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at Northeastern University

Conquering the Spectrum Above 100 GHz

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On the Road to 6G Systems

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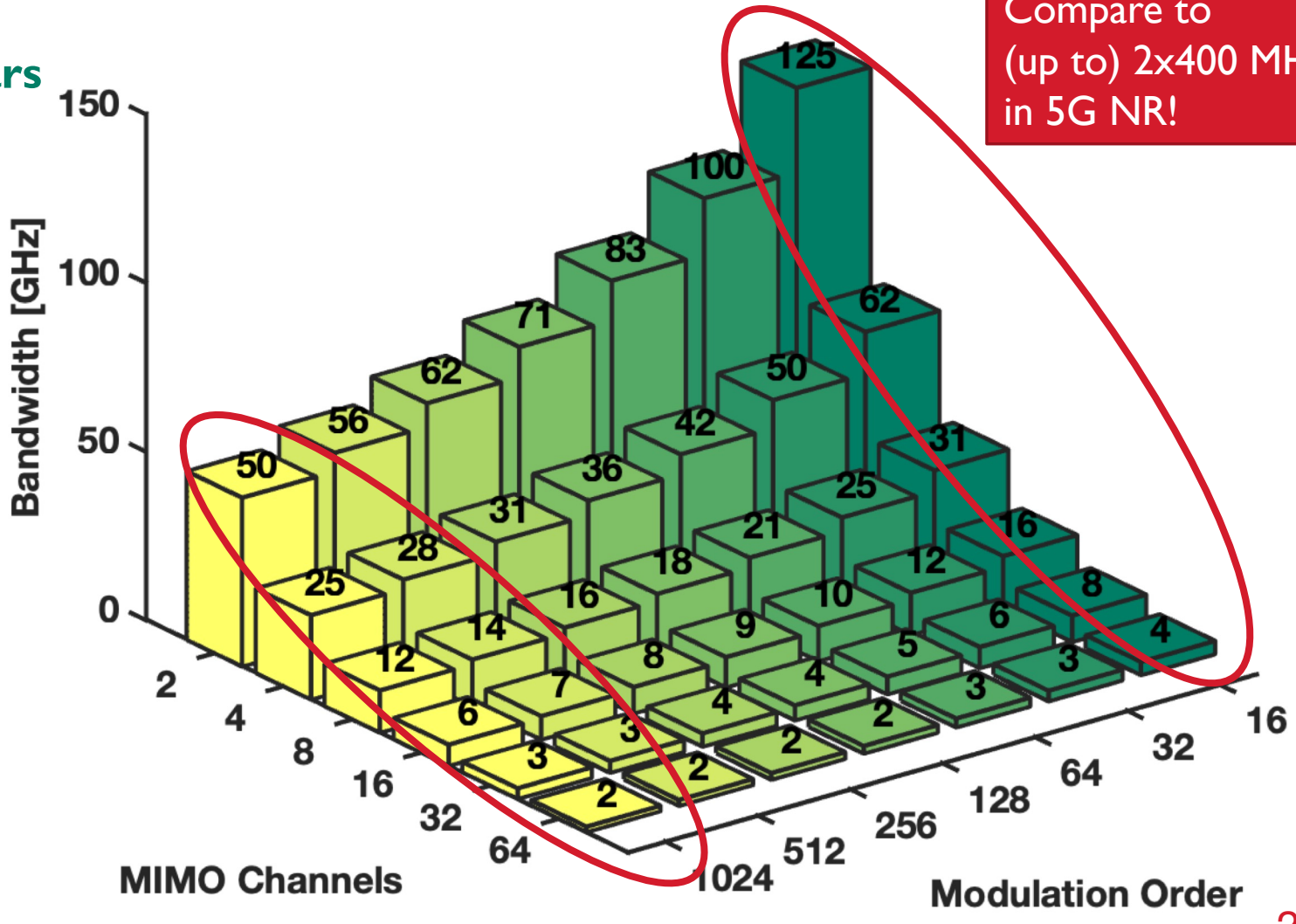
- 6G is happening within the next **6 years**
- Both academia and industry agree on **1 Terabit-per-second** (Tbps) peak data-rate as a reasonable goal
- **How much bandwidth do we need for this?**
  - It depends on:
    - Modulation order/channel
    - Number of MIMO channels



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On a Quest for Resources

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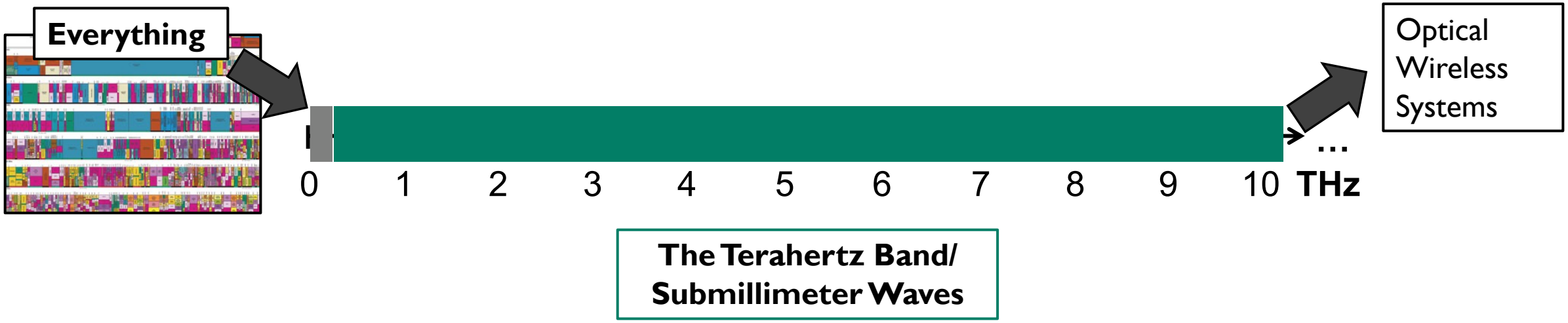
Where do we find such bandwidth?



I. F. Akyildiz, J. M. Jornet and C. Han, **"Terahertz Band: Next Frontier for Wireless Communications,"** Physical Communication, 2014.

I. F. Akyildiz, C. Han, Z. Hu, S. Nie, J. M. Jornet **"Terahertz Communications: An Old Problem Revisited and Research Directions for the Next Decade"** IEEE Transactions on Communications, 2022.

