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The Expanding World of Wireless Delivery: New Spectrum and Evolving Delivery Approaches

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Outline

- **The state of wireless traffic delivery**
- **The next great frontier for wireless traffic delivery**
- **New results for new 5G/6G mid-band spectrum (7-24 GHz)**
- **Energy Efficiency and Waste Factor: a unifying FoM is needed**
- **Conclusion**

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The Evolution of Wireless Internet Delivery

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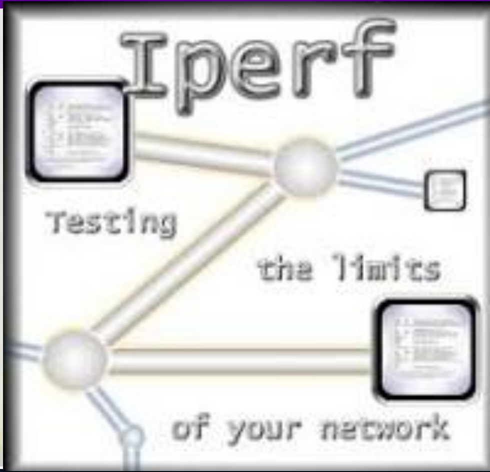

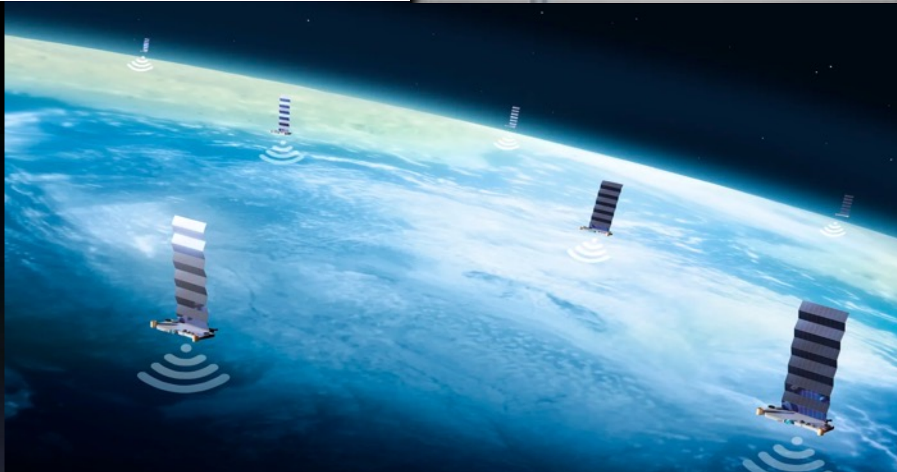

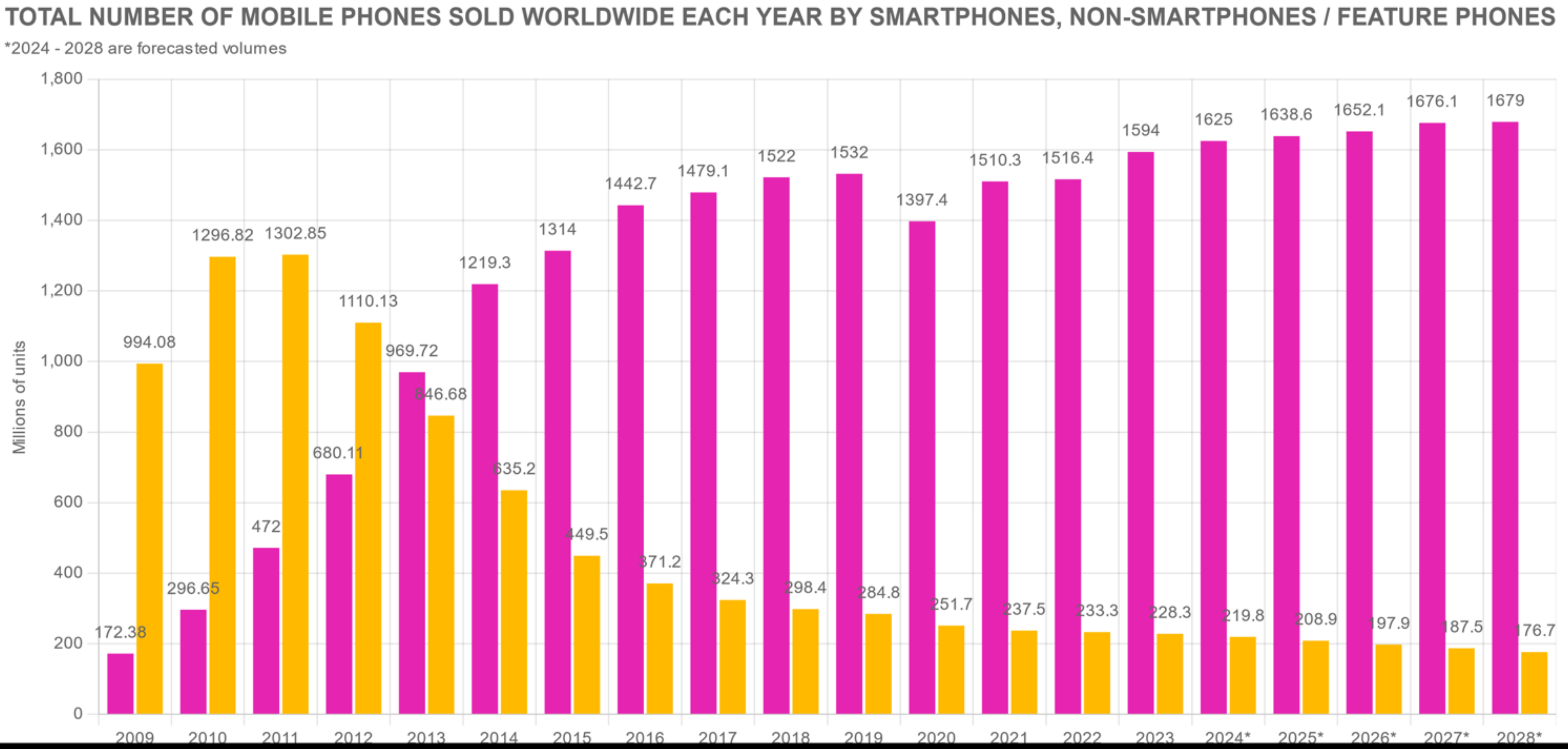
TOTAL NUMBER OF MOBILE PHONES SOLD WORLDWIDE EACH YEAR BY SMARTPHONES, NON-SMARTPHONES / FEATURE PHONES
*2024 - 2028 are forecasted volumes
Millions of units
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1,600
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1,200
1,000
800
600
400
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994.08
296.65
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Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!

THEODORE S. RAPPAPORT[1], SHU SUN[1], RIMMA MAYZUS[1], HANG ZHAO[1], YANIV AZAR[1], KEVIN WANG[1], GEORGE N. WONG[1], JOCELYN K. SCHULZ[1], MATHEW SAMIMI[1], AND FELIX GUTIERREZ[1]

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This work was supported by Samsung DMC R&D Communications Research Team and Samsung Telecommunications America, LLC.

ABSTRACT The global bandwidth shortage facing wireless carriers has motivated the exploration of the underutilized millimeter wave (mm-wave) frequency spectrum for future broadband cellular communication networks. There is, however, little knowledge about cellular mm-wave propagation in densely populated indoor and outdoor environments. Obtaining this information is vital for the design and operation of future fifth generation cellular networks that use the mm-wave spectrum. In this paper, we present the motivation for new mm-wave cellular systems, methodology, and hardware for measurements and offer a variety of

Mmwave 5G Market Soars With Worldwide Network Rollout

The global rollout of 5G networks is expected to propel the growth of the mmWave 5G market going forward. The rollout of 5G networks refers to the deployment and implementation of fifth-generation (5G) technology standards for cellular networks on a global scale. mmWave technology is used for global 5G deployment due to its ability to deliver high data rates, low latency, and high capacity. For instance, in April 2023, according to the report by 5G Americas, a US-based industry trade organization, Between the end of 2021 and the end of 2022, the number of 5G wireless connections worldwide climbed by 76%, to a maximum of 1.05 billion. From 922 million in Q3 2022 to 1.05 billion in Q4 2022, the numbers show a sequential quarterly gain of 14%. Therefore, the global rollout of 5G networks is driving the growth of the mmWave 5G market.

Major companies operating in the mmWave 5G market report are **Samsung Electronics Co Ltd., Verizon Communications Inc., AT&T Inc., Huawei Technologies Co Ltd., Intel Corporation, Qualcomm Incorporated, NEC Corporation, Nokia Corporation, Telefonaktiebolaget LM Ericsson, ZTE Corporation, NXP Semiconductors N.V., Analog Devices Inc., Microchip Technology Inc., Skyworks Solutions Inc., Keysight Technologies Inc., Qorvo Inc., Rohde & Schwarz GmbH & Co KG, Viavi Solutions Inc., Xilinx Inc., MACOM Technology Solutions Holdings Inc., ADVA Optical Networking SE, Ceragon Networks Ltd., Casa Systems Inc., Inseego Corp, Airspan Networks Holdings Inc., Anokiwave Inc., Akoustis Technologies Inc., Movandi Corporation, Cohere Technologies Inc., E-Band Communications LLC**

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WIRELESS

UScellular CTO says FWA offering is 'wildly successful'

By Sue Marek · May 9, 2023 3:55pm

us cellular | fixed wireless access | network sharing

Millimeter wave FWA gains gro ×

https://rethinkresearch.biz/articles/millimeter-wave-fwa-gains-ground-as-verizon-unveils-new-device/

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11 October 2022

Millimeter wave FWA gains ground as Verizon unveils new device

By Phil Hunter

Slowly but surely millimeter wave is making its way into fixed wireless access (FWA) services in certain regions, driven by advances in both transmission and CPE technology, making this option cost-effective for operators in a growing range of deployment scenarios. Among recent developments was launch of Verizon's latest 5G FWA CPE at Mobile World Congress Las Vegas, spanning mmWave, midrange and 4G, designed for operators to combine different connectivity options cost effectively for a

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12 February 2024
5G RedCap to dominate cellular IoT growth, but when does the door shut for LTE and Unlicensed?

Non-standalone and Standalo × | AT&T Internet Air Wireless Ho ×

https://www.att.com/internet/internet-air/

Delivered over the reliable AT&T 5G network

Internet Air gives you the connection you need.

Non-standalone and Standalo × | AT&T Rolls Out 5G+ Across th ×

https://about.att.com/pages/5g-plus.html

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AT&T rolls out 5G+ across the U.S.

UScellular, in Collaboration with Qualcomm and Inseego, Launches 5G mmWave High-Speed Internet Service in 10 Cities

- **UScellular's Home Internet+ service uses 5G mmWave technology to provide high-speed internet to homes and businesses.**
- **Companies plan to expand service to dozens of more cities throughout 2022.**

CHICAGO (April 28, 2022) – UScellular, in collaboration with Qualcomm Technologies, Inc. and Inseego, has launched its 5G mmWave high-speed internet service in parts of 10 cities. The carrier's Home Internet+ solution delivers speeds of up to 300 Mbps, an increase of 10-15 times compared to its 4G LTE home internet offering, and is a significant milestone in its multi-technology approach to providing High-Speed Internet solutions.

UScellular's Home Internet+ is delivered by the Inseego Wavemaker™ FW2010 outdoor 5G CPE, powered by the Qualcomm® 5G Fixed Wireless Access Platform Gen 1 featuring Snapdragon® X55 5G Modem-RF System, and provides high-speed internet access wirelessly to customers' homes or businesses. This Fixed Wireless Access (FWA) service is available now in parts of East Moline and Rock Island, Ill.; Bettendorf, Cedar Falls, Davenport, Dubuque and Waterloo, Iowa; Yakima, Wash.; and Beloit and Janesville, Wis.

Throughout 2022, UScellular plans to increase its Home Internet+ service within those cities and expand to dozens more in both urban and rural areas, including Springfield and Tipton, Mo., Knoxville, Tenn., and Kenosha and Milwaukee, Wis. Interested residents can go to www.uscellular.com/home-internet-5G and enter their address to determine their eligibility and sign up for future updates.

Contact UScellular
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UScellular touts 100,000 FWA customers

UScellular said it now counts 100,000 fixed wireless access (FWA) customers, and hinted at plans to expand the service with more spectrum and installation options. #pressrelease

August 1, 2023 | 2 Min Read

CHICAGO – UScellular has officially surpassed 100,000 Home Internet customers and is planning for additional growth over the coming years.

The advancement of fixed wireless technology has helped enable the growth of UScellular's Home Internet product and its ability to provide the speed and reliability that a typical household needs. With fixed wireless, a home or business connects wirelessly to a nearby cell tower, providing a high-speed broadband connection via a wireless signal, as opposed to the wired connection provided by fiber or cable. In 2022, fixed wireless services accounted for 90% of home broadband net additions, according to Leichtman Research Group.

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Millimeter Waves Travel More Than 10 Kilometers in Rural Virginia 5G Experiment

› Previous experiments have focused on cities, because millimeter waves were thought to be of limited use to rural residents

BY AMY NORDRUM | 07 NOV 2016 | 5 MIN READ

FWA to remain 'biggest disruptor' through 2024

Wells Fargo predicts fixed wireless access (FWA) services will gobble up 80-90% of industrywide net broadband subscriber additions through 2024, growing to 12-13% of the market by 2025.

