visible 7 GHz

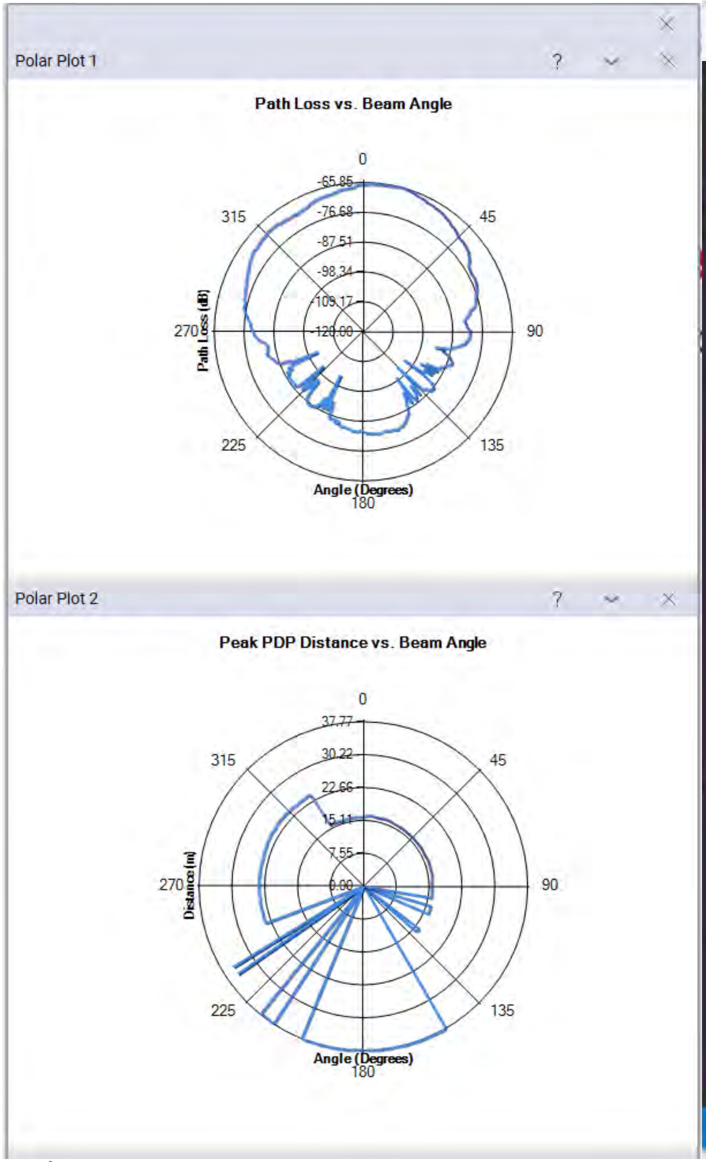


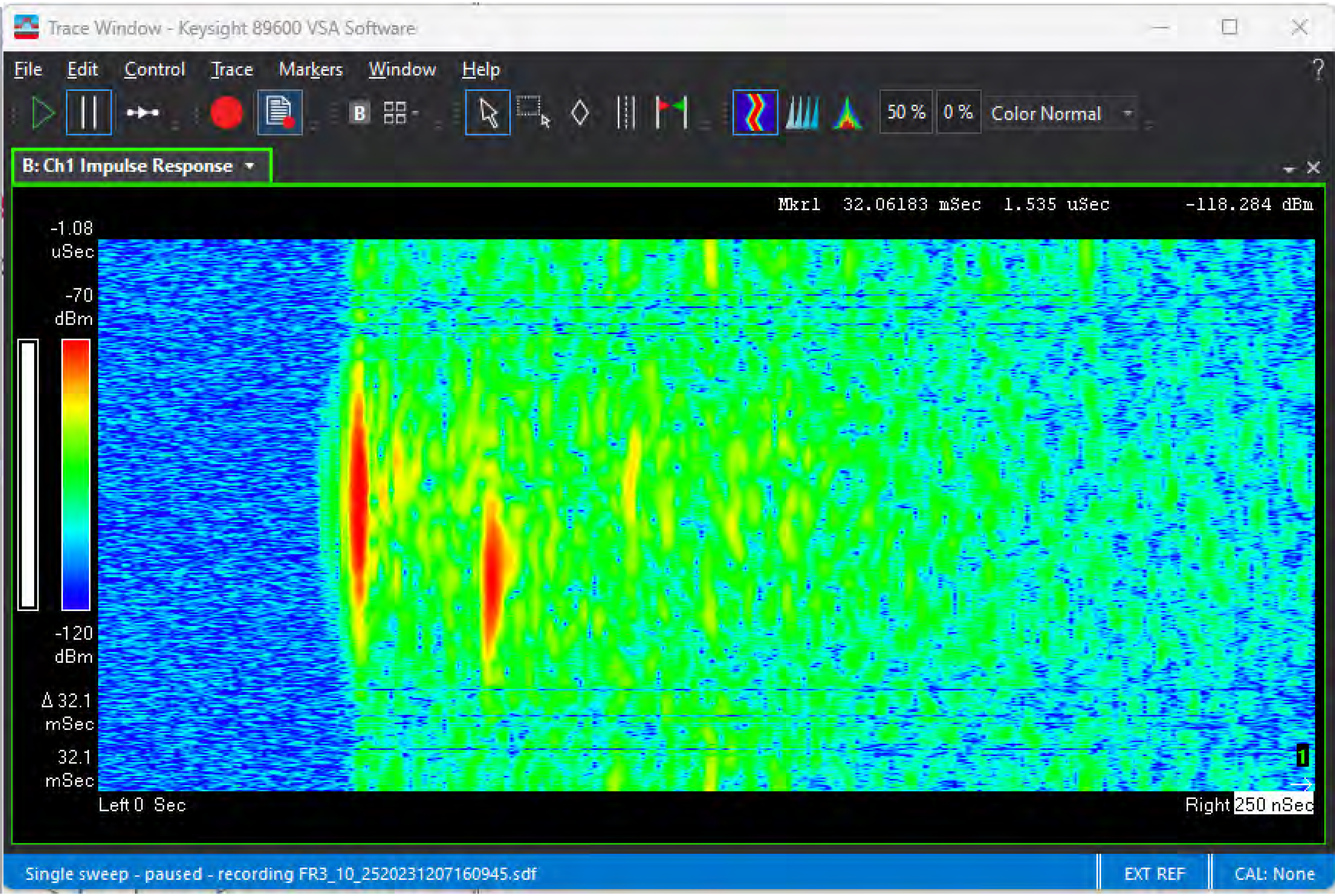


LOS Obstruction 7 GHz

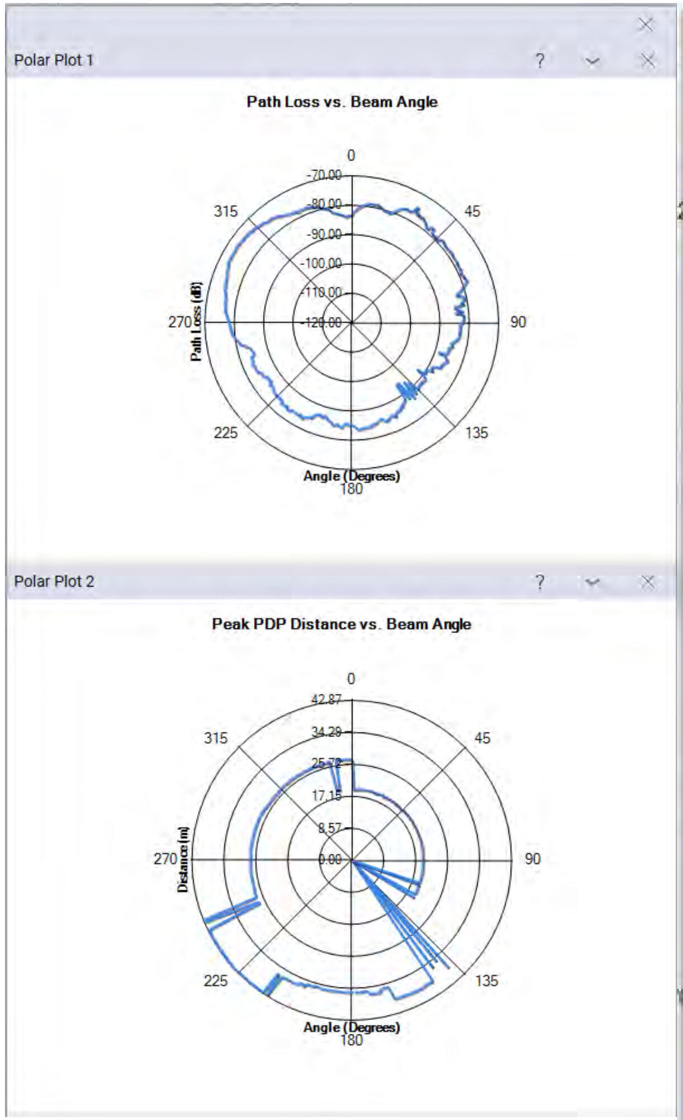


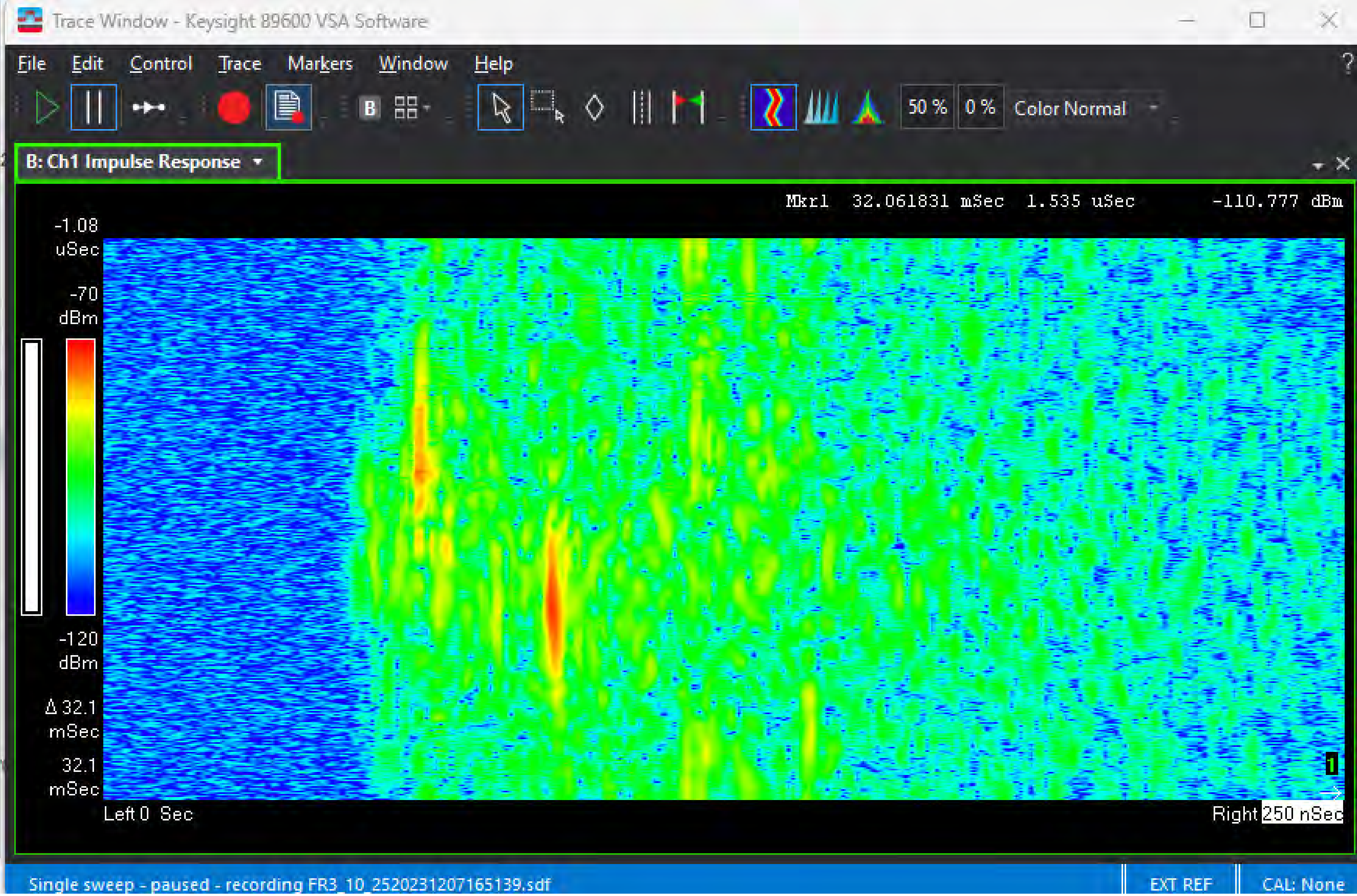
LOS Visible 10.25 GHz



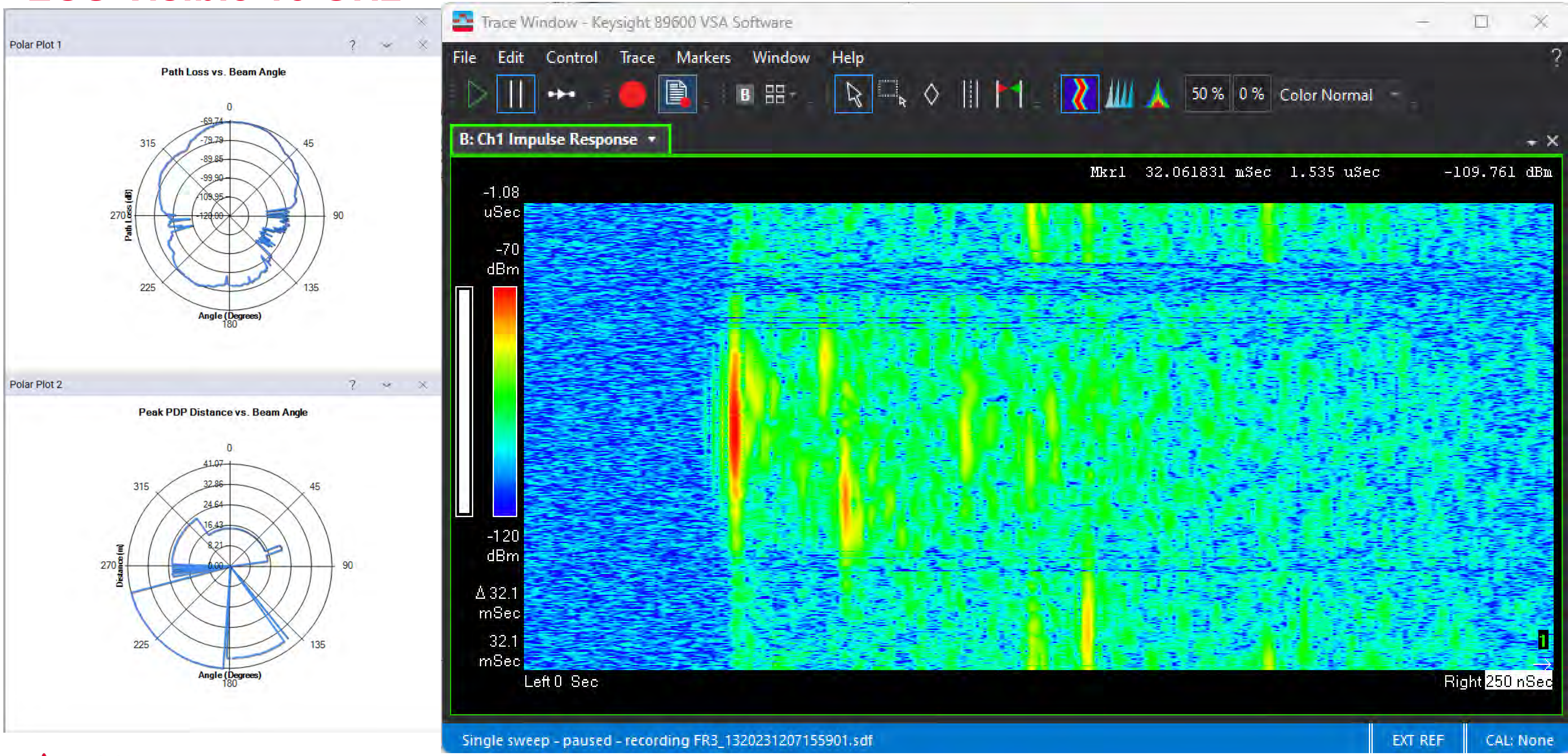


LOS Obstruction 10.25 GHz

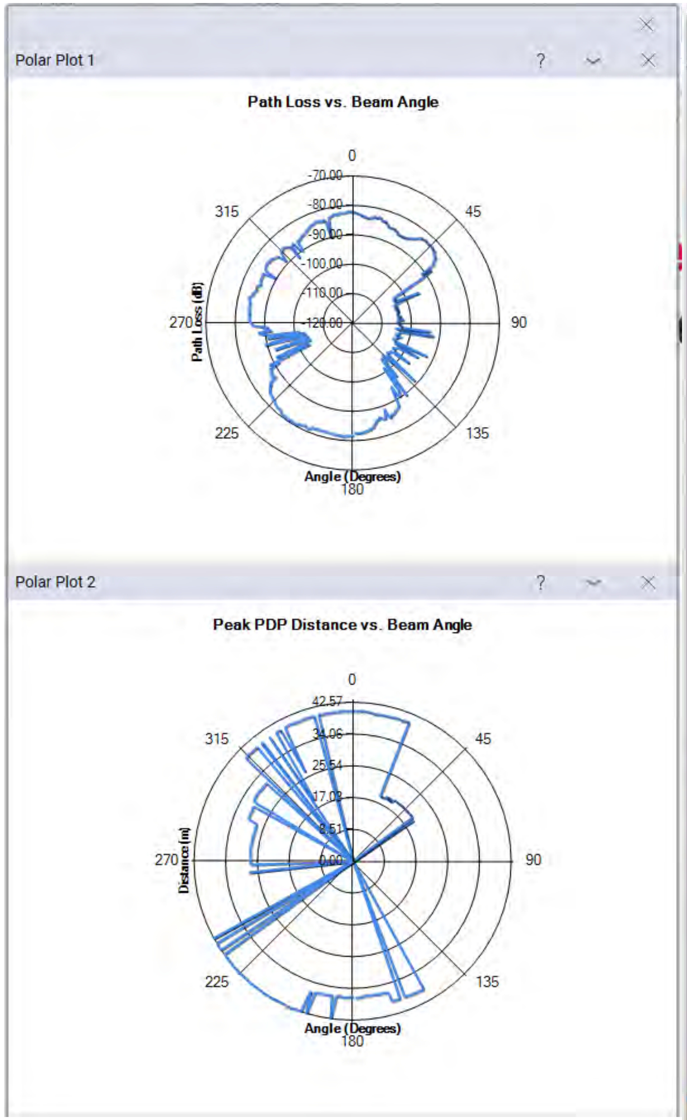


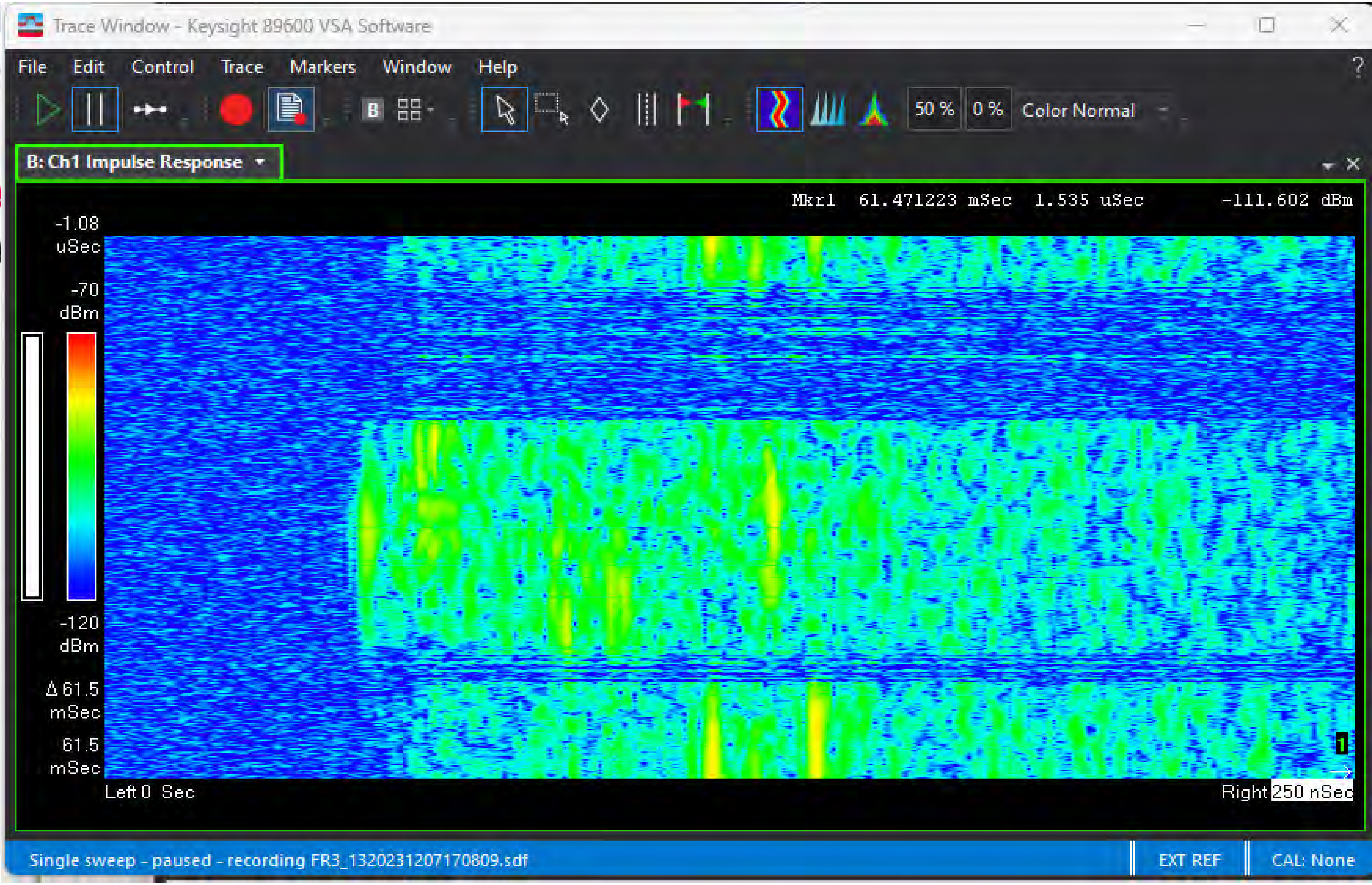


LOS Visible 13 GHz



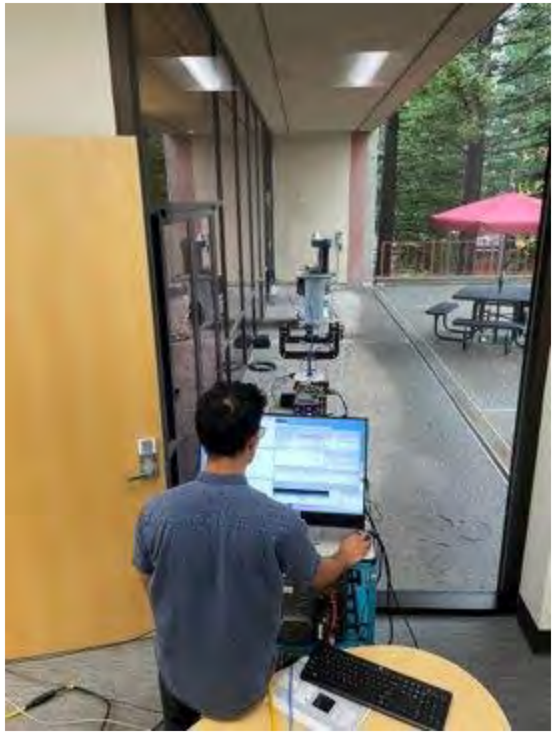
LOS Obstruction 13 GHz



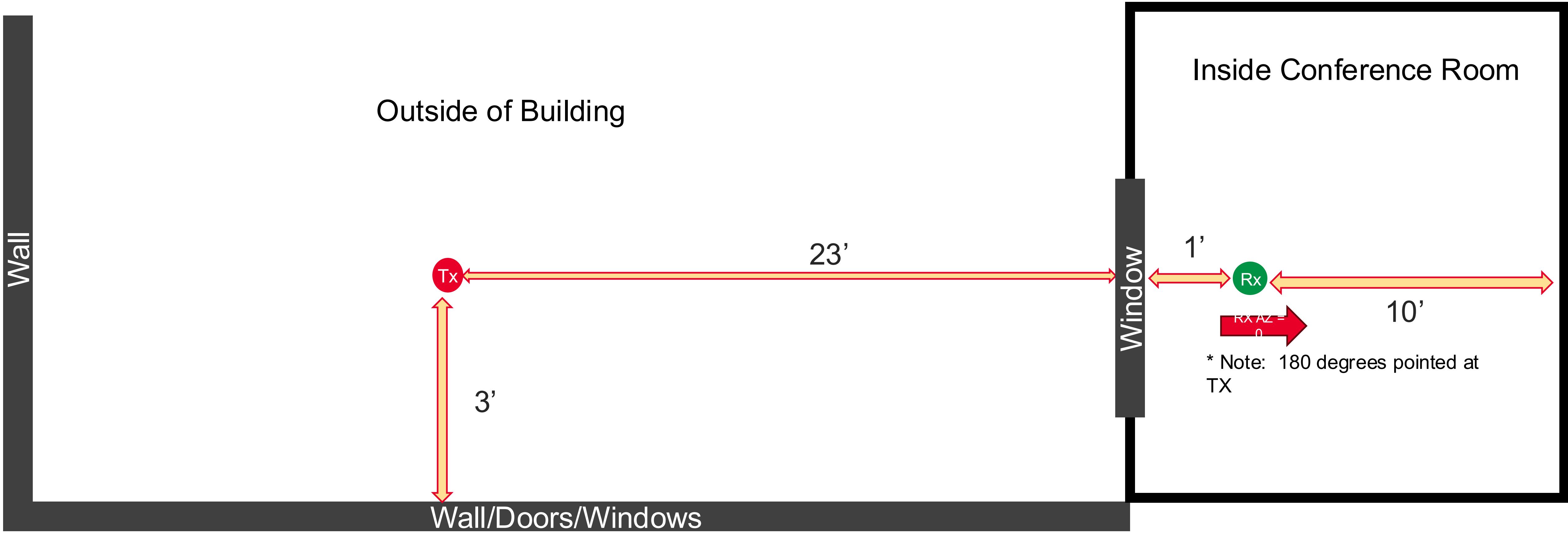


Indoor/Outdoor Glass Measurements

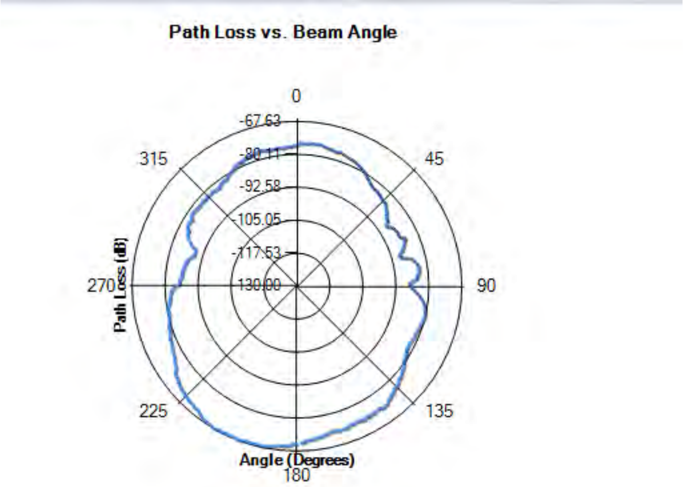
- Conference Room to External transmitter at TX distance of 7m



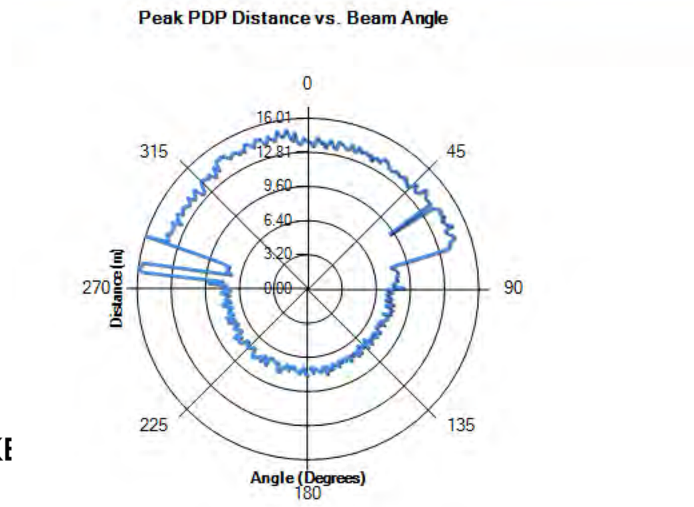
Indoor/Outdoor Measurements



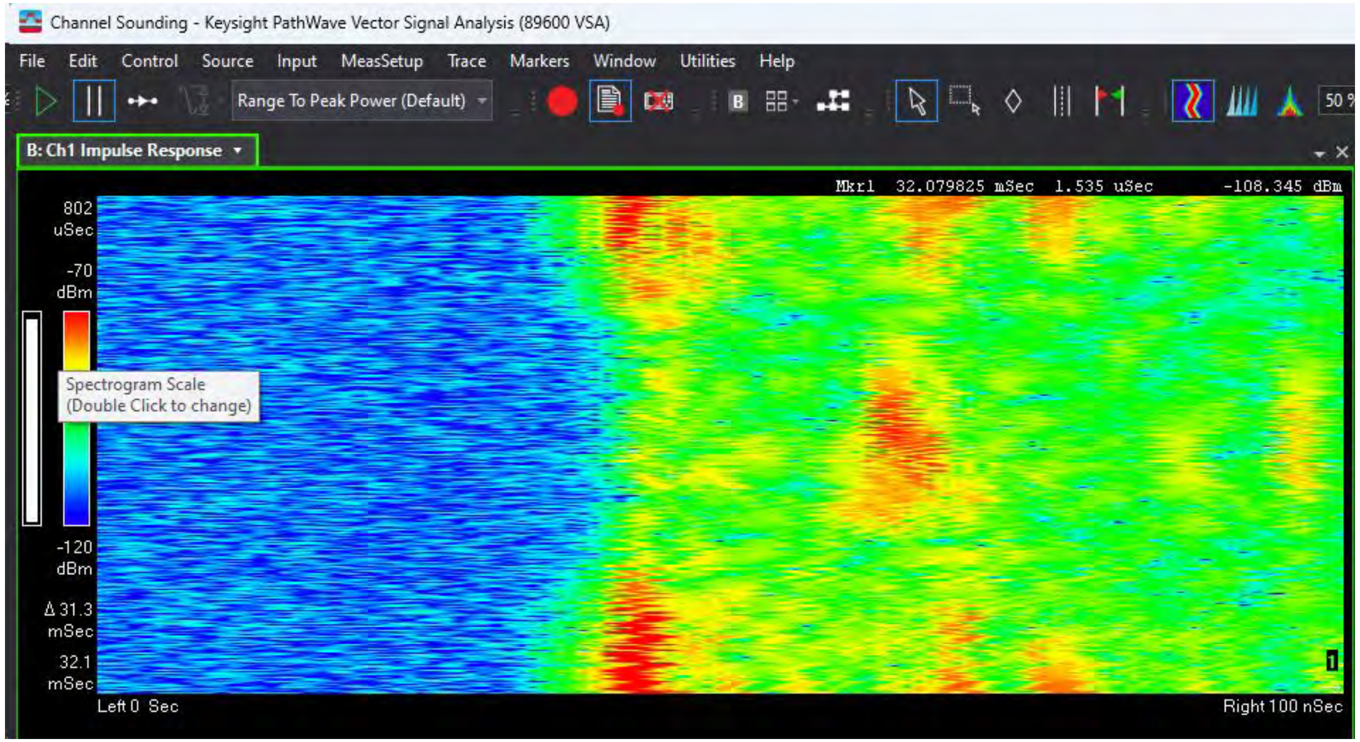
7 GHz



Path Loss vs. Beam Angle
0
45
90
135
180
225
270
315
-67.63
-80.11
-92.58
-105.05
-117.53
-130.00
Path Loss (dB)
Angle (Degrees)

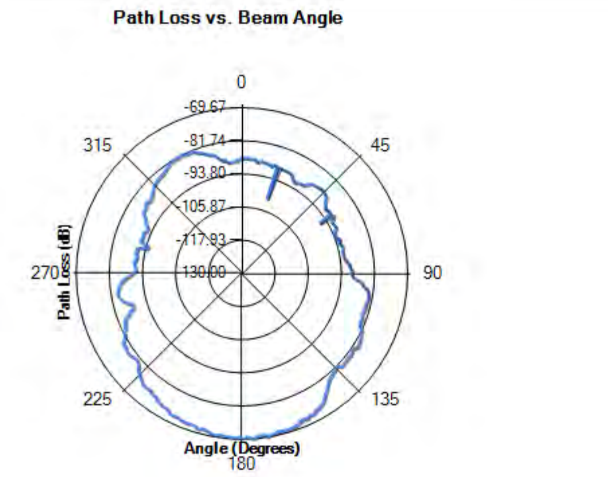


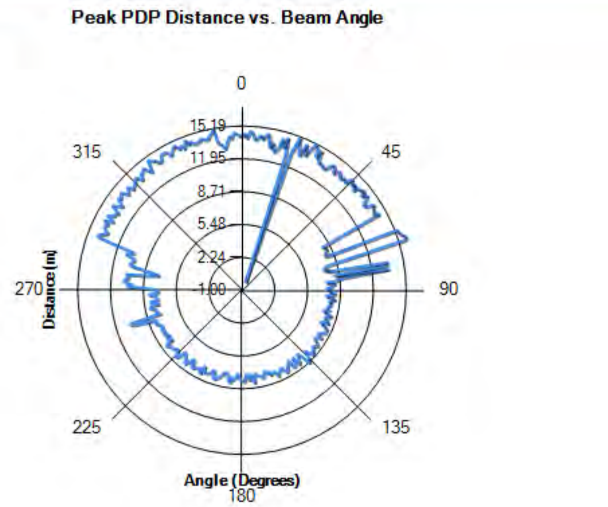
Peak PDP Distance vs. Beam Angle
0
45
90
135
180
225
270
315
16.01
12.81
9.60
6.40
3.20
0.00
Distance (m)
Angle (Degrees)