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Opportunities at Terahertz Frequencies

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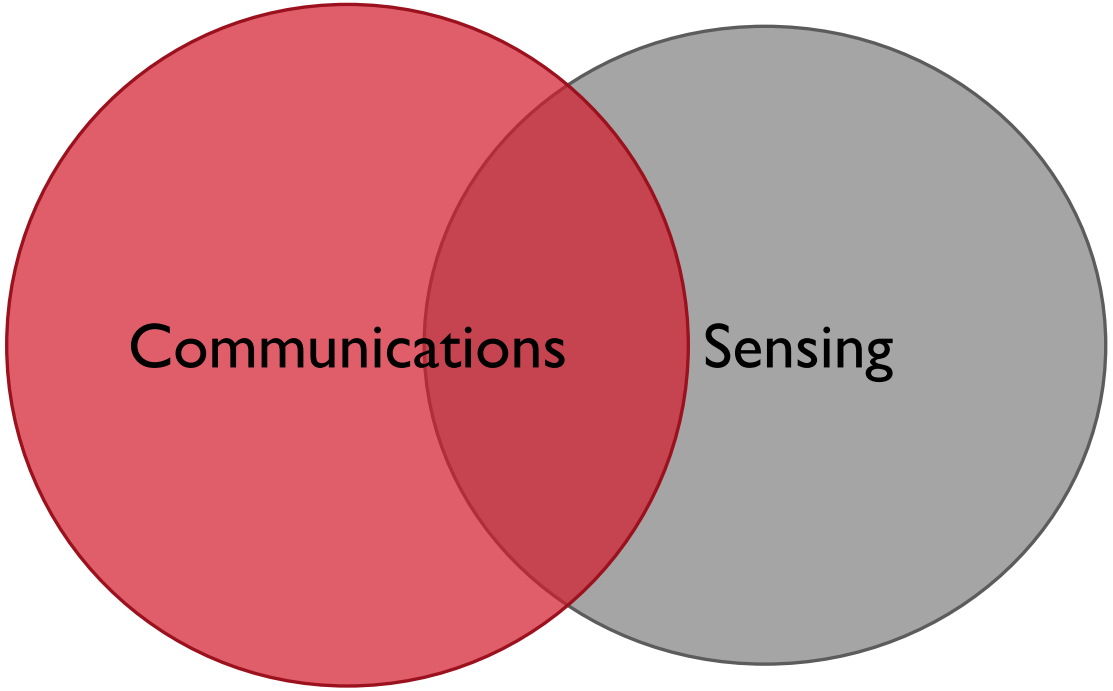
Terabit WPAN
Terabit WLAN/cellular fronthaul
Terabit wireless backhaul
Inter-satellite and Space Networks

Bridging the Digital Divide



High resolution radar/localization
Non-damaging imaging
Spectroscopy
Earth and space exploration

Climate Change Studies

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Joint THz Communications and Sensing

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Ultrabroadband
Ultra-directional Links

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Joint THz Communications and Sensing

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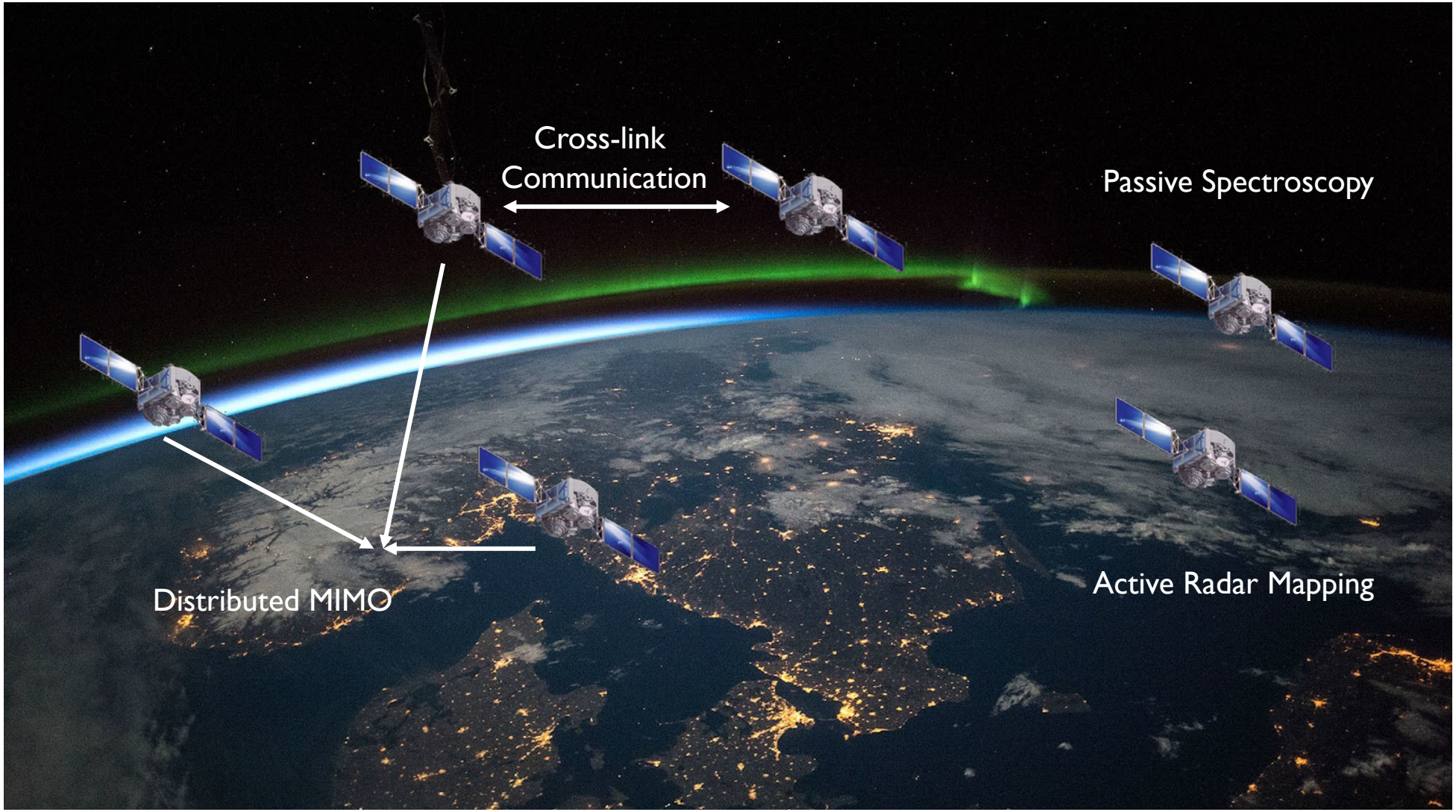
S. Aliaga, A. Al Qaraghuli, J. M. Jornet **"Joint Terahertz Communication and Atmospheric Sensing in Low Earth Orbit Satellite Networks: Physical Layer Design,"** in Proc. of the 2nd IEEE WoWMoM Workshop on NTN for 6G, 2022.



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Opportunities at Terahertz Frequencies