Mike Dano

June 29, 2023

5 Min Read

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BROADBAND

NTIA's BABA waiver for BEAD gets industry approval

Fixed wireless access outlook

Over 330 million FWA connections expected by 2029

#MobilityReport #Core #RAN

Available in English Português

Key findings

- The number of service providers offering Fixed Wireless Access (FWA) over 5G is growing in all regions.
- Over half of the global FWA growth during the last 12 months came from launches in emerging markets.
- FWA over 5G is offered by 121 service providers globally, representing half of total FWA service providers.

Figure 20: Regional FWA service provider adoption 2023

% of Mobile Service Providers Offering FWA to consumers

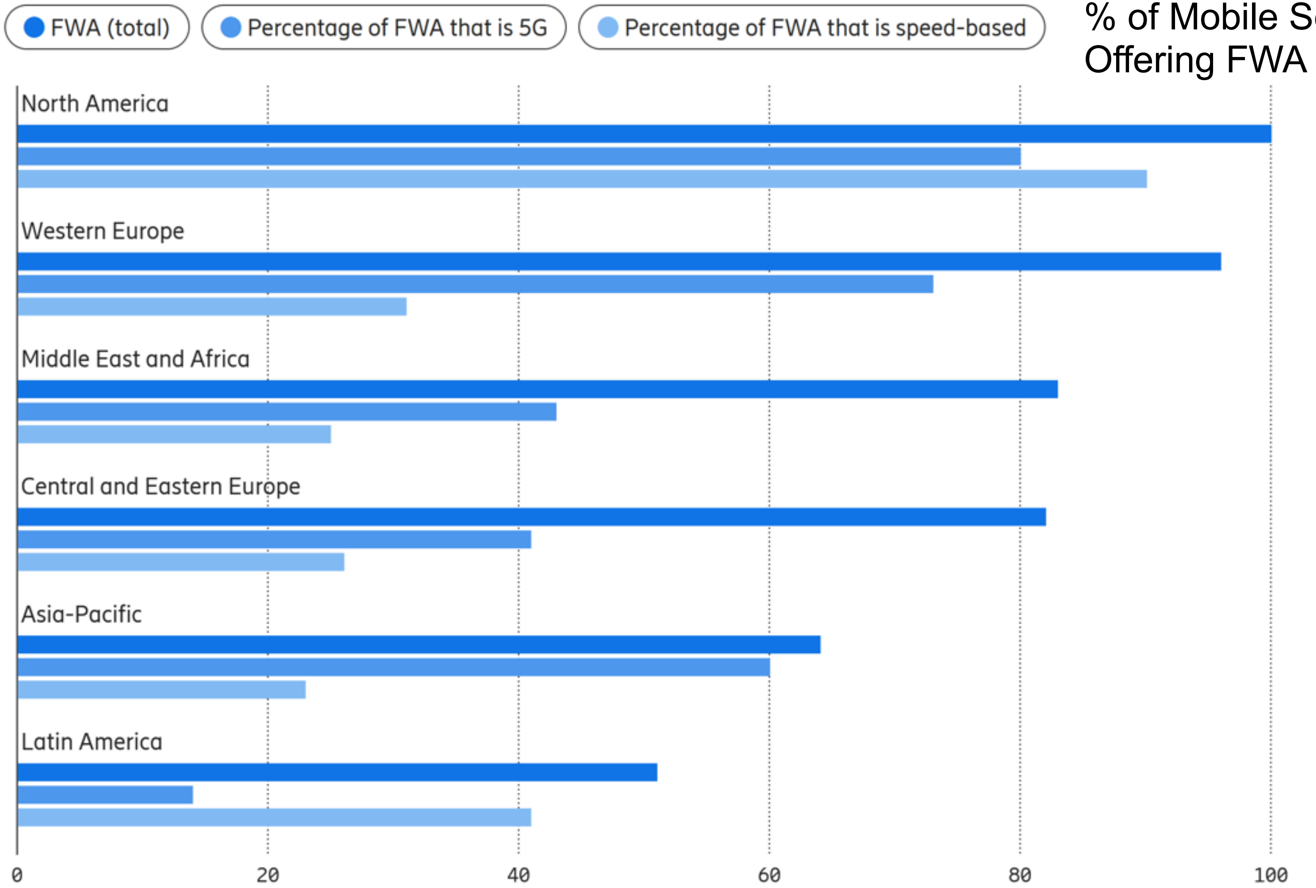
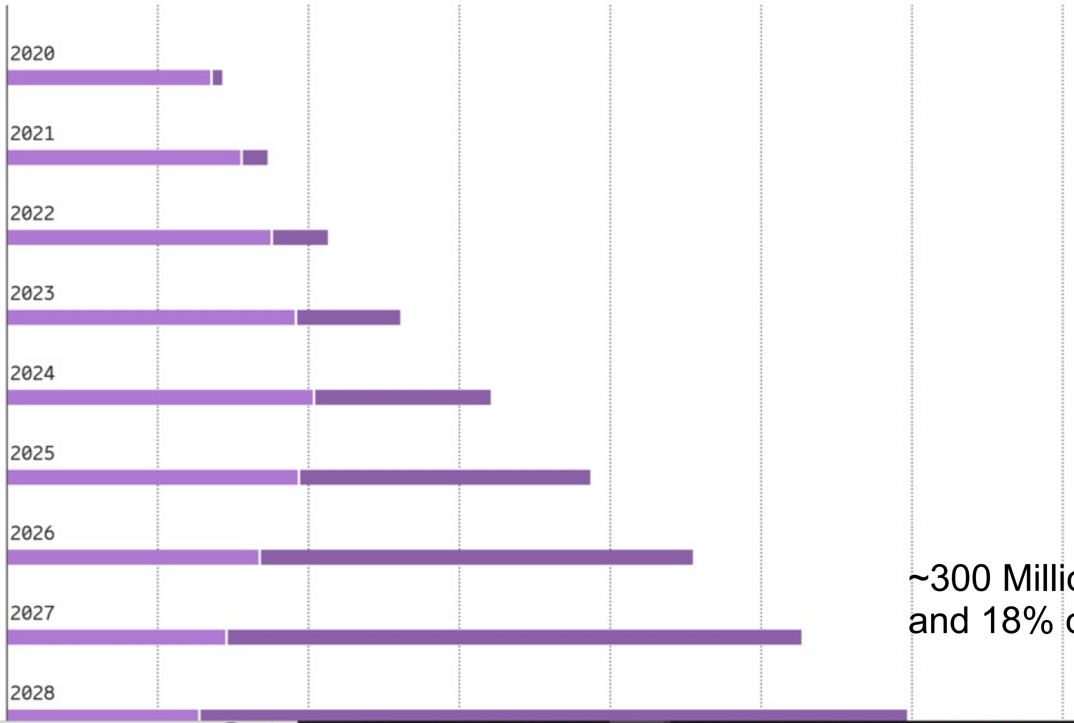


Figure 21: FWA connections

4G and other technology FWA connections | 5G FWA connections



Definition of FWA

FWA is a connection that provides primary broadband access through mobile network-enabled CPE. This includes various form factors of CPE, such as indoor (desktop and window) and outdoor (rooftop and wall-mounted). It does not include portable battery-based Wi-Fi routers or dongles.

~300 Million broadband connections by 2028 and 18% of global fixed connections by 2029

The Satellite Internet Goldrush (?)

- Massive satellite launches are now happening

- Big bets continue to try and defy the laws of physics

- I am skeptical, it has never worked in the past!
- …….. here’s why

The Satellite Internet Goldrush (?)

- SpaceX's Starlink has 5,000 satellites deployed, goal of up to 42,000
- FCC limited them to 7,500 over worries of space debris, interference
- Starlink uses the 10 – 14 GHz band for DL and UL: 25-200/5-20 Mbps
- SpaceX and Rocket Lab's Electron liquid fuel orbiters are rapid, reusable

- But law of physics does not support spectrum reuse from space:
  - Large coverage area from antennas in space prohibit spectrum reuse
  - Latency on 340 mile one-way path is 18 ms; not competitive in the future
  - Heavy rains in troposphere will degrade throughput to users, gateways
  - History has shown satellites can never compete with terrestrial

The Evolution of Wireless Internet Delivery

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Iridium, Officially Bankrupt, End ×

https://www.nytimes.com/2000/03/20/business/iridium-officially-bankrupt-ends-services.html

BUSINESS — The New York Times

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Business

British satellite firm OneWeb emerges from bankruptcy

Reuters

November 20, 2020 4:56 PM EST · Updated 3 years ago

(Reuters) - Satellite operator OneWeb said on Friday it has emerged from Chapter 11 bankruptcy protection with $1 billion (752.67 million pounds) in equity investment from a consortium of the UK Government and India's Bharti Enterprises, the new owners of the UK-based company.

The investment puts OneWeb on track to compete with Elon Musk's SpaceX in the race to use low-Earth orbit satellites to provide high-bandwidth and low-latency communication services.

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The birth and demise of an idea: Te ×

https://archive.seattletimes.com/archive/?date=20021007&slug=teledesic070

The birth and demise of an idea: Teledesic's 'Internet in the sky'

Oct 7, 2002

By Sharon Pian Chan
Seattle Times technology reporter

This is how a plan to take over the world ended with a whimper.

Last week, Teledesic laid off all but 10 employees and suspended its satellite contract.

With that, the Bellevue company started by Craig McCaw and Bill Gates deep-sixed its plans to build a global broadband satellite network.

Teledesic blames the collapse of the telecommunications industry.

"We think there's still demand in the market for these services," said Todd Wolfenbarger, spokesman for Teledesic. "But absent of some other partner, it's not going to happen."

But while the state of telecom delivered the fatal blow, observers say the satellite industry was on its last legs anyway and the delays and

https://www.nytimes.com/2003/01/16/business/globalstar-bankrupt-satellite-company-to-be-sold-for-55-mil

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Globalstar, Bankrupt Satellite Company, to Be Sold for $55 Million

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By Barnaby J. Feder

Jan. 16, 2003

Globalstar, the bankrupt satellite phone company, agreed yesterday to sell control of itself to an investment firm run by

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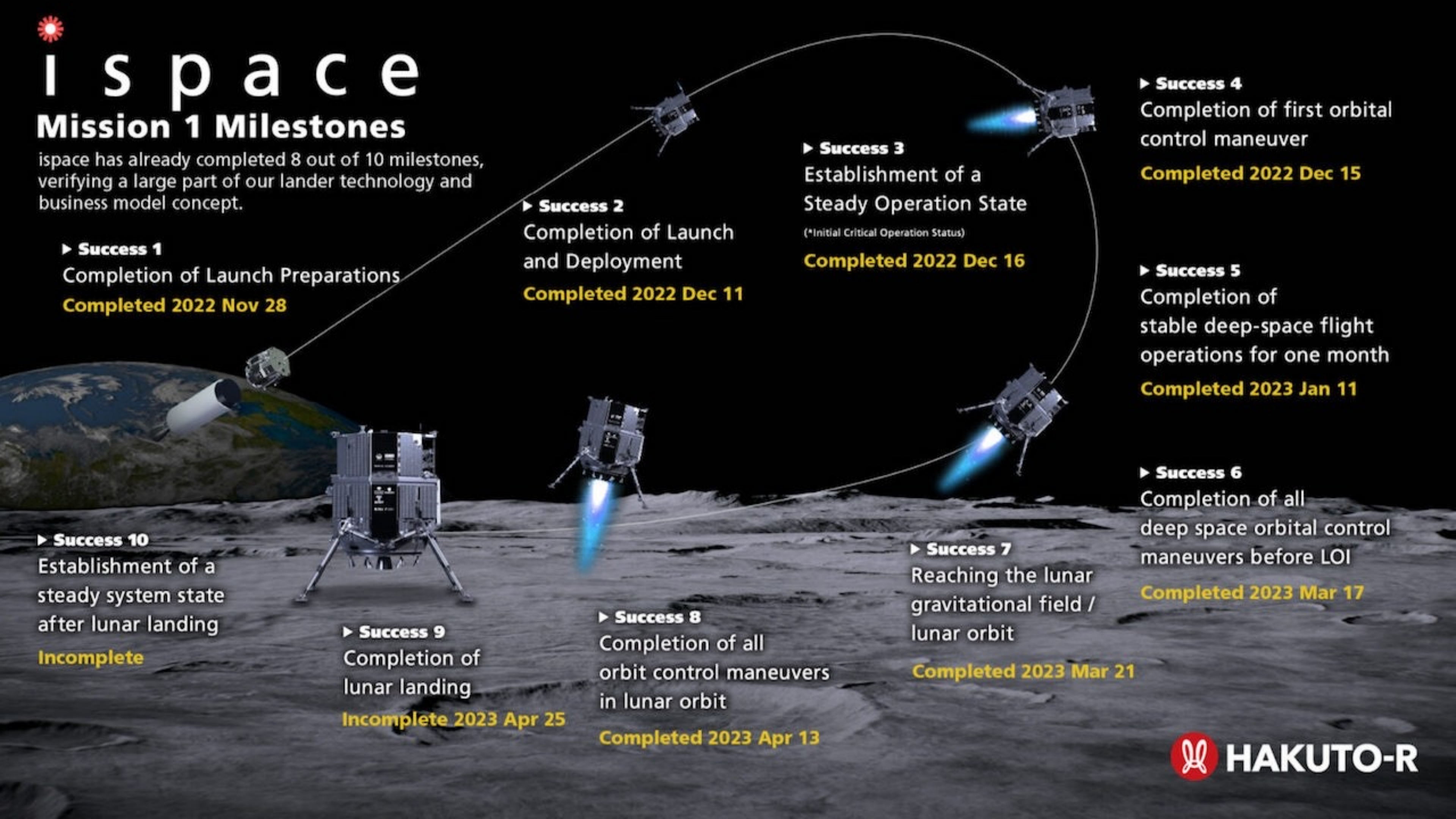
ispace
Mission 1 Milestones
ispace has already completed 8 out of 10 milestones, verifying a large part of our lander technology and business model concept.
▶ Success 1
Completion of Launch Preparations
Completed 2022 Nov 28
▶ Success 2
Completion of Launch and Deployment
Completed 2022 Dec 11
▶ Success 3
Establishment of a Steady Operation State
(*Initial Critical Operation Status)
Completed 2022 Dec 16
▶ Success 4
Completion of first orbital control maneuver
Completed 2022 Dec 15
▶ Success 5
Completion of stable deep-space flight operations for one month
Completed 2023 Jan 11
▶ Success 6
Completion of all deep space orbital control maneuvers before LOI
Completed 2023 Mar 17
▶ Success 7
Reaching the lunar gravitational field / lunar orbit
Completed 2023 Mar 21
▶ Success 8
Completion of all orbit control maneuvers in lunar orbit
Completed 2023 Apr 13
▶ Success 9
Completion of lunar landing
Incomplete 2023 Apr 25
▶ Success 10
Establishment of a steady system state after lunar landing
Incomplete
HAKUTO-R