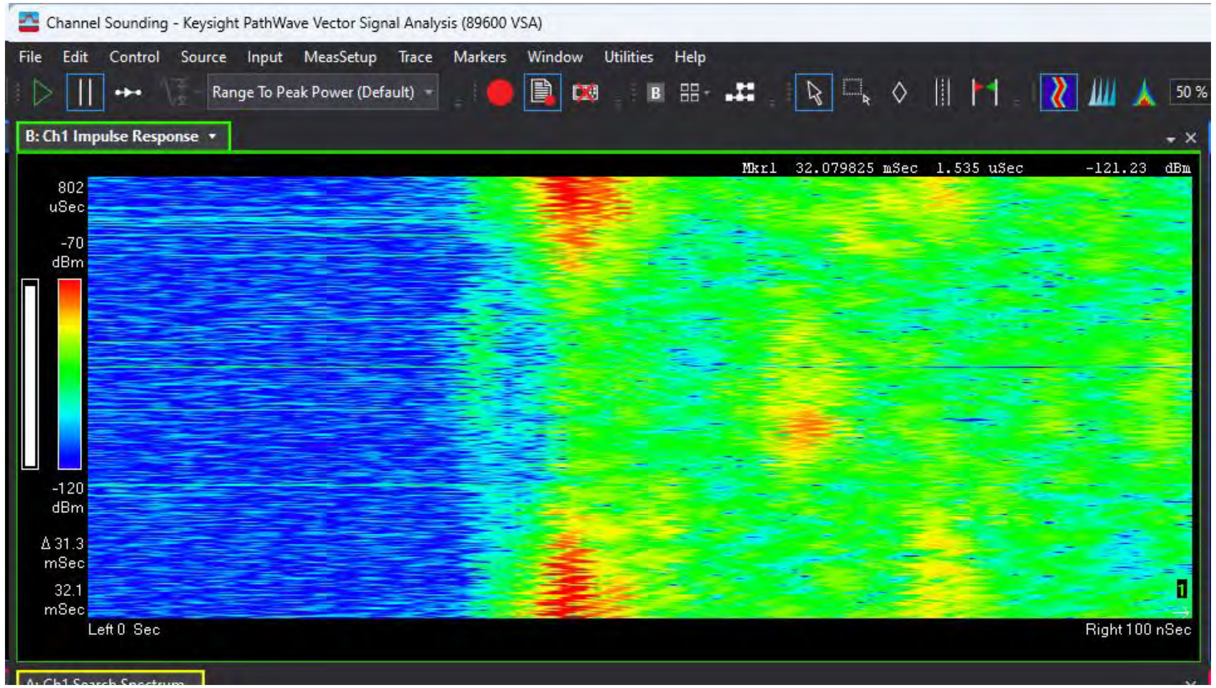


Channel Sounding - Keysight PathWave Vector Signal Analysis (89600 VSA)
File Edit Control Source Input MeasSetup Trace Markers Window Utilities Help
Range To Peak Power (Default)
B: Ch1 Impulse Response
Mkr1 32.079825 mSec 1.535 uSec -108.345 dBm
802 uSec
-70 dBm
Spectrogram Scale (Double Click to change)
-120 dBm
Δ 31.3 mSec
32.1 mSec
Left 0 Sec
Right 100 nSec

10 GHz

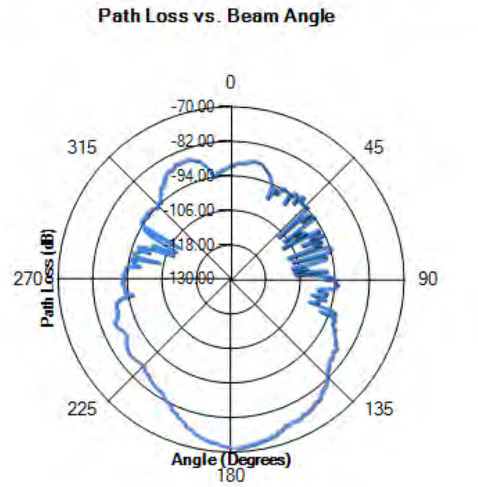


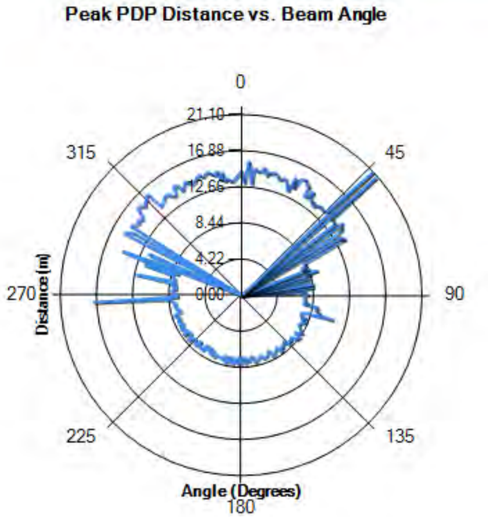


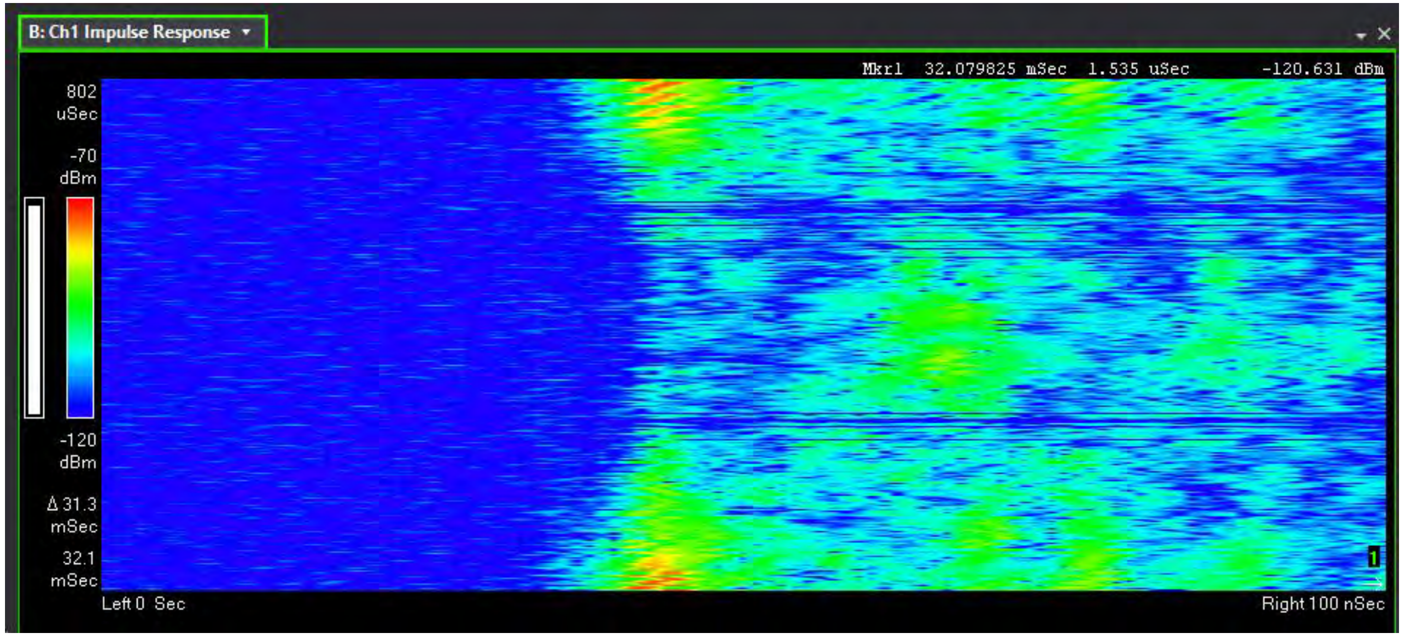


- Recording-20240112_102912.webm

13 GHz

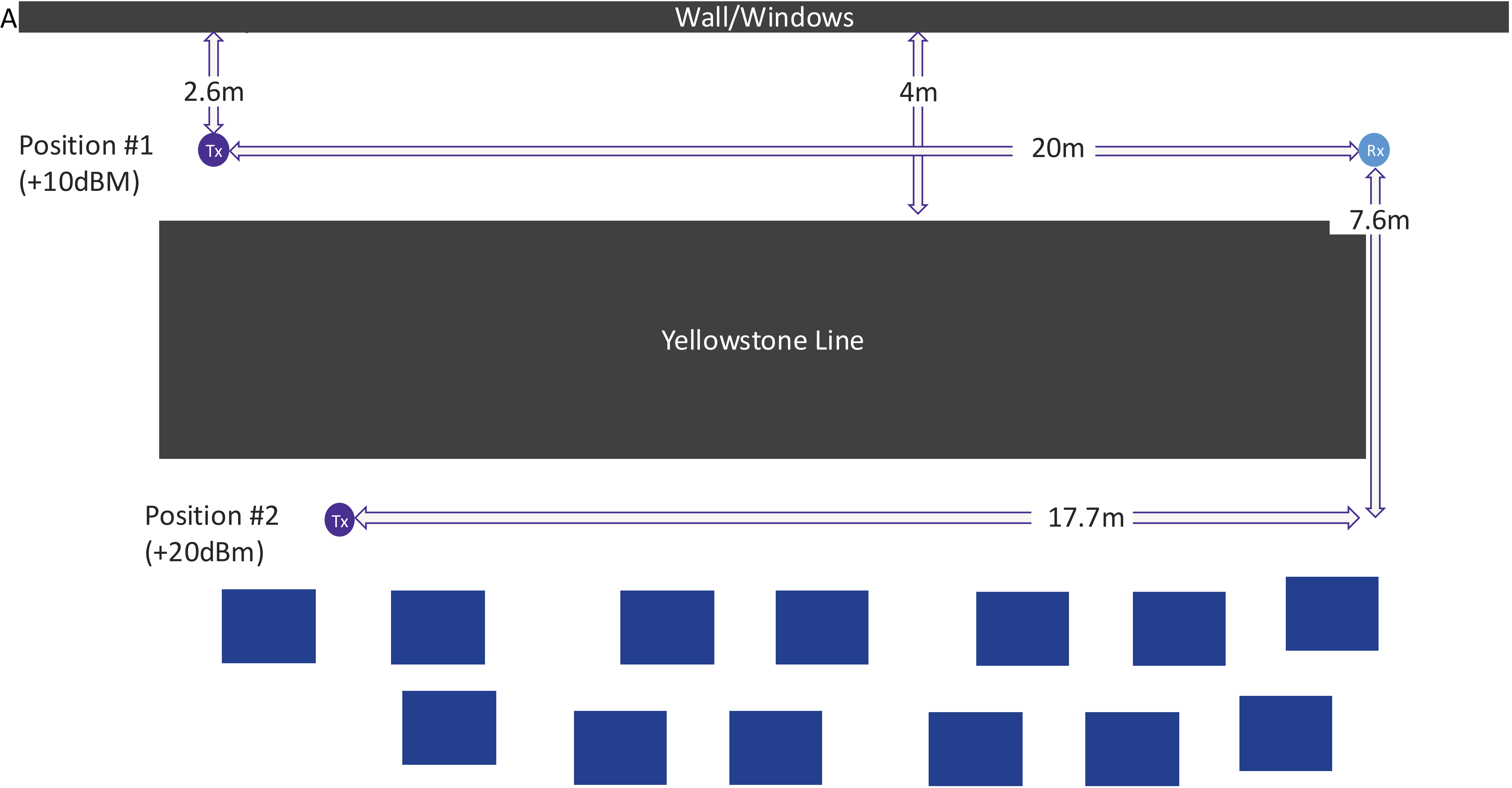

Path Loss vs. Beam Angle
0
45
90
135
180
225
270
315
-70.00
-82.00
-94.00
-106.00
-118.00
-130.00
Path Loss (dB)
Angle (Degrees)


Peak PDP Distance vs. Beam Angle
0
45
90
135
180
225
270
315
21.10
16.88
12.66
8.44
4.22
0.00
Distance (m)
Angle (Degrees)


B: Ch1 Impulse Response
Mkr1 32.079825 mSec 1.535 uSec -120.631 dBm
802 uSec
-70 dBm
-120 dBm
Δ 31.3 mSec
32.1 mSec
Left 0 Sec
Right 100 nSec

Factory Scenario

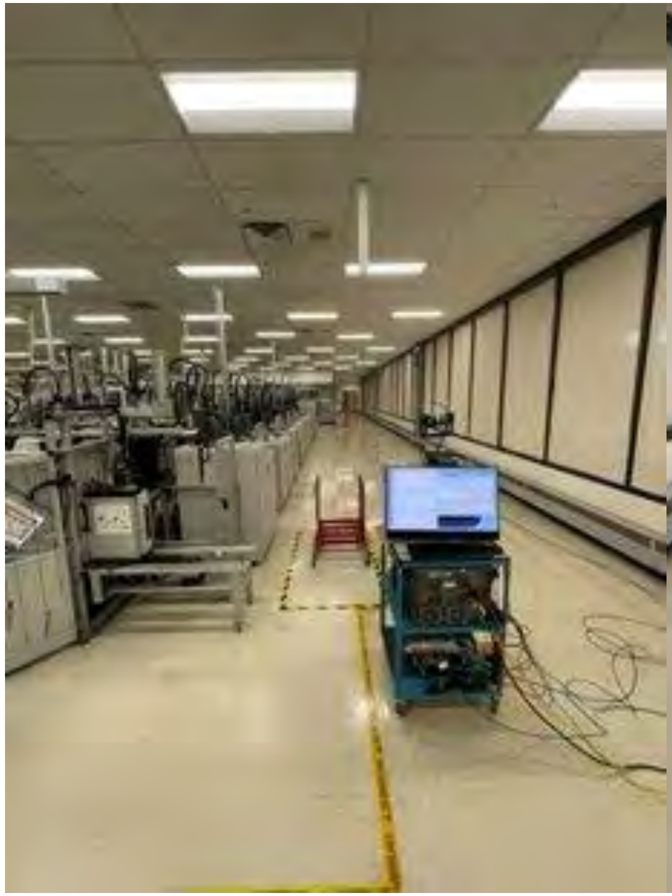
Keysight Manufacturing Facility, Automated robots moving equipment down manufacturing line for testing.


A
Wall/Windows
2.6m
4m
Position #1
(+10dBM)
Tx
20m
Rx
7.6m
Yellowstone Line
Position #2
(+20dBm)
Tx
17.7m

KEYSIGHT

LOS Measurement

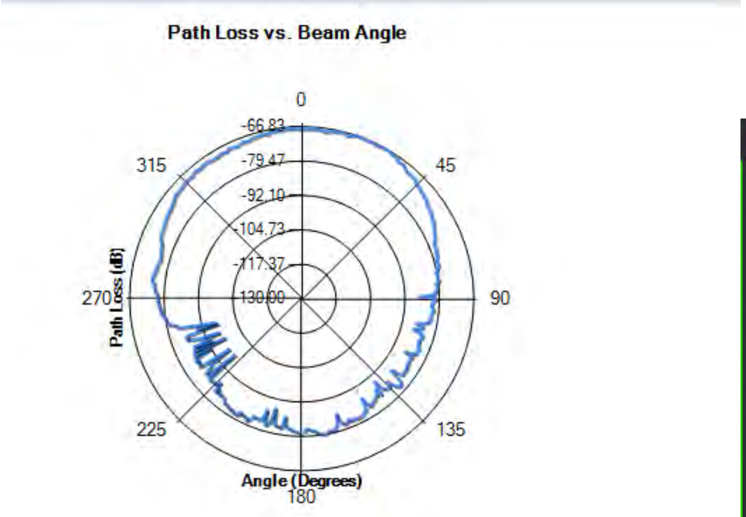
- Direct Line of Sight, 20m distance
- Objects moving around on one side, windows on the other.

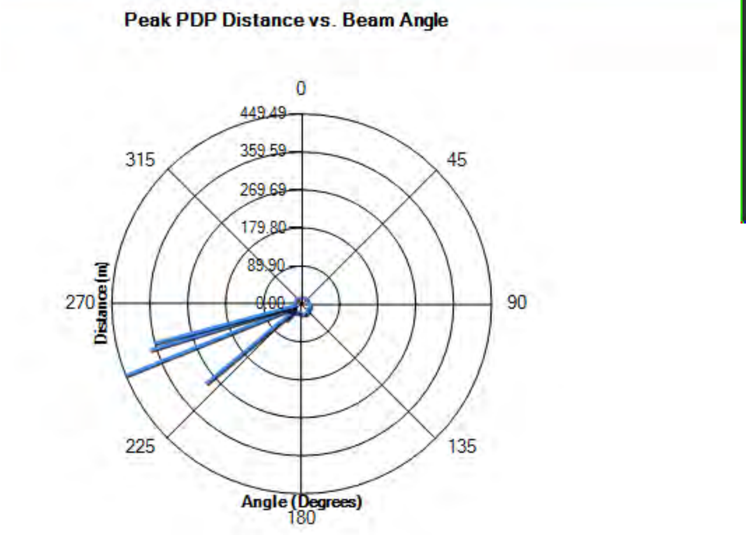


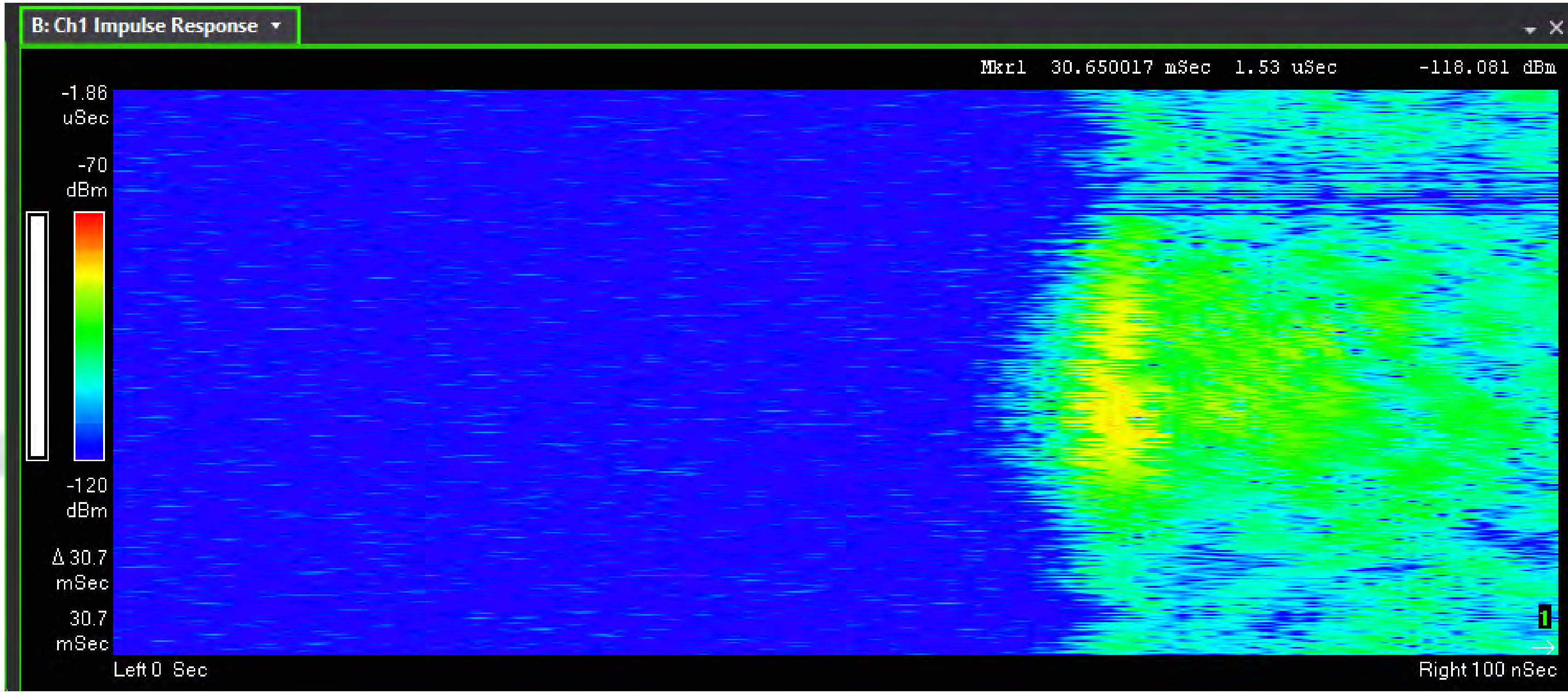
RX

TX

7 GHz

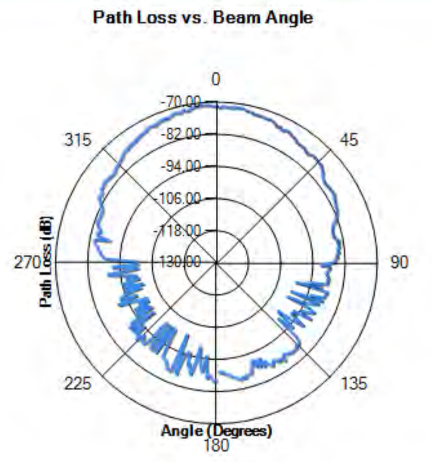


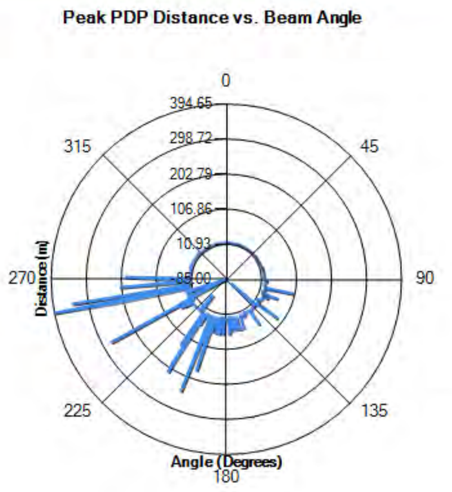


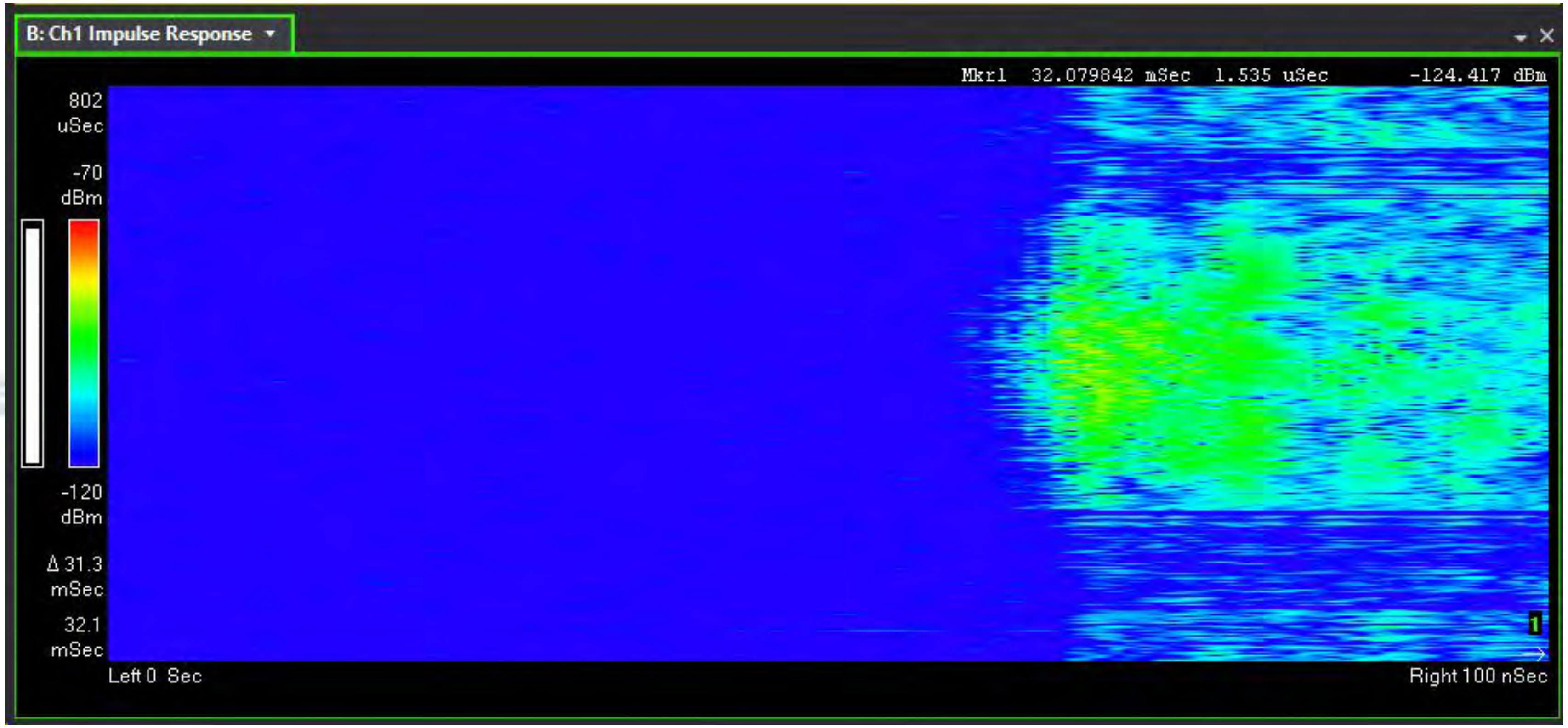


Larger Time = Larger Distance between TX to RX

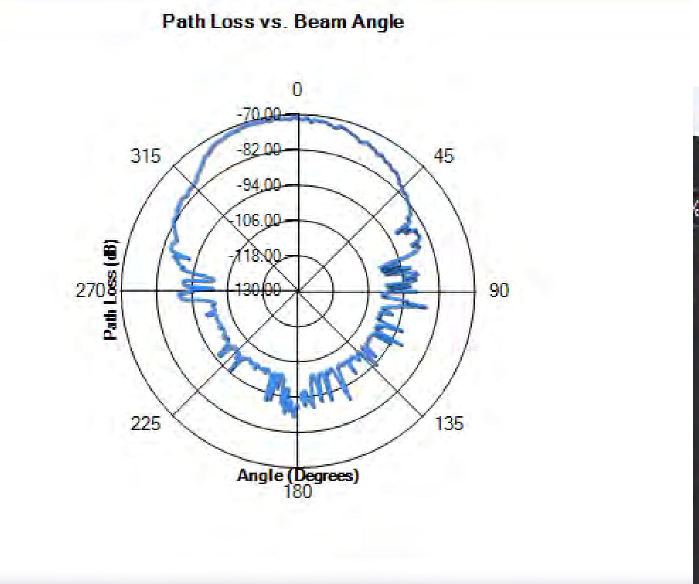
10.25 GHz

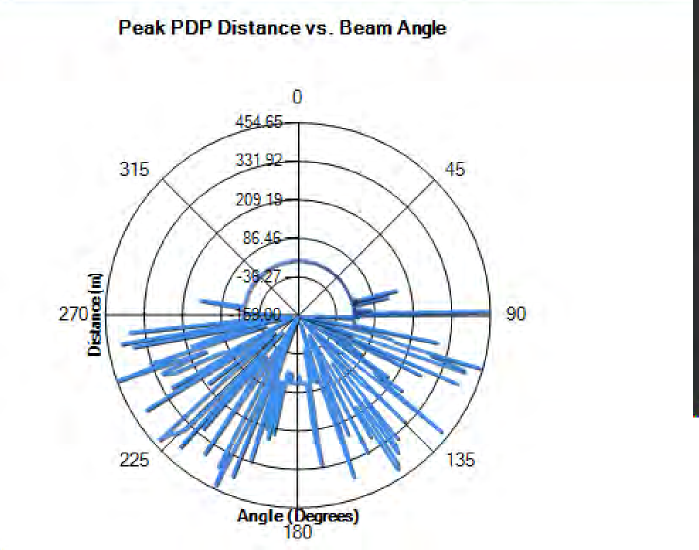

Path Loss vs. Beam Angle
0
45
90
135
180
225
270
315
-70.00
-82.00
-94.00
-106.00
-118.00
-130.00
Path Loss (dB)
Angle (Degrees)

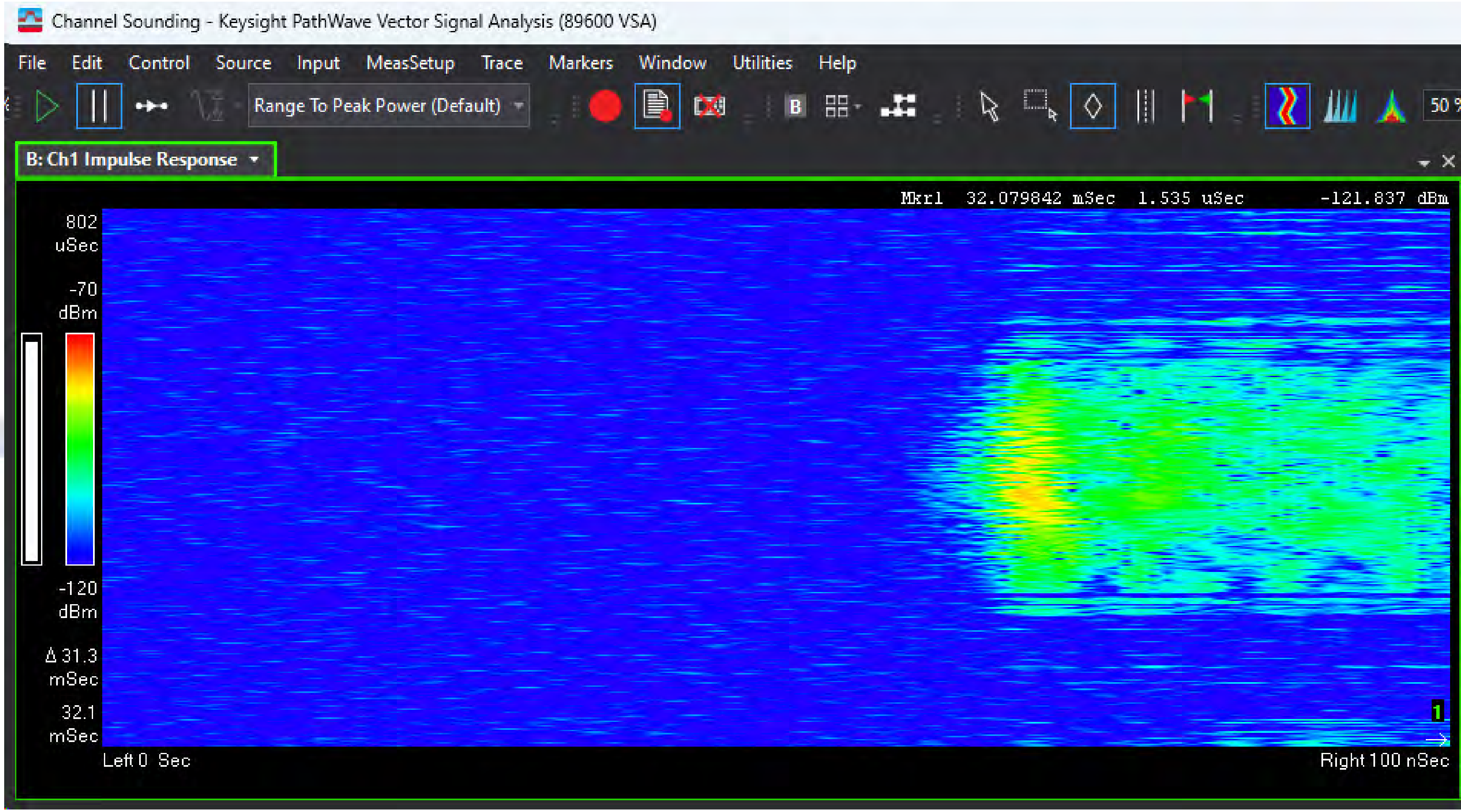

Peak PDP Distance vs. Beam Angle
0
45
90
135
180
225
270
315
394.65
298.72
202.79
106.86
10.93
-85.00
Distance (m)
Angle (Degrees)


B: Ch1 Impulse Response
Mkr1 32.079842 mSec 1.535 uSec -124.417 dBm
802
uSec
-70
dBm
-120
dBm
Δ 31.3
mSec
32.1
mSec
Left 0 Sec
Right 100 nSec

13 GHz


Path Loss vs. Beam Angle
0
45
90
135
180
225
270
315
-70.00
-82.00
-94.00
-106.00
-118.00
-130.00
Path Loss (dB)
Angle (Degrees)


Peak PDP Distance vs. Beam Angle
0
45
90
135
180
225
270
315
454.65
331.92
209.19
86.46
-36.27
-159.00
Distance (m)
Angle (Degrees)

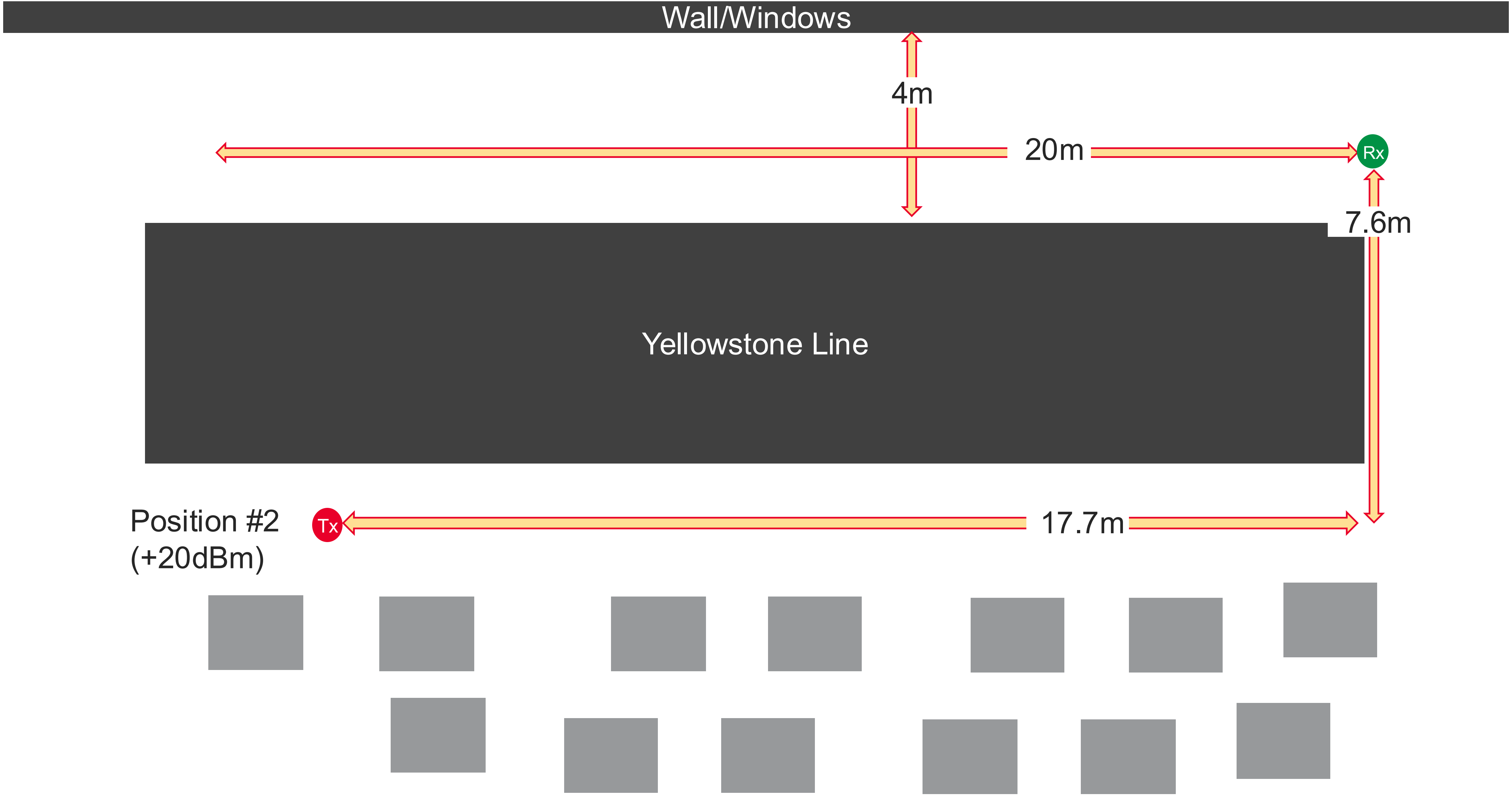

Channel Sounding - Keysight PathWave Vector Signal Analysis (89600 VSA)
File Edit Control Source Input MeasSetup Trace Markers Window Utilities Help
Range To Peak Power (Default)
B: Ch1 Impulse Response
Mkr1 32.079842 mSec 1.535 uSec -121.837 dBm
802 uSec
-70 dBm
-120 dBm
Δ 31.3 mSec
32.1 mSec
Left 0 Sec
Right 100 nSec