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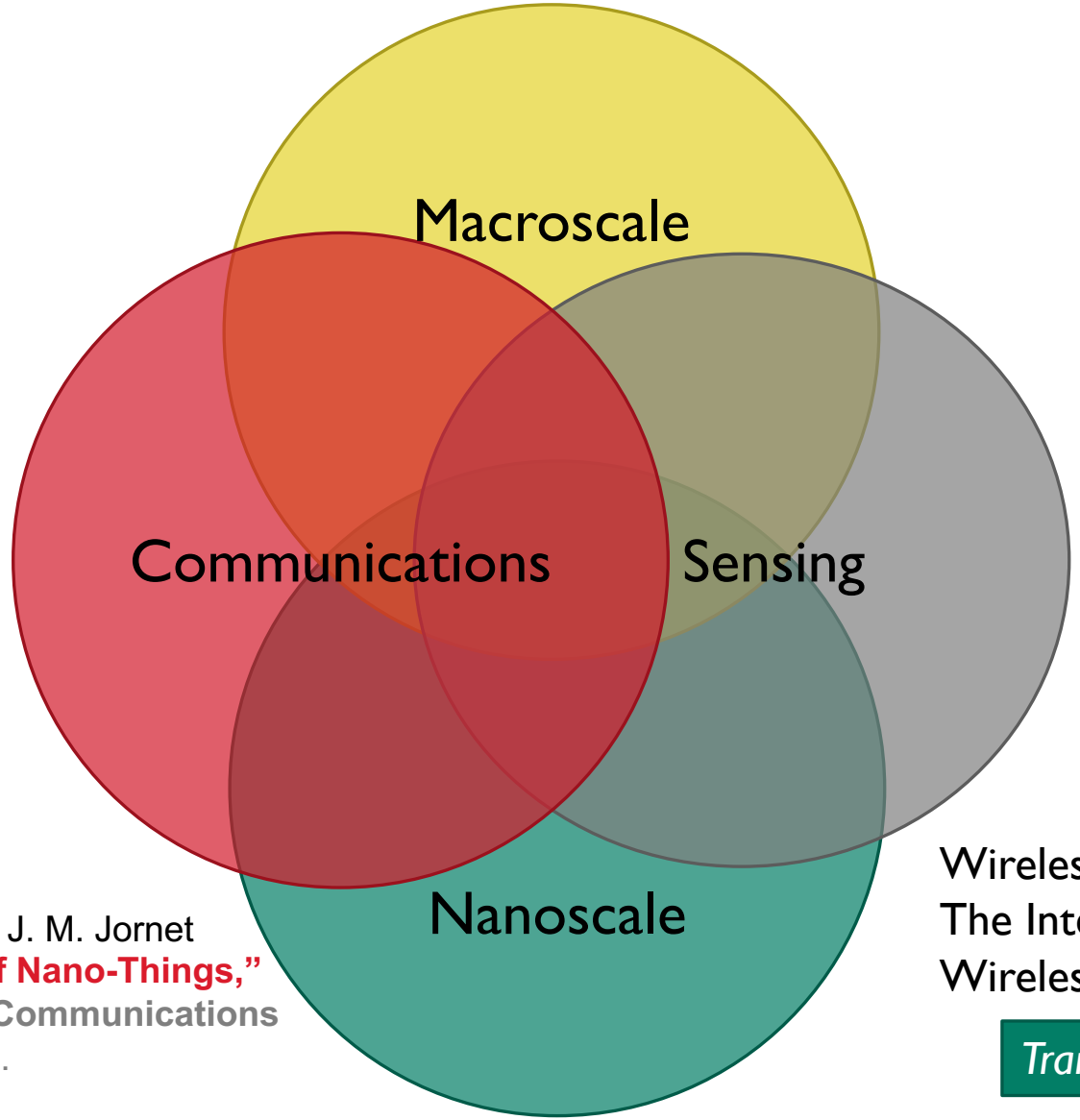

Terabit WPAN
Terabit WLAN/cellular fronthaul
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Bridging the Digital Divide

High resolution radar/localization
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Earth and space exploration

Climate Change Studies

Wireless Networks on Chip
The Internet of Nano-Things
Wireless Nano-bio Networks

Transforming Healthcare

I. F. Akyildiz and J. M. Jornet
"The Internet of Nano-Things,"
IEEE Wireless Communications Magazine, 2010.

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Joint Nano-bio Communication and Sensing

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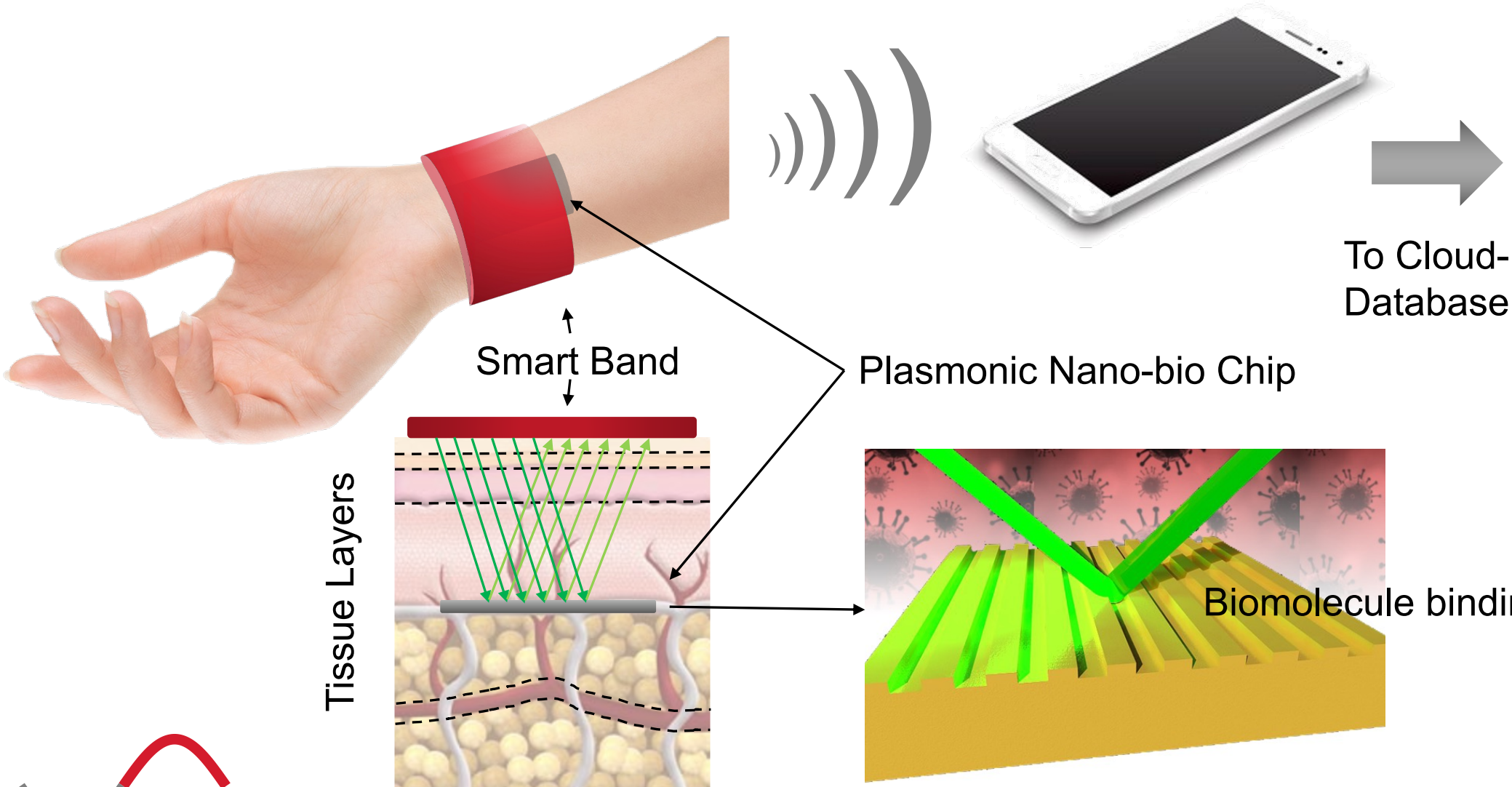

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A. Sangwan and J. M. Jornet, **"Plasmonic Nano-systems for Joint Communication and Bio-sensing in the Internet of Nano-Bio Things,"** **IEEE JSAC**, November 2022.

