Project: IEEE P802.15 Standing Committee Terahertz

Submission Title: Physical Layer Solutions to Maximize Throughput and Optimize Coexistence in the THz Band

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Abstract: Physical layer enhancements for throughput and coexistence are presented, namely a spread spectrum mode for coexistence, hierarchical bandwidth modulations for single-transmitter multiple-receiver scenarios, and MIMO systems.

Purpose: To share findings and stimulate discussion with SC THz

Physical Layer Solutions to Maximize Throughput and Optimize Coexistence in the THz Band

Motivations for Physical Layer Enhancements in the THz Band

- IEEE Std 802.15d-2017 was a strong first attempt to make THz research tangible
- Is there room for improvement?
  - Frequency Range: 252 GHz to 325 GHz
    - 15 GHz of spectrum is shared with sensitive passive devices
  - Optimizing performance of all THz devices
    - Communications (Ground-based, earth-to-satellite, intrasatellite, intrabody, etc.)
    - Sensing (Imaging, Radar, Spectroscopy, etc.)
  - Combining THz applications
    - Joint communications & sensing
- We want to do all this while also considering the THz band's unique properties.

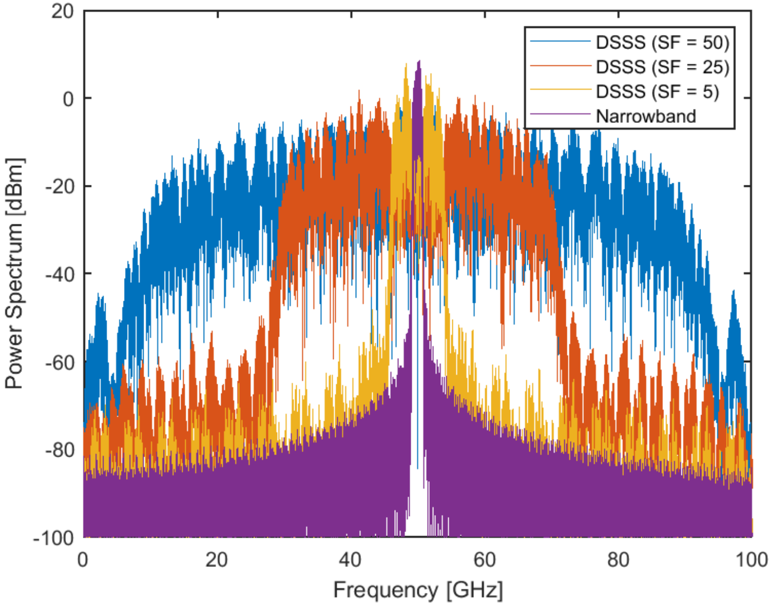
As a wireless communications group, we can speak to what kind of solutions allow for <u>coexistence between devices</u> and <u>optimize THz-band communications</u>.

Outline

- Solutions for Coexistence
  - Spread Spectrum
- Solutions for Maximizing Throughput
  - Hierarchical Bandwidth Modulations
  - MIMO

Co-existence using Direct Sequence Spread Spectrum

- Information signal is multiplied by a unique spreading sequence
  - Increases bandwidth while distributing power across the larger spectrum
- Shown to facilitate…
  - Increased security
  - Increased aggregate data rates
    - Parallel Spread Spectrum can allow for higher data rates [2]
  - Coexistence [1]
    - Other users in the same system (e.g. CDMA)
    - Narrowband active users (e.g. radar)
    - Passive sensing system (e.g., atmospheric sensing)



[1] Bosso, Christopher, et al. "Ultrabroadband Spread Spectrum Techniques for Secure Dynamic Spectrum Sharing Above 100 GHz Between Active and Passive Users." *2021 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*. IEEE, 2021.
[2] KrishneGowda, Karthik, et al. "Towards 100 Gbps wireless communication in THz band with PSSS modulation: A promising hardware in the loop experiment." *2015 IEEE International Conference on Ubiquitous Wireless Broadband (ICUWB)*. IEEE, 2015.