NLOS

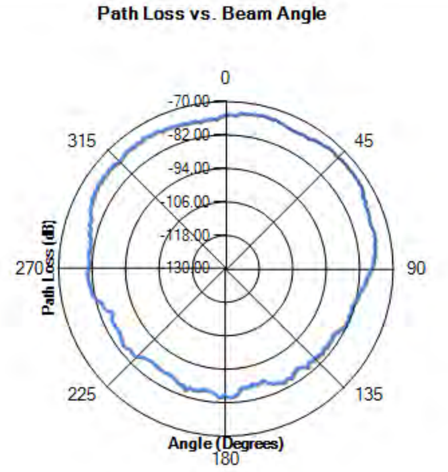
- Transmitter behind the Yellowstone line.
- Straight line distance ~20m

RX

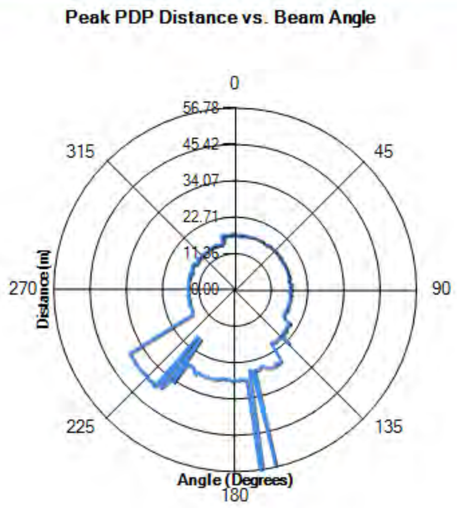
TX


Wall/Windows
4m
20m
Rx
7.6m
Yellowstone Line
Position #2
(+20dBm)
Tx
17.7m

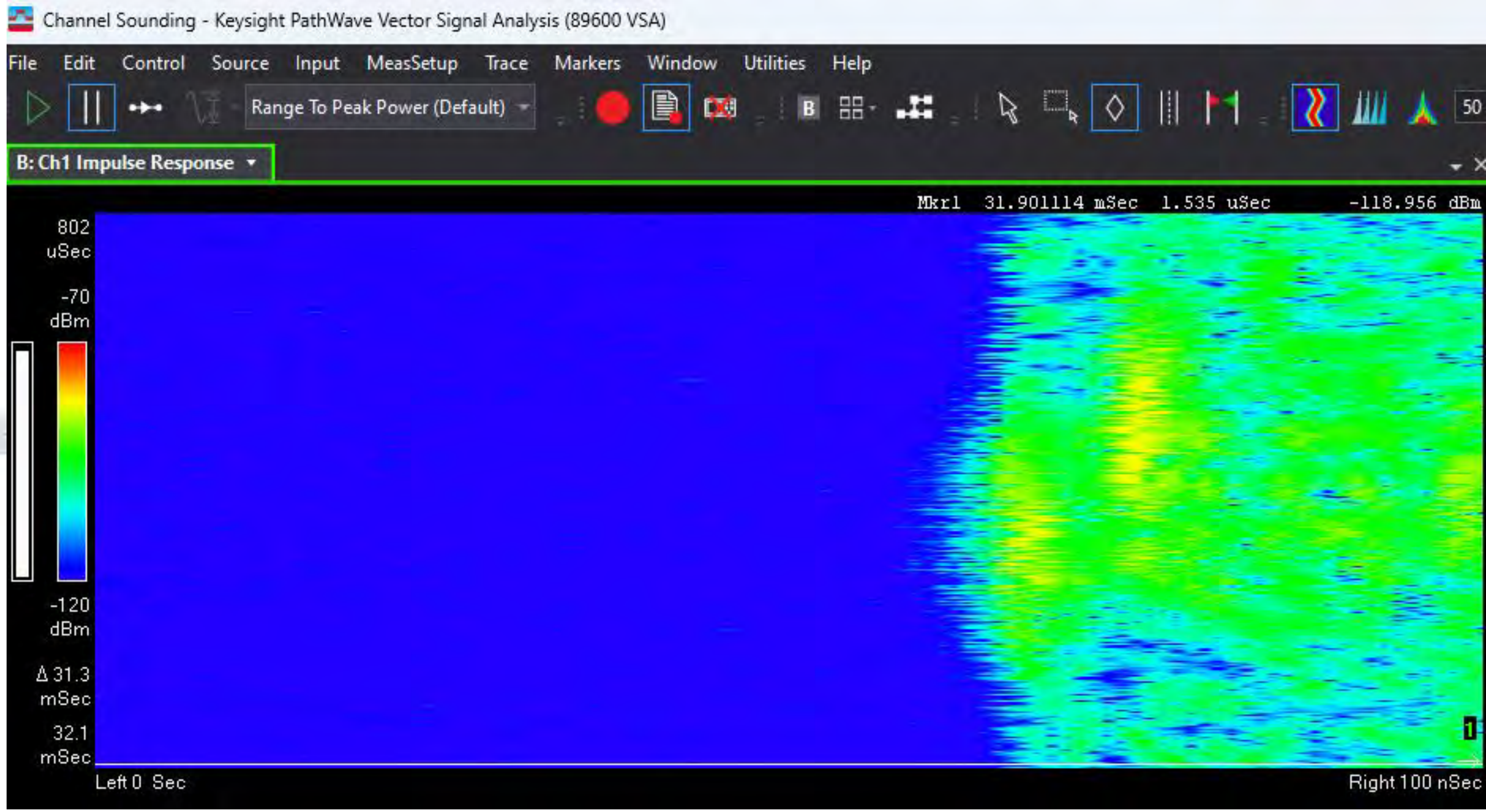
7 GHz



Path Loss vs. Beam Angle
0
45
90
135
180
225
270
315
-70.00
-82.00
-94.00
-106.00
-118.00
-130.00
Path Loss (dB)
Angle (Degrees)

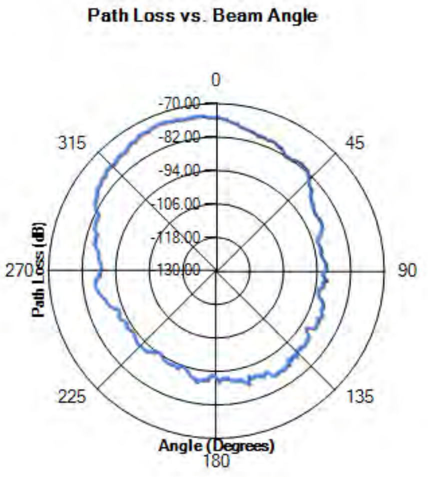


Peak PDP Distance vs. Beam Angle
0
45
90
135
180
225
270
315
56.78
45.42
34.07
22.71
11.36
0.00
Distance (m)
Angle (Degrees)

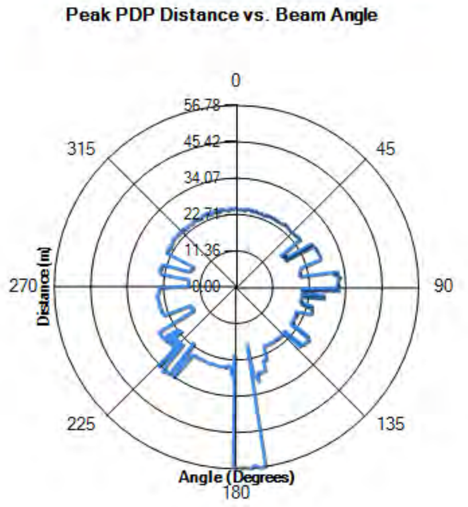


Channel Sounding - Keysight PathWave Vector Signal Analysis (89600 VSA)
File Edit Control Source Input MeasSetup Trace Markers Window Utilities Help
Range To Peak Power (Default)
B: Ch1 Impulse Response
Mkr1 31.901114 mSec 1.535 uSec -118.956 dBm
802 uSec
-70 dBm
-120 dBm
Δ 31.3 mSec
32.1 mSec
Left 0 Sec
Right 100 nSec

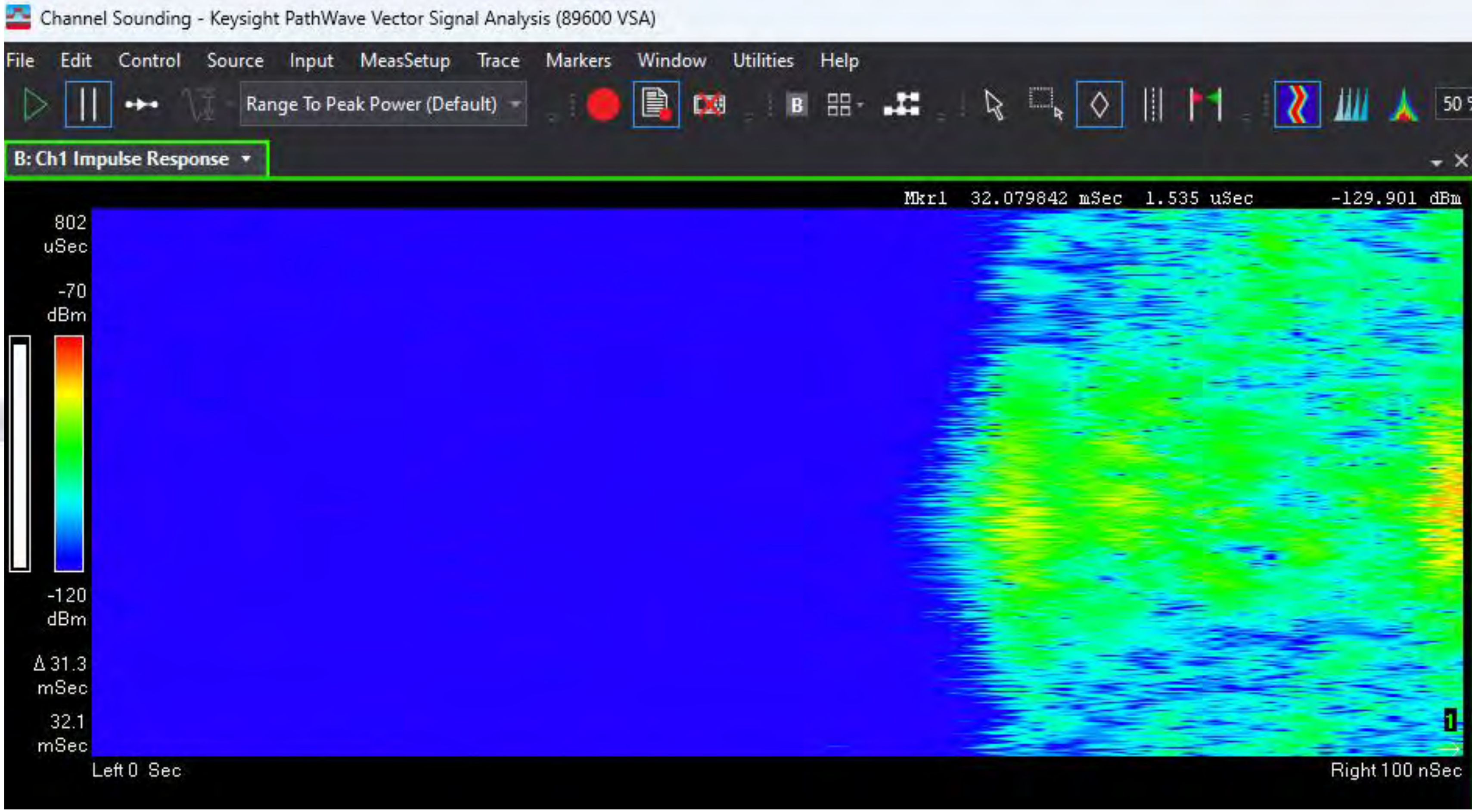
10.25 GHz



Path Loss vs. Beam Angle
0
45
90
135
180
225
270
315
-70.00
-82.00
-94.00
-106.00
-118.00
-130.00
Path Loss (dB)
Angle (Degrees)

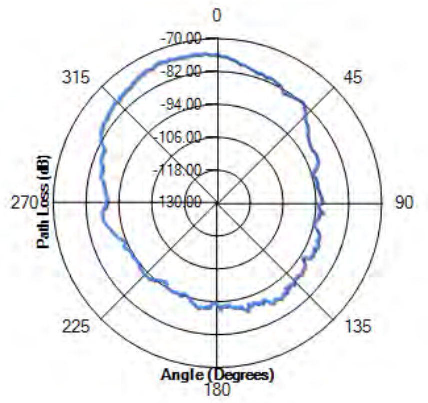


Peak PDP Distance vs. Beam Angle
0
45
90
135
180
225
270
315
56.78
45.42
34.07
22.71
11.36
0.00
Distance (m)
Angle (Degrees)

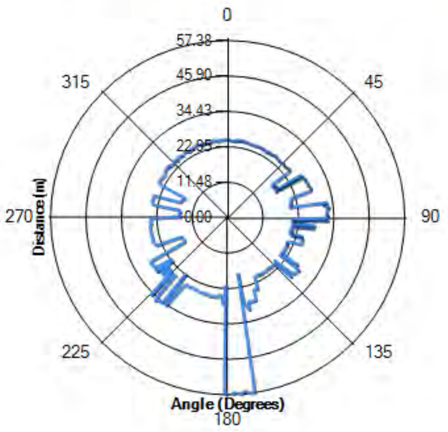


Channel Sounding - Keysight PathWave Vector Signal Analysis (89600 VSA)
File Edit Control Source Input MeasSetup Trace Markers Window Utilities Help
Range To Peak Power (Default)
B: Ch1 Impulse Response
Mkr1 32.079842 mSec 1.535 uSec -129.901 dBm
802 uSec
-70 dBm
-120 dBm
Δ 31.3 mSec
32.1 mSec
Left 0 Sec
Right 100 nSec

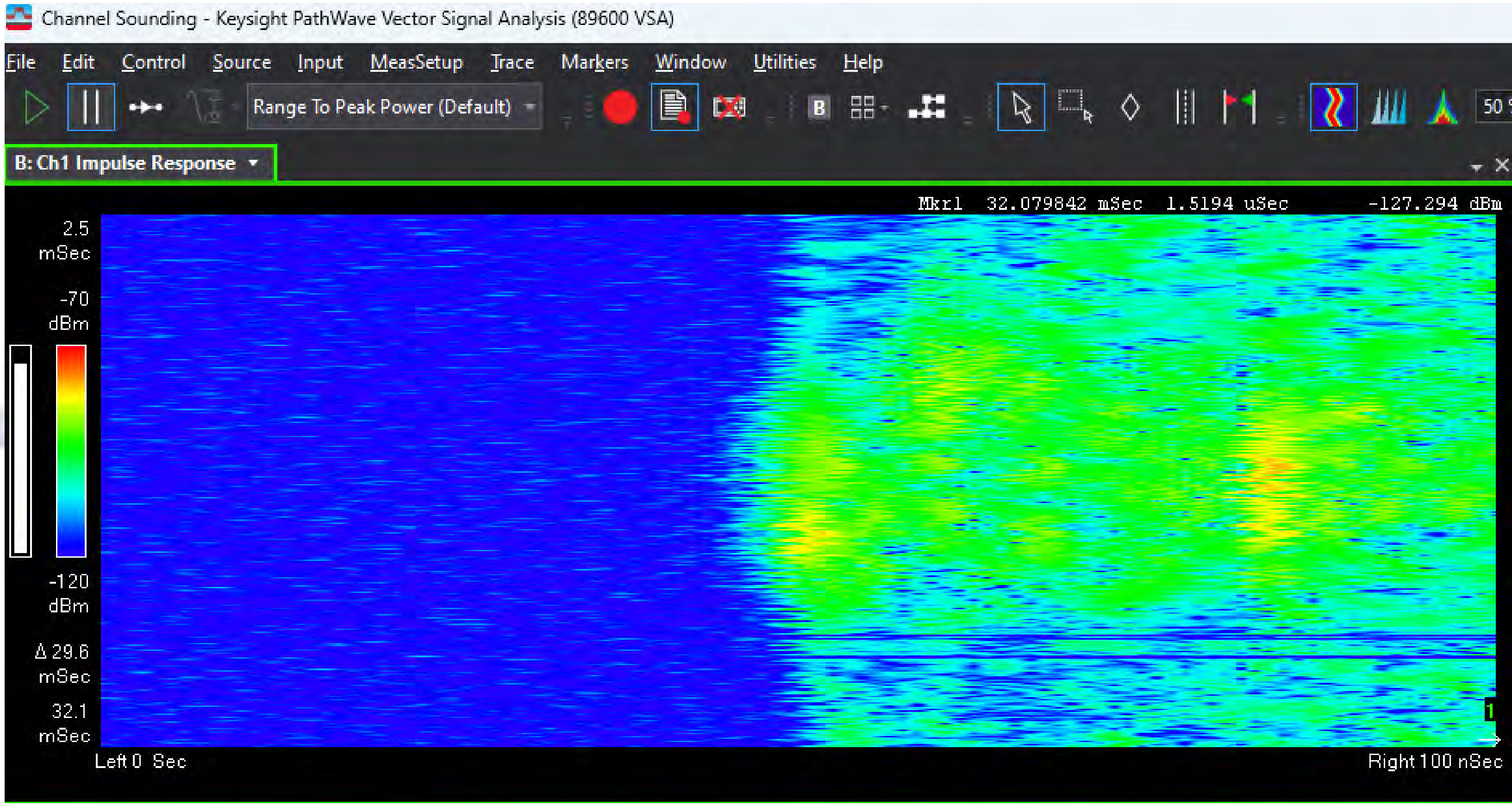
13 GHz



Path Loss vs. Beam Angle
0
45
90
135
180
225
270
315
-70.00
-82.00
-94.00
-106.00
-118.00
-130.00
Path Loss (dB)
Angle (Degrees)



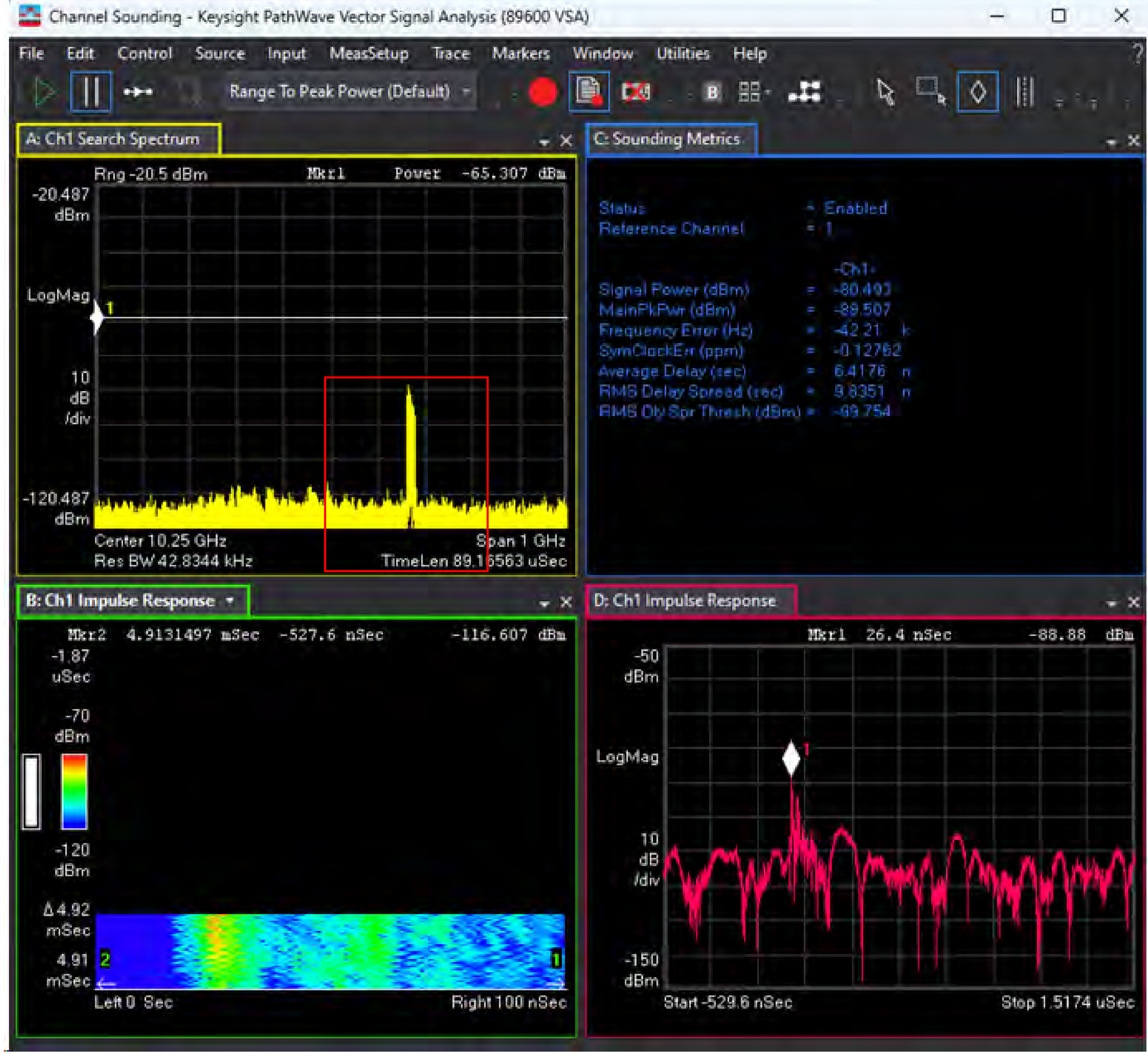
Peak PDP Distance vs. Beam Angle
0
45
90
135
180
225
270
315
57.38
45.90
34.43
22.95
11.48
0.00
Distance (m)
Angle (Degrees)



Channel Sounding - Keysight PathWave Vector Signal Analysis (89600 VSA)
File Edit Control Source Input MeasSetup Trace Markers Window Utilities Help
Range To Peak Power (Default)
B: Ch1 Impulse Response
Mkr1 32.079842 mSec 1.5194 uSec -127.294 dBm
2.5 mSec
-70 dBm
-120 dBm
Δ 29.6 mSec
32.1 mSec
Left 0 Sec
Right 100 nSec

10.5 GHz Issue

- Found issue to be HP laptops transmitting second harmonic of Wi-Fi.
- Pointed a sounding measurement with a laptop uploading through Wi-Fi.
- Note that this is NOT out of spec today. This may be expected behavior in these bands.



Conclusions

- Based on analysis done internally on the channel models, we believe that the existing channel models TS 38.901 can be scaled to these new frequencies.
- We can see that the lower frequency of the range that we measured is much like FR1 while the higher end of the band acts closer to the FR2 band. This is very obvious when looking at the cafeteria measurements we have made.
- For the factory scenarios we can see how intense reflections can cause significant time delays in signal path.

Outdoor Measurements

FR3 Channel Sounding Measurement Location

Keysight Santa Rosa Campus

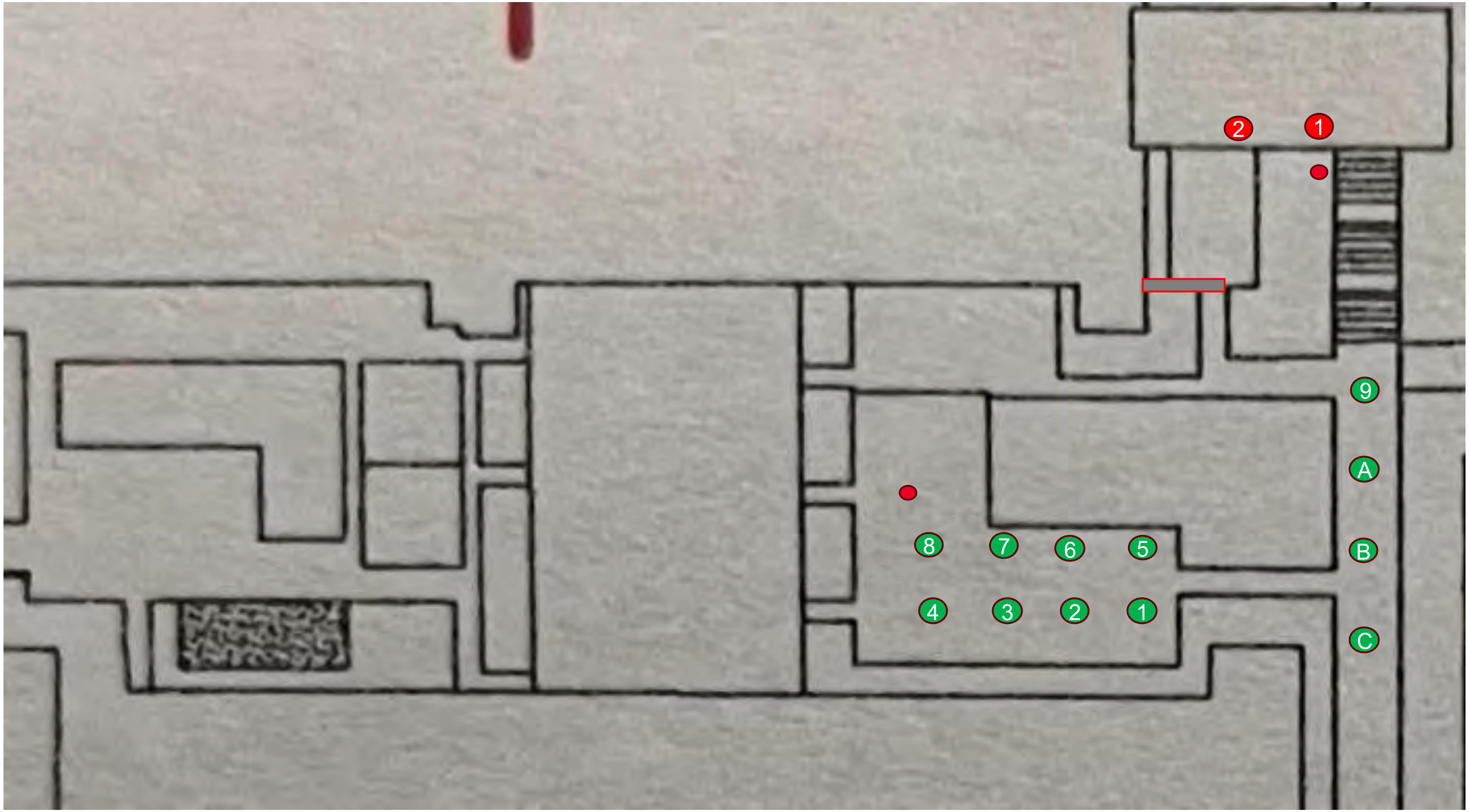


Transmitter Locations

TX1 Antenna Location:
0.59 meters from railing
16.93 meters from building on right side
1.85 meters above ground

TX2 Antenna Location:
0.61 meters from railing
12.80 meters from building on right side
1.85 meters above ground

Measurements 4/27 (Red TX, Green RX)




TX1RX1


TX2RX1


TX1RX2


TX2RX2


TX1RX3


TX2RX3


TX1RX4


TX2RX4


TX1RX5


TX2RX5


TX1RX7


TX2RX7


TX1RX9


TX2RX9


TX1RXA

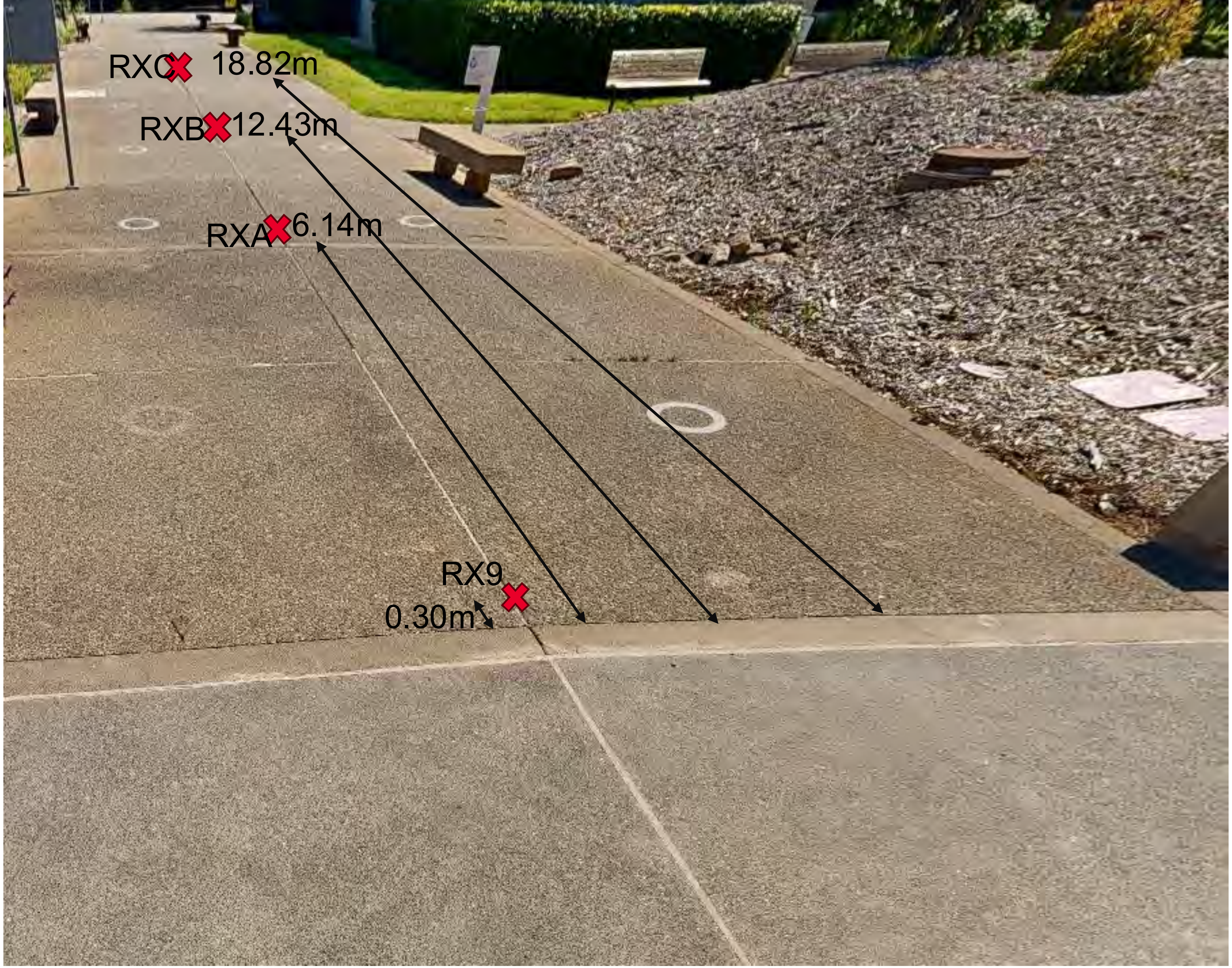

TX2RXA


TX1RXB


TX2RXB


TX1RXC


TX2RXC



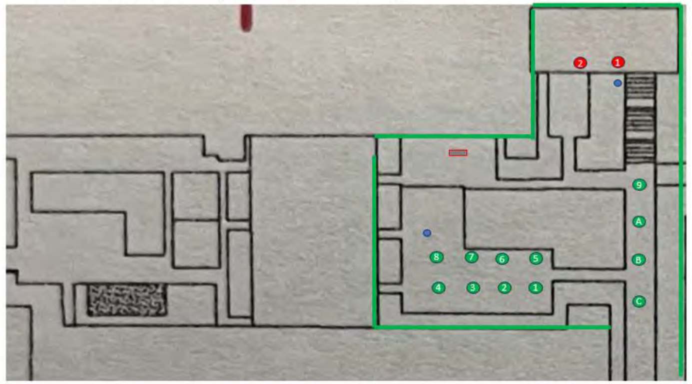
RX9 Antenna Location:
0.00 m from center line of sidewalk
0.30 m back from seam in sidewalk
1.61 m from ground

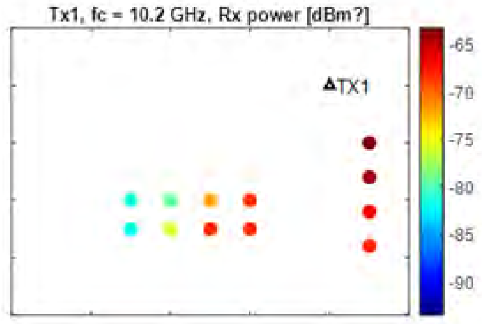
Estimated 100 ns for LOS time alignment

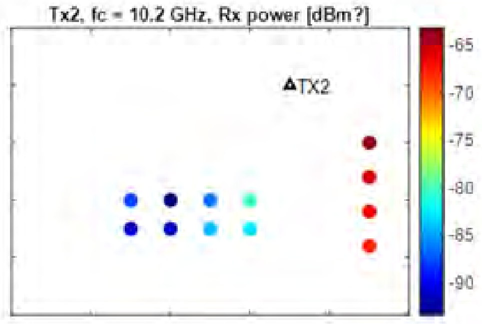
Sample Outdoor Measurement Result

- Comparison of measurement data to 38.901 models for path loss and large-scale parameters will be presented during phase 2 of the NGA project
- Lower NLOS signal level at 10.25 GHz compared to 7 and 13 GHz
  - NLOS path was reflection from building with glass windows
  - Root cause of difference will be investigated as part of phase 2 sounding and material measurements

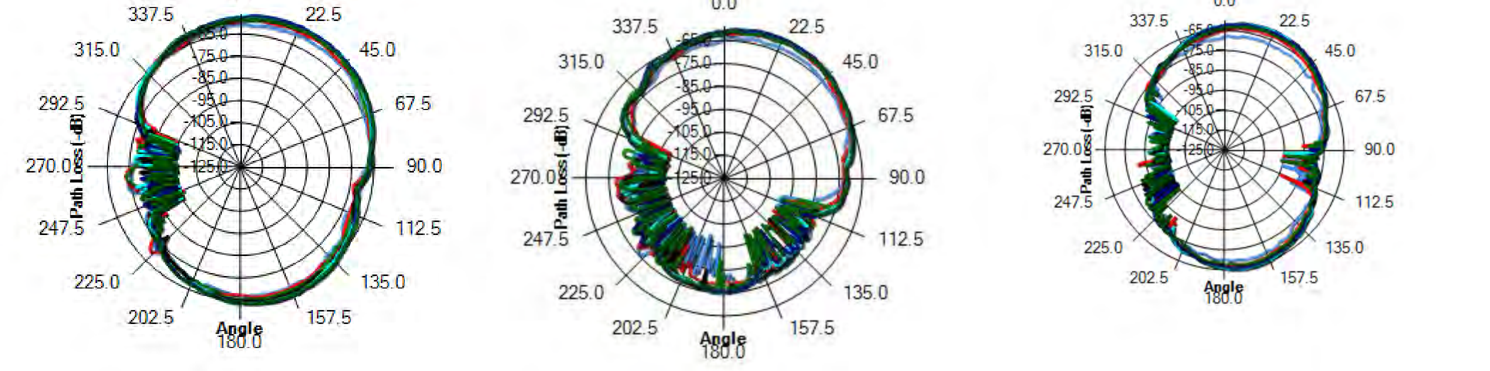
Measurements 4/27 (Red TX, Green RX)