From Materials to Standards

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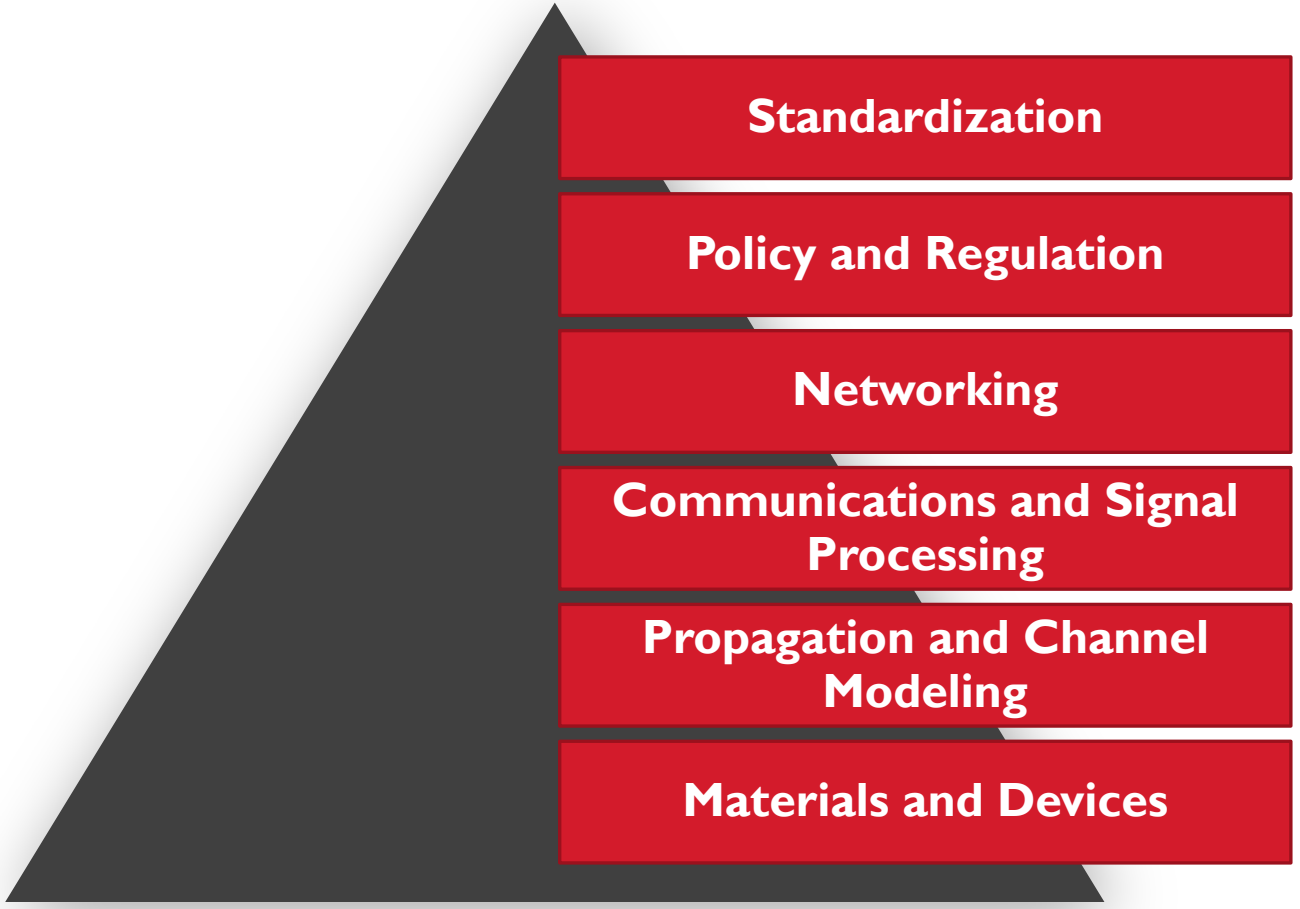

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The Terahertz Technology Gap

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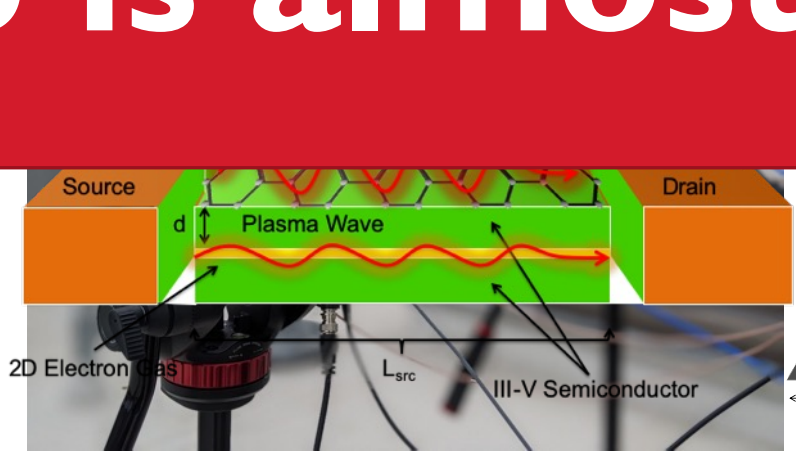
Ultra-high-speed Digital Back-ends	Ultrabroadband Analog Front-ends	Ultradirectional Antenna Systems
• The interface between the digital processors • Digital-to-Analog and Analog-to-Digital Converters with high: •	• Generate, modulate, amplify, filter signals with: • THz carrier frequencies f_c • Multi-GHz bandwidths B	• Control THz radiation in: • Transmission • Reception • Reflection ses

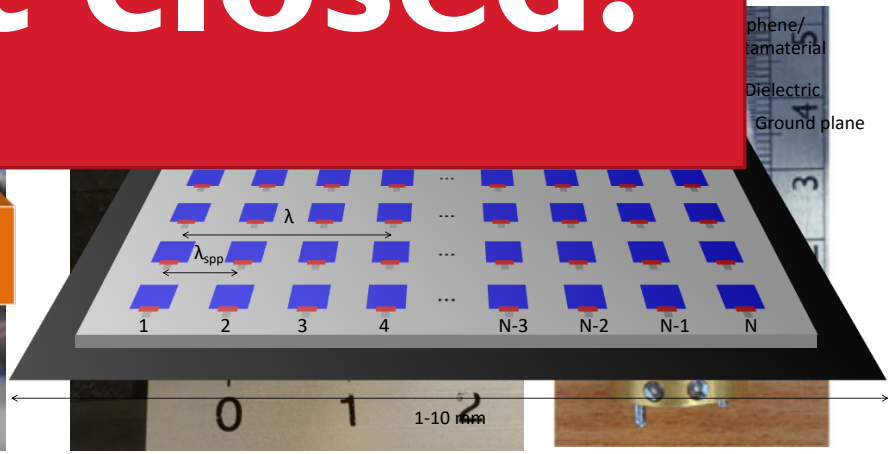
The gap is almost closed!