Enabling Coexistence with Passive Users through DSSS

DSSS is shown to allow for coexistence between narrowband passive users

NASA's Aura Satellite Coexistence Analysis

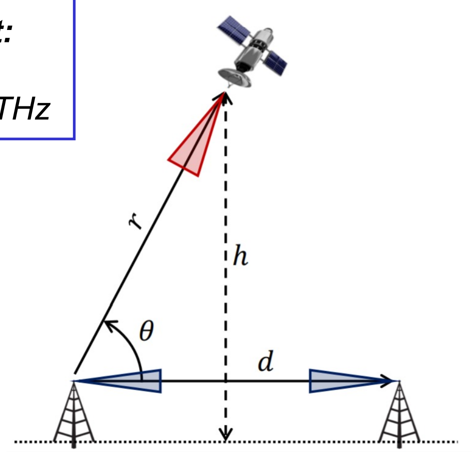
Sensitivity: *-166 dBW*

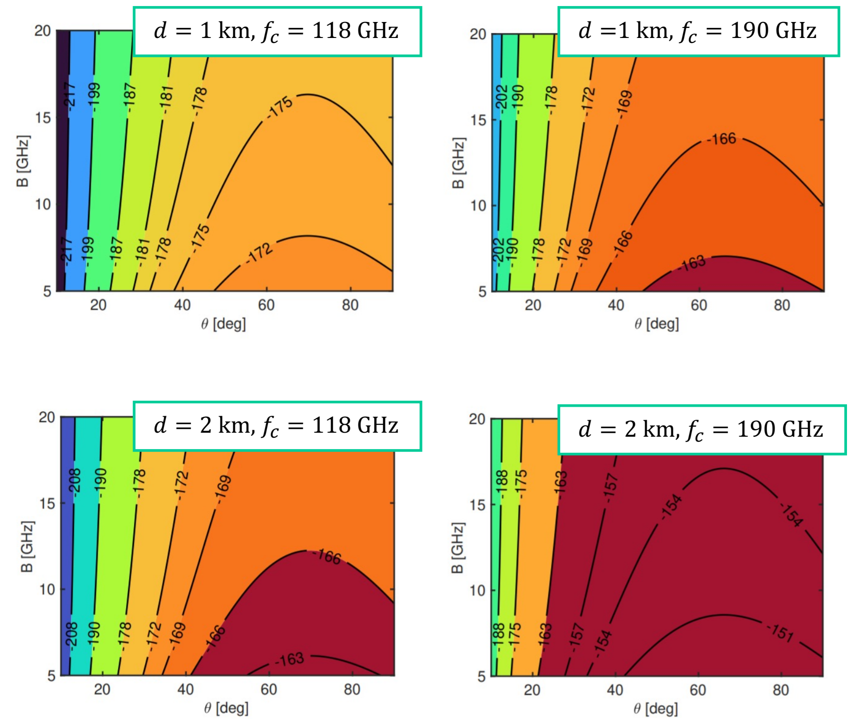
Height: *705 km*

Frequencies of Interest:

118 GHz, 190 GHz,

240 GHz, 640 GHz, 2.5 THz





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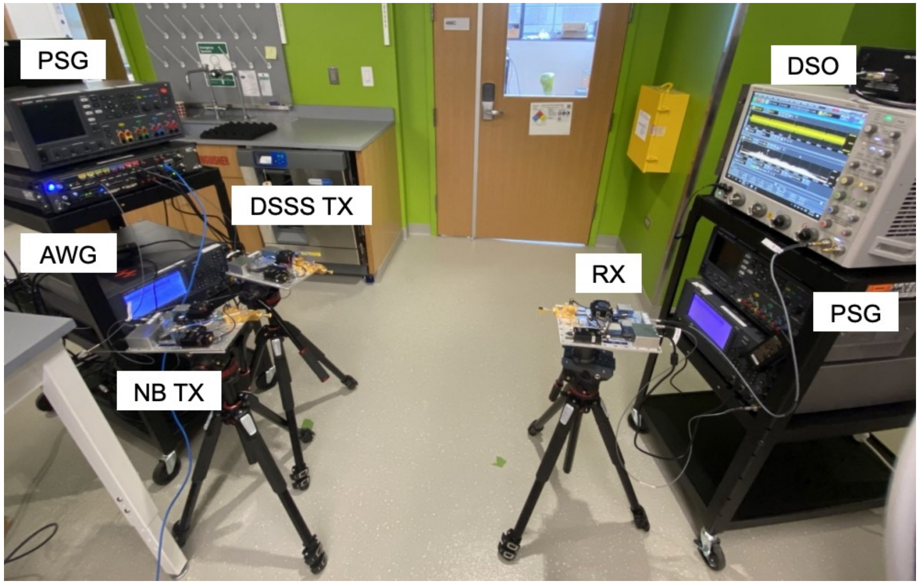
Experimental Results for Coexistence with DSSS