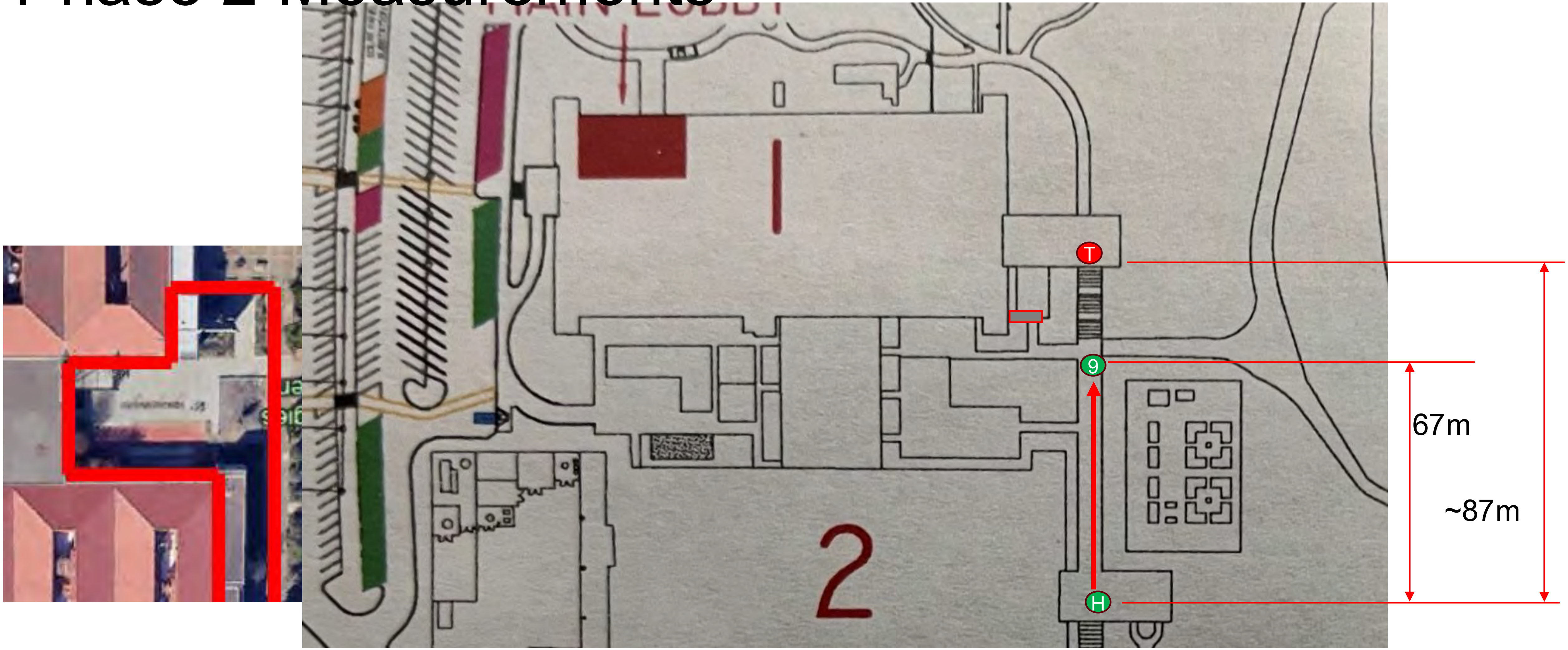


Path Loss at Location TX1-RX1



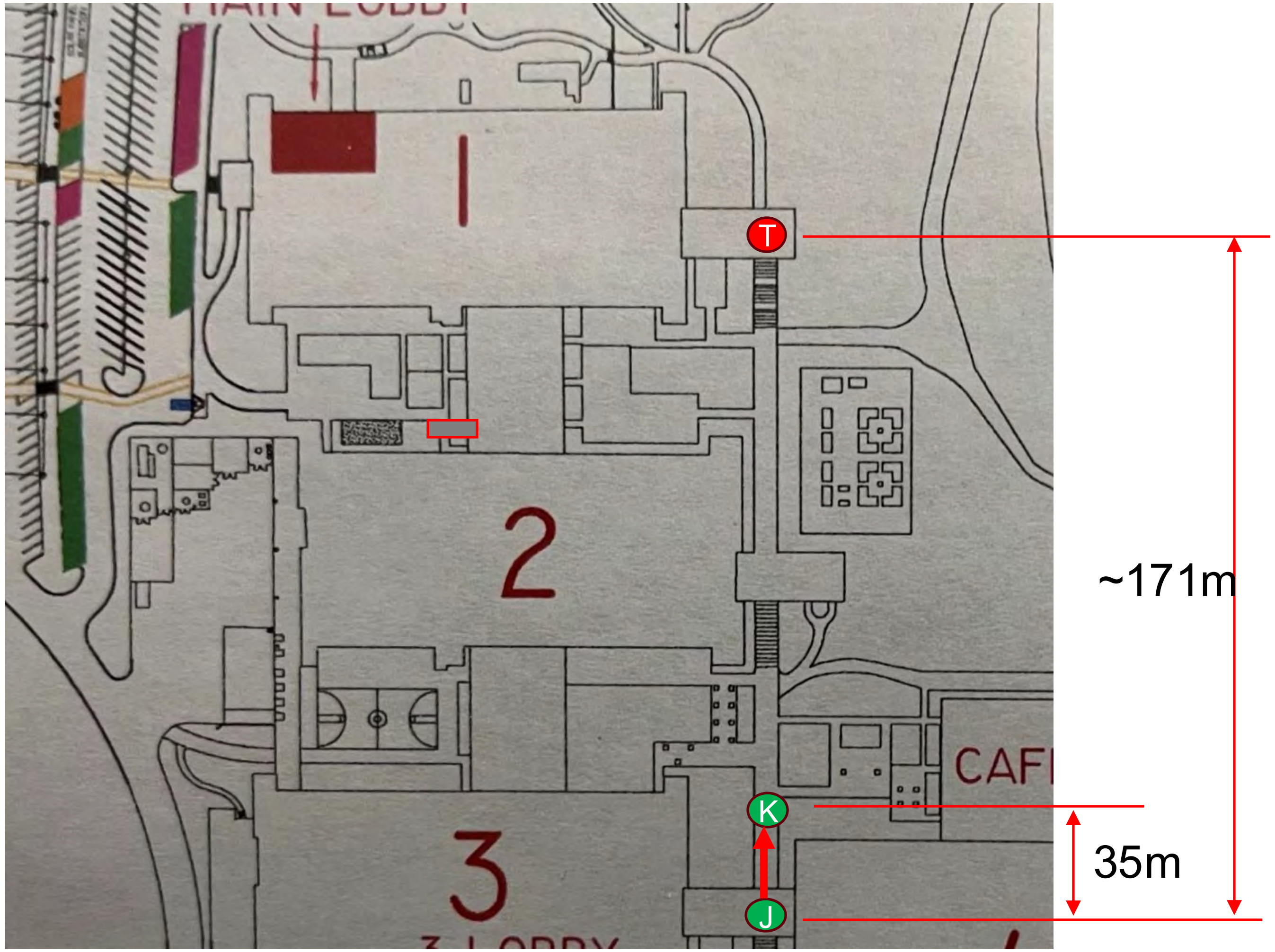
7 GHz 10.25 GHz 13 GHz

Phase 2 Measurements



Move Receiver over distance of ~67 meters, measuring every 10 cm.
One RX Azimuth setting (LOS to TX Antenna)
Data: Path loss at each position, plot of path loss vs. distance vs. frequency
Frequency: 7 GHz, 10.25 GHz, 13 GHz

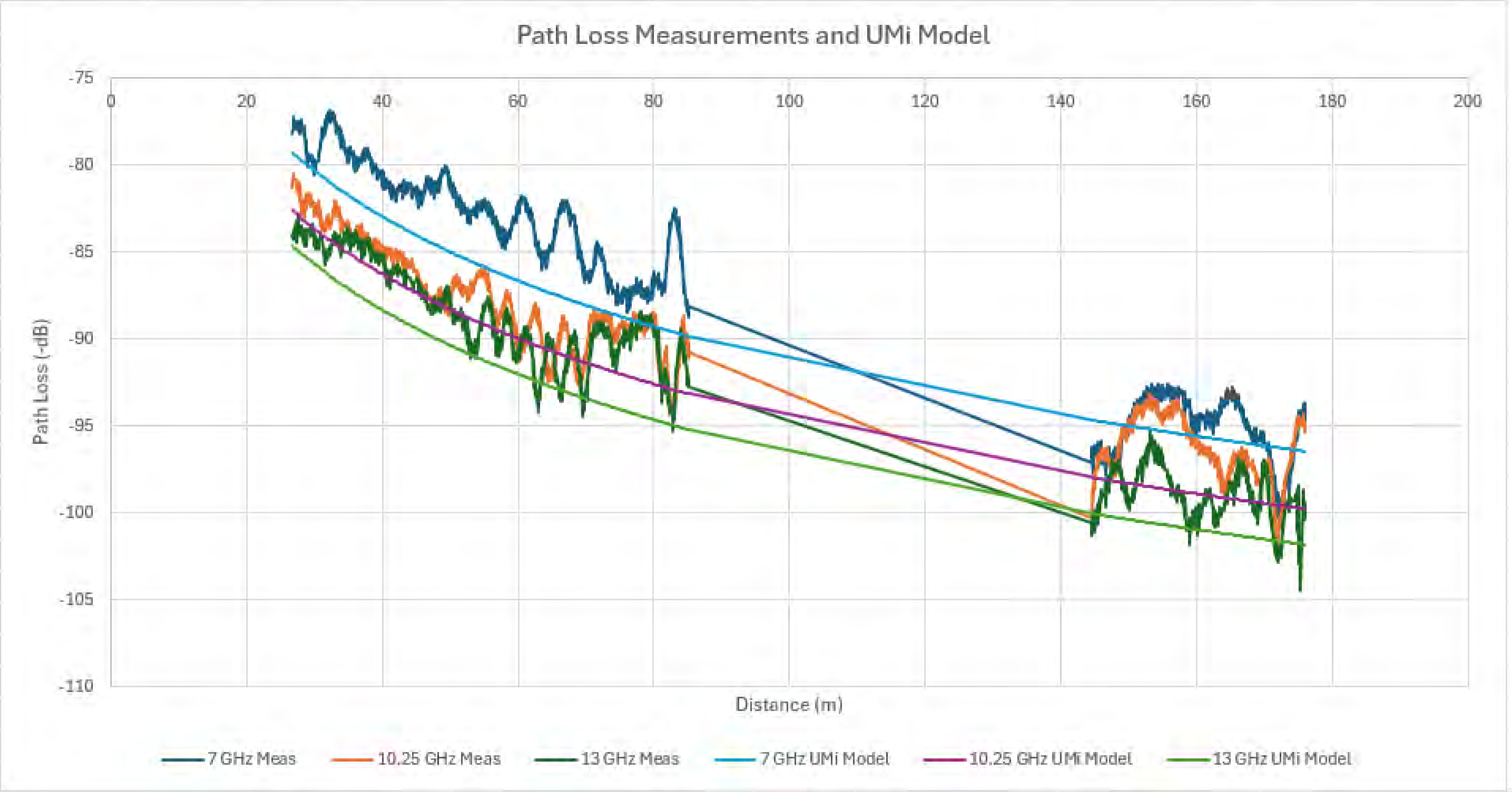
Phase 2 Measurements



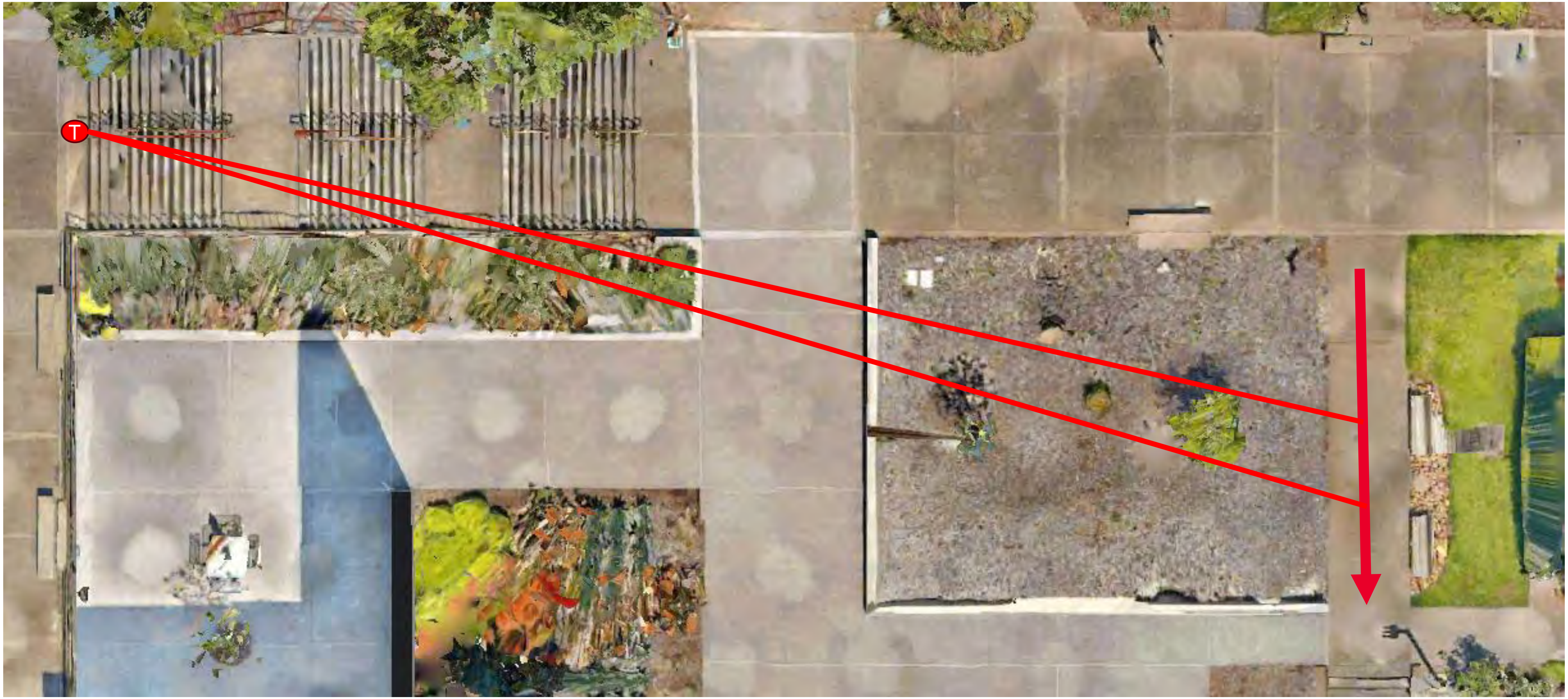
Move Receiver over distance of 35 meters, measuring every 10 cm.
Data: Path loss at each position, plot of path loss vs. distance vs. frequency
Frequency: 7 GHz, 10.25 GHz, 13 GHz

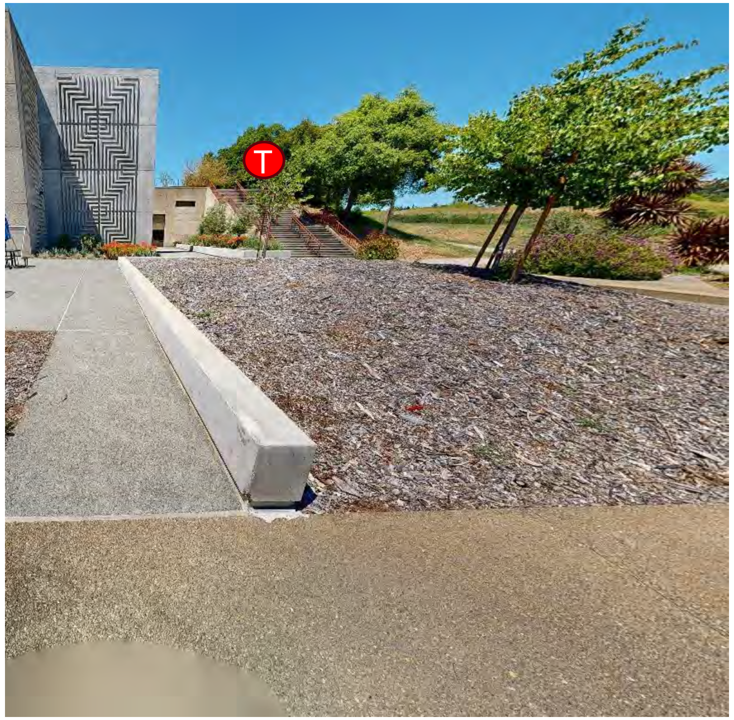

Exterior
TX Cart Antenna 2 m

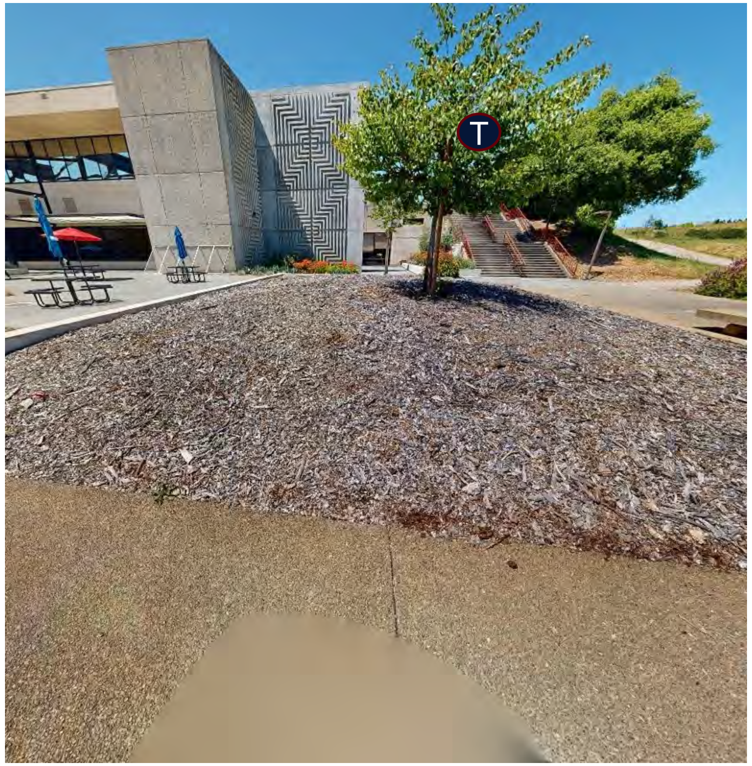
Path Loss Measurements

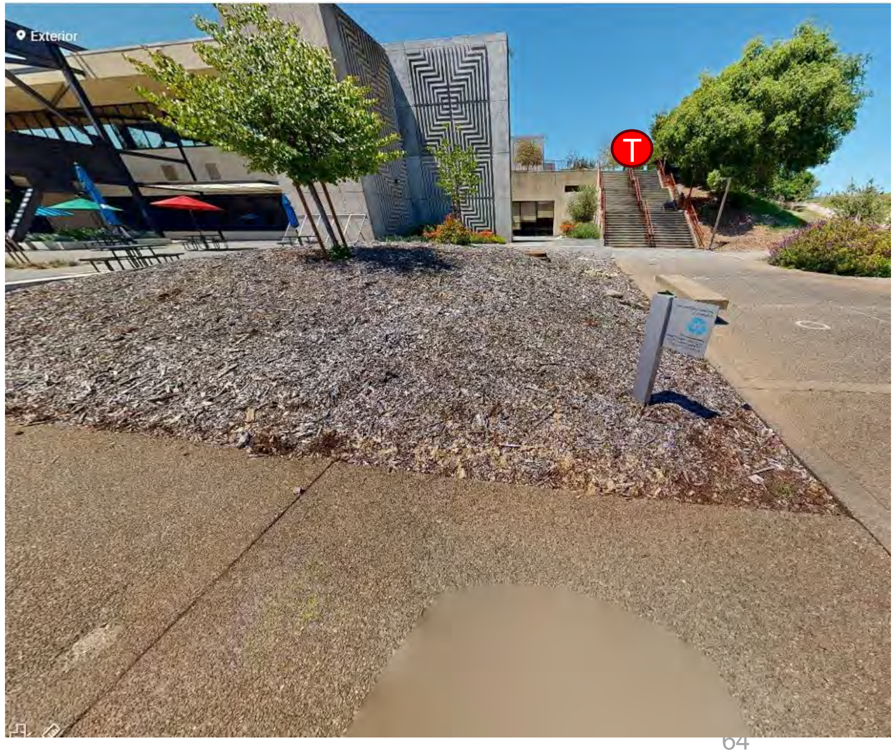


eet Canyon	LOS	$PL_{\text{UMi-LOS}} = \begin{cases} PL_1 & 10\text{m} \le d_{2D} \le d'_{BP} \\ PL_2 & d'_{BP} \le d_{2D} \le 5\text{km} \end{cases}$, see note 1 $PL_1 = 32.4 + 21\log_{10}(d_{3D}) + 20\log_{10}(f_c)$ $PL_2 = 32.4 + 40\log_{10}(d_{3D}) + 20\log_{10}(f_c) - 9.5\log_{10}((d'_{BP})^2 + (h_{BS} - h_{UT})^2)$	$\sigma_{SF} = 4$	$1.5\text{m} \le h_{UT} \le 22.5\text{m}$ $h_{BS} = 10\text{m}$

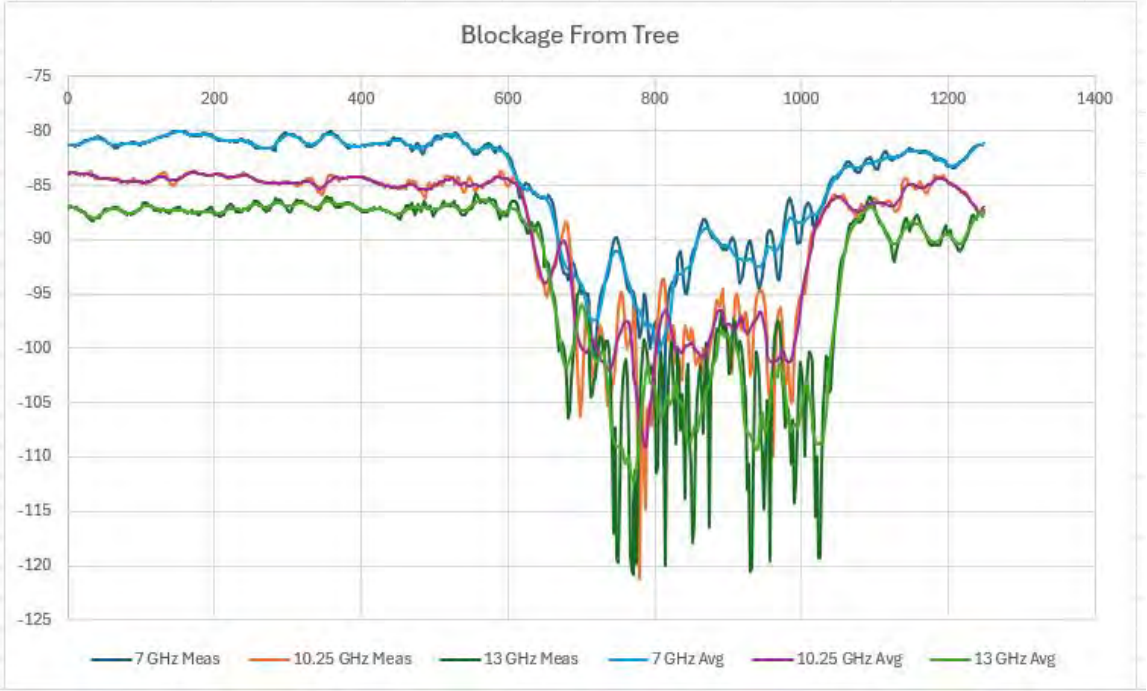

T

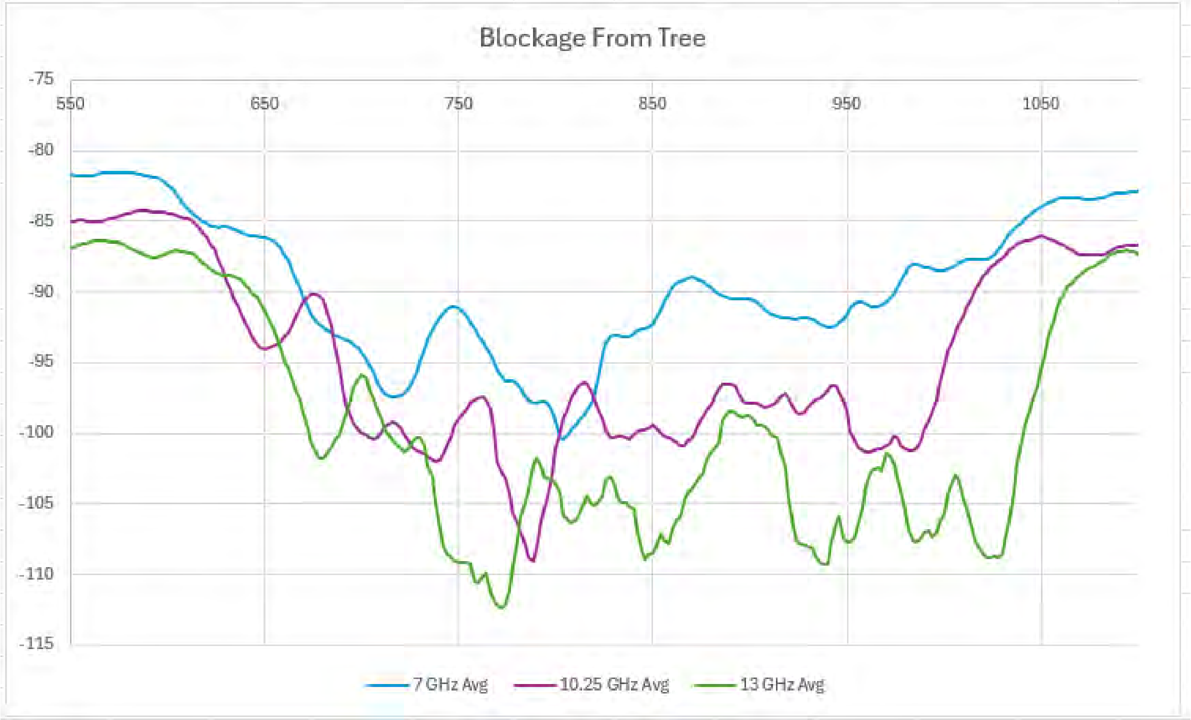

T


T


Exterior
T

Path Loss Measurements With Tree Blockage





Observations:

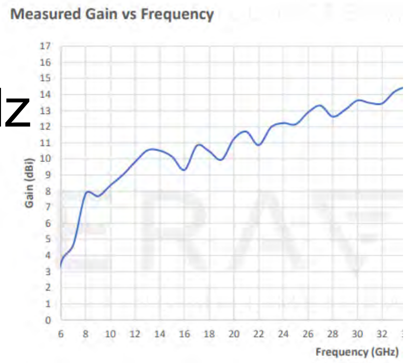
Blockage ~ 10 dB at 7 GHz, 15 dB at 10.25 GHz 20 dB at 13 GHz

Blockage “depth” and “width” increased with frequency

Antenna beamwidth decreases with frequency

Could account for difference in “width”

“Average” traces use a running average of 11 points



Conclusion

- Studies are ongoing with this setup, with outdoor measurements being conducted now.
- Other scenarios and materials being considered for Joint Communication and Sensing scenarios.

KEYSIGHT
10 YEAR ANNIVERSARY

Challenges of Achieving 100 Gbps for 6G

Using Extreme Sub-THz Bandwidths and MIMO Techniques

Greg Jue, greg_jue@keysight.com
Keysight Technologies

Outline

- **Challenges of Achieving 100 Gbps**
- Case Study: Extreme Bandwidths
- Case Study: MIMO
- Additional Resources

Challenges of Achieving 100 Gbps

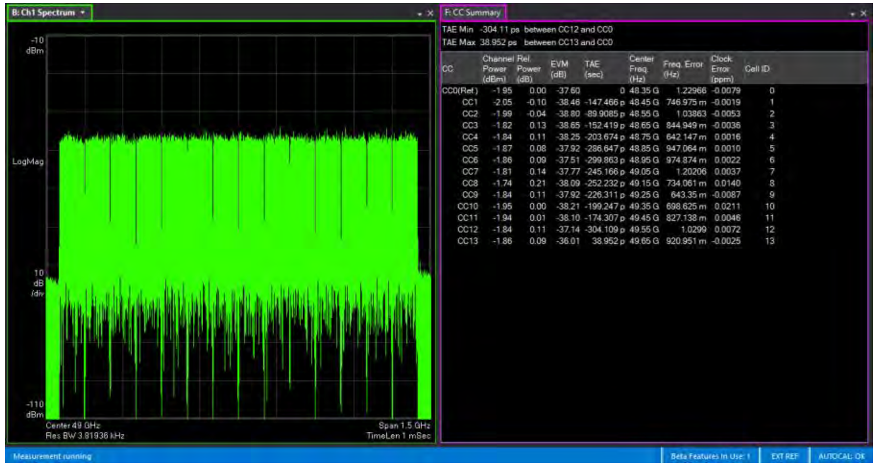
Three Fundamental Approaches:

- More Spectrum Bandwidth
- Higher-Order Modulation
- Multiple and Independent Streams of Data (MIMO)

Challenges of Achieving 100 Gbps

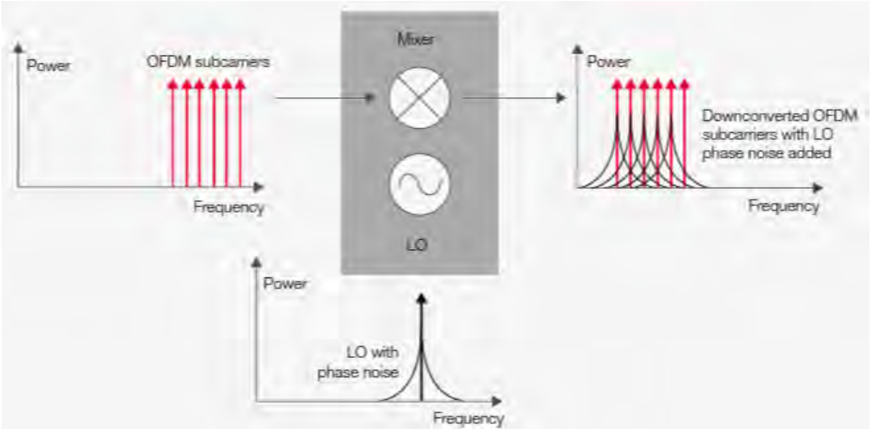
Industry Trends and Challenges

High Carrier Frequencies and Wide Bandwidths



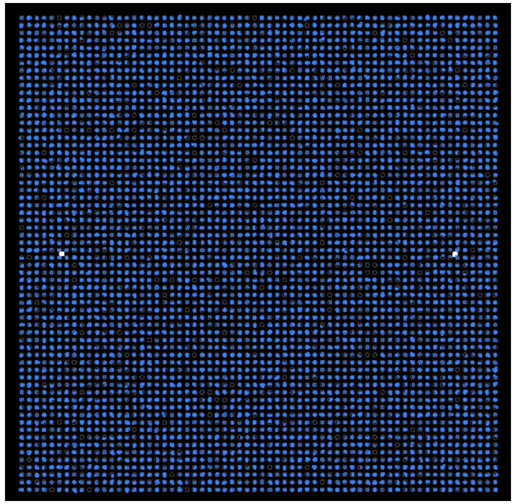
- Dynamic range/ SNR becomes more challenging
- Amplitude and phase flatness over wide bandwidths

OFDM



- High peak-to-average signal
- Back-off for non-linear components

Higher Order QAM

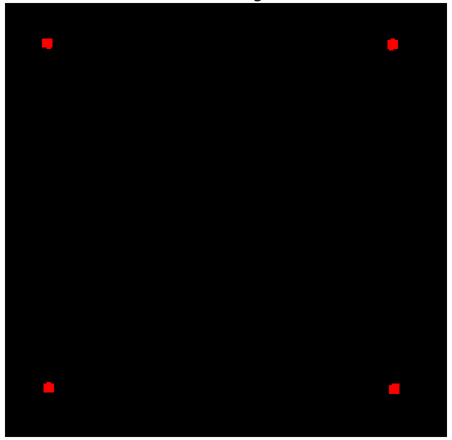


- Closer symbol states
- Tighter EVM requirement

Challenges of Achieving 100 Gbps

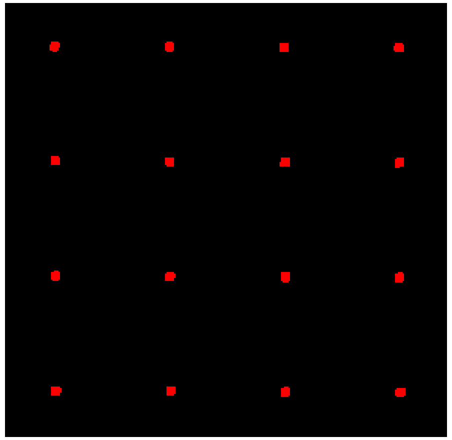
QAM Order: Increase Data Throughput within Spectrum/Channel Bandwidth