ROCKETLAB

3GPP Mobile Telecommunications Technology on the Moon

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***Abstract*— Under NASA's Artemis program, NASA is planning to send astronauts back to the Moon in the next couple of years. Near term missions will be analogous but much more sophisticated versions of the last couple of Apollo missions. However, unlike Apollo, this time NASA intends to put the infrastructure in place to support long term human presence and eventual industrialization of the Moon. To make this vision a reality, NASA plans to collaborate with commercial and international partners as much as possible as opposed to developing, building, and operating equipment on its own. Lunar infrastructure will eventually be built over time by many organizations, public and private, to support sustained human exploration, science, and industrial activities. Obviously, this vision for the future will be impossible without a robust lunar communications and navigation system that can support many users with varying degrees of services. On Earth, most people are very familiar with the 3rd Generation Partnership Project**

1. INTRODUCTION

With the Artemis program, NASA will establish a long-term human presence on the Moon. Lunar activity will also include scientific research and eventually commercial operations. This sustained growth in lunar activity will require robust communications, navigation, and networking capabilities. NASA's Space Communications and Navigation (SCaN) office has developed the LunaNet [1] architecture to meet these needs.

LunaNet will leverage innovative networking techniques, standards, and an extensible framework to rapidly expand network capabilities at the Moon. This framework will allow industry, academia, and international partners to build and operate LunaNet nodes alongside NASA. These nodes will

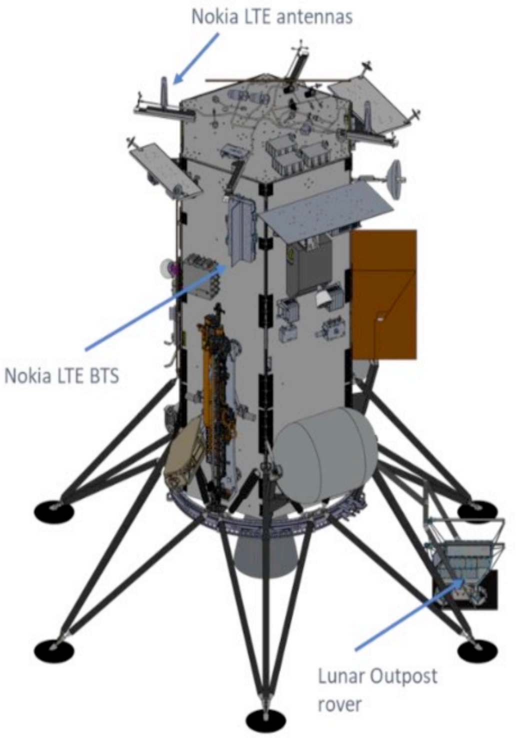

Figure 1. Intuitive Machines lander with Nokia LT
BTS and Lunar Outpost rover (stowed configuratio

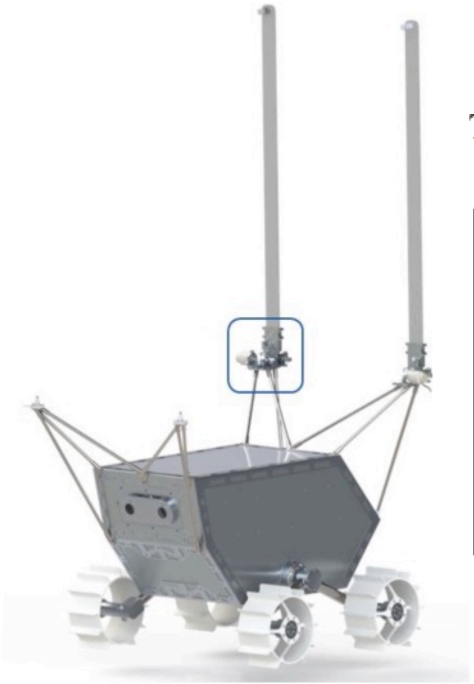

Figure 2. Lunar Outpost rover with Nokia UE and deployed rover antennas.

Table 1. Summary of SFCG 32-2R4 recommended bands for 3GPP use

Ref. #	3GPP Band	Frequencies (MHz)
SFCGb1	N7/38/41	2.5035 – 2.6550
SFCGb2	N48/77/78	3.5000 – 3.8000
SFCGb3	N46	5.1500 – 5.8350
SFCGb4	N47	5.8550 – 5.9250
SFCGb5	N258	25.2500 – 25.5000
SFCGb6	N257/258	27.2250 – 27.5000
SFCGb7	N257/261	27.5000 – 28.3500

B. Edwards *et al.*, "3GPP Mobile Telecommunications Technology on the Moon," *2023 IEEE Aerospace Conference*, Big Sky, MT, USA, 2023, pp. 1-12

APPENDICES

A. RADIO RESTRICTED AREA OF THE MOON

Given the interest of using 3GPP transmission sites at the lunar south pole and beyond the Earth observable limb, there has been concern with protection of the Shielded Zone of the Moon (SZM). The SZM is defined by the ITU Radio Regulations (RR) Article 22 Section V as:

> *"The shielded zone of the Moon comprises the area of the Moon's surface and an adjacent volume of space which are shielded from emissions originating within a distance of 100 000 km from the centre of the Earth."*

100,000 km from Earth allows a significant angle of lunar latitude and longitude to be visible from the potential RF emitters zone into the lunar surface far side, and thus to be excluded from the surface portion of the SZM. The Earth-Moon (centre to centre) distance during the Moon's orbit around the Earth varies during the year due to the influence of Sun's gravity on Earth-Moon orbital dynamics and corresponding orbital parameters, ranging from 356,400 km to 406,700 km, which results in an instantaneous (largest 100,000-km zone parallax) angle of 16.00° from the polar lunar limb at closest perigee down to 13.98° at the equatorial limb at furthest apogee, into the far side, that is not shielded by the Moon if the sub-Earth point was at 0°N, 0°W

The lunar poles are well outside of the SZM, as are 100% of near-side locations that can support direct-to-Earth (DTE) communications. Indeed, the lunar poles, important for human and robotic missions, are over 687 km from the SZM, and even with potential realistic extreme maximum lunar surface line-of-sight of 264 km (5-km mountain to 5-km mountain), it is possible to position transmitters 423 km or more into the far side from the lunar poles, approximately the distance from Pittsburgh to Philadelphia, with no line-of-sight into the surface portion of the SZM. Additionally, no transmitter at 264 km from the surface SZM at an altitude below approximately 20 km above the lunar reference ellipsoid can be received by a spacecraft in the full SZM volume.

To better protect the SZM, and to better understand the impacts of surface network transmitters upon this area, we propose the concept of a RF Restricted Area of the Moon (RRAM). The RRAM range corresponds to anywhere south of 76°S and north of 76°N on the lunar surface on the lunar far side (and anywhere on the lunar near side). Therefore, this allows for wireless surface communications for near-term human exploration-class missions to the Moon in a wide range of frequencies with no impact on radioastronomy in the SZM. Wireless surface communications in the SZM and RRAM can then be restricted to limited bands, with a potential reduction in communications range, data rates, and

ITU-R RA.479-5 [7] aligns with this analysis as described in Annex 1 Introduction, where it states the SZM boundary to be "*23.2° beyond the mean limb of the Moon as seen from the centre of the Earth*". The Figure 10 cross-sectional diagram shows this SZM boundary.

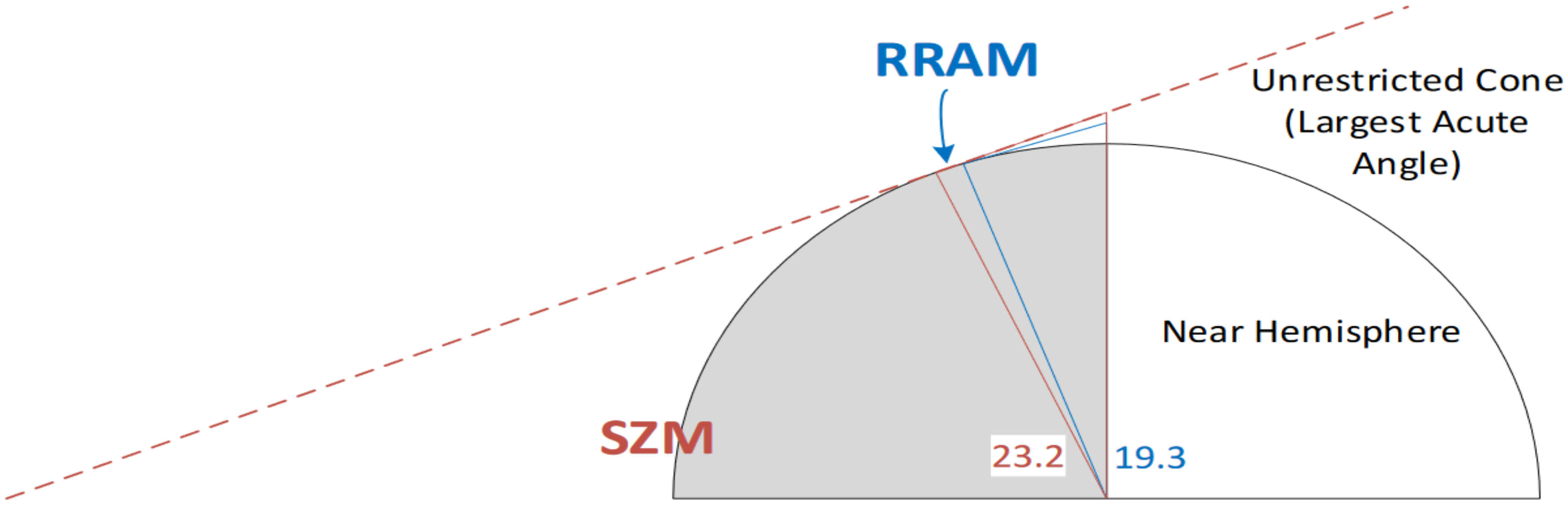

Figure 10. Diagram of SZM and proposed RRAM.