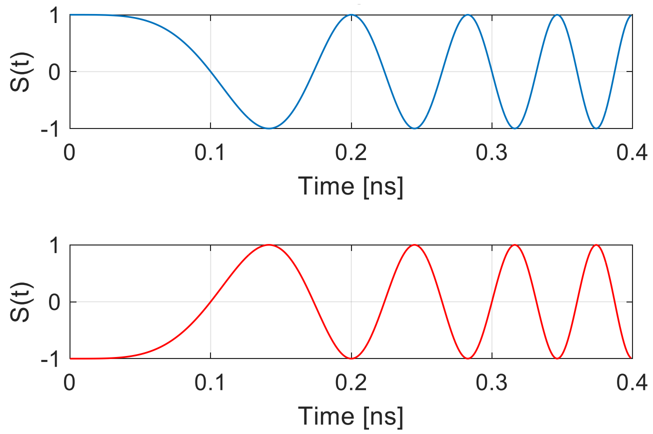
- Considering different transmit powers, transmission distances, and modulation orders we explore coexistence between a DSSS and NB user
- We observe what we would expect
  - The BER for DSSS and NB increase for lower spreading factors and higher modulation orders

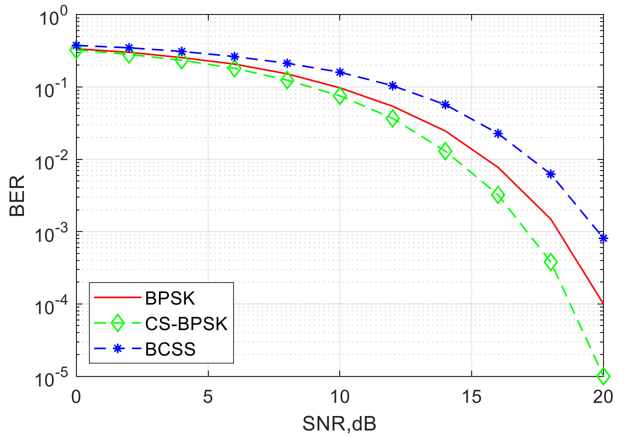


Bosso, Christopher, et al. "Ultrabroadband Spread Spectrum Techniques for Secure Dynamic Spectrum Sharing Above 100 GHz Between Active and Passive Users." *2021 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*. IEEE, 2021.

Phase-Modulated Chirp Signals

In order to coexist with devices, it might make sense to use parts of the spectrum that might be considered undesirable by some (i.e. transmitting over absorption lines).





- Power is spread over the bandwidth, which makes it robust against frequency-selective attenuation.
- Compatible with any phase-shift keying constellation

Sen, Priyangshu, Honey Pandey, and Josep M. Jornet. "Ultra-broadband chirp spread spectrum communication in the terahertz band." *Next-Generation Spectroscopic Technologies XIII*. Vol. 11390. International Society for Optics and Photonics, 2020.

Phase-Modulated Chirp Signals Experimental Results

- CS-BPSK outperforms BPSK and BCSS in the presence of absorption, aligning with our theoretical and analytical results

BPSK

Data rate (Gbps)	Dist. (cm)	SNR (dB)	BER
2.5	10	8.7	0
	20	2.5	1×10^{-2}
	30	-0.8	9×10^{-2}
5	10	6.8	1.6×10^{-3}
	20	0.8	7×10^{-2}
	30	-1.9	2.5×10^{-1}

BCSS

Data rate (Gbps)	Dist. (cm)	SNR (dB)	BER
2.5	10	7.7	8.4×10^{-4}
	20	2.5	2.5×10^{-2}
	30	-0.5	1.2×10^{-1}
5	10	6.1	4.1×10^{-3}
	20	1.2	1×10^{-1}
	30	-1.5	2.4×10^{-1}