2 bits/symbol



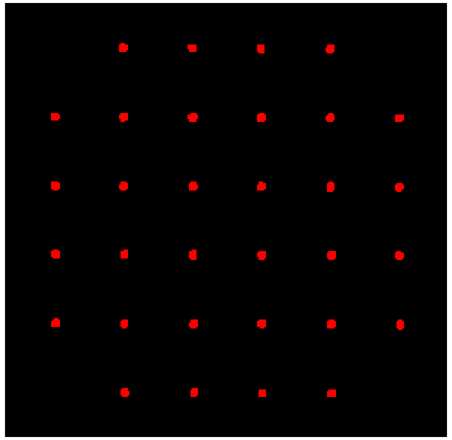
QPSK

4 bits/symbol



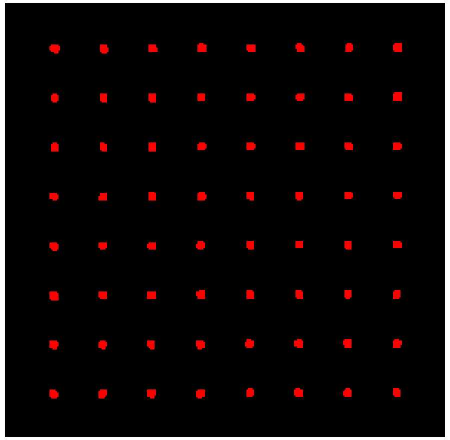
16QAM

5 bits/symbol



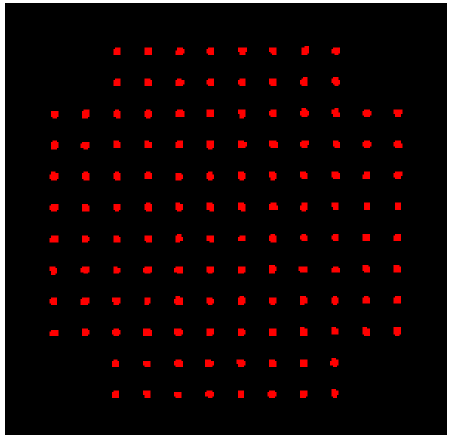
32QAM

6 bits/symbol



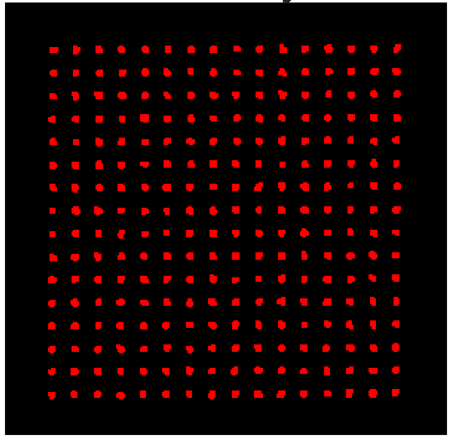
64QAM

7 bits/symbol



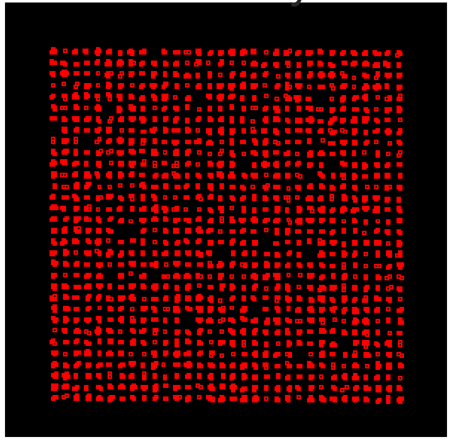
128QAM

8 bits/symbol



256QAM

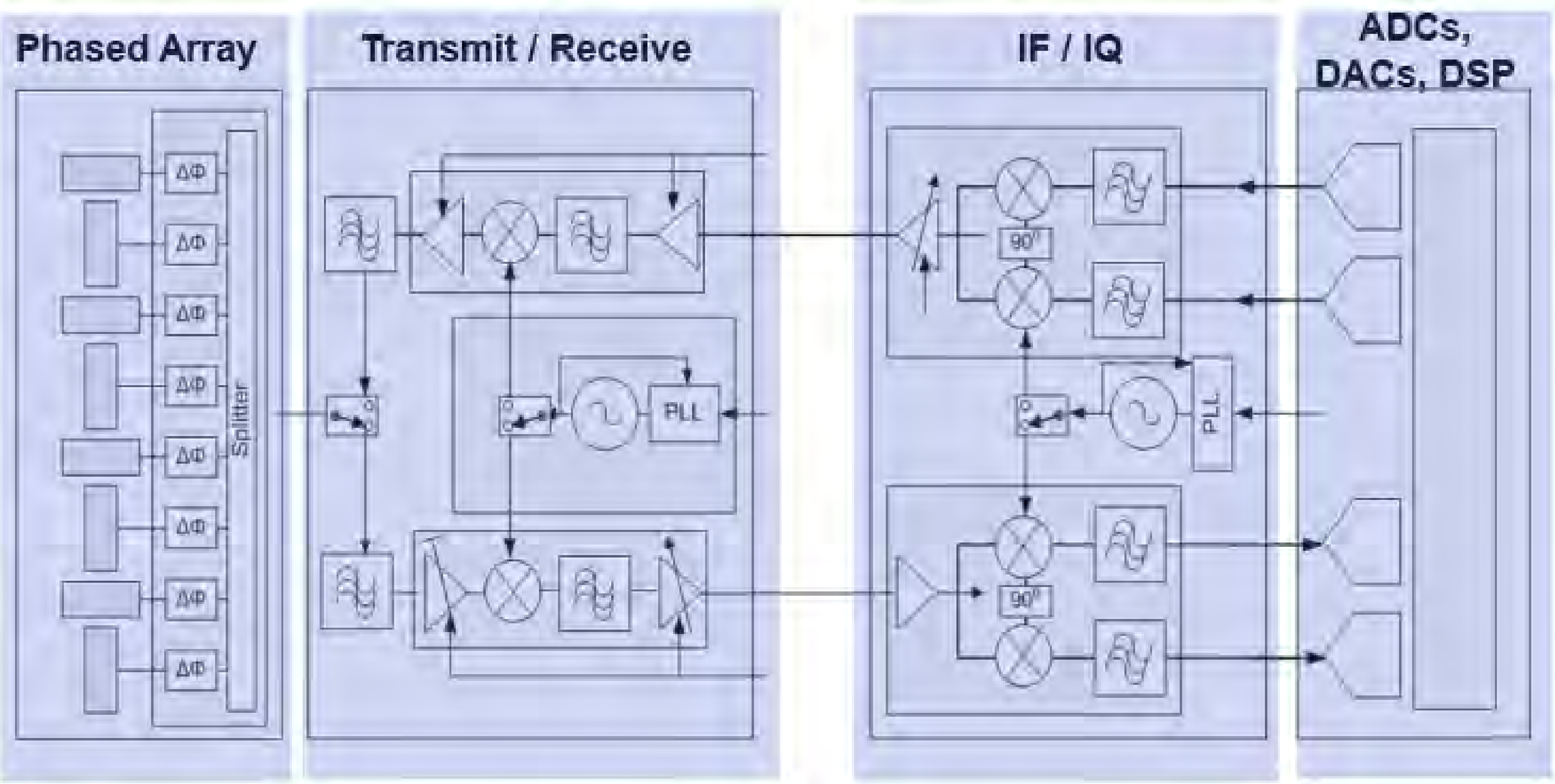
10 bits/symbol



1024QAM

Challenges of Achieving 100 Gbps

DUT Error Contributors



Phased Array:
- Phased Array Calibration
- Beam Steering Accuracy
- Sufficient Gain/SNR for Link Budget
- Noise Figure

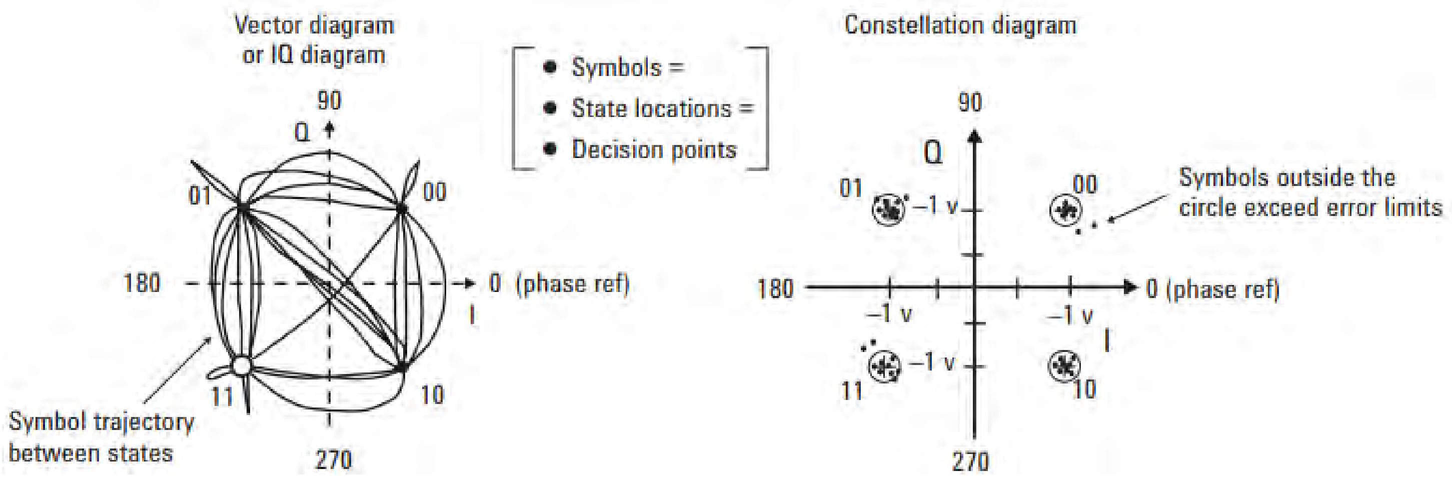
Transmit Receive:
- LO Phase Noise
- Linear Ampl./Phase Flatness (BPFs)
- Nonlinear Distortion (Mixers, Amps)
- In-band Mixing Products

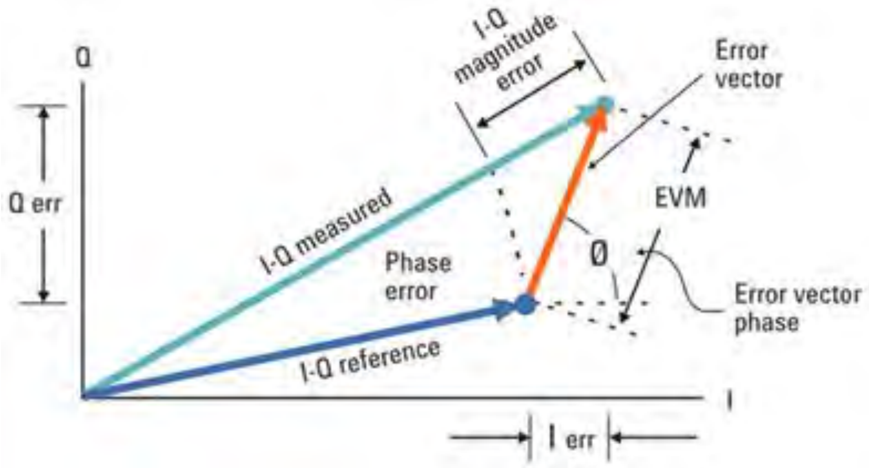
IF / IQ:
- IQ Gain Imbalance
- Quadrature Error
- Linear Ampl./Phase Errors (LPFs)
- Nonlinear Errors (VCAs)

ADCs / DACs / DSP:
- Quantization / # Bits of Vertical Res.
- Clock Jitter
- Scaling to Maximize Dynamic Range, but Minimizing Crest Factor Clipping
- FIRs/ Equalization/ Fixed Pt.

Challenges of Achieving 100 Gbps

Error Vector Magnitude: Convenience of a Single Number Metric





$$EVM[n] = \sqrt{I\,err[n]^2 + Q\,err[n]^2}$$

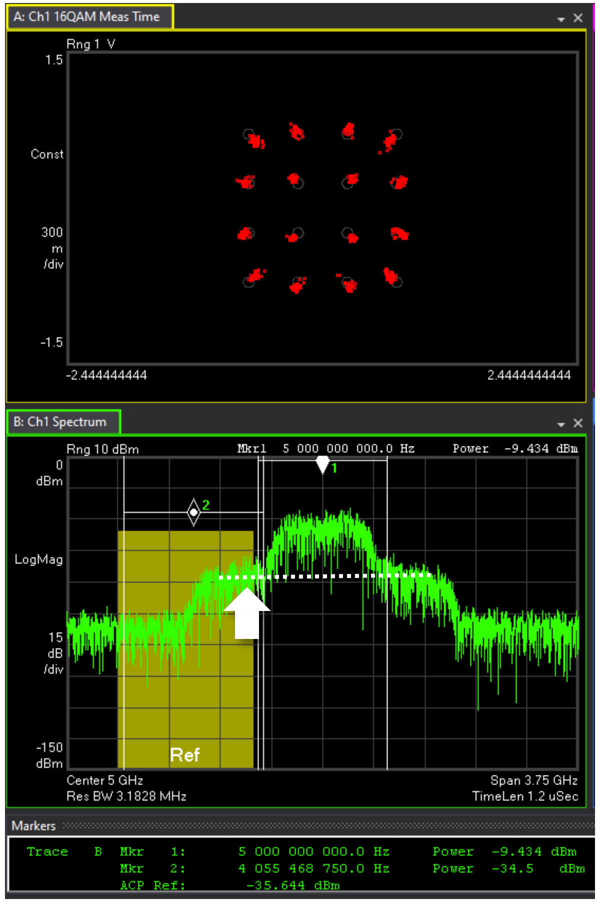
where [n] = measurement at the symbol time

I err = I ref - I meas

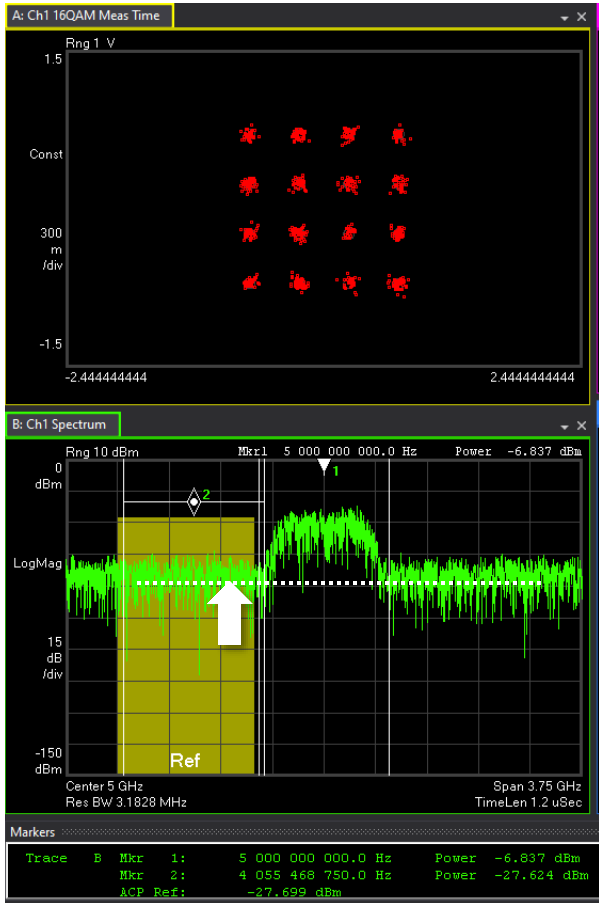
Q err = Q ref - Q meas

Challenges of Achieving 100 Gbps

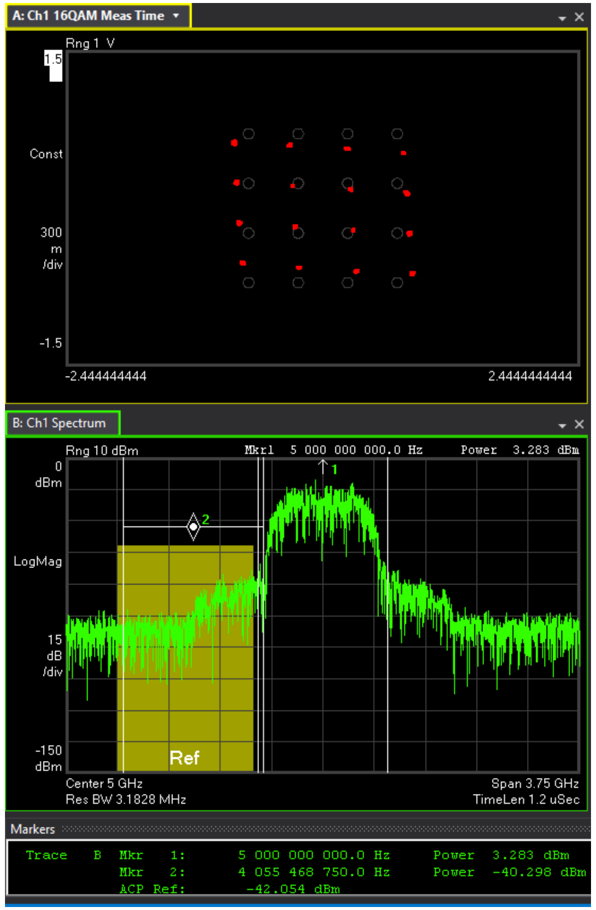
Identifying EVM Impairments in the Spectral and IQ Domains



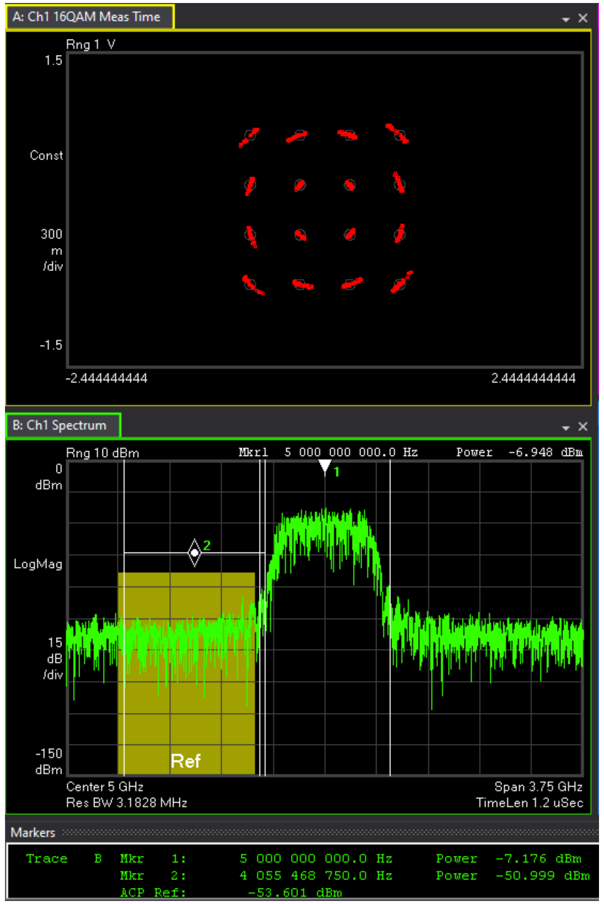
Distortion



White Noise



IQ imbalance



Phase noise

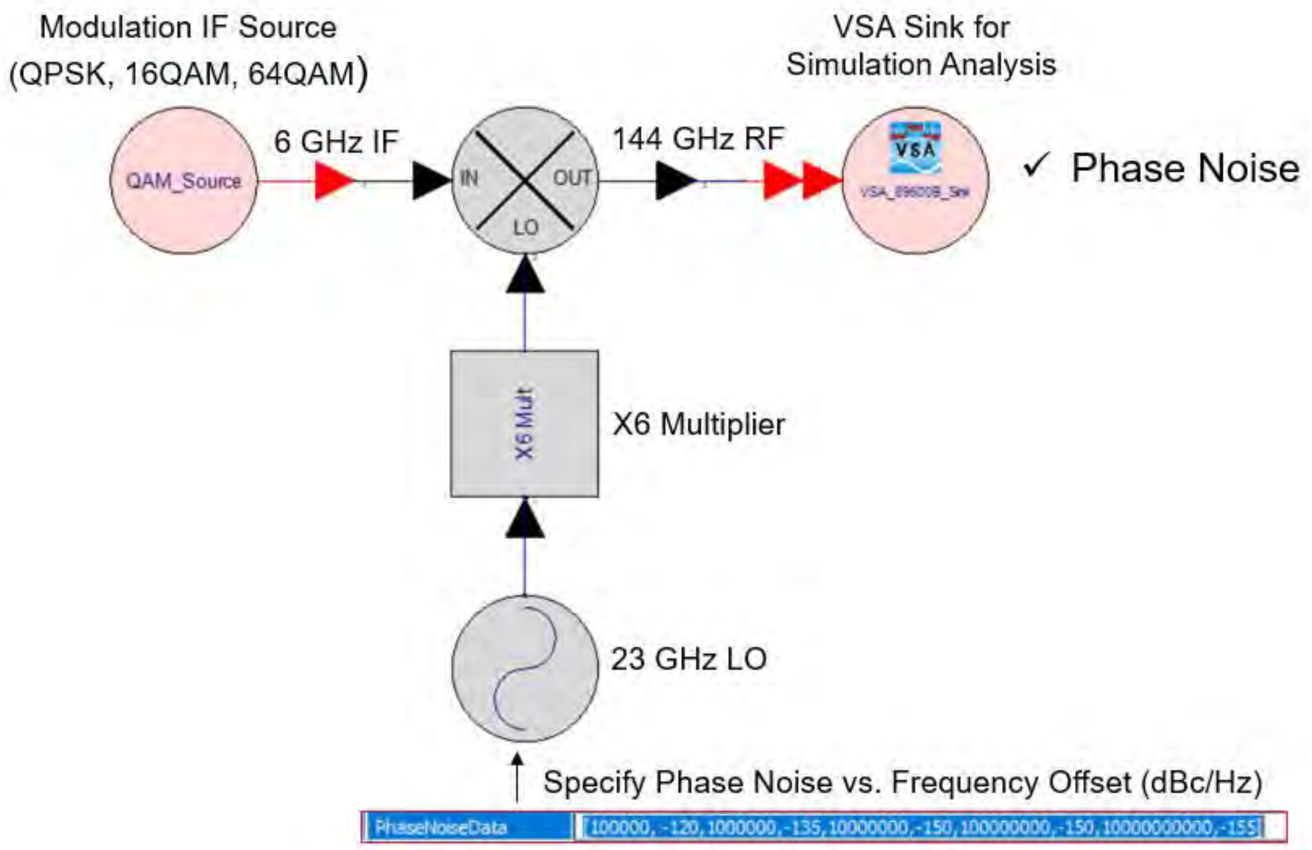
Challenges of Achieving 100 Gbps

OFDM and Single Carrier Signal Errors

Impairment	OFDM	Single Carrier
IQ gain balance	State spreading (uniform/carrier)	Distortion of constellation
IQ quadrature skew	State spreading (uniform/carrier)	Distortion of constellation
IQ channel mismatch	State spreading (non-uniform/carrier)	State spreading
Uncompensated frequency error	State spreading	Spinning constellation
Phase noise	State spreading (uniform/carrier)	Constellation phase rotation
Nonlinear distortion	State spreading	State Spreading (may be more pronounced on outer states)
Linear distortion	Usually no effect (equalized)	State spreading if not equalized
Carrier leakage	Offset constellation for center carrier only (if used)	Offset constellation
Frequency error	State spreading	Constellation phase rotation
Amplifier droop	Radial constellation distortion	Radial constellation distortion
Spurious	State spreading or shifting of affected subcarrier	State Spreading, generally circular

Challenges of Achieving 100 Gbps

Simulation Case Study



Challenges of Achieving 100 Gbps

Simulation Case Study

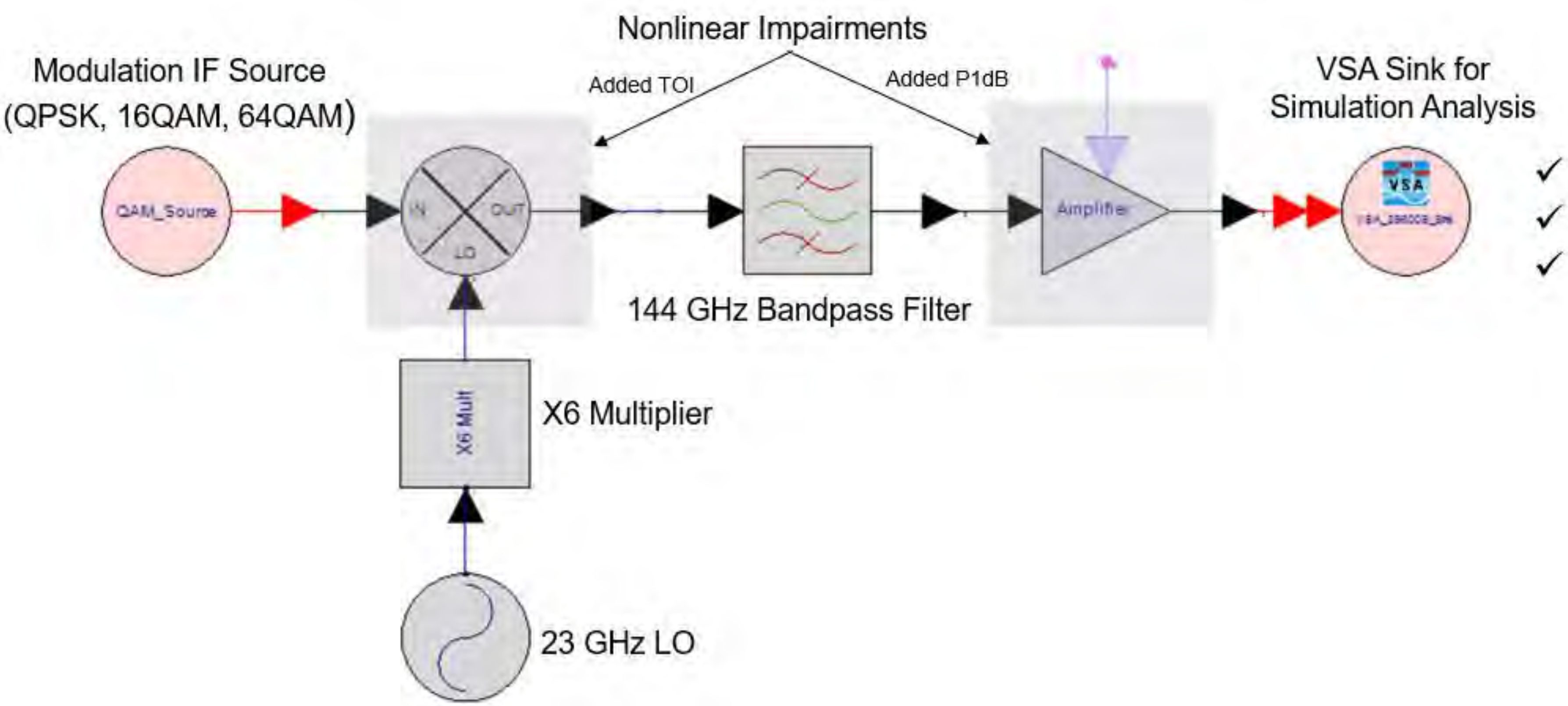
✓ Phase Noise

Simulated Using dBc/Hz from Phase Noise Profile in Previous Slide

Increased Phase Noise by 10 dBc/Hz for Higher Frequency Offsets

Challenges of Achieving 100 Gbps

Simulation Case Study

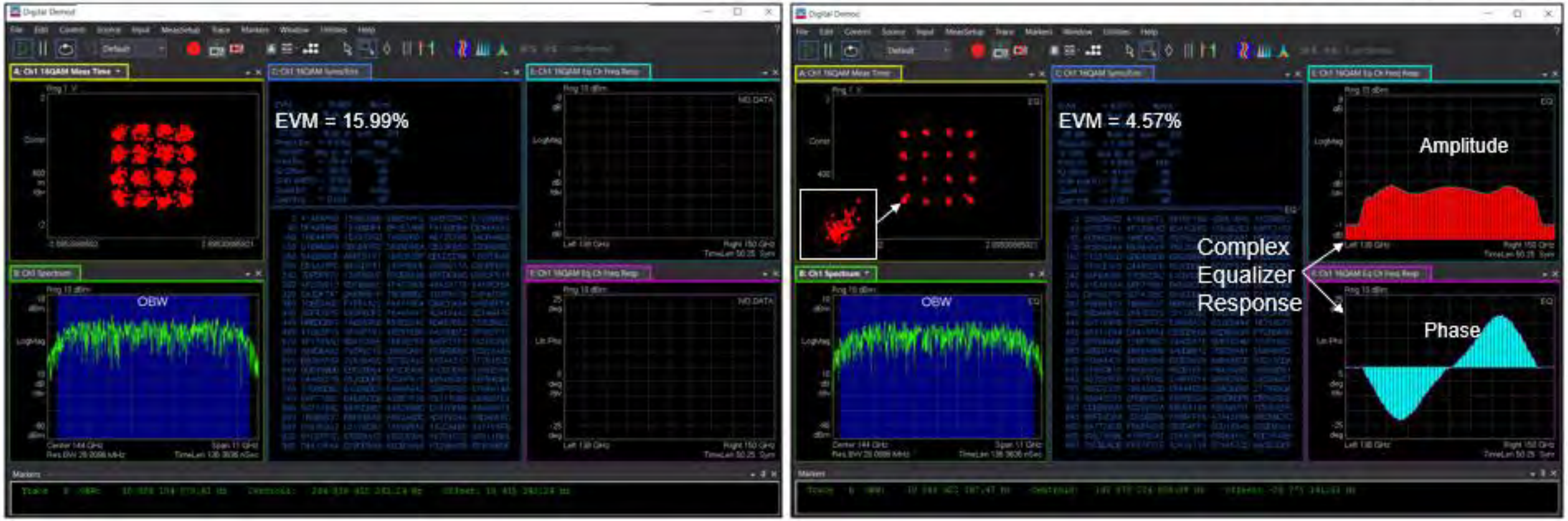


- ✓ Phase Noise
- ✓ Linear Impairments
- ✓ Nonlinear Impairments

Challenges of Achieving 100 Gbps

Simulation Case Study

- ✓ Phase Noise
- ✓ Linear Impairments
- ✓ Nonlinear Impairments



Outline

- Challenges of Achieving 100 Gbps
- **Case Study: Extreme Bandwidths**
- Case Study: MIMO
- Additional Resources

Sub-THz Testbed for 6G Research, 220-330 GHz

Conducted EVM Measurements

Sub-THz Testbed for 6G Research, 220-330 GHz

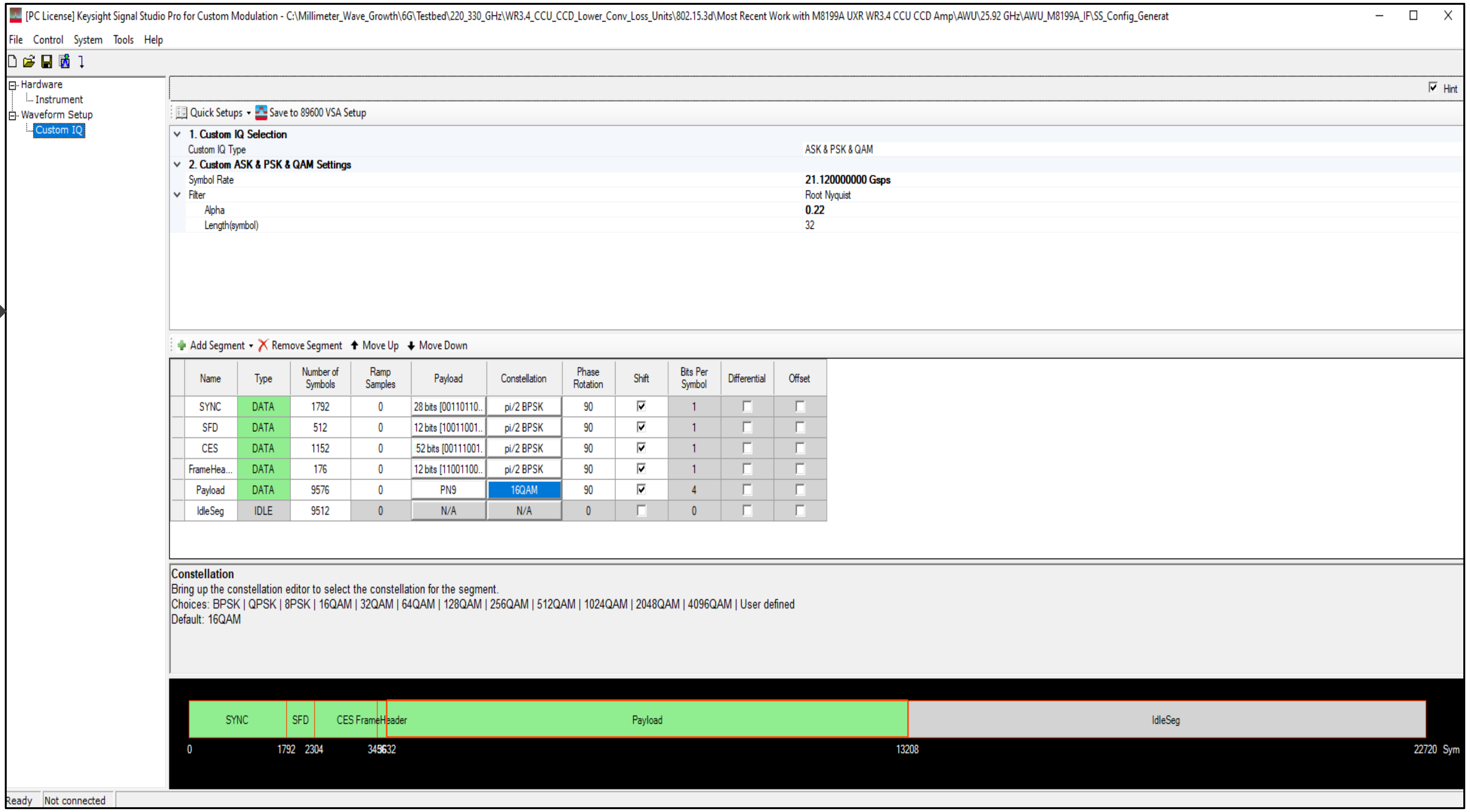
Signal Generation Software

802.15.3d Bandwidths

Description
Bandwidth 2.16 GHz
Bandwidth 4.32 GHz
Bandwidth 8.64 GHz
Bandwidth 12.96 GHz
Bandwidth 17.28 GHz
Bandwidth 25.92 GHz
Bandwidth 51.84 GHz
Bandwidth 69.12 GHz

Source IEEE Std 802.15.3d-2017
Figure 2. IEEE 802.15.3d supported bandwidths.