Available Today: RFSoC with 8 DAC/ADC channels at 4 GSps each



Coming up: Ultra-dense nano-electronic front-end, 200-240 GHz, 200 mW

Available today: electronic front-end, 200-240 GHz, 200 mW



Coming up: Plasmonic nano-antenna array with >1024 elements

Available today: Compact antennas with gain > 20 dBi

Our Platform: The TeraNova Testbed

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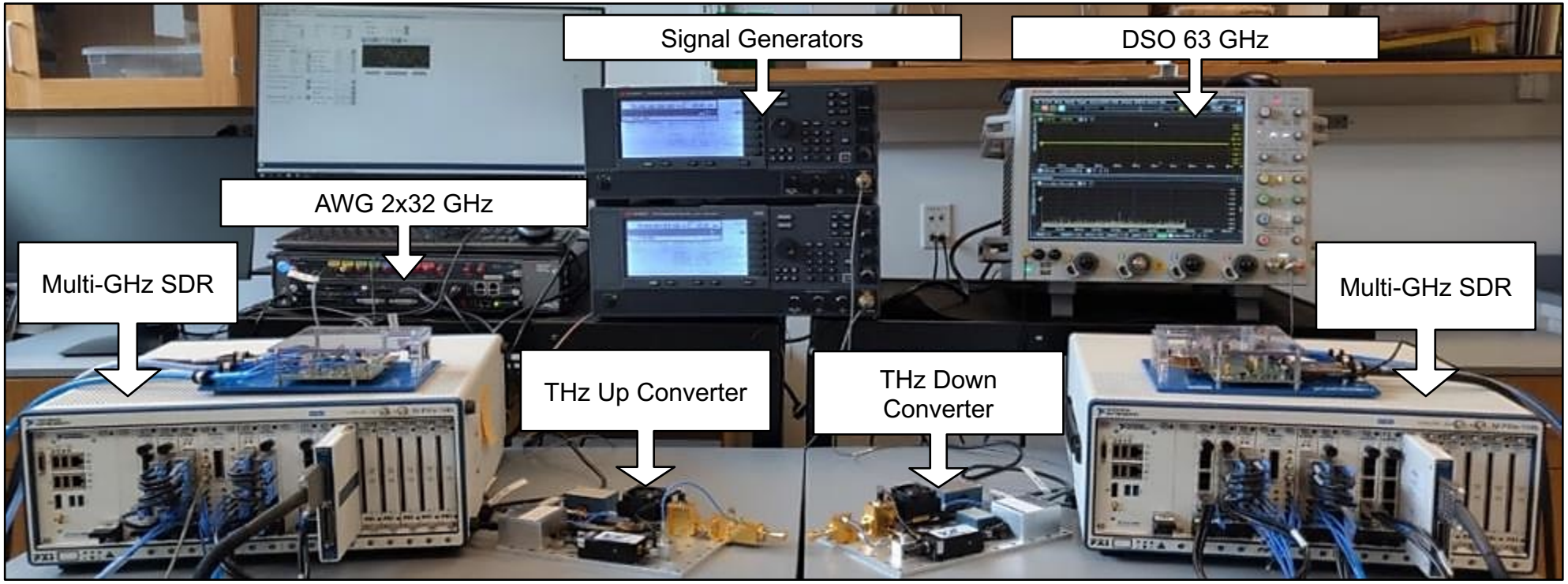
- The world's first integrated testbed for ultra-broadband communication networks in the THz band:
  - **Frequencies:** 120-140 GHz, 200-240 GHz, and 1-1.05 THz
  - **Bandwidths:** from 2 GHz to 32 GHz, per channel (data converters operating up to 92 GSps/160 GSps)



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P. Sen, V. Ariyarathna, A. Madanayake, and J. M. Jornet, **"Experimental Wireless Testbed for Ultrabroadband Terahertz Networks,"** Elsevier Computer Networks, 2021.
Shorter version in Proc. of ACM WiNTECH, 2020.

Answering Questions

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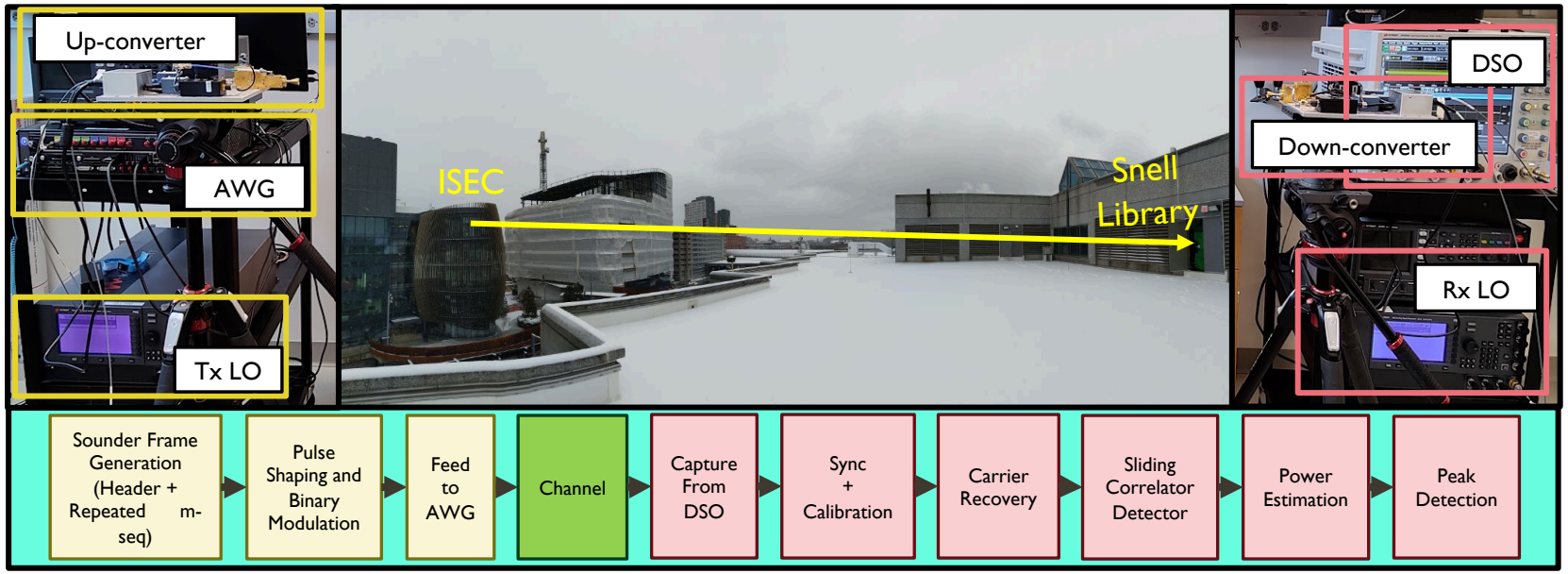
Can we use THz communications when it rains or snows?

- Standardization
- Policy and Regulation
- Networking
- Communications and Signal Processing
- **Propagation and Channel Modeling**
- Materials and Devices

Outdoor channel sounding campaign



- **Goal:** To characterize the impact of adverse weather (rain and snow) on terahertz links
- **Outcome:** it works! (but requires some smart physical layer solutions)

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P. Sen, J. Hall, M. Polese, V. Petrov, D. Bodet, T. Melodia, J. M. Jornet.
"Terahertz Communications Can Work in Rain and Snow: Impact of Adverse Weather Conditions on Channels at 140 GHz" to appear in **Proc. of ACM mmNets**, 2022.