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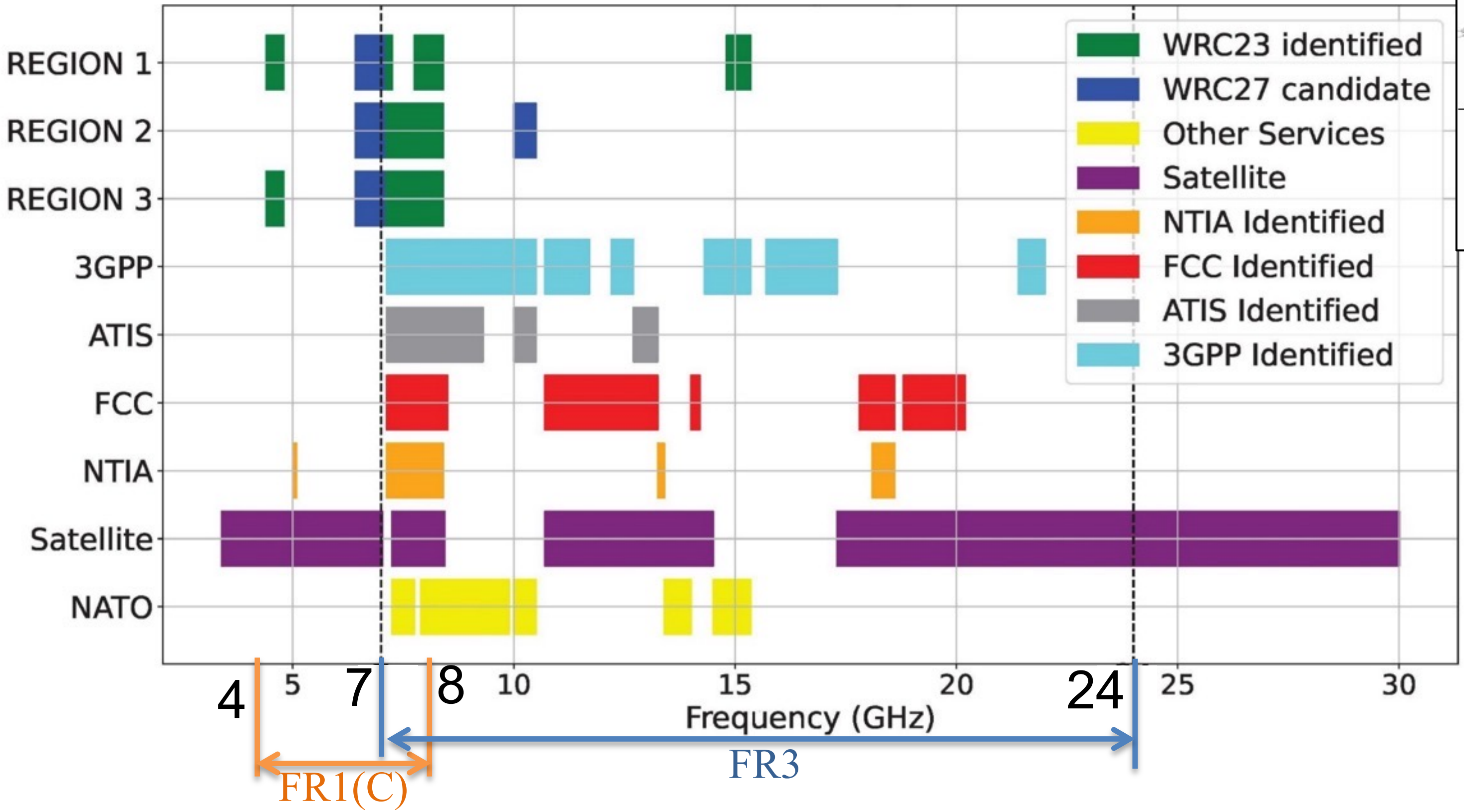
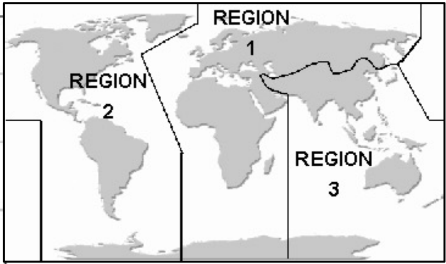
Spectrum Allocations in the FR1(C) and FR3 spectrum





New Spectrum Allocations in the FR1(C) and FR3 Upper Mid-band Frequencies (4–24 GHz) [1]–[3]

[1] A. Davidson, "National spectrum strategy implementation plan," *National Telecommunications and Information Administration*, Tech. Rep., Mar. 2024. https://www.ntia.gov/report/2024/national-spectrum-strategy-implementation-plan

[2] 3GPP, "Study on the 7 to 24 GHz frequency range for NR," *3rd Generation Partnership Project (3GPP)*, Technical Specification (TS) 38.820, 2021, https://www.3gpp.org/DynaReport/38820.htm.

[3] T. Wen and Z. Peiying, *6G: The Next Horizon, New Spectrum*. Cambridge University Press, 2021, p. 146–157. https://www.cambridge.org/core/books/6g-the-next-horizon/new-spectrum/

3GPP RAN1 Meeting #116-bis **R1-2403280**

Changsha, China, 15 April – 19 April, 2024

Prof. Jianhua Zhang, BUPT
Dr. Mansoor Shafi, SPARK NZ

Source: **BUPT, Spark NZ Ltd**

Title: **Discussion on channel model validation of TR38.901 for 7-24GHz**

Agenda item: **9.8.1**

Document for: **Discussion and Decision**

---

1. Introduction

In RAN#102, a study on channel modelling enhancements for 7-24 GHz for NR was approved [1]:

> **Justification:** Additional considerations may also include the number/power of paths, cluster structure, material/building penetration loss models, and spatial consistency between a UE and different non-co-located TRPs, for example.
>
> **The objectives of this study are:**
>
> - Validate using measurements the channel model of TR38.901 at least for 7-24 GHz
>   - Note: Only stochastic channel model is considered for the validation.
>   - Note: The validation may consider all existing scenarios: UMi-street canyon, UMa, Indoor-Office, RMa and Indoor-Factory.

TR 38.901 TSG RAN WG1 #116bis **R1-2402407**
Changsha, Hunan Province, China, April 15th –19th, 2024

Source: **Sharp, NYU WIRELESS**
Title: **Channel model validation of TR 38.901 for 7-24 GHz**
Agenda Item: **9.8.1**
Document for: **Discussion and Decision**

1. Background

Study on channel modelling enhancements for 7-24 GHz identified two major objectives [1]:

1. *Validate using measurements the channel model of TR38.901 at least for 7-24 GHz*
2. Adapt/extend as necessary the channel model of TR38.901 at least for 7-24 GHz

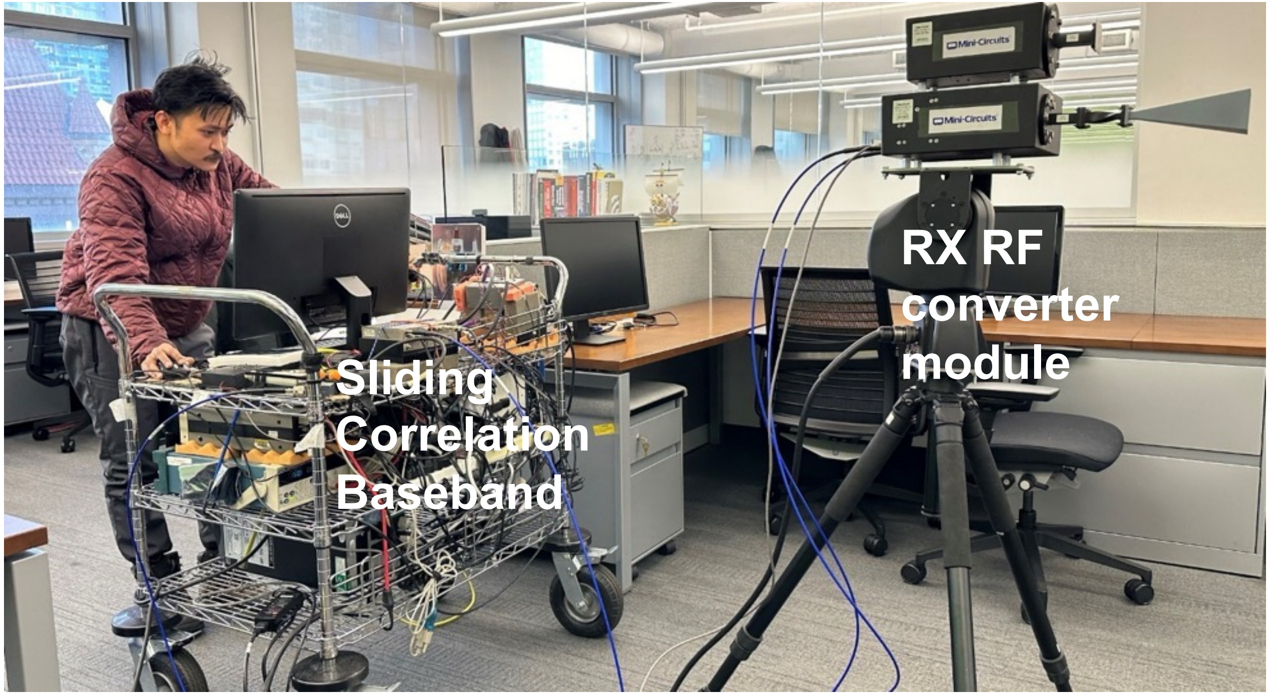
In this agenda item i.e. 9.8.1 we focus on "*Validate using measurements the channel model of TR38.901 at least for 7-24 GHz.*" This agenda item encompasses the following:

- Only stochastic channel model is considered for the validation.
- The validation may consider all existing scenarios: UMi-street canyon, UMa, Indoor-Office, RMa and Indoor-Factory.

Note 1: Continuity of the channel model in the frequency domain below 7 GHz and above 24 GHz shall be ensured.

Note 2: Mathematical and/or theoretical aspects (if any) may be studied before results of measurement campaigns are available. While measurement results may be available and submitted at any time, the study of measurement results may start later (e.g., Q3 2024).

Radio Propagation Research at FR1(C) and FR3



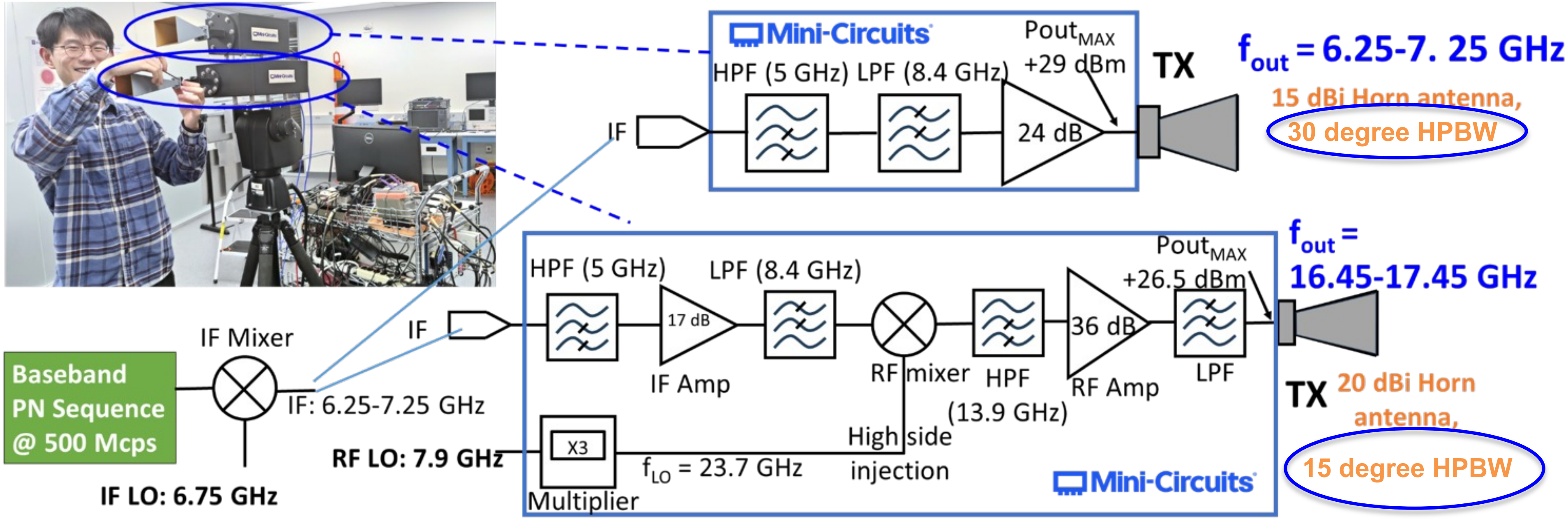
Indoor radio propagation measurements at 16.95 GHz.

- Specialized **FR1(C) and FR3 Channel sounder at NYU**.
- Propagation measurement campaigns in: **Indoor (20 T-R locations), Outdoor (18 T-R locations), Factory (12 T-R locations).**
- **Time-domain channel sounder** leveraging spread spectrum correlation [1].
- Uses **sliding correlation with a pseudorandom-noise (PN) sequence**, providing a **39 dB processing gain** [2].
- Uses **Rubidium clocks** with **patent pending Precision Time Protocol Sync.** for **absolute timing** [2].

[1] D. Shakya, M. Ying, H. Poddar, P. Ma, Y. Wang, I. Al-Wazani, and T.S. Rappaport, "Wideband Radio Propagation Penetration Loss through Building Materials and Partitions at 6.75 GHz in FR1(C) and 16.95 GHz in the FR3 Upper Mid-band spectrum", in (Submitted) 2024 Global Communications Conference (GLOBECOM), pp 1–6.

[2] D. Shakya, H. Poddar and T. S. Rappaport, "A Sub-Terahertz Sliding Correlator Channel Sounder with Absolute Timing using Precision Time Protocol over Wi-Fi," in 2023 IEEE GLOBECOM, 2023. Link: https://ieeexplore.ieee.org/abstract/document/9447829

Wideband FR1(C) / FR3 Channel Sounder



- Minicircuits RF heads at 6.75 and 16.95 GHz.[1]
- Similar RF heads used at the RX side for down-converting received signal for generating Power Delay Profiles [1].