N7608C Signal Studio Pro for Custom Modulation, Custom IQ



Sub-THz Testbed for 6G Research, 220-330 GHz

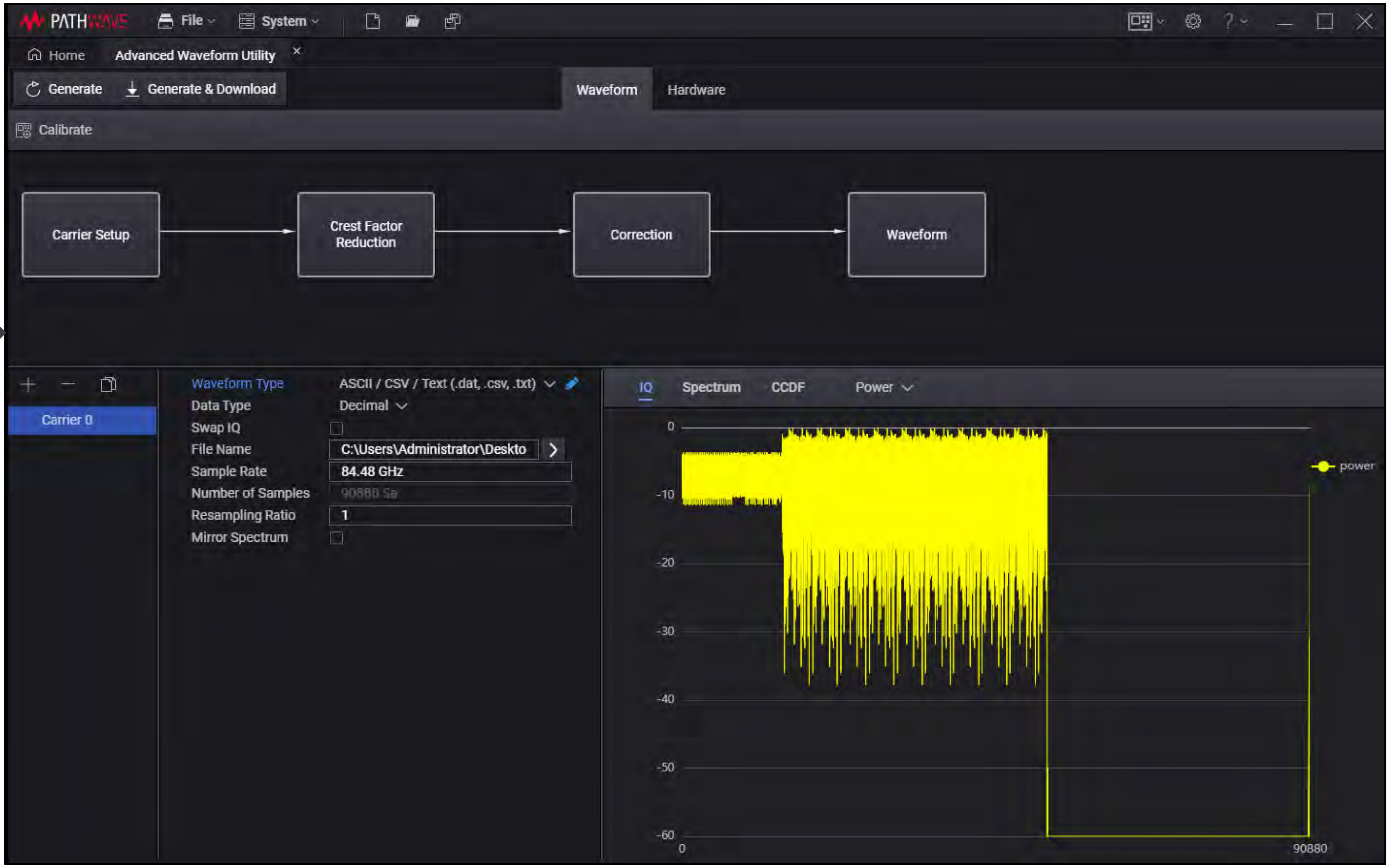
Signal Generation Software

Description
Bandwidth 2.16 GHz
Bandwidth 4.32 GHz
Bandwidth 8.64 GHz
Bandwidth 12.96 GHz
Bandwidth 17.28 GHz
Bandwidth 25.92 GHz
Bandwidth 51.84 GHz
Bandwidth 69.12 GHz

Source IEEE Std 802.15.3d-2017
Figure 2. IEEE 802.15.3d supported bandwidths.

802.15.3d Bandwidths

PathWave Signal Generation (PWSG) Advanced Waveform Utility (AWU)



M8199A 128 GSa/s AWG
65 GHz 3dB Bandwidth

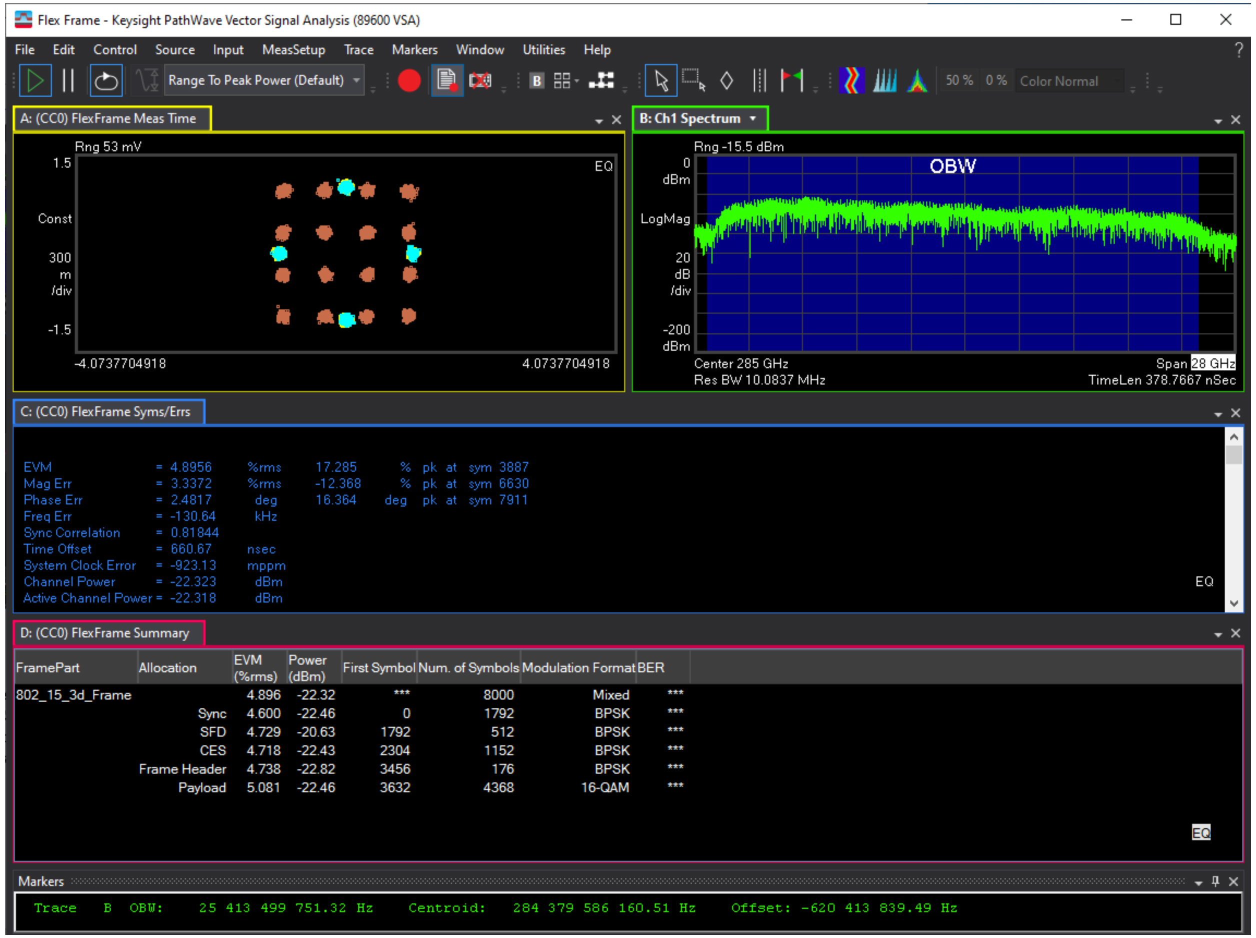
16 GHz IF Before Upconversion

Sub-THz Testbed for 6G Research, 220-330 GHz

Conducted EVM Measurements: 285 GHz with 25.92 GHz Bandwidth

110 GHz UXR, 256 GSa/s

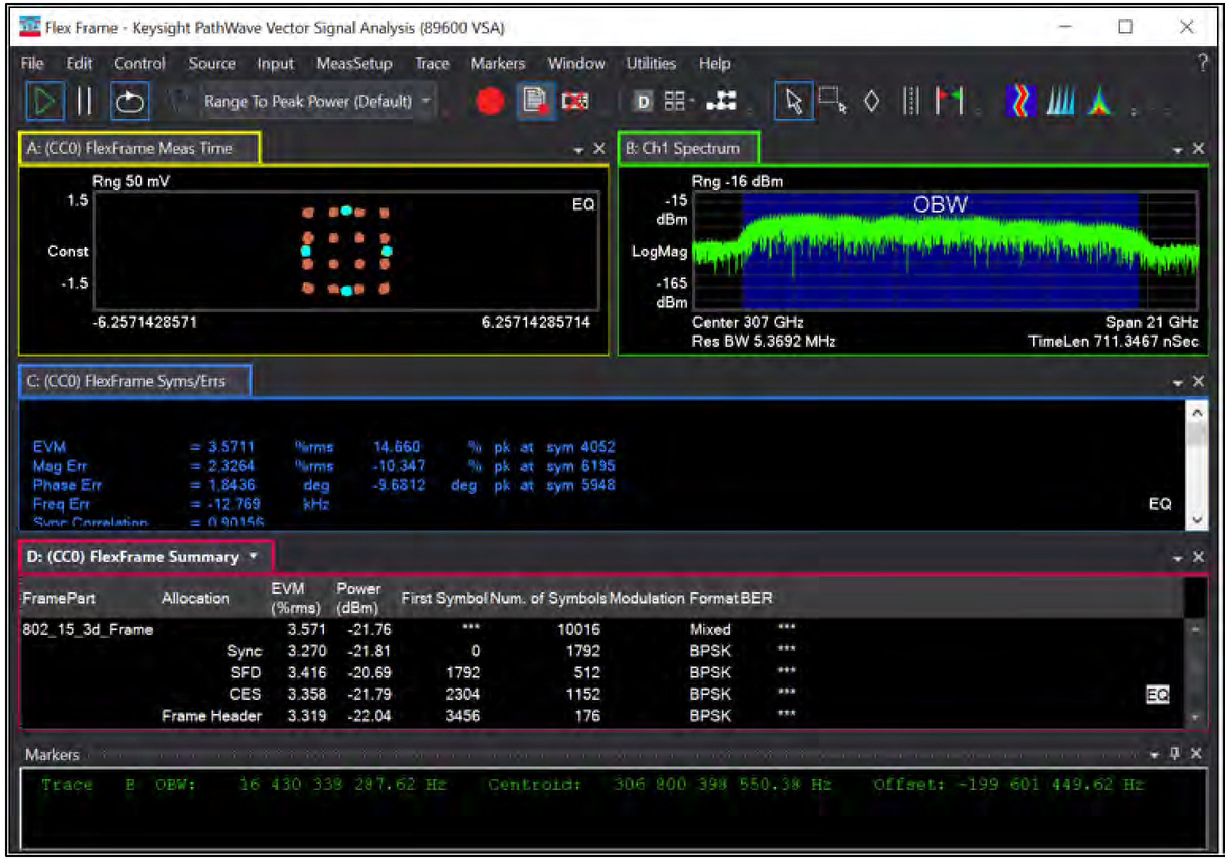
VSA Flex Frame Demodulation of 16 GHz IF After Downconversion



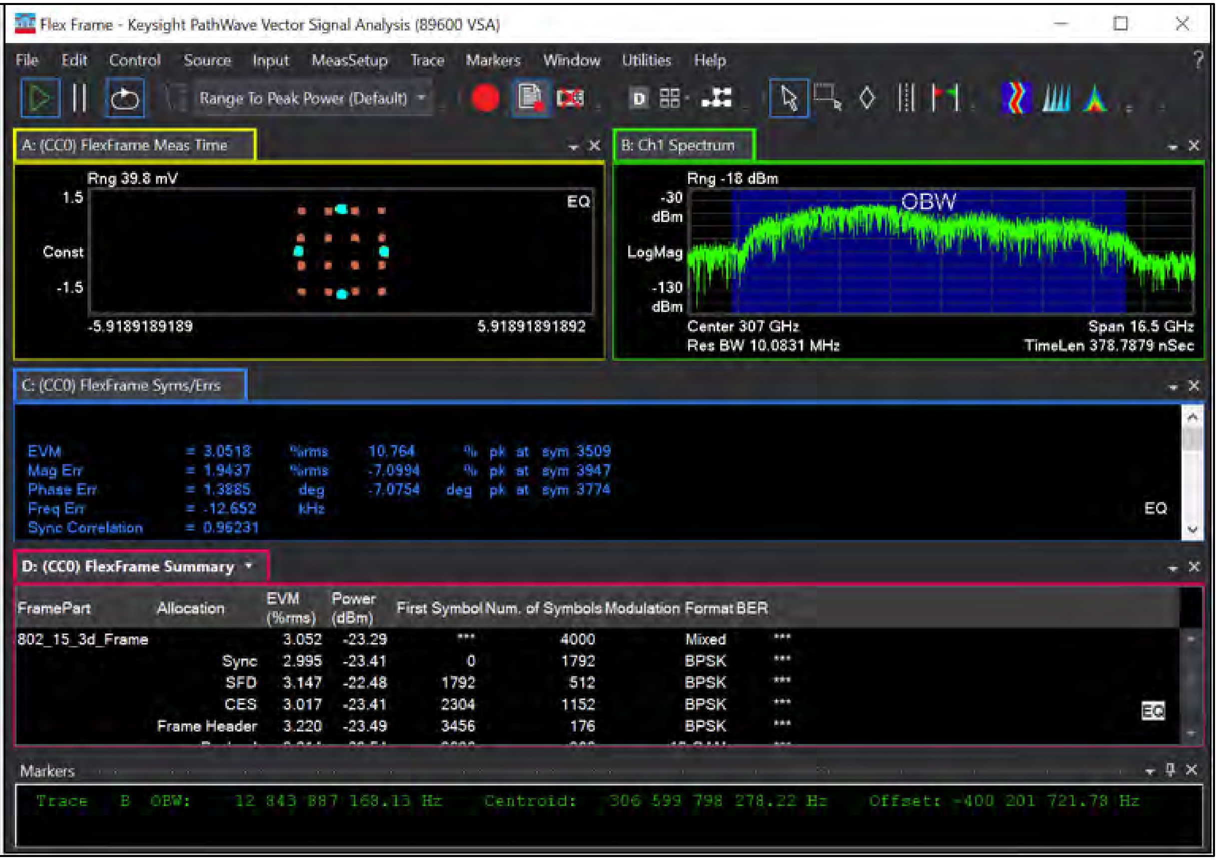
Sub-THz Testbed for 6G Research, 220-330 GHz

Conducted EVM Measurements at 307 GHz with Narrower Bandwidths

17.28 GHz Bandwidth



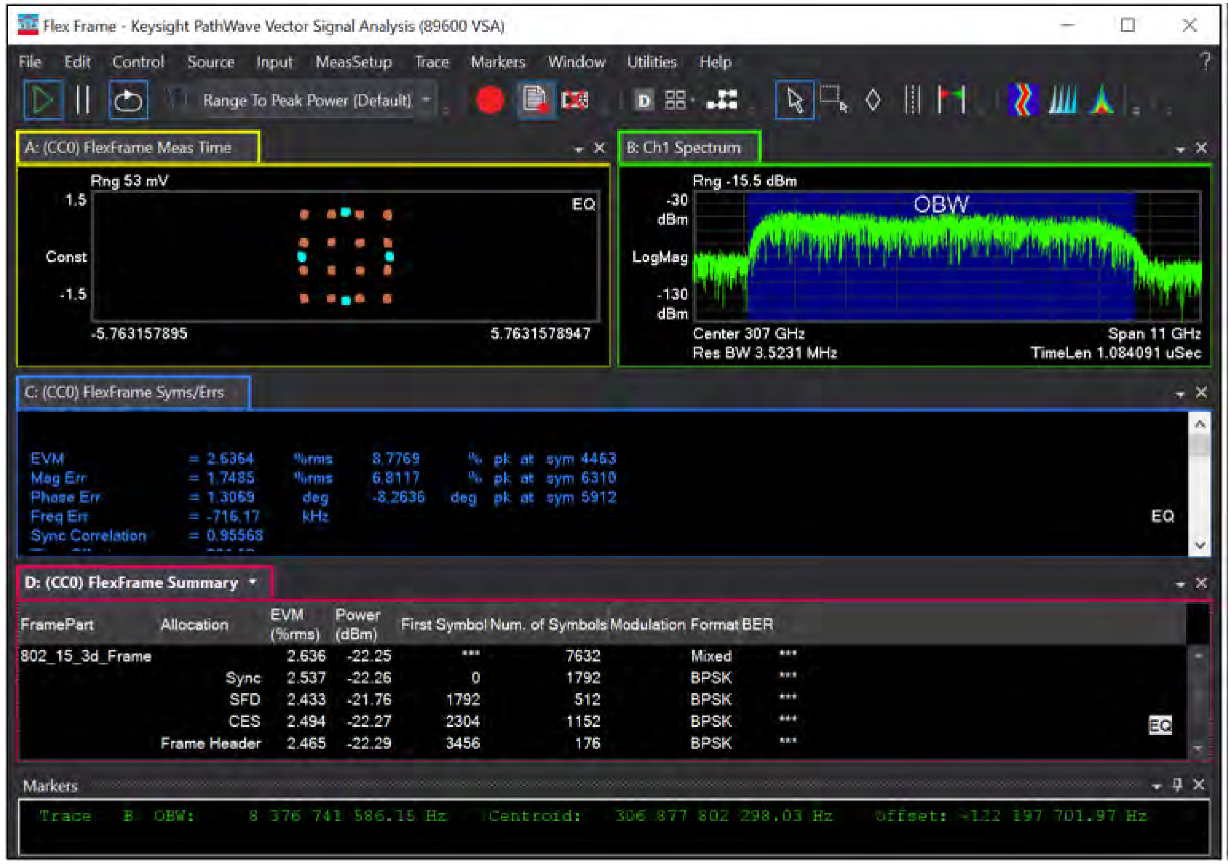
12.96 GHz Bandwidth



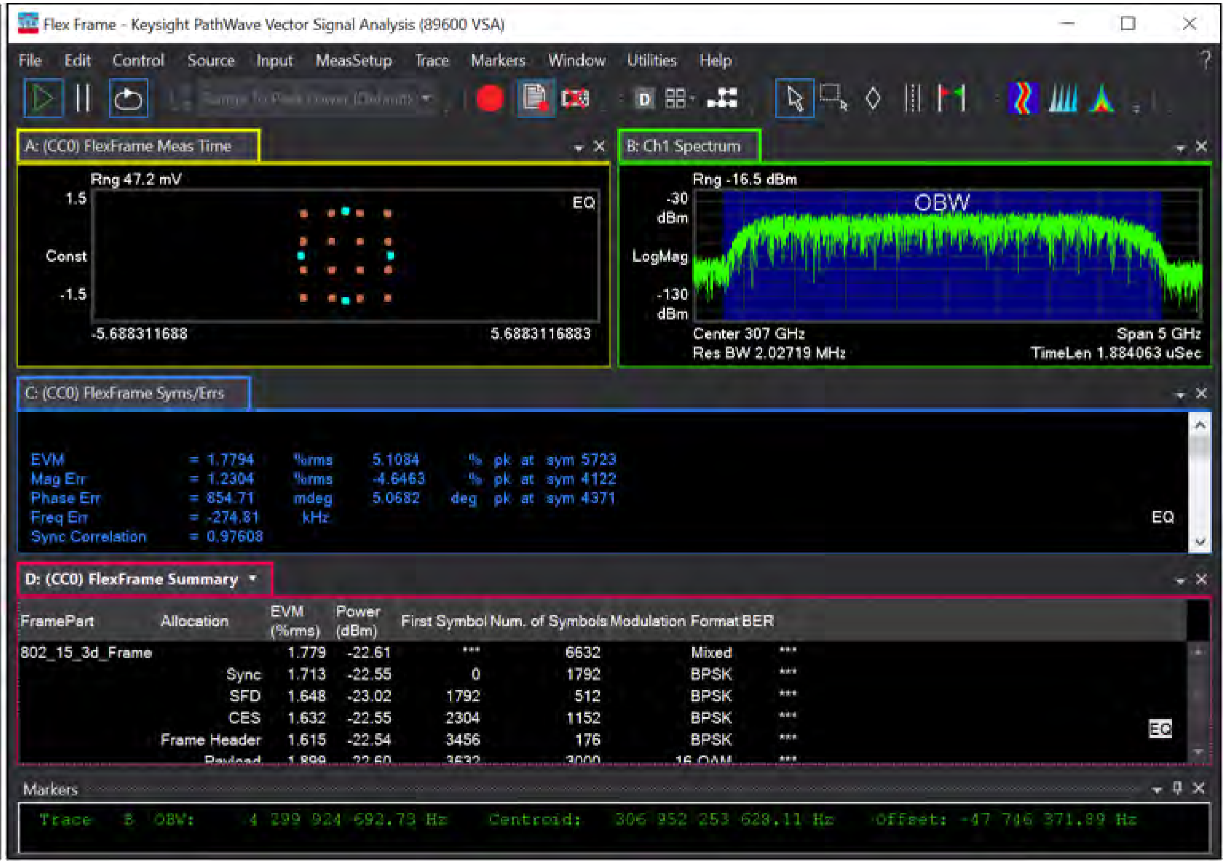
Sub-THz Testbed for 6G Research, 220-330 GHz

Conducted EVM Measurements at 307 GHz with Narrower Bandwidths

8.64 GHz Bandwidth



4.32 GHz Bandwidth



Sub-THz Testbed for 6G Research, 220-330 GHz

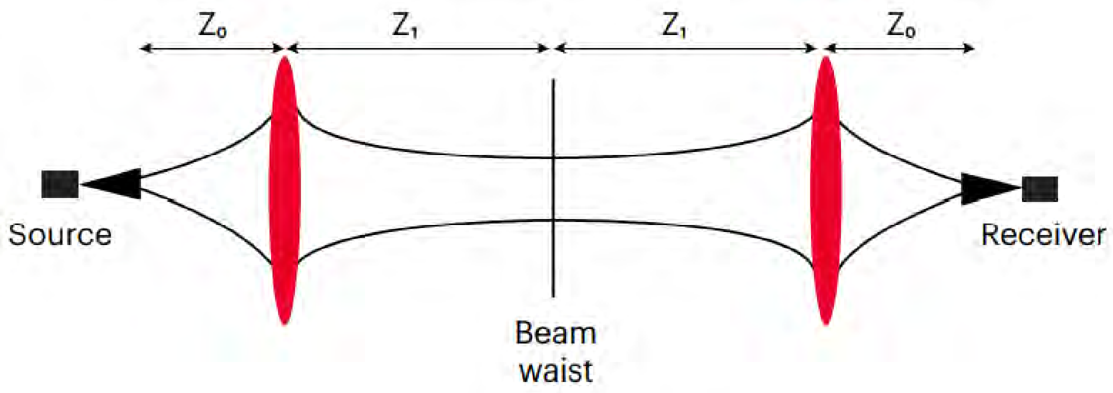
Quasioptic OTA Measurements at 285 GHz with 30 GHz Bandwidth

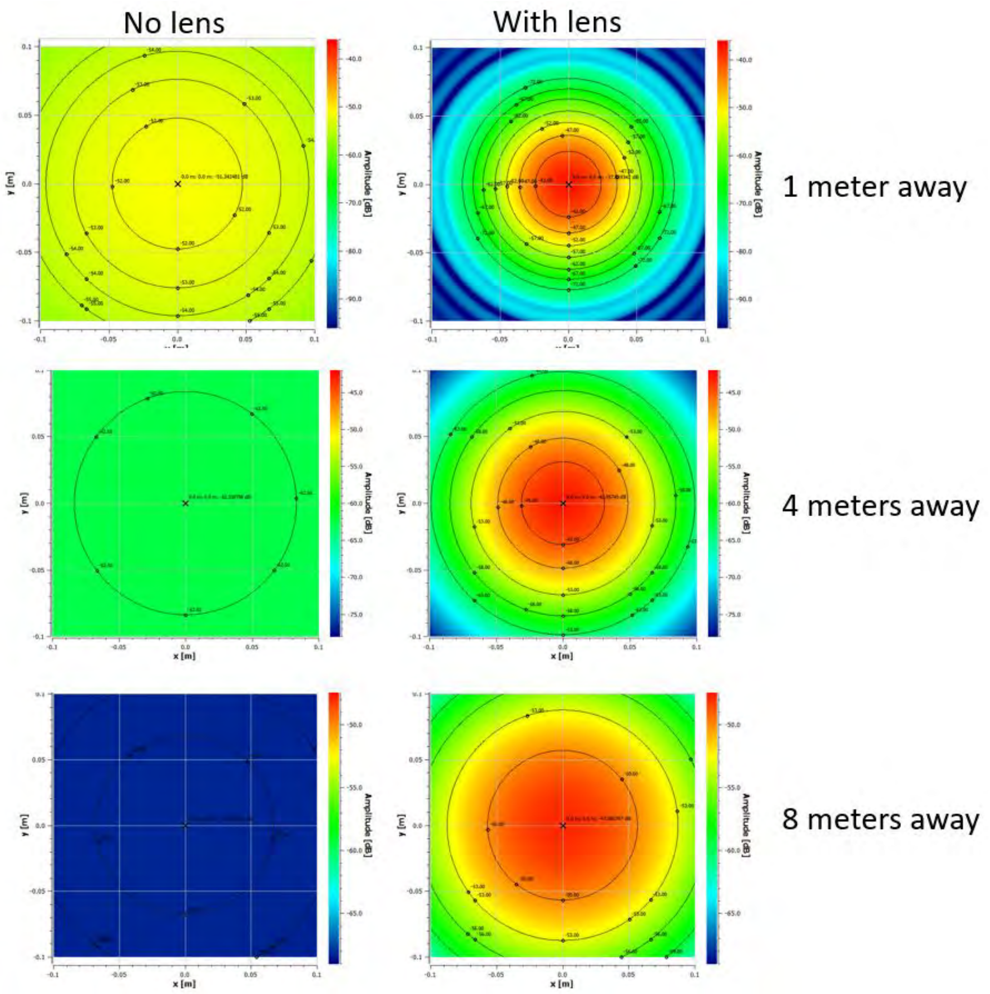
Transmit Side: Side View

Transmit Side: End View

Sub-THz Testbed for 6G Research, 220-330 GHz

Quasioptic OTA Measurements at 285 GHz with 30 GHz Bandwidth



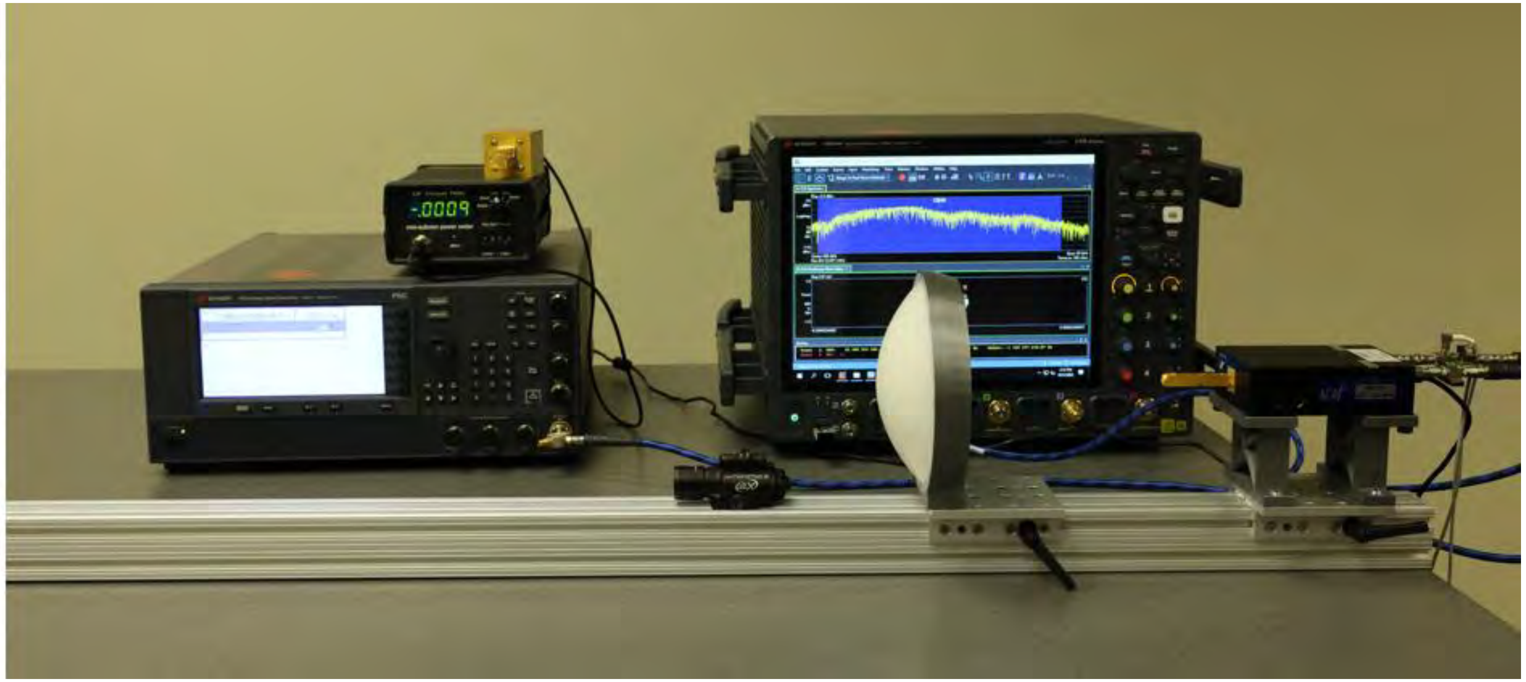


Sub-THz Testbed for 6G Research, 220-330 GHz

Quasioptic OTA Measurements at 285 GHz with 30 GHz Bandwidth

Receive Side: End View

Receive Side: Side View



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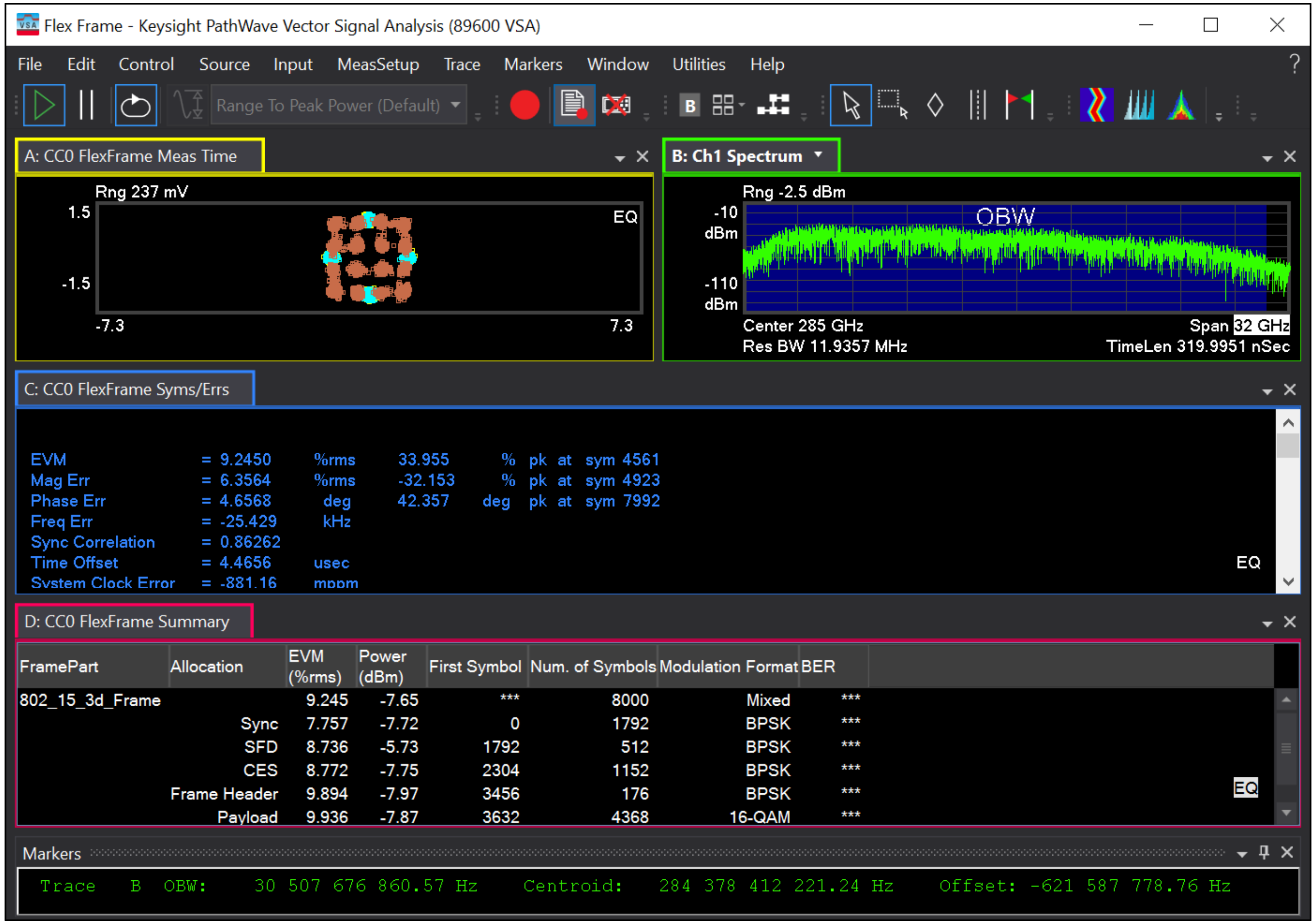

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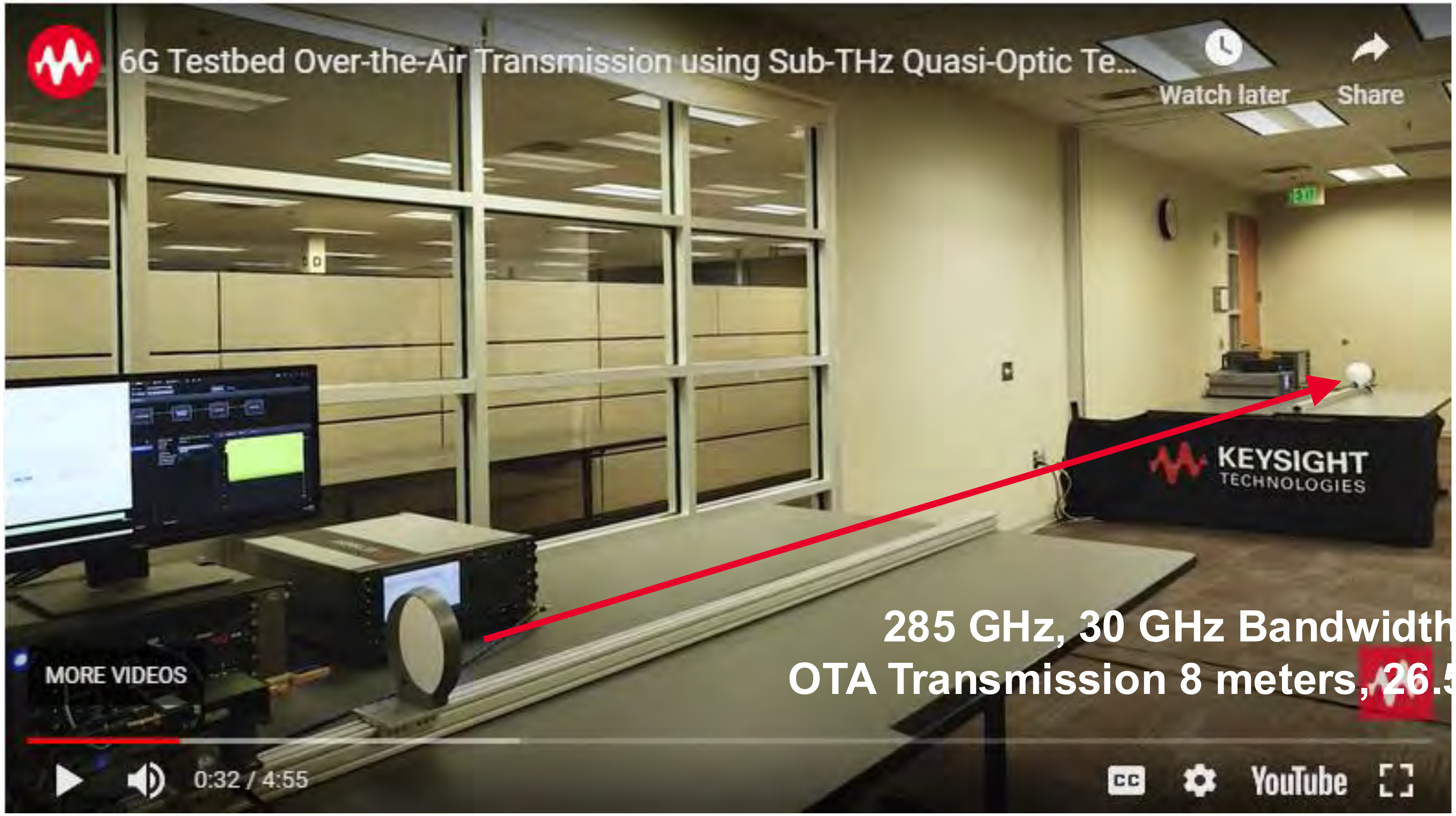


https://www.keysight.com/discover/6g/6g-testbed-over-the-air-transmission-using-sub-thz-quasi-optic-techniques