CS-BPSK

Data rate (Gbps)	Dist. (cm)	SNR (dB)	BER
2.5	10	7.5	0
	20	2.8	1.4×10^{-2}
	30	0.1	8.4×10^{-2}
5	10	6	0
	20	1.5	4.7×10^{-2}
	30	-1.9	1.6×10^{-1}

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Outline

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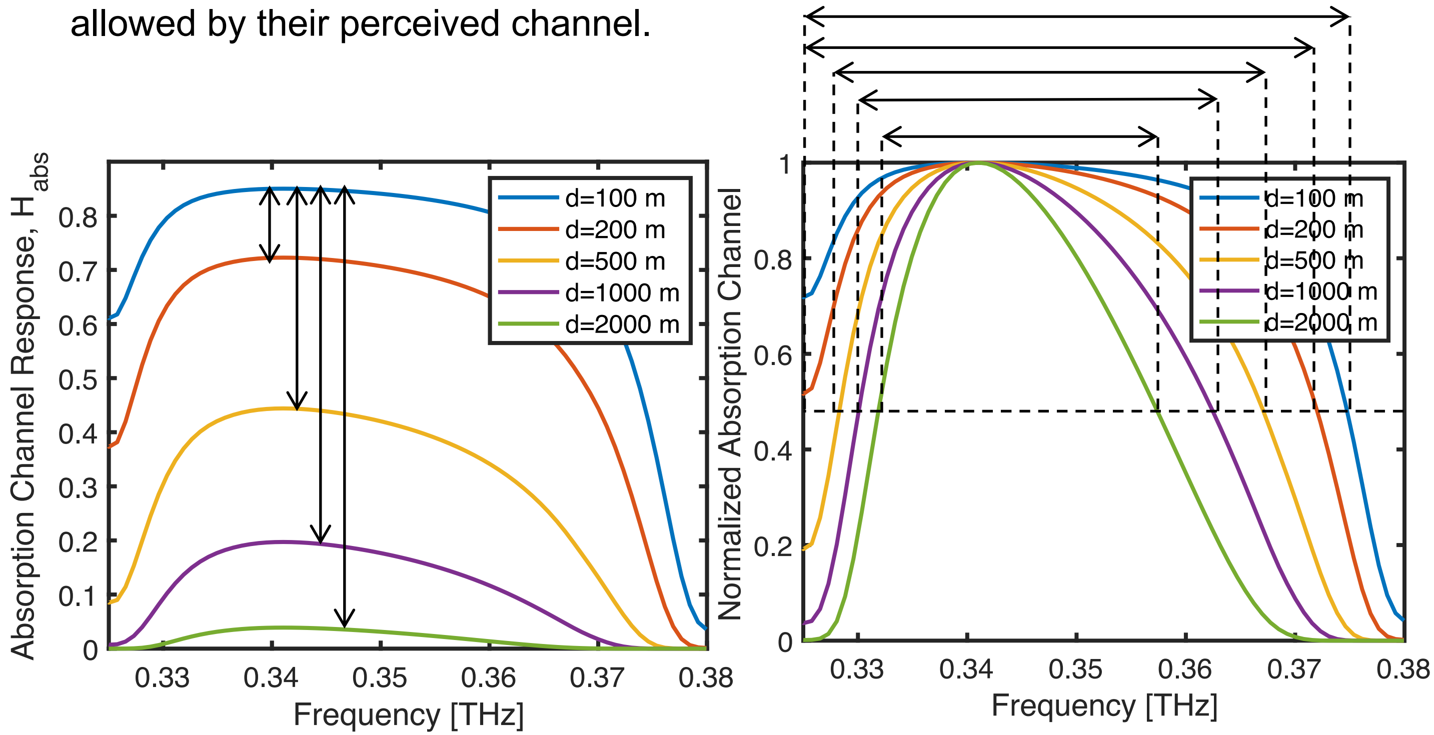
  - Spread Spectrum
- Solutions for Maximizing Throughput
  - Hierarchical Bandwidth Modulations
  - MIMO

Hierarchical Nature of Available Bandwidth at THz Frequencies

- Consider a single-transmitter multiple-receiver (STMR) system
  - Receivers closer to the transmitter have a wider available...
  - Ideally, we can service all receivers at the maximum rate (with the maximum bandwidth) allowed by their perceived channel.