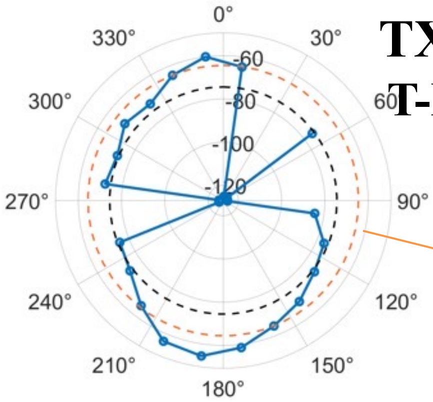
[1] D. Shakya, H. Poddar and T. S. Rappaport, "A Sub-Terahertz Sliding Correlator Channel Sounder with Absolute Timing using Precision Time Protocol over Wi-Fi," in 2023 IEEE GLOBECOM, 2023. Link: https://ieeexplore.ieee.org/abstract/document/9447829

Measurements at each location

TX1-RX2 (16.95 GHz)

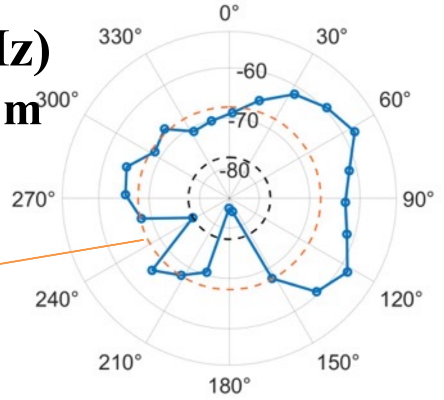
T-R separation: 27.05 m

Mast mounted TX for emulating indoor access points near ceiling

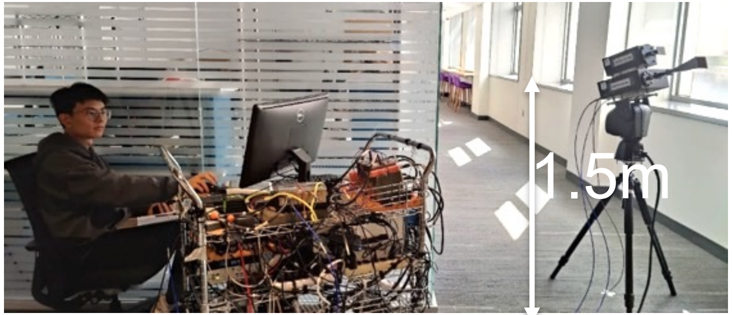


AOD PAS at the TX

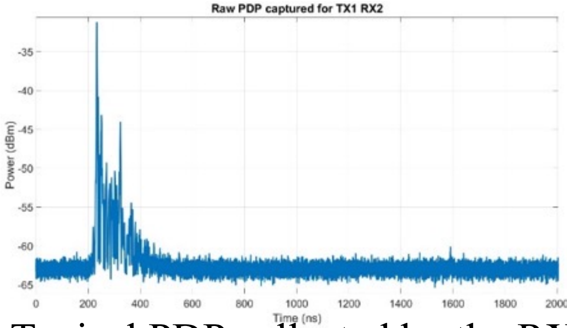
10 dB spatial lobe threshold [1]



AOA PAS at the RX



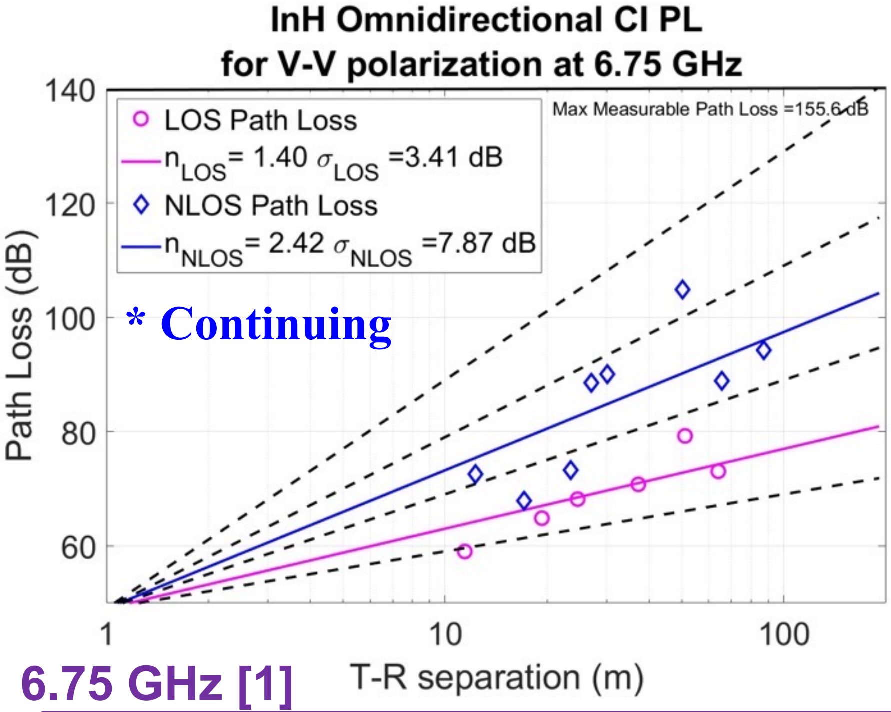
RX close to typical cellphone height (~1.5 m) sweeping the azimuth

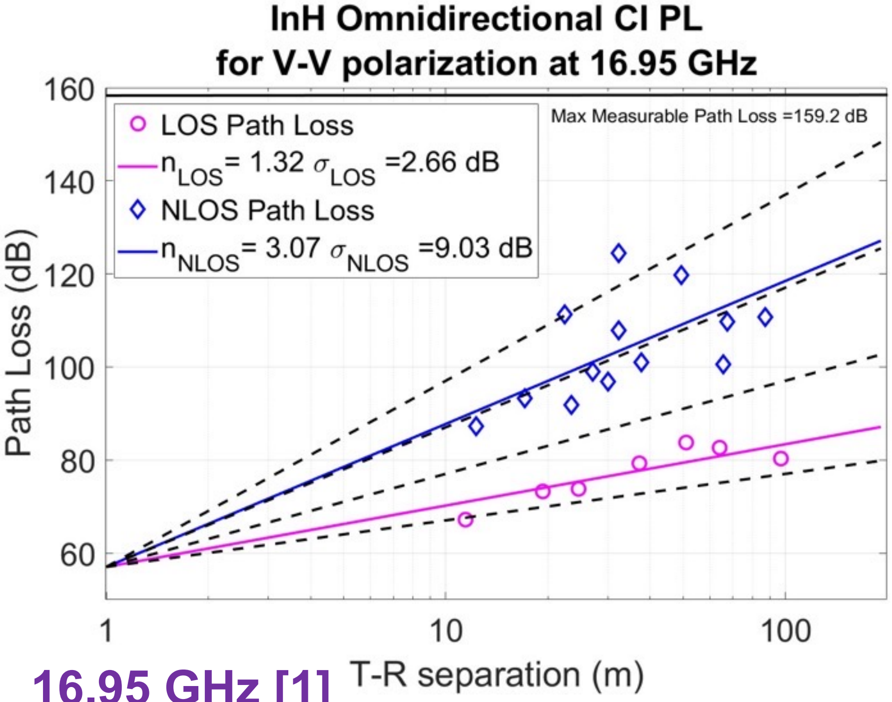


Typical PDP collected by the RX

[1] D. Shakya, S. Ju, O. Kanhere, H. Poddar, Y. Xing and T. S. Rappaport, "Radio Propagation Measurements and Statistical Channel Models for Outdoor Urban Microcells in Open Squares and Streets at 142, 73, and 28 GHz," *in IEEE Transactions on Antennas and Propagation*, vol. 72, no. 4, pp. 3580-3595, April 2024. https://ieeexplore.ieee.org/abstract/document/10444718

Omnidirectional Path Loss





6.75 GHz [1]

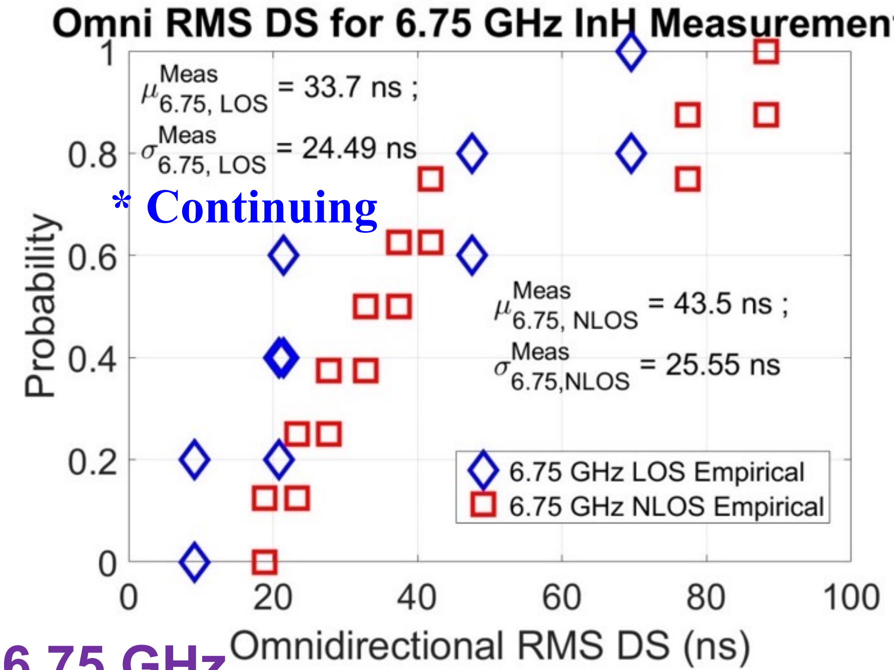
n_{LOS}=1.4; σ_{LOS}= 3.41 dB
n_{NLOS}= 2.4; σ_{NLOS}= 7.87 dB

16.95 GHz [1]

n_{LOS}=1.3; σ_{LOS}= 2.66 dB
n_{NLOS}= 3.1; σ_{LOS}= 9.03 dB

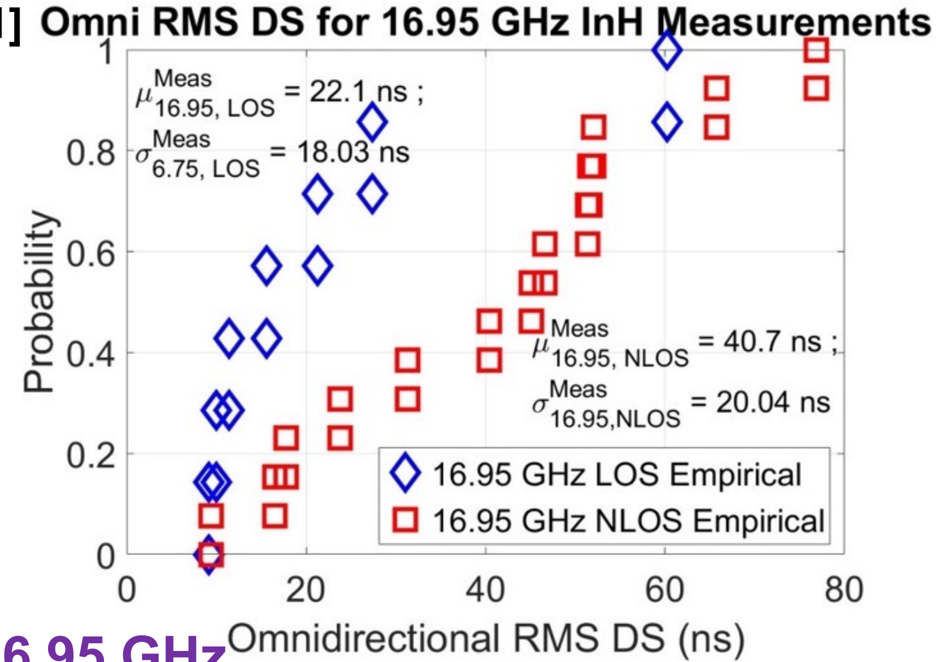
[1] D. Shakya, M. Ying, H. Poddar, P. Ma, Y. Wang, I. Al-Wazani, and T.S. Rappaport, " FR3 and FR1C propagation measurements and results for Indoor Office environment", in (Submitted) *2024 Global Communications Conference (GLOBECOM)*, 2024, pp 1–6.