Answering Questions

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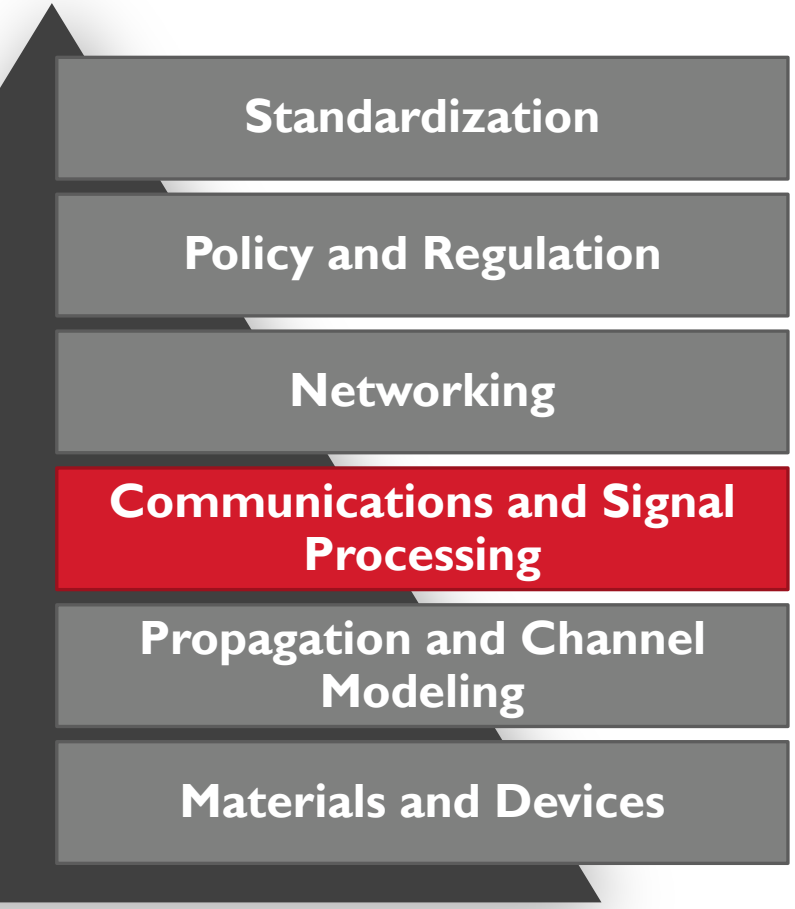
What Waveform Are We Going to Use?



- In the short range, where absorption is effectively non-existent:
  - **Femtosecond-long Pulse-based Communications**

J. M. Jornet and I. F. Akyildiz, **"Femtosecond-long Pulse-based Modulation for Terahertz Band Communication in Nanonetworks,"** IEEE Transactions on Communications, May 2014.

- For longer communication distances, where the **absorption broadening** results in a distance-dependent bandwidth
  - **Hierarchical Bandwidth Modulations**

D. Bodet, P. Sen, Z. Hossain, N. Thawdar and J. M. Jornet, **"Hierarchical Bandwidth Modulations for Ultra-broadband Communications in the Terahertz Band,"** IEEE Transactions on Wireless Communications, early access, 2022. Shorter version in IEEE ICC 2019.

- To both overcome frequency selectivity and facilitate spectrum sharing,
  - **Ultra-broadband Spread Spectrum (DSSS, CSS)**

C. Bosso, P. Sen, X. Cantos-Roman, C. Parisi, N. Thawdar and J. M. Jornet, **"Ultrabroadband Spread Spectrum Techniques for Secure Dynamic Spectrum Sharing Above 100 GHz Between Active and Passive Users,"** in **Proc. of IEEE DySPAN 2021.**

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Answering Questions

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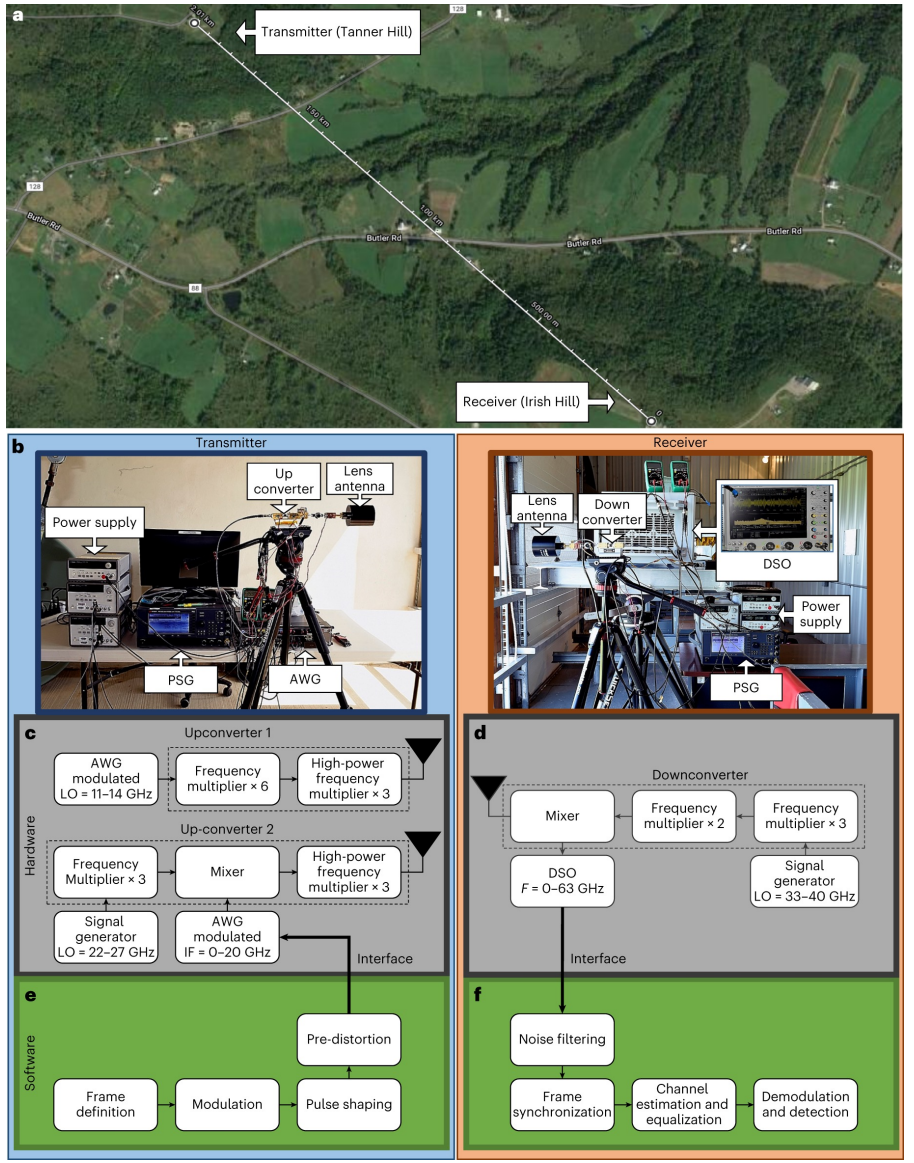
Are Terahertz Communications only for Short Links?

- Standardization
- Policy and Regulation
- Networking
- **Communications and Signal Processing**
- Propagation and Channel Modeling
- Materials and Devices

We have experimentally demonstrated a 2.03 km-long link at 225 GHz carrying multi-Gbps streams error free.