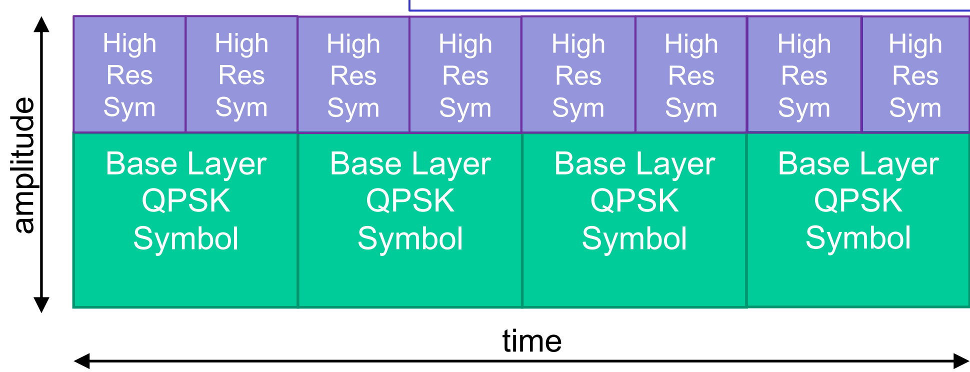


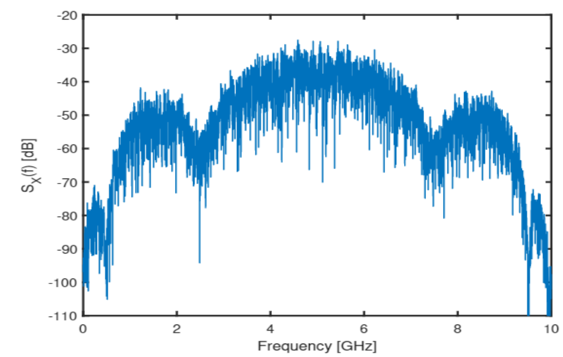
…HBM allows us to accomplish this by serving users at different symbol rates.

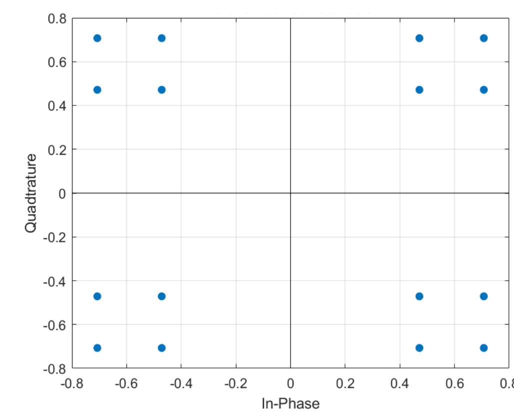
Coexistence Between Active Users via Hierarchical Bandwidth Modulations

- Inspired by distance-dependent bandwidth of the THz channel, HBM uses a hierarchical constellation to introduce a hierarchy in signal bandwidth to optimally serve users at different distances
- Enable more than point-to-point links currently available for the standard with little additional overhead