Omnidirectional Delay Spread



6.75 GHz

μ_{LOS}=33.7 ns; σ_{LOS}= 24.49 ns
μ_{NLOS}= 43.5 ns; σ_{NLOS}= 25.55 ns

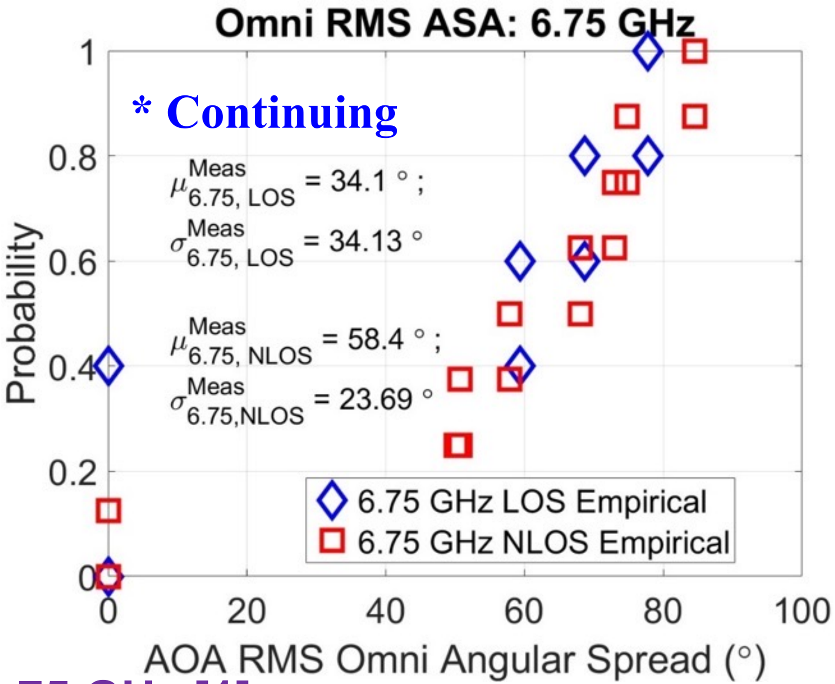


16.95 GHz

μ_{LOS}=22.1 ns; σ_{LOS}= 18.03 ns
μ_{NLOS}= 40.7 ns; σ_{LOS}= 20.04 ns

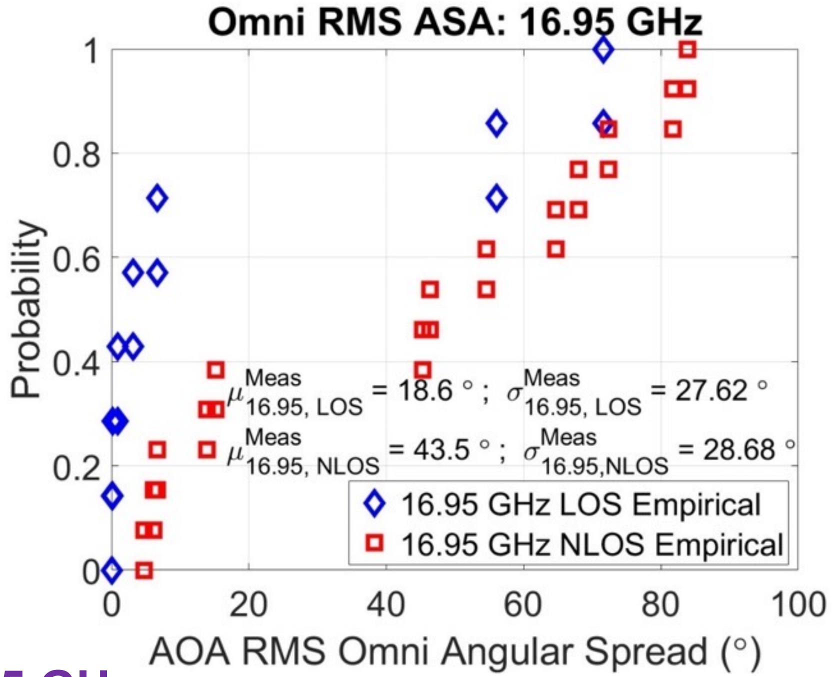
[1] S. Sun, G. R. MacCartney, M. K. Samimi and T. S. Rappaport, "Synthesizing Omnidirectional Antenna Patterns, Received Power and Path Loss from Directional Antennas for 5G Millimeter-Wave Communications," *2015 IEEE GLOBECOM*, San Diego, CA, USA, 2015. https://ieeexplore.ieee.org/abstract/document/7417335

Omnidirectional Angular Spread



6.75 GHz [1]

$\mu_{LOS}= 34.1°$; $\sigma_{LOS}= 34.13°$
$\mu_{NLOS}= 58.4°$; $\sigma_{NLOS}= 23.69°$



16.95 GHz

$\mu_{LOS}= 18.6°$; $\sigma_{LOS}= 27.62°$
$\mu_{NLOS}= 43.5°$; $\sigma_{NLOS}= 28.68°$

[1] D. Shakya, M. Ying, H. Poddar, P. Ma, Y. Wang, I. Al-Wazani, and T.S. Rappaport, " FR3 and FR1C propagation measurements and results for Indoor Office environment", in (Submitted) *2024 Global Communications Conference (GLOBECOM)*, 2024, pp 1–6.

Comparison of InH Statistics (1/2)

Frequency		6.75 GHz	16.95 GHz	28 GHz [1]	73 GHz [2]	142 GHz [1],[2]
Dir Path Loss Exponent	LOS [μ (dB)]	1.6	1.5	1.7	1.6	2.1
	$NLOS_{Best}$ [μ (dB)]	2.7	3.5	3.3	3.3	3.2
	NLOS [μ (dB)]	3.1	3.9	4.4	5.5	4.6
Omni Path Loss Exponent	LOS [μ (dB)]	1.4	1.3	1.2	1.4	1.8
	NLOS [μ (dB)]	2.4	3.1	2.7	2.3	3.6

PLEs with respect to 1 m free space reference

[1] S. Ju, Y. Xing, O. Kanhere and T. S. Rappaport, "Millimeter Wave and Sub-Terahertz Spatial Statistical Channel Model for an Indoor Office Building," in *IEEE Journal on Selected Areas in Communications*, vol. 39, no. 6, pp. 1561-1575, June 2021.
https://ieeexplore.ieee.org/abstract/document/9411894
[2] Y. Xing, T. S. Rappaport and A. Ghosh, "Millimeter Wave and Sub-THz Indoor Radio Propagation Channel Measurements, Models, and Comparisons in an Office Environment," in *IEEE Communications Letters*, vol. 25, no. 10, pp. 3151-3155, Oct. 2021.
https://ieeexplore.ieee.org/abstract/document/9450830

Comparison of InH Statistics (2/2)

Frequency		**6.75 GHz**	**16.95 GHz**	**28 GHz [1]**	**73 GHz [2]**	**142 GHz [1],[2]**
Dir RMS DS	LOS [μ (ns)]	19.3	19.5	10.6	3.5	2.7
	NLOS [μ (ns)]	21.7	14.9	14.5	10.0	7.2
Omni RMS DS	LOS [μ (ns)]	33.7	22.1	10.8	6.2	3.0
	NLOS [μ (ns)]	43.5	40.7	17.1	12.3	9.2

Decreasing delay spread with frequency

[1] S. Ju, Y. Xing, O. Kanhere and T. S. Rappaport, "Millimeter Wave and Sub-Terahertz Spatial Statistical Channel Model for an Indoor Office Building," in *IEEE Journal on Selected Areas in Communications*, vol. 39, no. 6, pp. 1561-1575, June 2021. https://ieeexplore.ieee.org/abstract/document/9411894

[2] Y. Xing, T. S. Rappaport and A. Ghosh, "Millimeter Wave and Sub-THz Indoor Radio Propagation Channel Measurements, Models, and Comparisons in an Office Environment," in *IEEE Communications Letters*, vol. 25, no. 10, pp. 3151-3155, Oct. 2021. https://ieeexplore.ieee.org/abstract/document/9450830

Wideband FR3 and FR1(C) Penetration Loss (1/4)

Fig. Different materials measured for penetration loss

Wideband FR3 and FR1(C) Penetration Loss (2/4)

Measured Penetration Loss of Common Materials and Partitions [1]

S.N.	Material	Thickness (cm)	Pol	Frequency 6.75 GHz μ (dB)	Frequency 16.95 GHz μ (dB)	Δ (dB)
1	Cinderblock Wall	22	Co	13.4	15.0	1.6
			Cross	10.7	11.5	0.9
2	Low-e tinted glass wall	3	Co	33.7	42.3	8.6
			Cross	38.4	46.5	8.2
3	Low-e glass window	2	Co	29.7	32.7	3.0
			Cross	15.4	18.5	3.1
4	Clear Glass	1	Co	3.6	3.7	0.1
			Cross	4.2	4.4	0.2
5	Birch Wood panel	2	Co	2.4	6.1	3.7
			Cross	2.0	5.5	3.5

[1] D. Shakya, M. Ying, H. Poddar, P. Ma, Y. Wang, I. Al-Wazani, and T.S. Rappaport, " FR3 and FR1C propagation measurements and results for Indoor Office environment", in (Submitted) *2024 Global Communications Conference (GLOBECOM)*, 2024, pp 1–6.

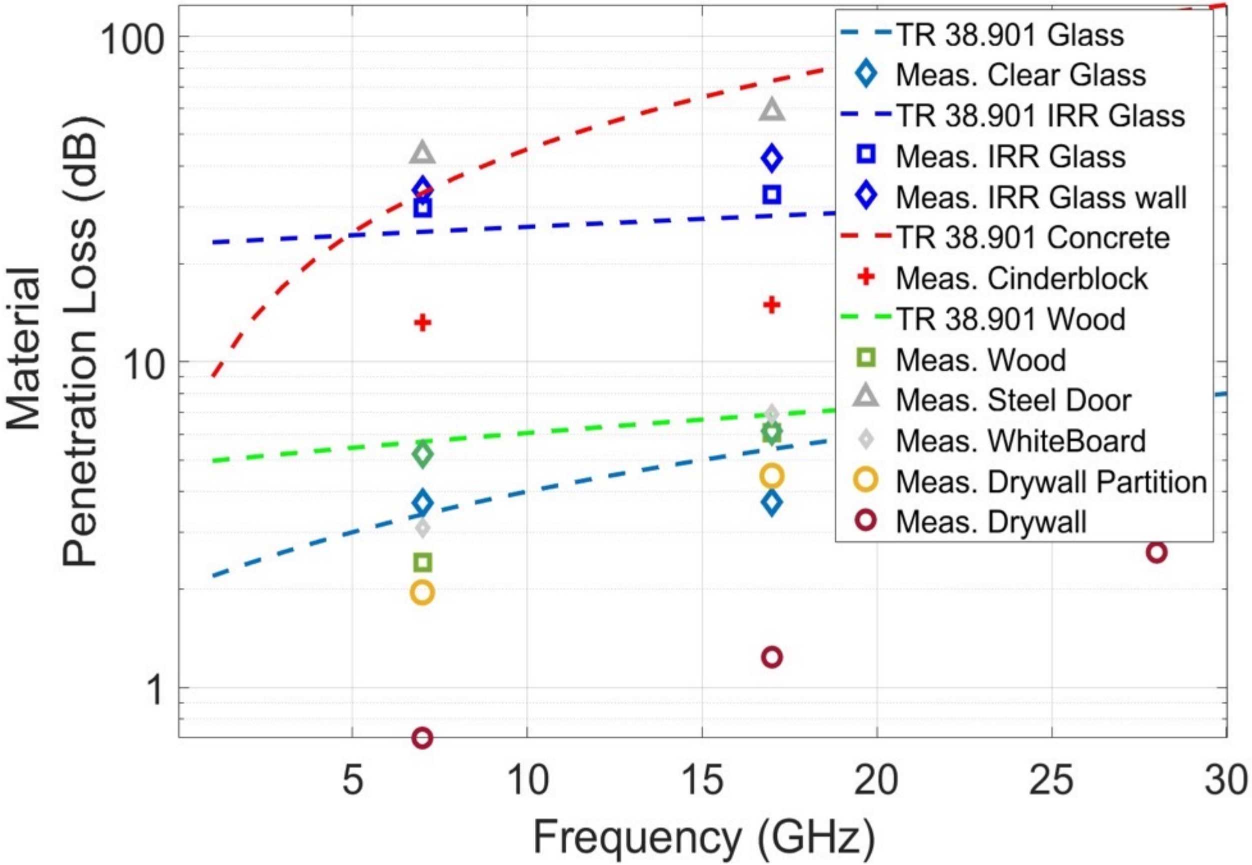
Wideband FR3 and FR1(C) Penetration Loss (2/4)

Measured Penetration Loss of Common Materials and Partitions [1]

S.N.	Material	Thickness (cm)	Pol	Frequency 6.75 GHz μ (dB)	Frequency 16.95 GHz μ (dB)	Δ (dB)
6	Wooden door	4.5	Co	5.8	6.1	0.3
			Cross	7.1	7.7	0.6
7	Steel door	4.7	Co	43.2	58.5	15.3
			Cross	41.8	56.4	14.6
8	Drywall Partition	13.7	Co	2.1	4.5	2.4
			Cross	3.0	6.1	3.2
9	Drywall panel	3	Co	0.6	1.2	0.6
			Cross	1.5	2.3	0.8
10	White Board	3	Co	3.1	6.9	3.8
			Cross	4.1	7.5	3.4

[1] D. Shakya, M. Ying, H. Poddar, P. Ma, Y. Wang, I. Al-Wazani, and T.S. Rappaport, " FR3 and FR1C propagation measurements and results for Indoor Office environment", in (Submitted) *2024 Global Communications Conference (GLOBECOM)*, 2024, pp 1–6.