P. Sen, J.V. Siles, N. Thawdar and J. M. Jornet, **"Multi-kilometer Multi-gigabit-per-second (sub) Terahertz Communications,"** to appear in **Nature Electronics, 2023.**



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NASA JPL

Answering Questions

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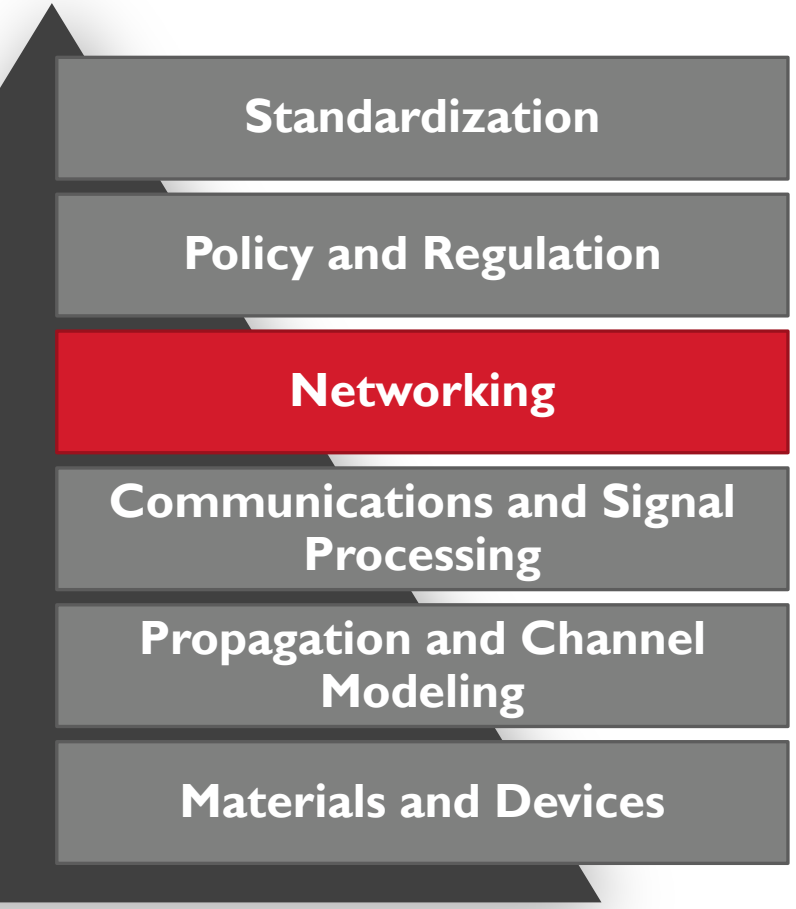
What Type of Protocols Do We Need?



- **Receiver-initiated MAC:**

  Q. Xia, Z. Hossain, M. Medley and J. M. Jornet, **"A Link-layer Synchronization and Medium Access Control Protocol for Terahertz-band Communication Networks,"** IEEE Transactions on Mobile Computing, 2021.

- **Expedited Neighbor Discovery:**

  Q. Xia and J. M. Jornet, **"Leveraging Antenna Side-lobe Information for Expedited Neighbor Discovery in Directional Terahertz Communication Networks,"** IEEE Transactions on Vehicular Technology, 2019.

- **Multi-hop Relaying:**

  Q. Xia and J. M. Jornet, **"Multi-hop Relaying Distribution Strategies for Terahertz-band Communication Networks: A Cross-layer Analysis,"** IEEE Transactions on Wireless Communications, 2022. Shorter version in IEEE WiMob 2017.

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Answering Questions

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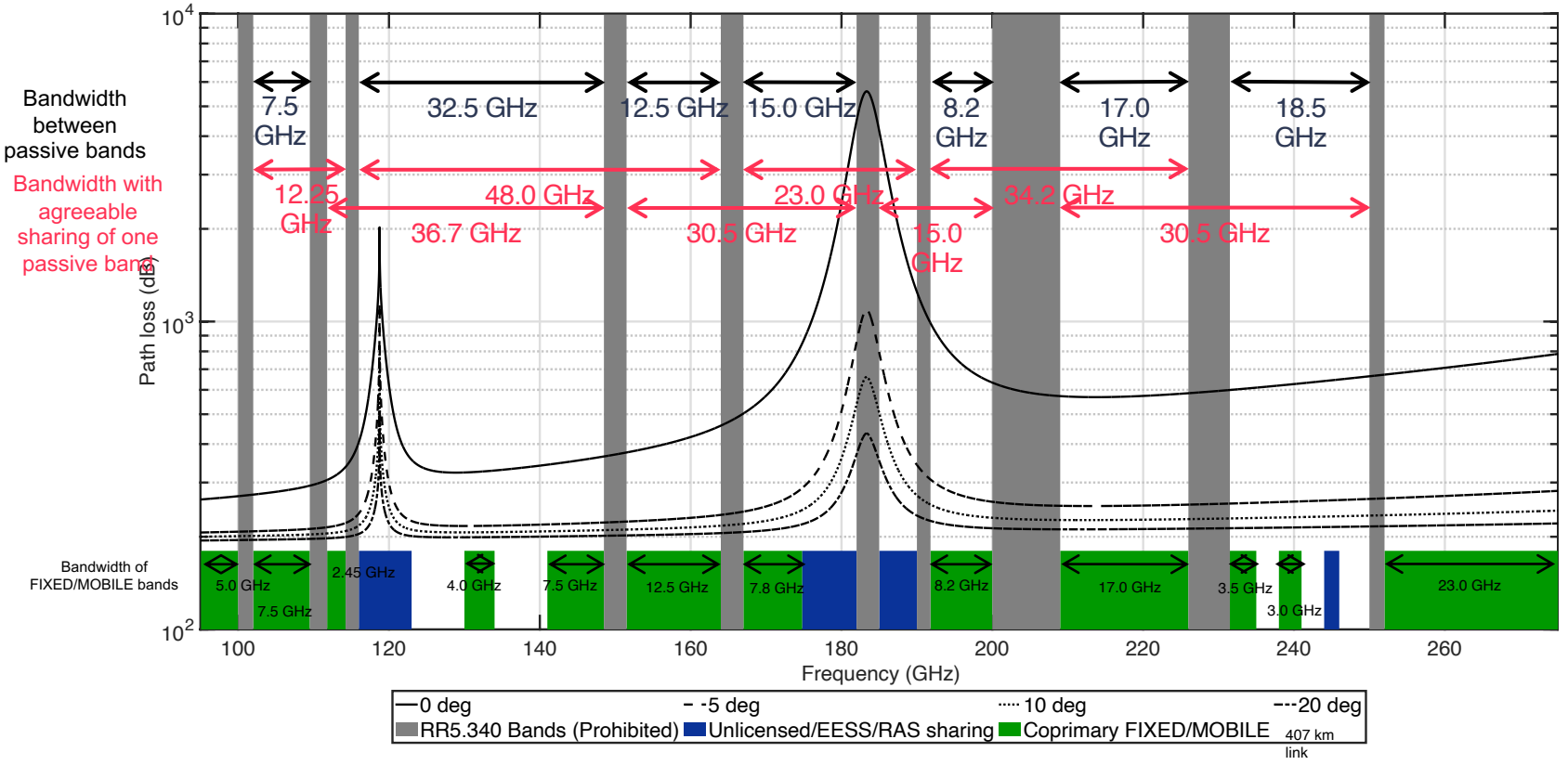
What Can We Legally Do above 100 GHz?