High Res Bitstream: 101100010101001
Base Layer Bitstream: 010100010010011

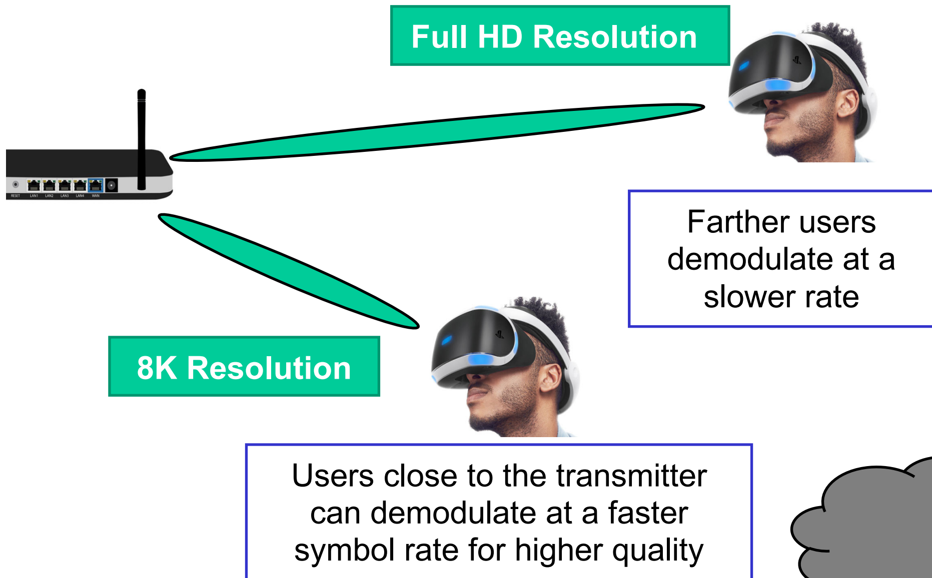




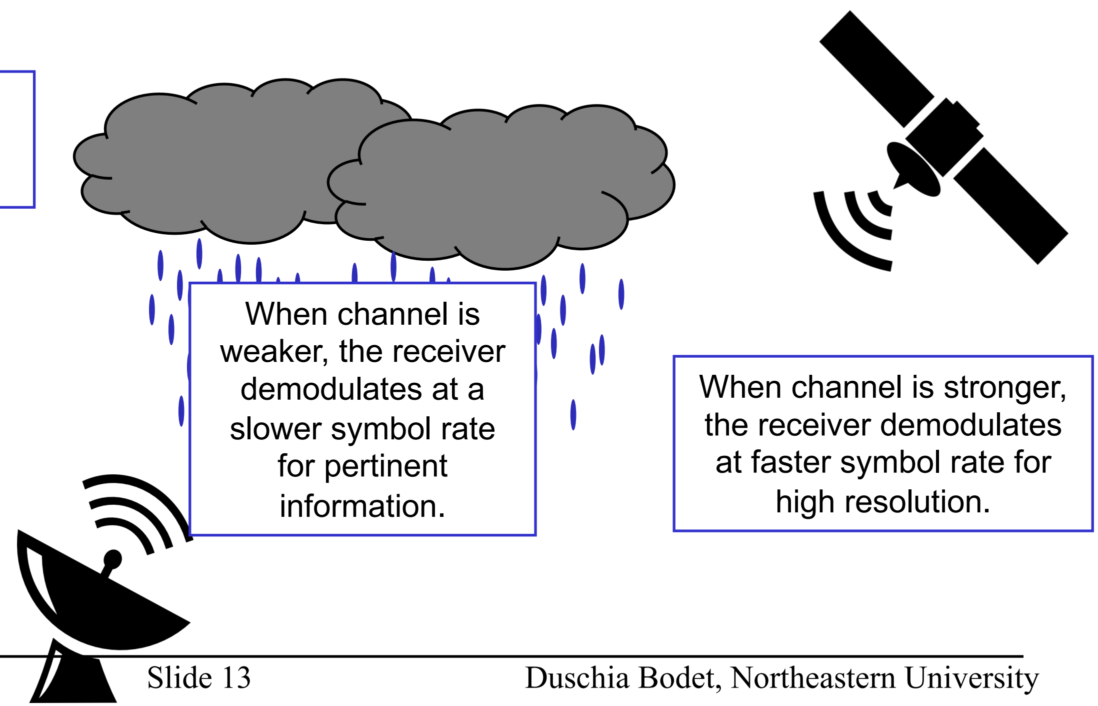


Hossain, Zahed, and Josep Miquel Jornet. "Hierarchical bandwidth modulation for ultra-broadband terahertz communications." *ICC 2019-2019 IEEE International Conference on Communications (ICC)*. IEEE, 2019.