Wideband FR3 and FR1(C) Penetration Loss (4/4)



Comparison of measured material penetrations with 3GPP standard material penetration loss curves [1], [2]

3GPP penetration losses need revision

[1] 3GPP, "Study on channel model for frequencies from 0.5 to 100 GHz," *3rd Generation Partnership Project (3GPP)*, Technical Report (TR) 38.901, 2021. https://ieeexplore.ieee.org/abstract/document/9411894

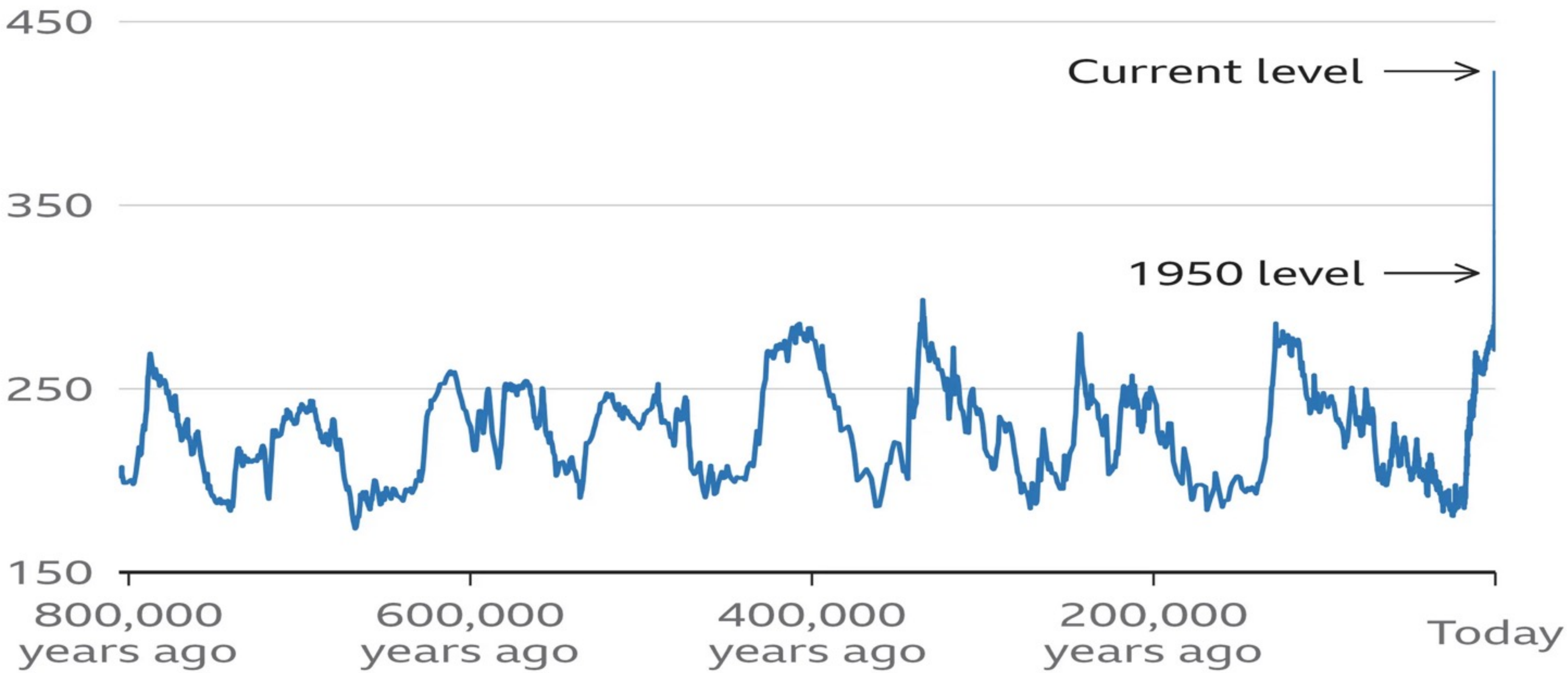
[2] D. Shakya, M. Ying, H. Poddar, P. Ma, Y. Wang, I. Al-Wazani, and T.S. Rappaport, "Wideband Radio Propagation Penetration Loss through Building Materials and Partitions at 6.75 GHz in FR1(C) and 16.95 GHz in the FR3 Upper Mid-band spectrum", in (Submitted) *2024 Global Communications Conference (GLOBECOM)*, pp 1–6.

Outline

- The state of wireless traffic delivery
- The next great frontier for wireless traffic delivery
- New results for new 5G/6G mid-band spectrum (7-24 GHz)
- Energy Efficiency and Waste Factor: a unifying FoM is needed
- Conclusion

Carbon dioxide levels are higher than any time in the last 800,000 years

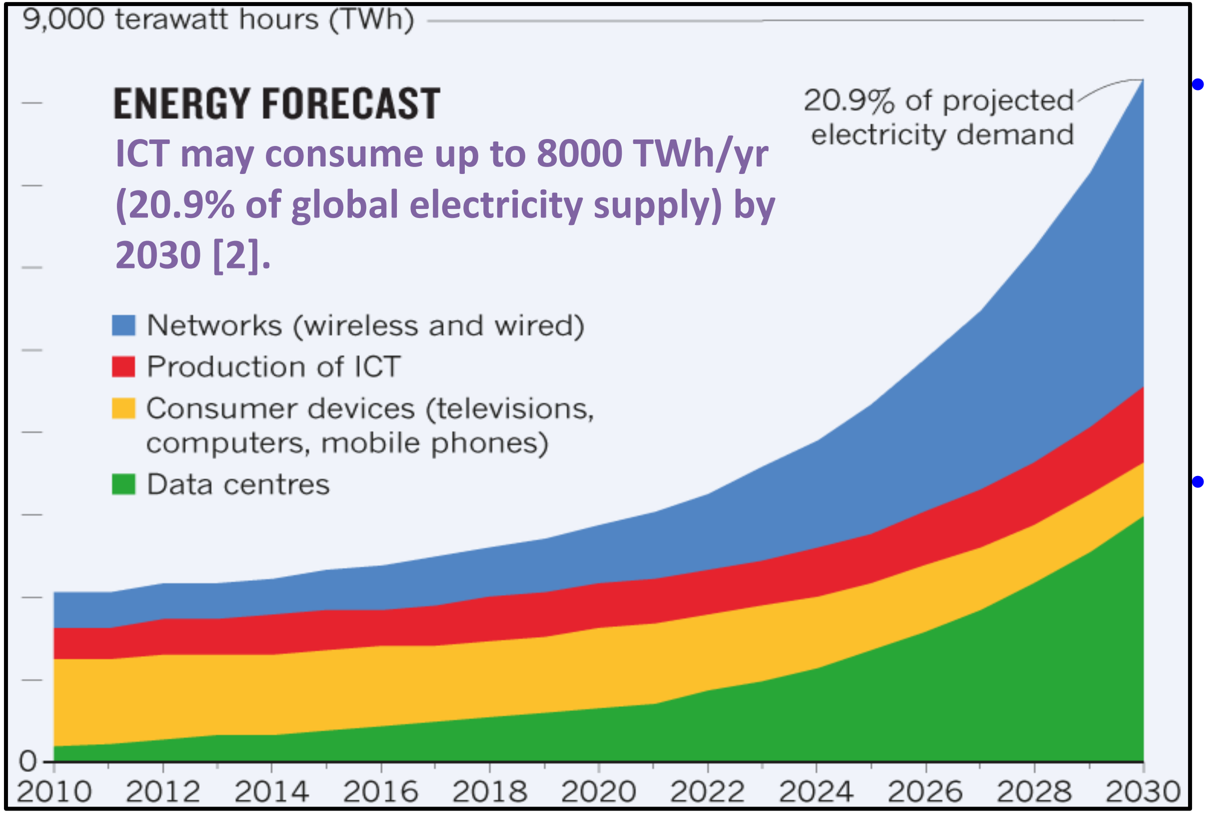
Atmospheric CO2 concentrations, parts per million



Source: NOAA/Bereiter et al., 2015

BBC

Energy Consumption in Future Networks



- **Energy consumption directly contributes to carbon emissions** with computing and communications likely to use dramatically more of Earth's energy, especially with AI/ML [1].
- **The Waste Factor (W)** or **Waste Figure (WF)** is a unifying analysis method for evaluating the energy efficiency of **ANY** communication device or cascaded network.

[1] https://www.scientificamerican.com/article/the-ai-boom-could-use-a-shocking-amount-of-electricity/ L. Leffer, Scientific American, Oct. 13, 2023
[2] N. Jones, "How to stop data centres from gobbling up the world's electricity," Nature, vol. 561, no. 7722, pp. 163-166, 2018. Available: https://www.nature.com/articles/d41586-018-06610-y
[3] J. N. Murdock and T. S. Rappaport, "Consumption Factor and Power-Efficiency Factor: A Theory for Evaluating the Energy Efficiency of Cascaded Communication Systems," in *IEEE Journal on Selected Areas in Communications*, Feb 2014. Available: https://ieeexplore.ieee.org/abstract/document/6522957 Also see Kanhere, et. al.. IEEE Wireless Comm. Magazine, IEEE Dec. 2022, and M. Xing, et. al., Globecom 2023

AI – more than just a fad

Artificial intelligence (AI) is disrupting the way we do things – in a good way. The Generative AI market is expected to grow from $40 Billion in 2022 to **$1.3 Trillion in 2032**[1].

The race to 1 million *Months it took companies to reach 1 million online users*[2]

AI today

Customer Service

Wendy's uses AI in the drive-through to handle customer questions and orders.[3]

Software Engineering

92% of U.S. developers are already using AI coding tools.[4]

Product Enhancement

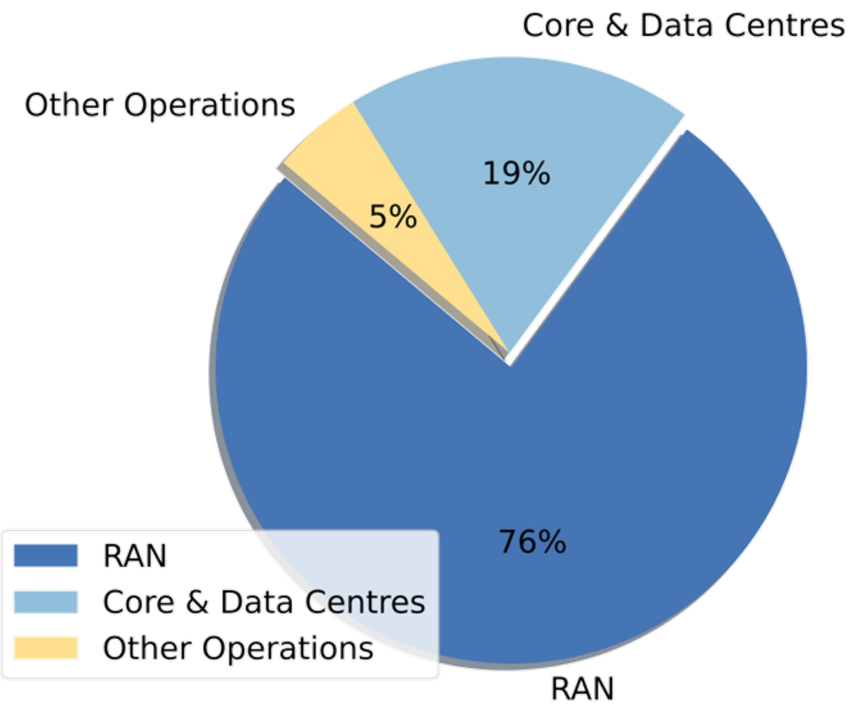
Spotify developed an AI DJ to create customized playlists for users and provide commentary.[5]

Content Generation

Buzzfeed us leveraging AI to generate content, such as personality quizzes and articles.[6]

1 Bloomberg, "Generative AI to become a $1.3T market by 2032, research finds", 6/1/23 2 Source: Source: Statista, with data from company announcements via Business Insider/LinkedIn, as of January 24, 2023. Airbnb measuredas one million nights booked, Instagram measured as one million downloads 3 Wendys.com, "AI and Beyond", 6/2/23 4 Github, "Survey reveals AI's impact on the developer experience, 6/13/23 5 TechCrunch, "Spotify launches "DJ", a new feature offering personalized music with AI-powered commentary, 2/22/23 6 CBS, "BuzzFeed to use OpenAI technology to create content", 1/26/23

Energy Consumption in Mobile Networks



- In terms of the energy consumption of the mobile network, **the RAN consumes 76% of the total energy consumption [1].**
- Other energy-consuming parts include **Network Cores and Data centers (19%) [1].**
- **No unified power efficiency metric for the RAN and Data Centers!**

[1] E. Kolta and T. Hatt, "Going green: Measuring the energy efficiency of mobile networks," GSMA Intelligence, Tech. Rep., 2024. Available: https://data.gsmaintelligence.com/research/research/research-2024/going-green-measuring-the-energy-efficiency-of-mobile-networks

TechnicalFeature

Microwave Journal 2024

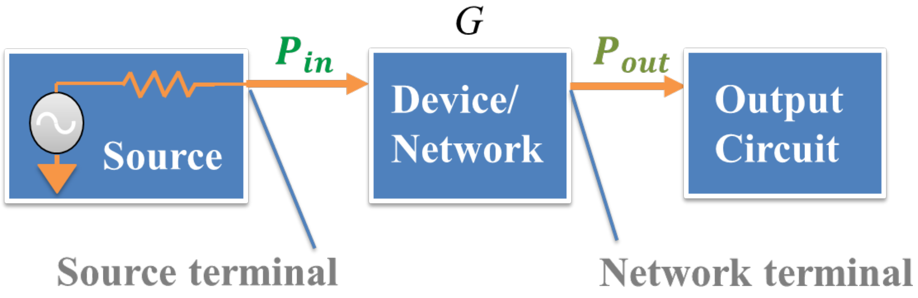
INVITED PAPER

Waste Figure and Waste Factor: New Metrics for Evaluating Power Efficiency in Any Circuit or Cascade

Theodore (Ted) S. Rappaport, Mingjun Ying and Dipankar Shakya
NYU WIRELESS, Tandon School of Engineering, New York University, Brooklyn, N.Y.