Sub-THz Testbed for 6G Research, 220-330 GHz

Quasioptic OTA Measurements at 285 GHz with 30 GHz Bandwidth

Data Throughput Calculation:

- 25 Gsps symbol rate
- Bits per symbol = 4 (16QAM)
- Total Number of Symbols: 127744
- Total Number of Non-Data Payload Symbols: 3760 (1792 Sync, 512 SFD, 1152 CES, 176 Frame Header, 128 Idol)
- Number of Data Payload Symbols: 123984
- Frame Length: 5.11 uSec

Throughput = Number of Payload Symbols * Bits/Symbol / Frame Length

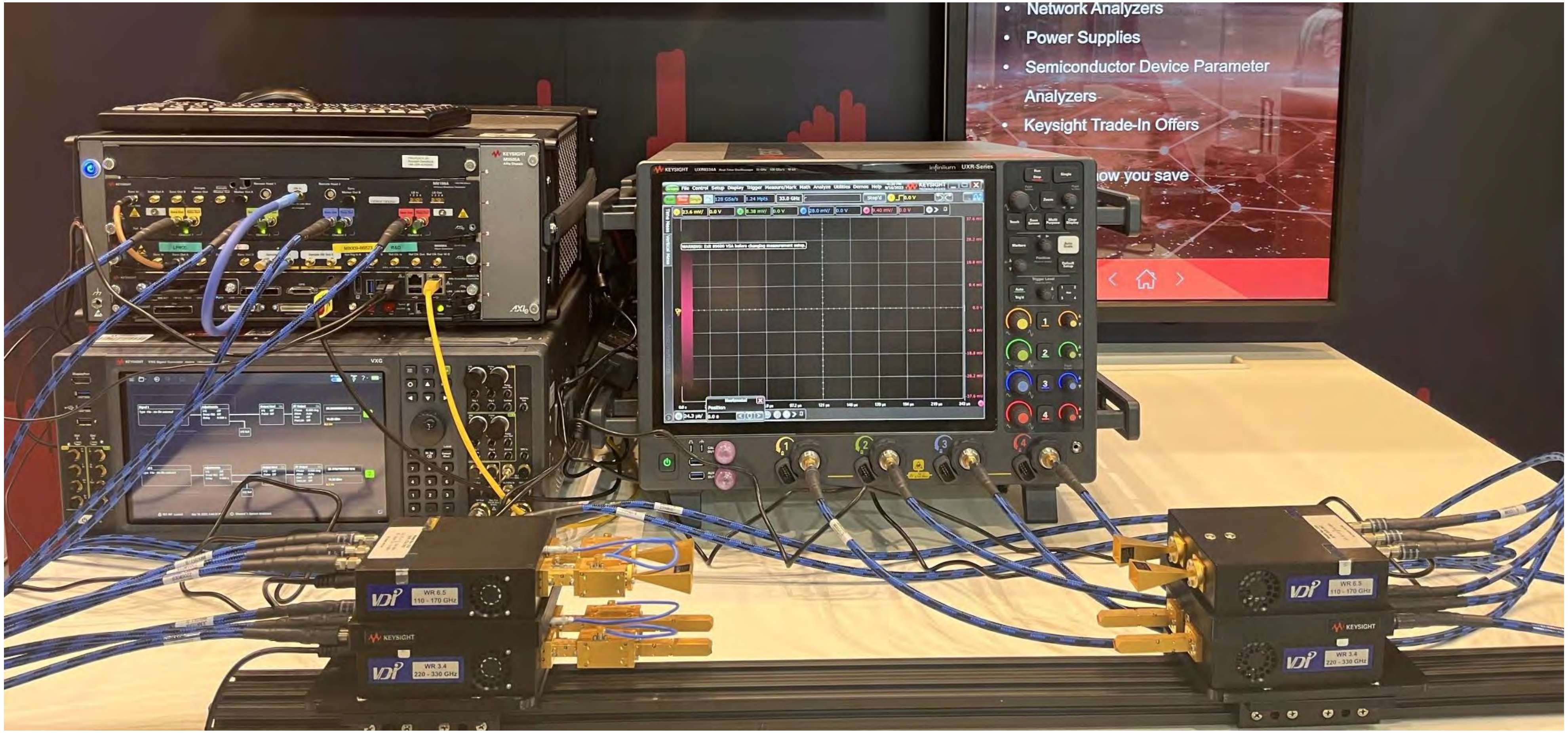
Throughput = 123984 * 4 / 5.11 uSec= ~**97.1 Gbps for 16QAM**

Outline

- Challenges of Achieving 100 Gbps
- Case Study: Extreme Bandwidths
- **Case Study: MIMO**
- Additional Resources

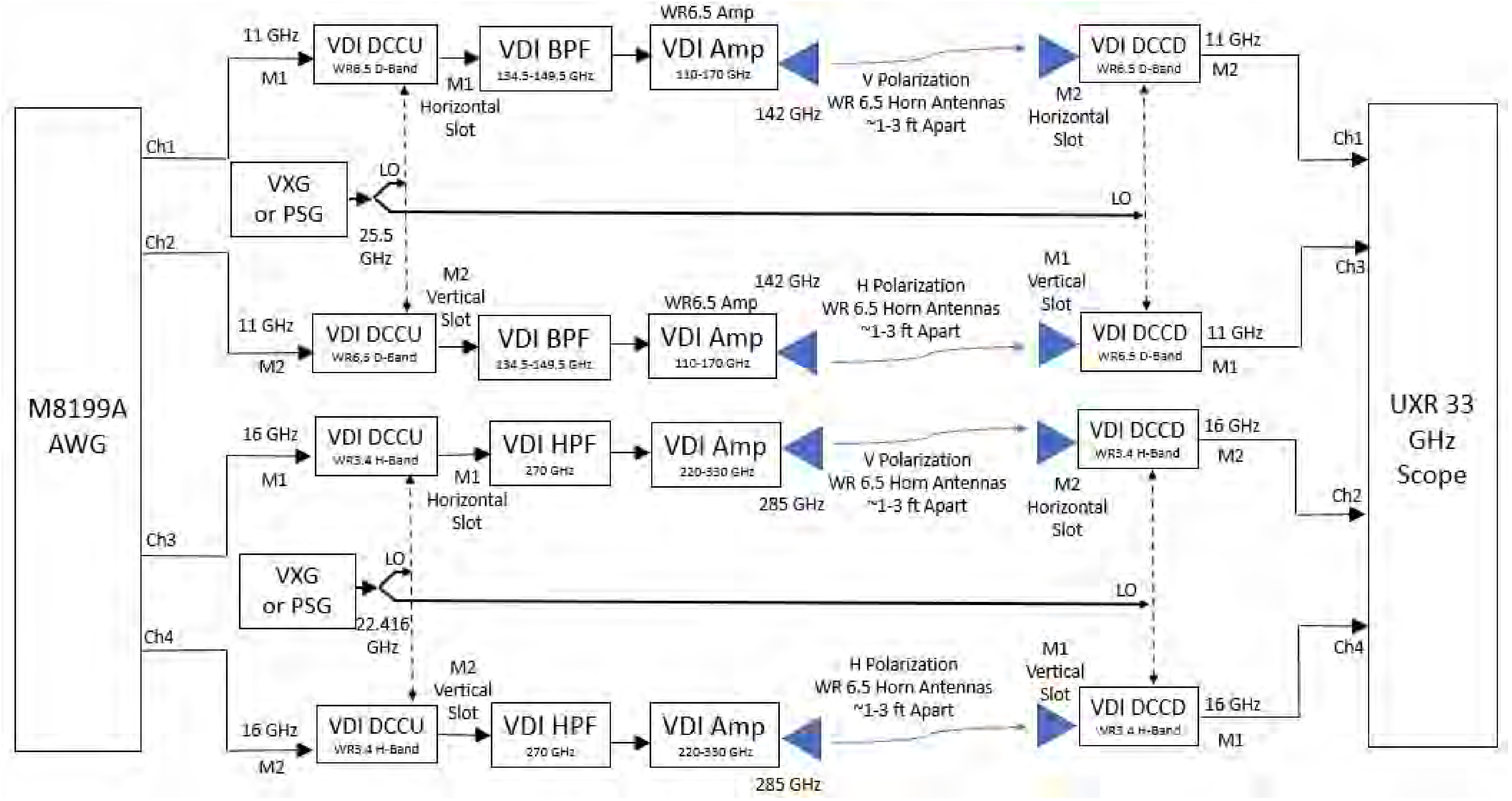
Simultaneous Sub-THz MIMO OTA Demo

2X2 MIMO: 142 GHz and 285 GHz with 12.5 GHz Bandwidth



Simultaneous Sub-THz MIMO OTA Demo

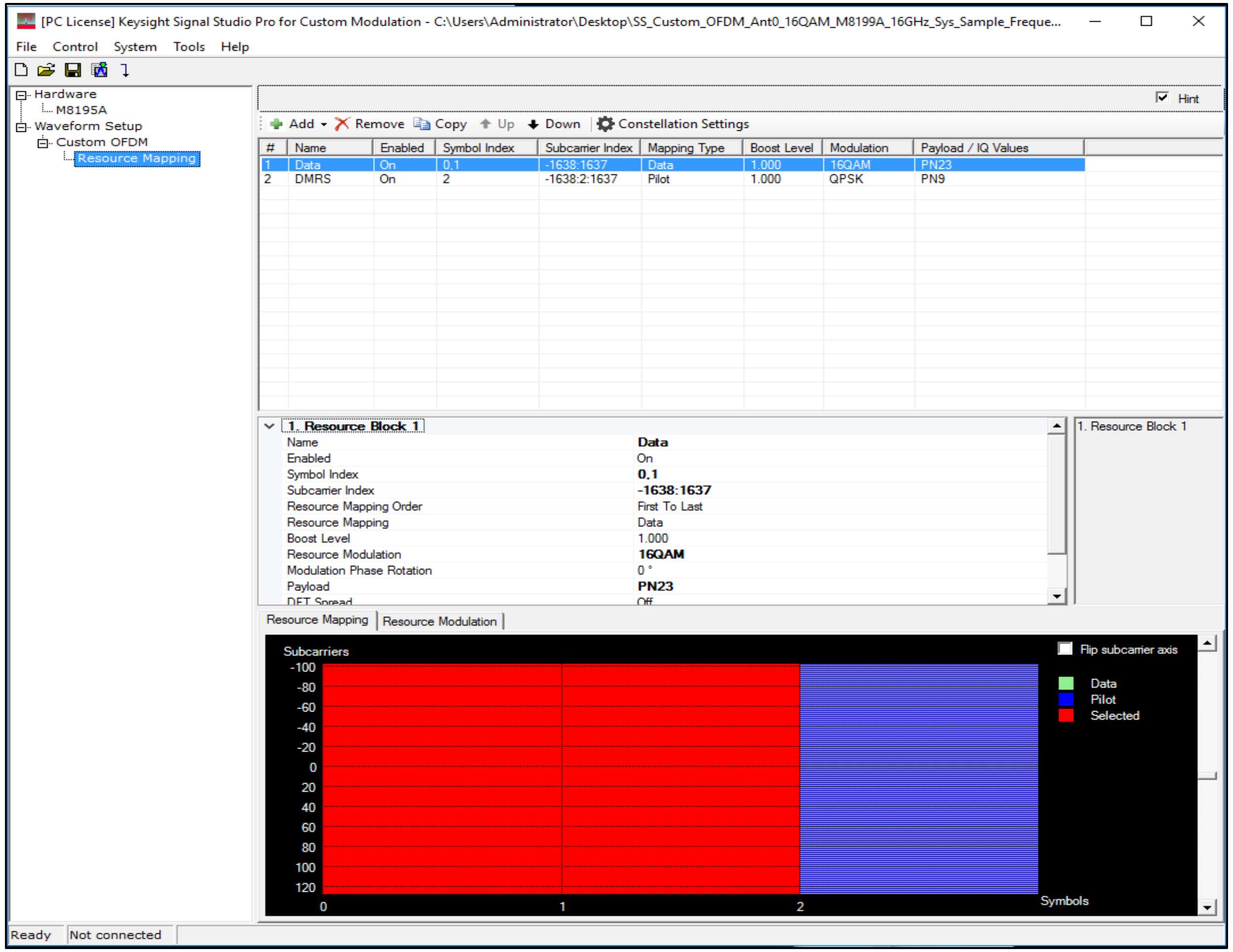
2X2 MIMO: 142 GHz and 285 GHz with 12.5 GHz Bandwidth



Simultaneous Sub-THz MIMO OTA Demo

Signal Generation Software

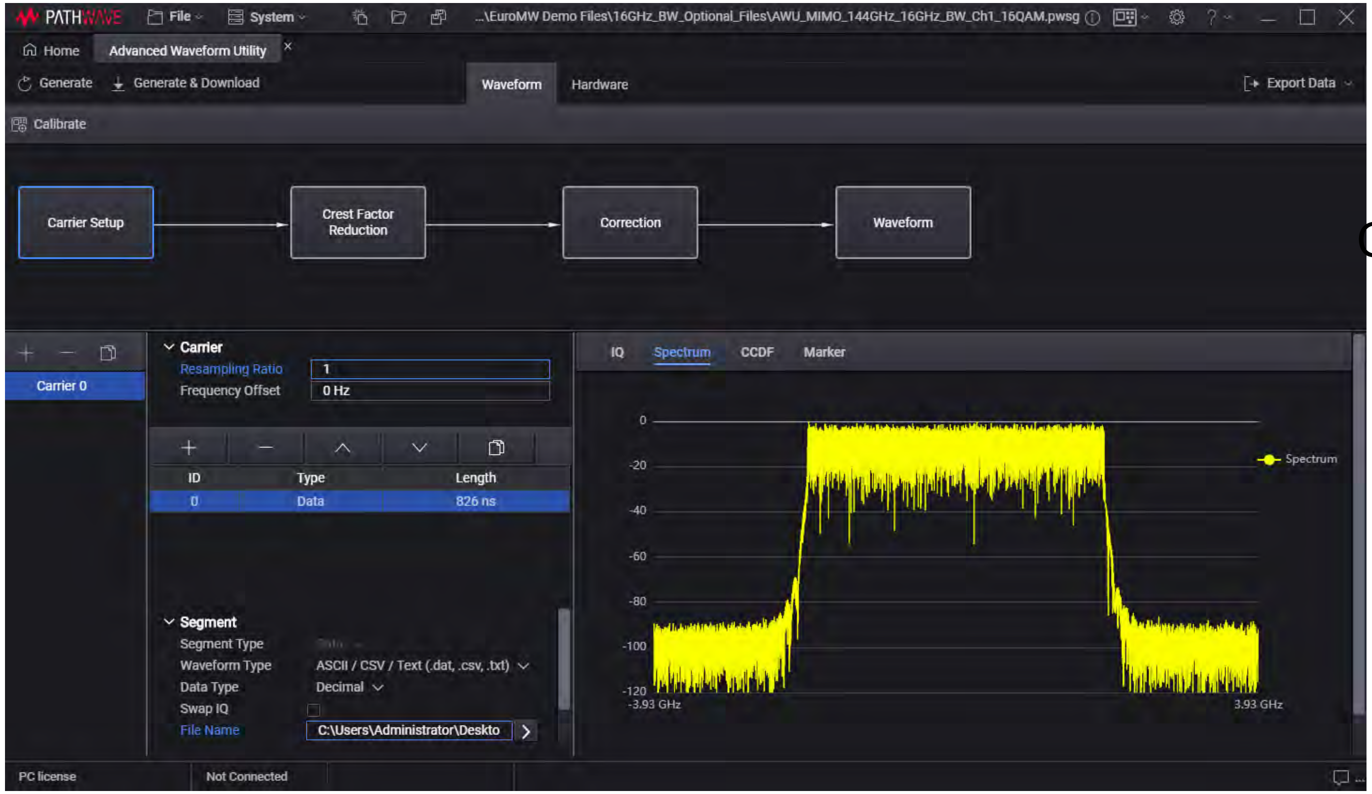
N7608C Signal Studio Pro for Custom Modulation, Custom OFDM



Simultaneous Sub-THz MIMO OTA Demo

Signal Generation Software

PathWave Signal Generation (PWSG) Advanced Waveform Utility (AWU)



M8199A 128 GSa/s AWG
65 GHz 3dB Bandwidth

Ch1- Ch4

11 or 16 GHz IF Before Upconversion

Simultaneous Sub-THz MIMO OTA Demo

Signal Generation Software, Optional Pre-Coding

Precoding matrix

$$\begin{bmatrix} 1 & 1 \\ j & -j \end{bmatrix}$$

1st waveform

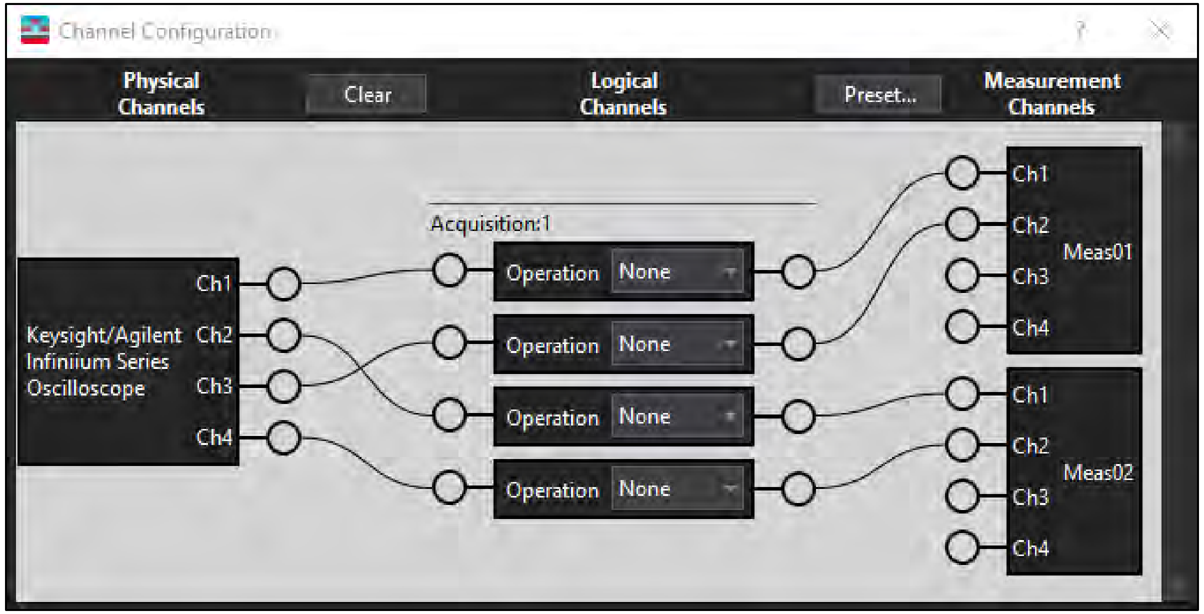
ID	Power	Phase	Timing Offset
0	0 dB	0 deg	0 s
1	0 dB	0 deg	0 s

2nd waveform

ID	Power	Phase	Timing Offset
0	0 dB	90 deg	0 s
1	0 dB	-90 deg	0 s

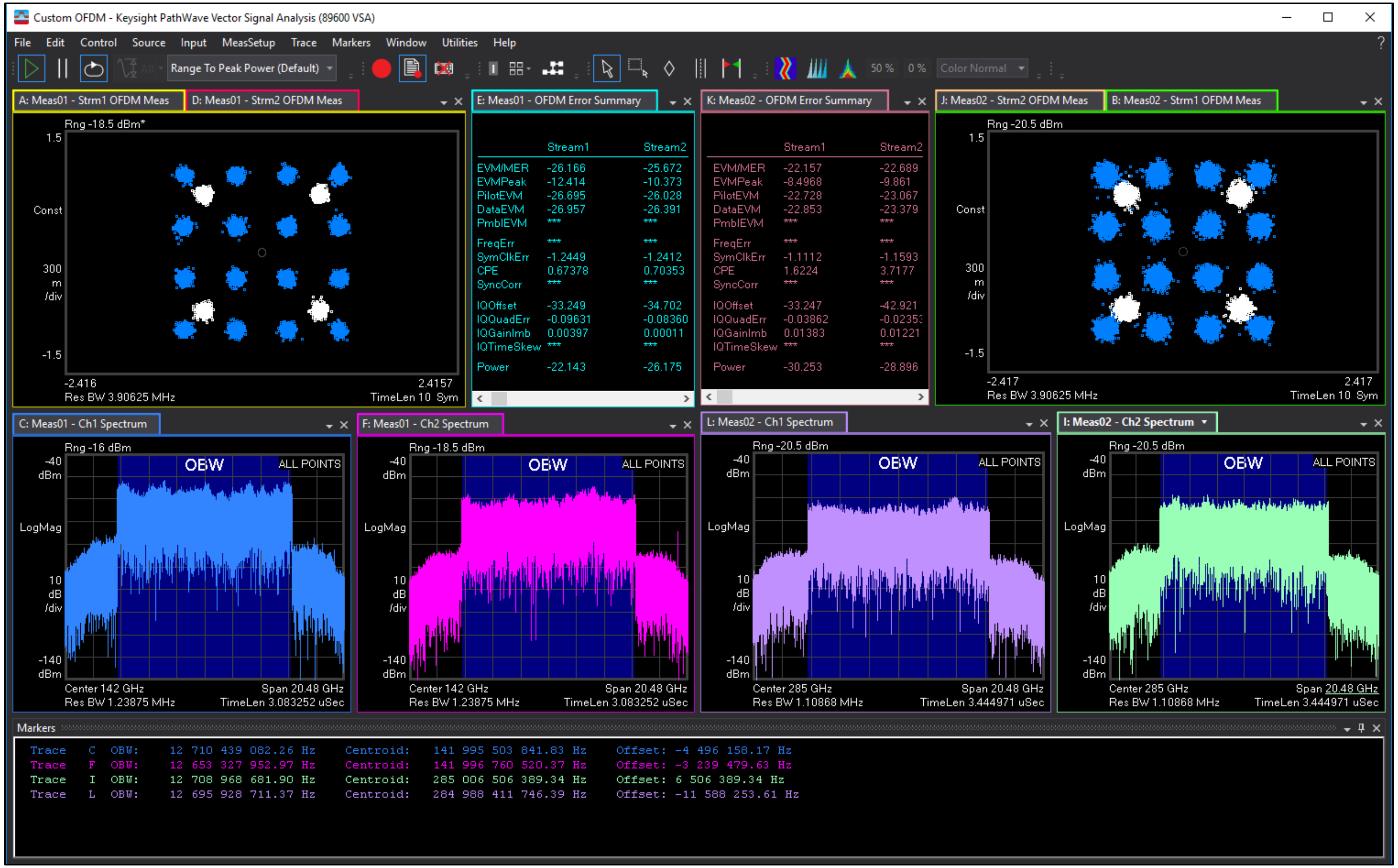
Simultaneous Sub-THz MIMO OTA Demo

VSA Measurement Channel Mapping for UXR Oscilloscope



Simultaneous Sub-THz MIMO OTA Demo

2X2 MIMO: 142 GHz and 285 GHz with 12.5 GHz Bandwidth



Note: Used two PSGs with Option UNY for LOs

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Simultaneous Sub-THz MIMO OTA Demo

2X2 MIMO: 142 GHz and 285 GHz with 12.5 GHz Bandwidth

Data Throughput Calculation:

- Used subcarriers in one OFDM symbol = 3276 (FFT size – lower/upper guard subcarriers)
- Bits per subcarrier = 4 (16QAM)
- Total data OFDM symbols = 2 (one OFDM symbol for DMRS)
- Total time length = 826 ns

Throughput = 3276*4 * 2/826 ns = 31.728 Gbps for 16QAM Considering this is 2-layer MIMO signal, the total throughput would be ~ 63.457 Gbps for 16QAM using V and H polarization with PN23 and PN15 data payloads

For Simultaneous D-Band AND H-Band the total data throughput across all four channels twice this **~ 126.915 Gbps for 16QAM**)

Outline

- Challenges of Achieving 100 Gbps
- Case Study: Extreme Bandwidths
- Case Study: MIMO
- **Additional Resources**

Whitepapers: Sub-THz Testbed for 6G Research

https://www.keysight.com/find/6G

WHITE PAPER

A New Sub-Terahertz Testbed for 6G Research

The first 5G networks are commercial and expanding. We are on the cusp of realizing the next generation of high-speed, high-reliability, and flexible mobile connectivity. This connectivity is driving advanced new consumer applications as the second generation of commercial 5G user equipment arrives on the market. It also opens up new possibilities in developing smart factories and smart cities and in meeting challenges in sectors as diverse as agriculture, public health, and global resource management.

The pace of innovation continues to accelerate. Even with 5G is its early stages of expansion, research has begun for 6G. Keysight has joined the multiparty 6G Flagship Program. As a founding member, Keysight will participate in groundbreaking 6G research that pushes the boundaries of high-speed, high-bandwidth communications. The vision for 6G includes concepts such as holographic communications and time-engineered systems that take the next step beyond the benefits of 5G — thus expanding into even more sectors that depend upon always-on connectivity.

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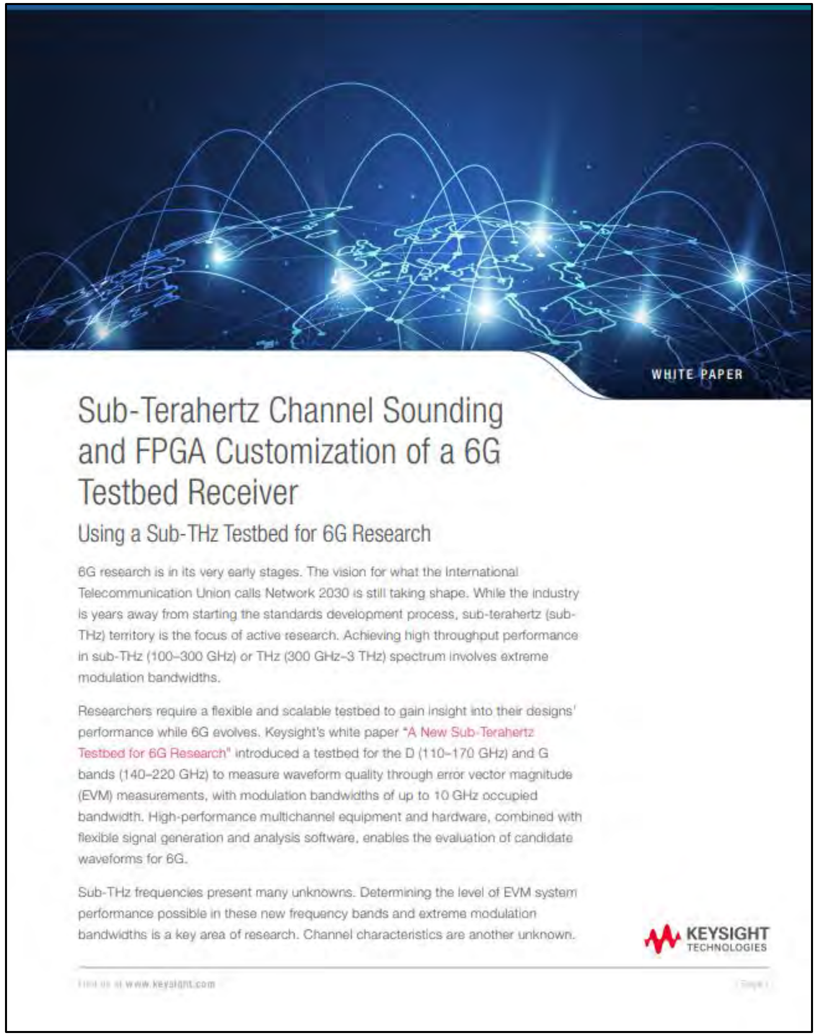

WHITE PAPER

Sub-Terahertz Channel Sounding and FPGA Customization of a 6G Testbed Receiver

Using a Sub-THz Testbed for 6G Research

6G research is in its very early stages. The vision for what the International Telecommunication Union calls Network 2030 is still taking shape. While the industry is years away from starting the standards development process, sub-terahertz (sub-THz) territory is the focus of active research. Achieving high throughput performance in sub-THz (100–300 GHz) or THz (300 GHz–3 THz) spectrum involves extreme modulation bandwidths.

Researchers require a flexible and scalable testbed to gain insight into their designs' performance while 6G evolves. Keysight's white paper "A New Sub-Terahertz Testbed for 6G Research" introduced a testbed for the D (110–170 GHz) and G bands (140–220 GHz) to measure waveform quality through error vector magnitude (EVM) measurements, with modulation bandwidths of up to 10 GHz occupied bandwidth. High-performance multichannel equipment and hardware, combined with flexible signal generation and analysis software, enables the evaluation of candidate waveforms for 6G.

Sub-THz frequencies present many unknowns. Determining the level of EVM system performance possible in these new frequency bands and extreme modulation bandwidths is a key area of research. Channel characteristics are another unknown.

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WHITE PAPER

6G: Going Beyond 100 Gbps to 1 Tbps

Exceeding 100 Gbps Data Throughput with a Sub-THz Testbed for 6G Research

6G research is in its very early stages. The vision for what the International Telecommunication Union calls Network 2030 continues to take shape. While the industry is years away from starting the standards development process, sub-terahertz (sub-THz) territory is a focus of active research.

Getting to 100 gigabits per second (Gbps) to 1 terabit per second (Tbps) data throughput is a key objective and an active area of research for 6G. This extreme data throughput could evolve into a Key Performance Indicator (KPI) for 6G. However, it poses significant challenges, both from an RF perspective and baseband perspective.

There are three fundamental approaches to increasing data throughput.

One approach involves using higher-order modulation schemes such as 64 QAM to increase the number of bits transmitted for each symbol. Given a fixed and finite spectrum bandwidth, increasing the modulation order from QPSK (transmitting two bits for each symbol) to 64 QAM (transmitting six bits for each symbol) would increase the data throughput by a factor of three, if channel conditions and radio performance allow. A 1 GHz QPSK symbol rate would result in a 2 Gbps theoretical raw calculated data throughput without forward error correction (FEC) coding rate redundancy. However, increasing the modulation order to 64 QAM would result in a 6 Gbps data throughput, while using the same spectrum occupied bandwidth.

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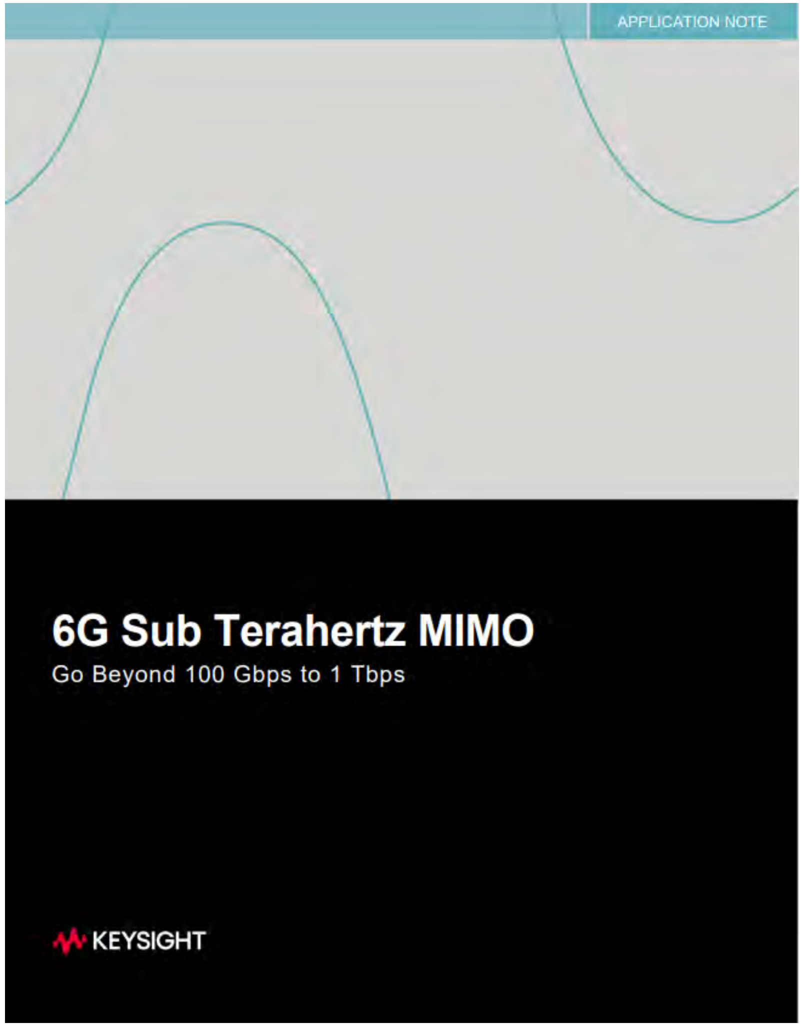
Latest Whitepaper: Early Insights into 220-330 GHz

https://www.keysight.com/zz/en/assets/7122-1129/white-papers/Early-Insights-into-the-220-to-330-GHz-Sub-terahertz-Band.pdf

Latest Application Note: 6G Sub Terahertz MIMO



https://www.keysight.com/us/en/assets/3124-1532/application-notes/6G-Sub-Terahertz-MIMO.pdf

Thank You!

KEYSIGHT

AI: Necessary Enabler for 6G

Jaydeep Ranade
Head of New AI/ML Products
February 2025

The Basics….
"AI/ML" 🙄 : What does this mean?