- Standardization
- **Policy and Regulation**
- Networking
- Communications and Signal Processing
- Propagation and Channel Modeling
- Materials and Devices



M. Polese, X. Cantos-Roman, A. Singh, M. Marcus, T. Maccarone, T. Melodia and J. M. Jornet, ***"Coexistence and Spectrum Sharing above 100 GHz"***, submitted for journal publication, 2021. arXiv:2110.15187

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Dynamic Spectrum Sharing for Coexistence

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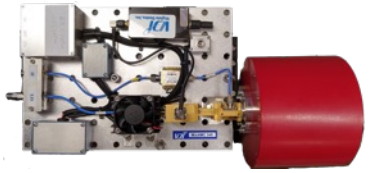
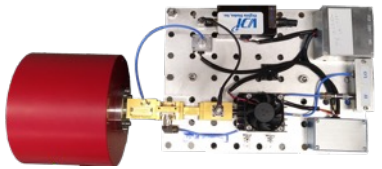
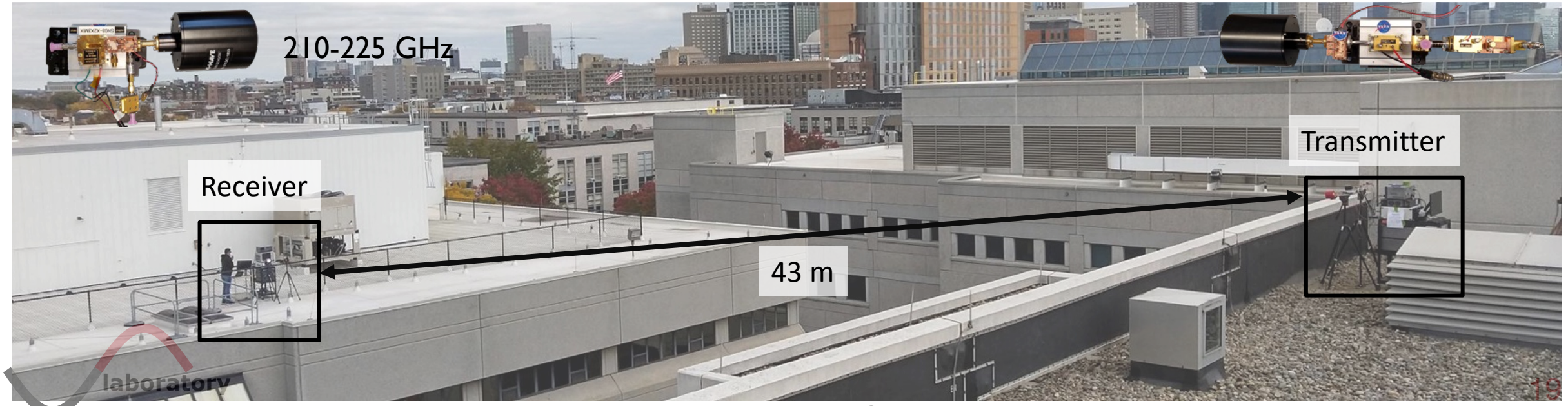
- **Our contribution:** we designed, built and tested a dual-band system able to switch between 120/240 GHz
  - Dynamically reconfigurable in real-time to avoid interference
  - Automated tracking of passive satellites

M. Polese, V. Ariyarathna, P. Sen, J.V. Siles, F. Restuccia, T. Melodia and J. M. Jornet, **"Dynamic Spectrum Sharing Between Active and Passive Users Above 100 GHz,"** **Nature Communications Engineering,** May 2022.



123.5-140 GHz





Many Pioneering Experiments

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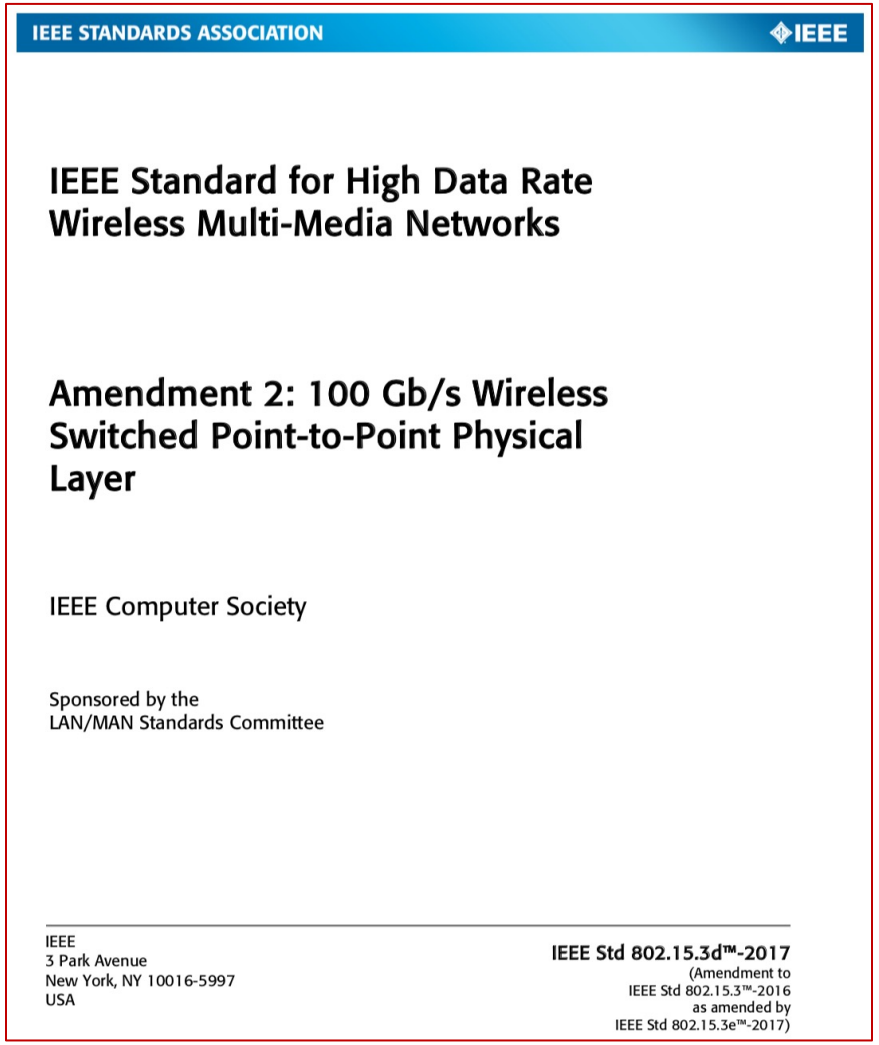
Are There Any Standards?

- **Standardization**
- Policy and Regulation
- Networking
- Communications and Signal Processing
- Propagation and Channel Modeling
- Materials and Devices



IEEE STANDARDS ASSOCIATION IEEE

IEEE Standard for High Data Rate Wireless Multi-Media Networks

Amendment 2: 100 Gb/s Wireless Switched Point-to-Point Physical Layer

IEEE Computer Society

Sponsored by the
LAN/MAN Standards Committee

IEEE
3 Park Avenue
New York, NY 10016-5997
USA

IEEE Std 802.15.3d™-2017
(Amendment to
IEEE Std 802.15.3™-2016
as amended by
IEEE Std 802.15.3e™-2017)

The standard is now under revision, and some of our results are in!

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Thank you!

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