Overview of Waste Factor

- Waste Factor (**W**): Ratio of total power consumed by the signal path components along a cascade, including additive wasted power, to the useful output signal power [1,2,3].



$$\text{Waste Factor } (\boldsymbol{W}) = \frac{P_{consumed,path}}{P_{in} G_{sys}}$$

* All consumed and useful powers are in Watts.

$$Effic.(\eta) = \frac{1}{W} = \frac{P_{out}}{P_{path}} \qquad Gain(G) = P_{out}/P_{in}$$

- Components waste power in a circuit network and reduce the total power efficiency at the network output terminal. i.e. $\boldsymbol{W \geq 1}$

$$W = \frac{1}{\eta} = \frac{P_{consumed,path}}{P_{out}} = \frac{P_{non-signal}+P_{out}}{P_{out}}$$

- Power waste at the output from the components within the cascaded Network alone:

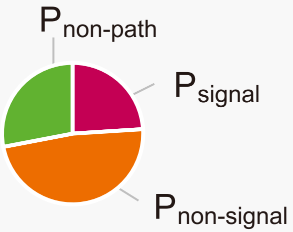
$$P_{wasted} = \boldsymbol{W} P_{out} - GP_{in} = (\boldsymbol{W} - \boldsymbol{1})GP_{in} = (\boldsymbol{W} - \boldsymbol{1})P_{out} \text{ Watts}$$

[1] J. N. Murdock and T. S. Rappaport, "Consumption Factor and Power-Efficiency Factor: A Theory for Evaluating the Energy Efficiency of Cascaded Communication Systems," in *IEEE Journal on Selected Areas in Communications*, February 2014.
[2] M. Ying, D. Shakya, H. Poddar, and T. S. Rappaport, "Waste Factor: A New Metric for Evaluating Power Efficiency in any Cascade," in *GLOBECOM 2023*, Malaysia, Dec. 2023, pp. 1-6. Available: https://arxiv.org/pdf/2309.01018v3.pdf
[3] T. S. Rappaport, M. Ying, and D. Shakya, "Waste figure and waste factor: New metrics for evaluating power efficiency in any circuit or cascade," *Microwave Journal*, vol. 67, no. 5, pp. 54–84, May 2024.

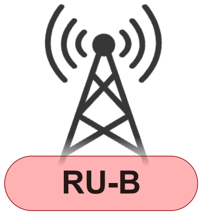
Comparison of RU power waste using W (1/2)

- We consider two different Radio Units

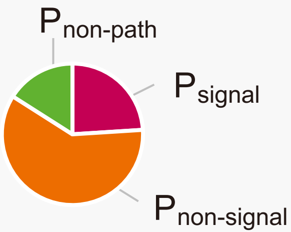
$$P_{\text{signal}A} = 120\ W$$
$$P_{\text{non-signal}A} = 240\ W$$
$$P_{\text{non-path}A} = 140\ W$$



$$P_{\text{consumed,total}A}$$
$$= P_{\text{signal}A} + P_{\text{non-signal}A} + P_{\text{non-path}A}$$
$$= 120 + 240 + 140 = 500\ \text{W}$$



$$P_{\text{signal}B} = 120\ W$$
$$P_{\text{non-signal}B} = 300\ W$$
$$P_{\text{non-path}B} = 80\ W$$



$$P_{\text{consumed,total}B}$$
$$= P_{\text{signal}B} + P_{\text{non-signal}B} + P_{\text{non-path}B}$$
$$= 120 + 300 + 80 = 500\ \text{W}$$

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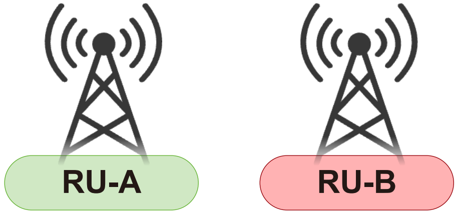
Comparison of RU power waste using W (2/2)



Radio Unit	P_{signal}	$P_{non\text{-}signal}$	$P_{non\text{-}path}$	EE	W
A	120 W	240 W	140 W	24%	3
B	120 W	300 W	80 W	24%	3.5

- **Energy Efficiency from ITU L.1310** [1]

$$\mathrm{EE}_{\mathrm{RF},A} = \frac{P_{\mathrm{signal}A}}{P_{\mathrm{consumed,total}A}} = \frac{120}{500} = 24\% \; = \; \mathrm{EE}_{\mathrm{RF},B} = \frac{P_{\mathrm{signal}A}}{P_{\mathrm{consumed,total}B}} = \frac{120}{500} = 24\%$$

The two RUs have the same energy efficiency according to ITU L.1310

- **Waste Factor**

$$W_A = \frac{P_{\mathrm{non-signal}A} + P_{\mathrm{signal}A}}{P_{\mathrm{signal}A}} = \frac{240+120}{120} = 3 \; < \; W_B = \frac{P_{\mathrm{non-signal}B} + P_{\mathrm{signal}B}}{P_{\mathrm{signal}B}} = \frac{300+120}{120} = 3.5$$

Using W we see that RU-A transmission requires 15% less energy consumption than RU-B !

[1] ITU, L.1310 : Energy efficiency metrics and measurement methods for telecommunication equipment

Problems of traditional EE metrics - Network

- **Network A** is composed of old generation equipment, whereas **Network B** is composed of new and more efficient equipment
  - **Network B** provides higher throughput and better spectral efficiency
  - **Network A** carries more data and have comparable energy consumption → Network A is more efficient according to standard metric [2]
- However, moving traffic to Network A would lead to poor user performance!

Networks	Data volume per site (GB/day)	Energy consumption per site (kWh/day)	Downlink PRB load	User downlink throughput (Mbps)	EE (GB/kWh)
A	569	34.8	54%	6.1	16.4
B	311	34.2	12%	21.6	9.1

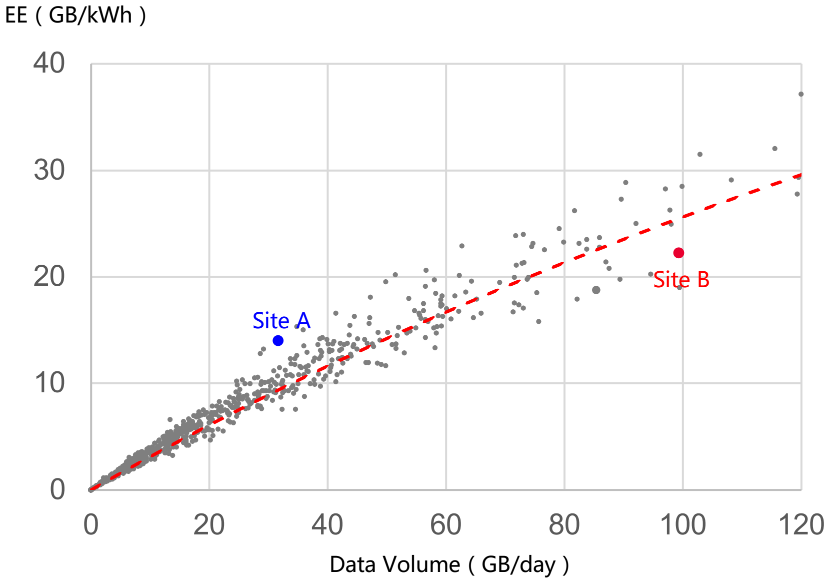
Example of the contradiction (data from [1])

[1] NGMN, Network Energy Efficiency Phase 2, Oct. 2023 https://www.ngmn.org/wp-content/uploads/NGMN_Network_Engergy_Efficiency_Phase2.pdf
[2] ETSI, TS 103 786 Measurement method for energy efficiency of wireless access network equipment https://www.etsi.org/deliver/etsi_ts/103700_103799/103786/01.01.01_60/ts_103786v010101p.pdf

NYU WIRELESS HUAWEI

Poor optimization with traditional metrics

- The EE metric in bit/J [1] may **be misleading for network optimization**
  - Site A has a better site efficiency than site B. However, due to its **lower volume load**, site A results in a **lower traditional EE metric**
  - Optimization techniques attempt to **move traffic towards the most EE cell**, in this case, towards Site B and not Site A
  - Moving traffic towards site A would be more beneficial



[1] ETSI, TS 103 786 Measurement method for energy efficiency of wireless access network equipment https://www.etsi.org/deliver/etsi_ts/103700_103799/103786/01.01.01_60/ts_103786v010101p.pdf

[2] NGMN, Network Energy Efficiency Phase 2, Oct. 2023 https://www.ngmn.org/wp-content/uploads/NGMN_Network_Engergy_Efficiency_Phase2.pdf

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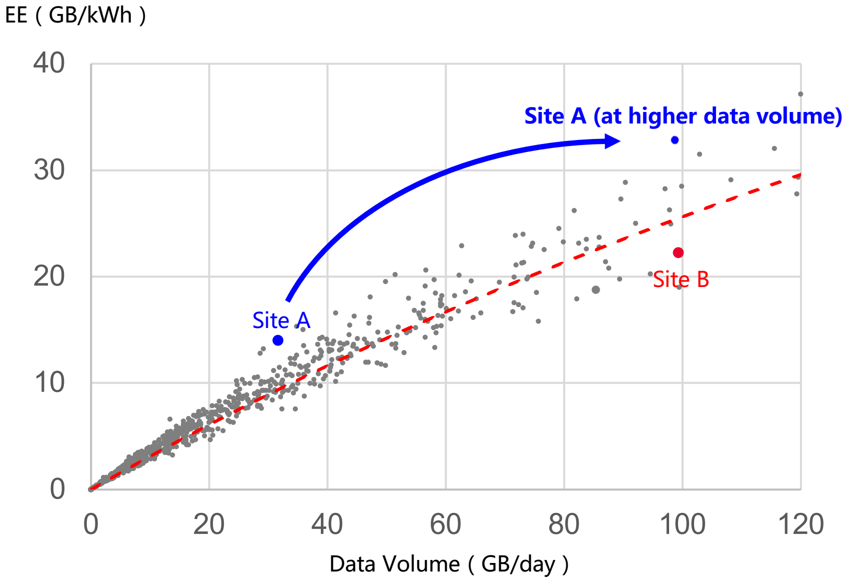
Poor optimization with traditional metrics

- The EE metric in bit/J [1] may also **be misleading for network optimization**
  - Site A has a better site efficiency than site B. However, due to its **lower volume load**, site A results in a **lower traditional EE metric**
  - Optimization techniques attempt to **move traffic towards the most EE cell**, in this case, towards Site B and not Site A
  - Moving traffic towards site A would be more beneficial



The Waste Factor solves this problem as it focuses on the power wasted on the signal path

[1] ETSI, TS 103 786 Measurement method for energy efficiency of wireless access network equipment https://www.etsi.org/deliver/etsi_ts/103700_103799/103786/01.01.01_60/ts_103786v010101p.pdf
[2] NGMN, Network Energy Efficiency Phase 2, Oct. 2023 https://www.ngmn.org/wp-content/uploads/NGMN_Network_Engergy_Efficiency_Phase2.pdf

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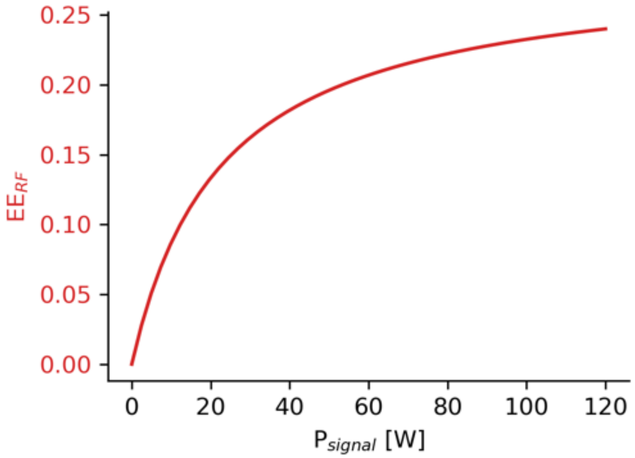
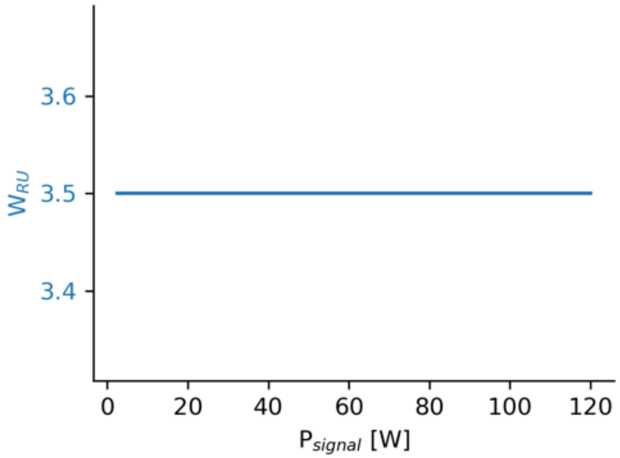
Waste Factor vs. Energy Efficiency

The energy efficiency metric defined in ITU L.1310 [1] is influenced by the P_{signal} level at which it is measured



Contrary to the energy efficiency metric, the waste factor is not influenced by the P_{signal} level at which it is measured



[1] ITU, L.1310 : Energy efficiency metrics and measurement methods for telecommunication equipment

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Conclusion

- Fixed Wireless Access is emerging, mmW is not dead
- Wireless networks are coming to the moon
- Midband spectrum is promsing, 3GPP needs revisions
- Waste Factor: great promise for real Energy Efficiency

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