Getting The Definitions Right

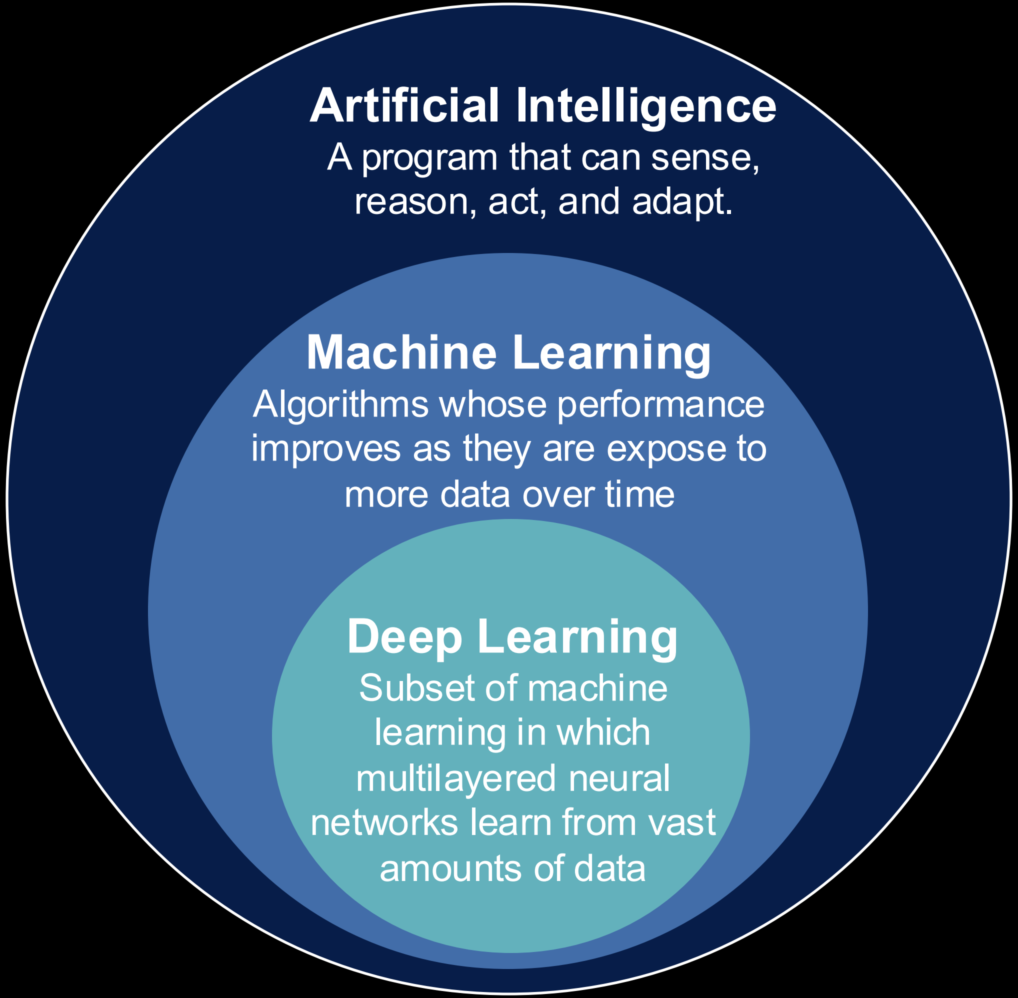
Artificial Intelligence

Goal: perform wide range of complex tasks requiring human intelligence

Broader application range: robotics, NLP, CV, etc.

Superset of ML: Includes rule-based, symbolic, expert systems, etc.

Designed to learn and adapt but <u>not all AI requires learning</u> capabilities



Machine Learning

Subset of AI: Uses data and algorithms to train models without explicit programming

Models analyze volumes of data, identify patterns and make predictions or decisions

Learns from data and experience; improves performance over time

Useful for pattern recognition, prediction, and data analysis

The Contours of AI/ML Solutions

- Supervised Learning
- Unsupervised Learning
- Reinforcement Learning
- Deep Learning
- Transfer Learning
- Federated Learning

- Prediction
- Classification
- Anomaly detection
- Pattern/Object Recognition
- Natural Language Processing
- Recommender System
- Generative AI

- CNN (Convolutional Neural Network)
- Transformers
- Auto-encoders
- GAN (Generative Adversarial Network)
- Diffusion

Recent History: Moving Very Fast

2000's:

Spelling Correction
Search Optimization
Mapping & Waze
Language Translation

2010's

SIRI, Alexa, Watson, AlphaGo et al.

TensorFlow, Transformers, PyTorch

ITU: 6G Will have Native AI

2020's

ChatGPT, Claude, Copilot, Llama, Gemini

Compute Hardware Innovation

3GPP Rel-18 & Rel-19 AI in air interface

EU AI Act, US- AISIC, etc.

Position for 6G:

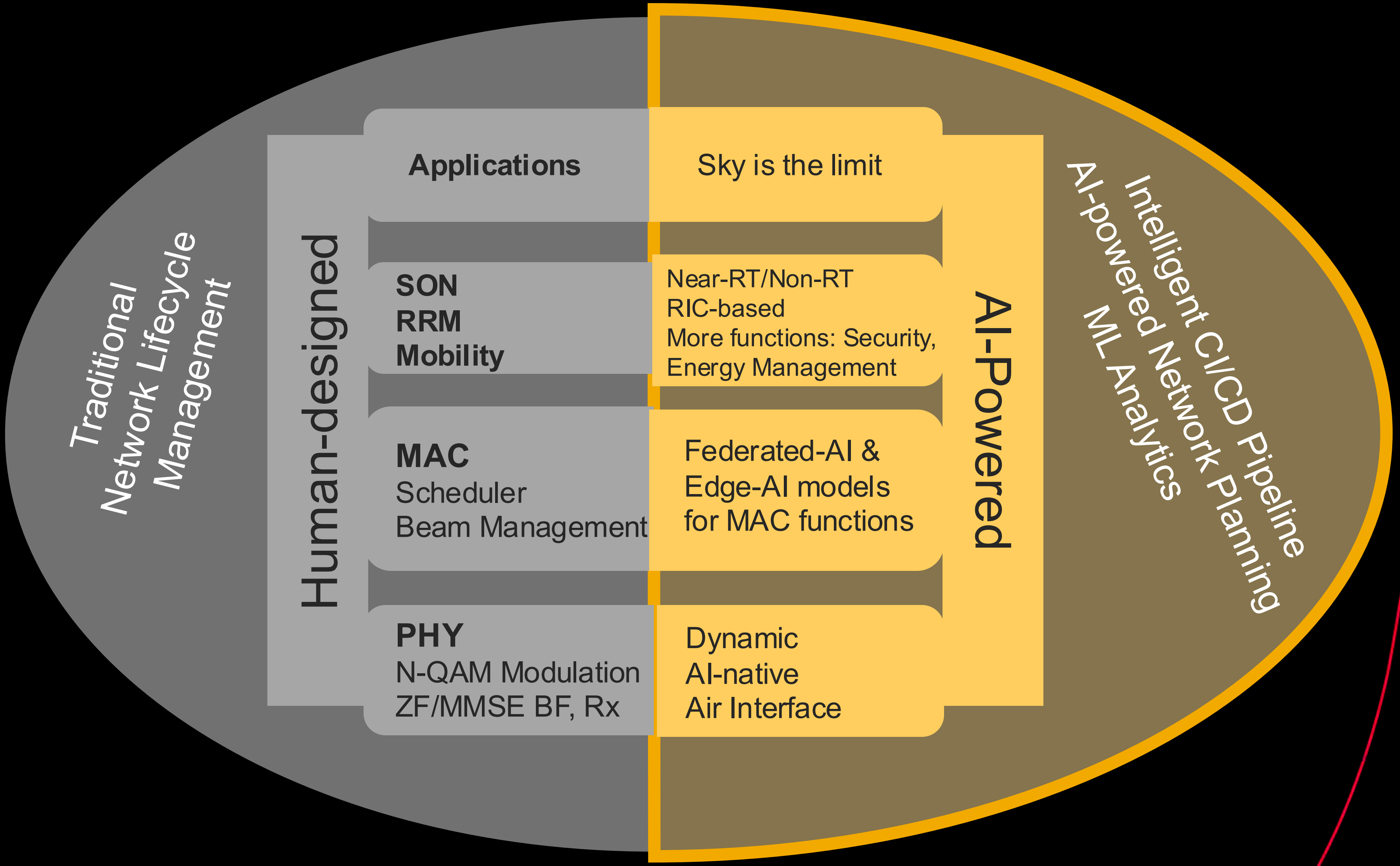
LLM & Chatbot Driving Massive Technology Investment

Technical Wireless Applications Will Benefit

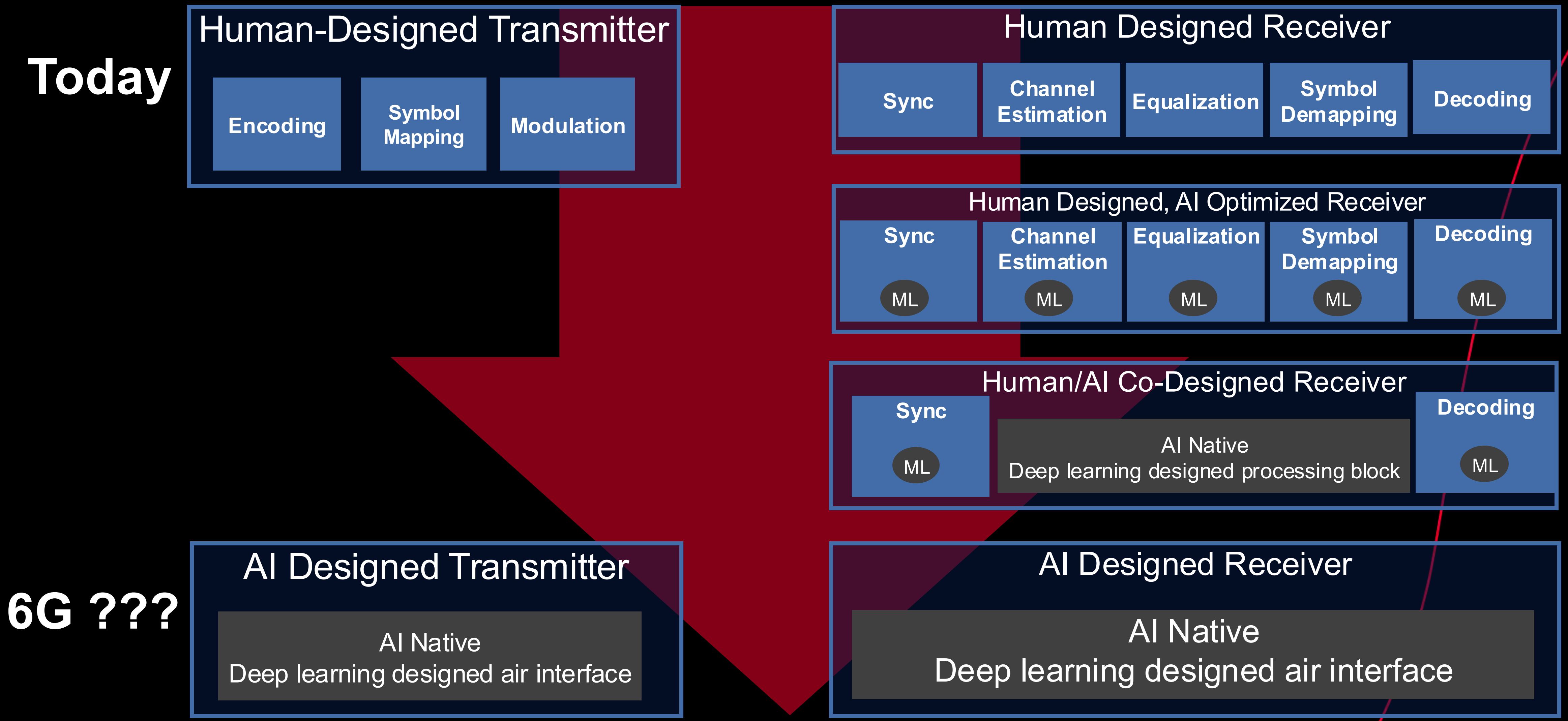
Policy-Makers are Waking Up

Standards Are In The Works

Paradigm Shift in Wireless Communication



AI in the Air Interface



AI as A Necessity in 6G?

Complexity Overwhelming Analytic Models

Growing Variety and Demand of Applications

New Radio Bands Mean New Radio Channels

Emphasis on Open Systems

Opportunities and Necessity to Improve Efficiency

Increasing Demand on Reliability and Resilience

Increasing Demand on Security

AI In Wireless: Many Opportunities, Many Challenges

RAN Performance
- Energy efficiency
- Mobility & handover
- Application latency/jitter
- Scheduling
- Beam Management
- Massive MIMO

Core NW Performance
- Traffic Routing
- Timing & Latency Provisioning
- Dynamic Slicing
- Resilience
- Capacity Management

Security
- Data Poisoning
- Rogue Element Detection
- Threat Pattern Analysis

FCAPS/ Analysis
- Root Cause Analysis
- Troubleshooting
- Anomaly detection
- Predictive Maintenance & Upgrades

The Great Technology, Economic, Energy, Standards, and Policy Filter:

Does the AI Model Accomplish the Right Combination of:

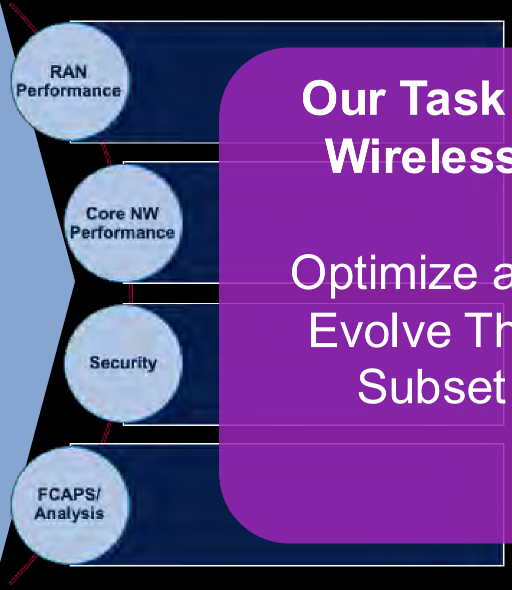
Yielding Better Results

Costing Less

Using Less Energy

Abiding by Standards

Abiding by Policy



Our Task in Wireless:

Optimize and Evolve This Subset

Developing & Deploying AI in Wireless

Challenges Being Addressed Today

1 Insufficient Training Data

Adequate, Unbiased, Secure

2 Inter-Vendor Cooperation

Data & Models: Open vs. Proprietary

3 Testing & Validation

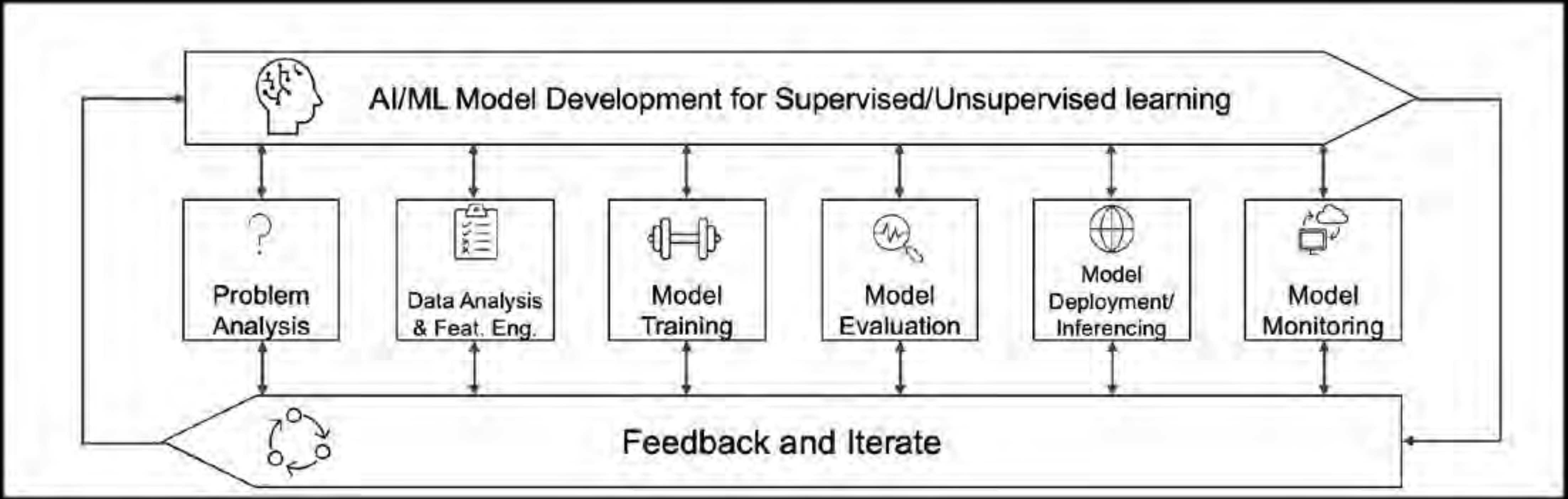
Nascent Methods, Rapid Evolution

4 Model Generalization

Nothing is "Guaranteed by Design"

New Paradigms in Development & Testing

Test Methodology for AI/ML Solutions



Problem Analysis
- Specify Metrics
- Evaluate feasibility

Data
- Bias
- Coverage
- Outliers
- Multi-Colinearity

Feature Engineering
- Importance
- Explainability

Model Training
- Generalization
- Hyperparameter optimization
- Fairness & Interpretability

Model Evaluation
- Stability
- Sensitivity
- Robustness to adversarial
- Robustness to outlier data
- Explainability
- Confidence

What Is Keysight Doing?
And how we want to continue this work

Keysight AI/ML

Approach:

Keysight is a market leader in the AI ecosystem; providing design, emulation, and test tools that enable faster and efficient deployment of our customers' AI infrastructure and services

Standards, Collaborations, Innovation:

3GPP

NextG Alliance

O-RAN ALLIANCE

FCC TAC

AI-RAN Alliance

University Collaborations

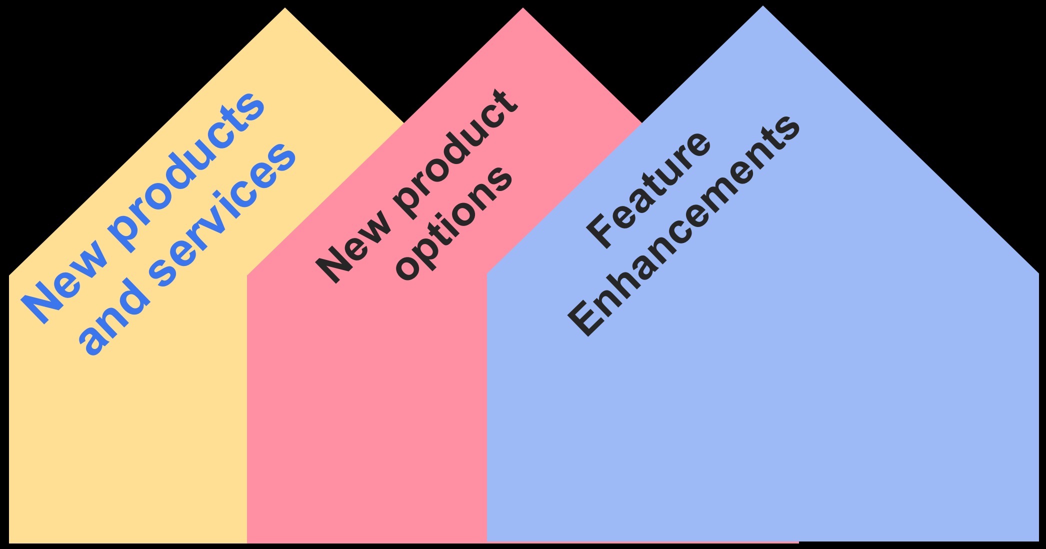
Commercial Collaborations

Enabling Industry's AI Infra buildout

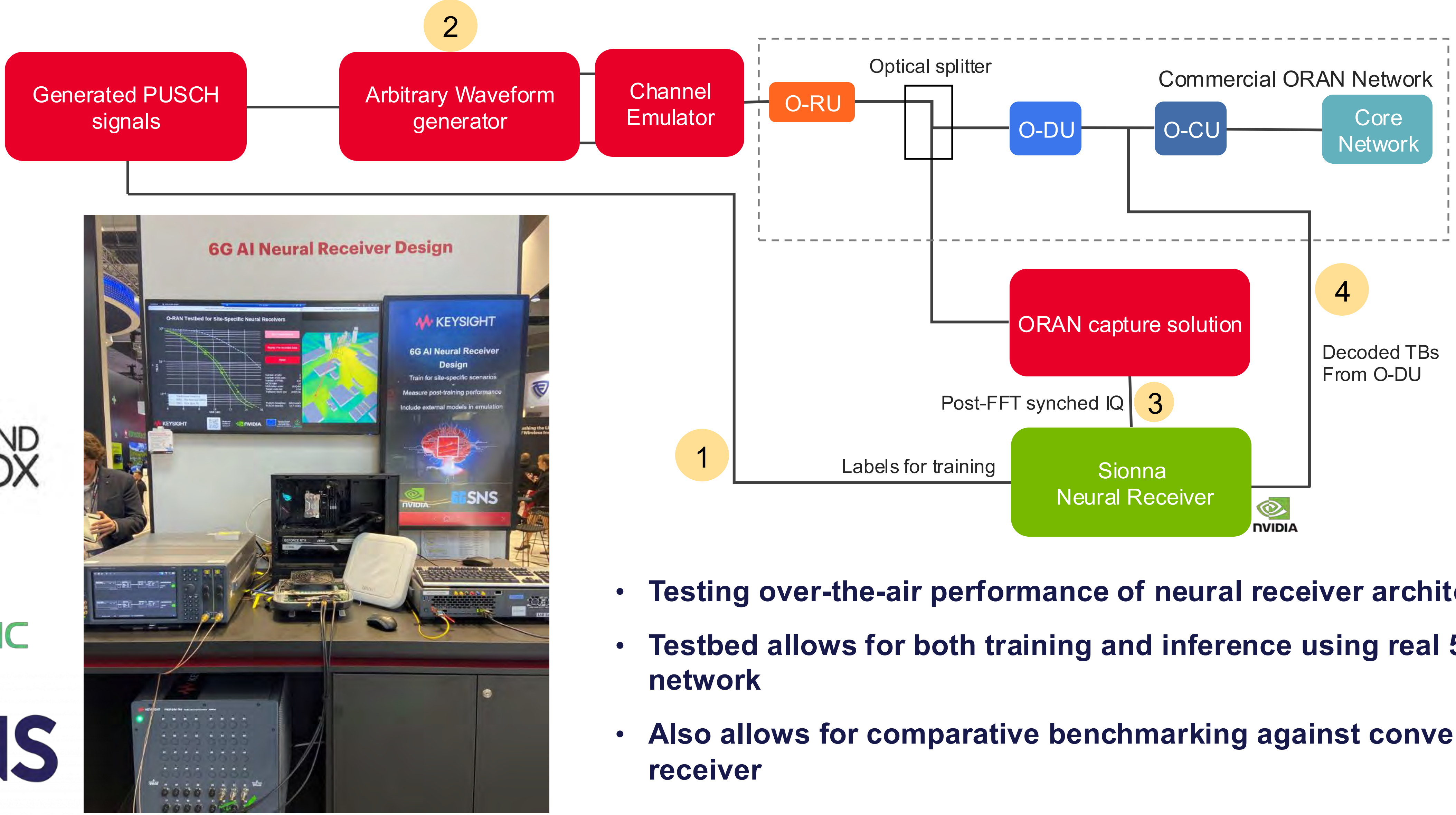
Market-leading solutions for the digital infrastructure marketplace (computer, power, network, memory)

Enhancing Industry's Productivity

Achieve breakthrough impacts by making products intelligent, efficient, and intuitive



Practical testing of AI air interface

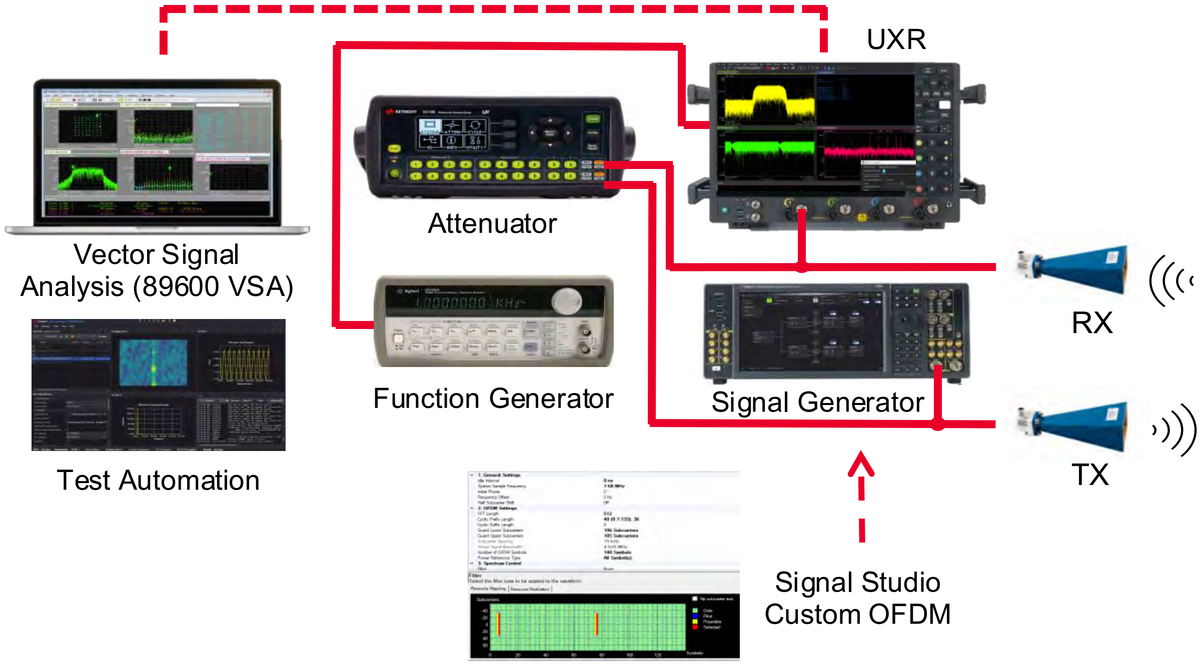


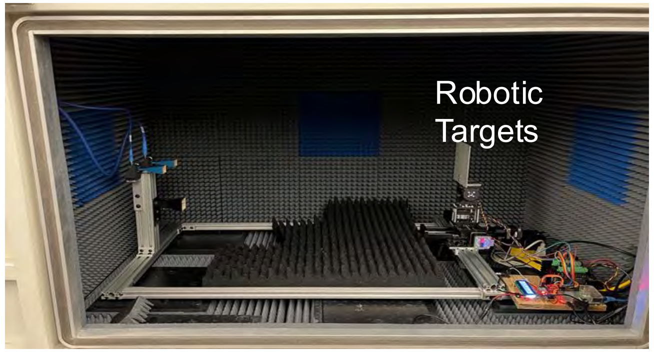
CENTRIC

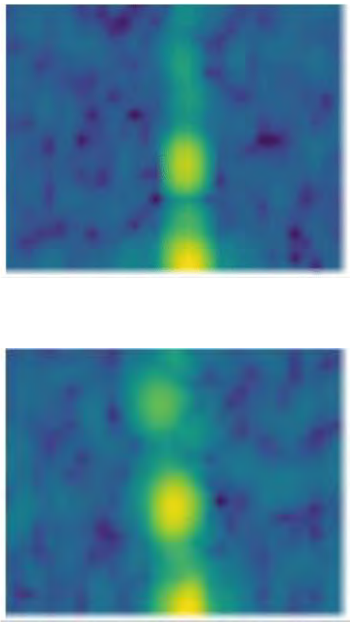
6GSNS

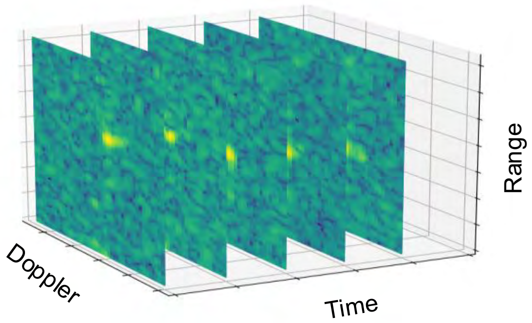
- **Testing over-the-air performance of neural receiver architecture**
- **Testbed allows for both training and inference using real 5G network**
- **Also allows for comparative benchmarking against conventional receiver**

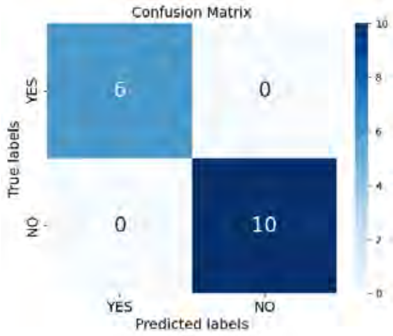
Use Case – Gesture Recognition using Sensing + ML



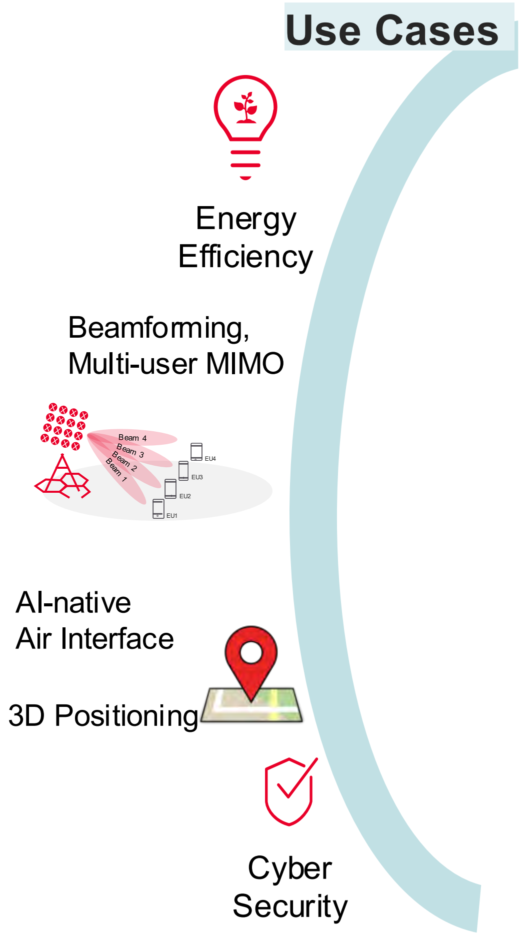




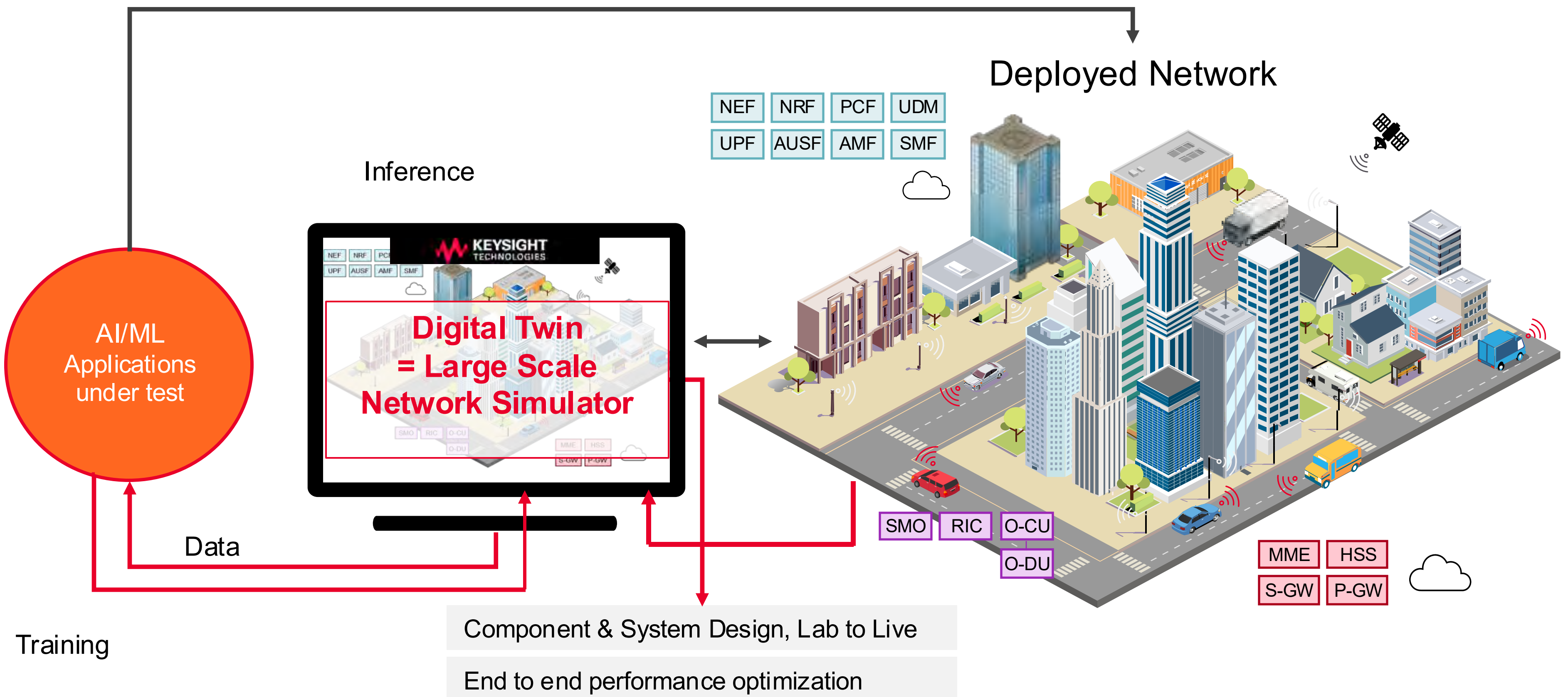




Role of Digital Twin for AI in 6G Networks



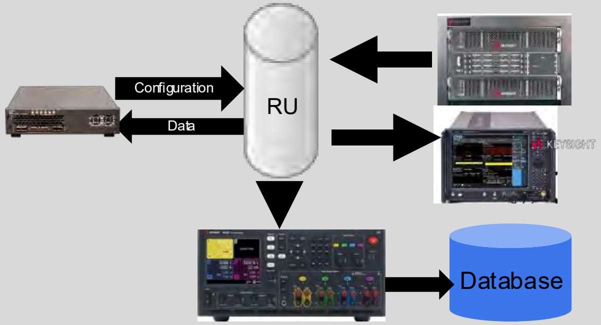
Integrated modeling of network, environment and users at scale
Enables validation of AI/ML solutions to complex RAN optimization problems



- Component & System Design, Lab to Live
- End to end performance optimization
- Smart Cities, Private Networks, Industrial IoT
- Emerging applications: Metaverse XR …
- Synthetic Data Generation

Keysight's Vision for ML-based Digital Twin Modeling

Characterization of Real-World Module



ML-based Model Generation

Digital Twin

KEYSIGHT

Performance Analysis

Examples of behavior modeling

- PHY behavior
- Application behavior
- Networking behavior
- Timing behavior
- Energy consumption behavior

Thank you

Backup

Standardization is Required: 3GPP Status

RAN1 Rel-19 Study & Rel-20 Work Items

Optimization Targets	Inputs	Outputs	Models Used
Beam Management	L1 RSRP of set B + and beam information	Predictions of all beams	CNN, DNN, Fully Connected, U-NET
Positioning Accuracy	CIR	TOA	CNN
CSI Optimization	SVD of sub-band/Channel Normalization	Precoding Vector per SB	Transformer, EVCSInet, CNN

3GPP RAN4 Major topics

Interoperability and testability for NR air interface

- How will different companies incorporate Test Equipment Vendors (TEV's), and model obfuscation?

General aspects for NR air interface

- Data Collection for training and inference, how to do it?
- What are performance testing goals?
- What are KPIs for the RAN1 deliverables, which are specific (i.e. NOT generic)

Edge inference and compute capability now enable continual learning frameworks. Testing AI in the loop will become more paramount.

Mastering this is critical for the next generation of ML enabled networks.

Continual Training and Inference Model