Potential Applications for HBM



- High Resolution Virtual Reality Streaming
- Adaptable Point-to-point links

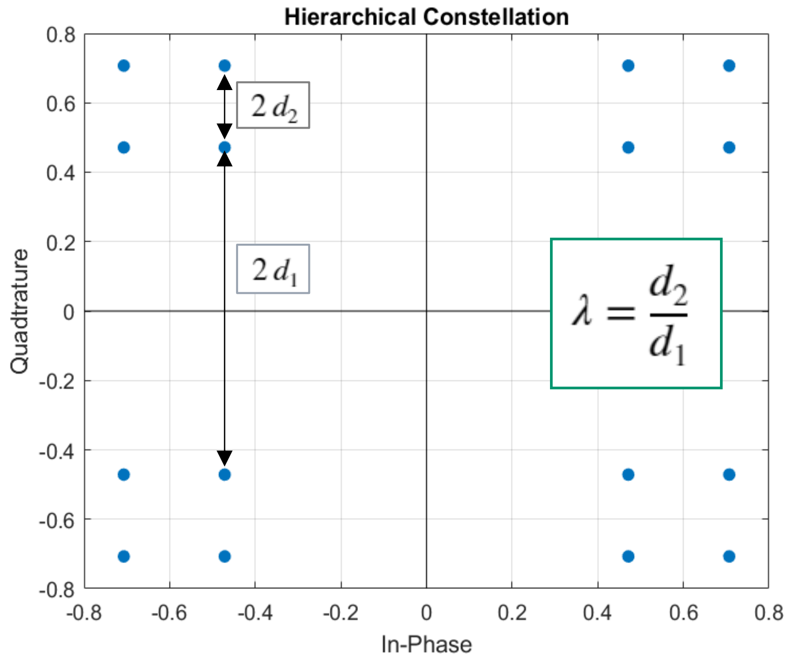


Design Considerations

- Power allocated to each resolution
  - Depends heavily on transmission distances and observed Es/No values at the receivers
- Thresholds for switching resolutions at the receiver
  - Depends on the speed of channel variations

$$\mathrm{SER}_{\mathrm{LowRes}} = Q\left(\sqrt{\frac{\frac{E'_s}{N_0}}{1+2\lambda+2\lambda^2}}\right) + Q\left((1+2\lambda)\sqrt{\frac{\frac{E'_s}{N_0}}{1+2\lambda+2\lambda^2}}\right)$$

$$\mathrm{SER}_{\mathrm{HighRes}} = 2\,Q\left(\lambda\sqrt{\frac{\frac{E_s}{N_0}}{1+2\lambda+2\lambda^2}}\right) + Q\left(\sqrt{\frac{\frac{E_s}{N_0}}{1+2\lambda+2\lambda^2}}\right)$$



Duschia Bodet, Priyangshu Sen, Zahed Hossain, Ngwe Thawdar, and Josep Miquel Jornet. "Hierarchical bandwidth modulation for ultra-broadband communications in the Terahertz Band." submitted for journal publication 2022.

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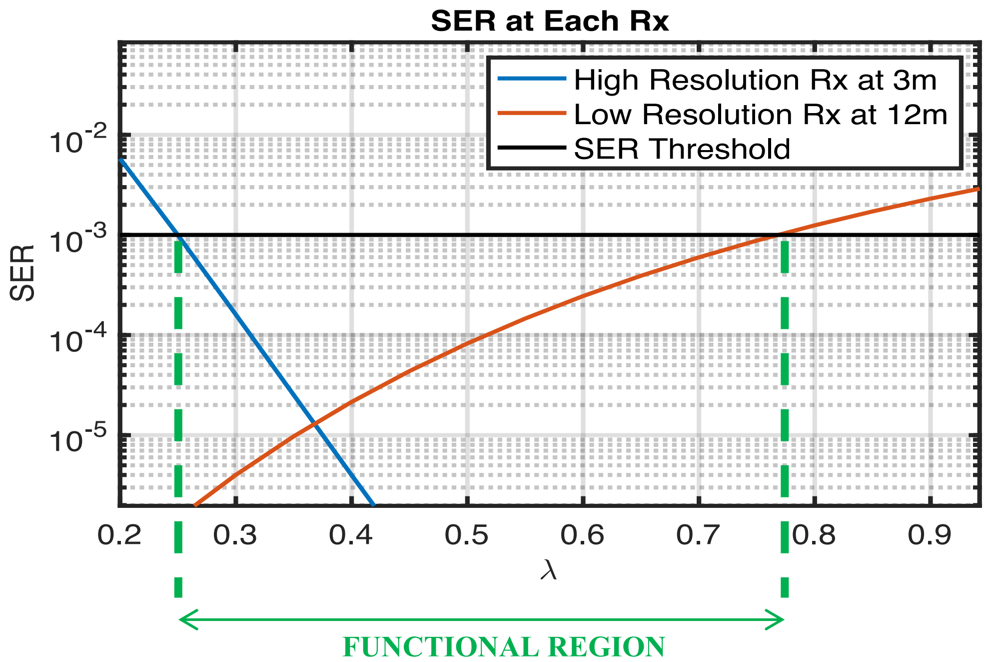

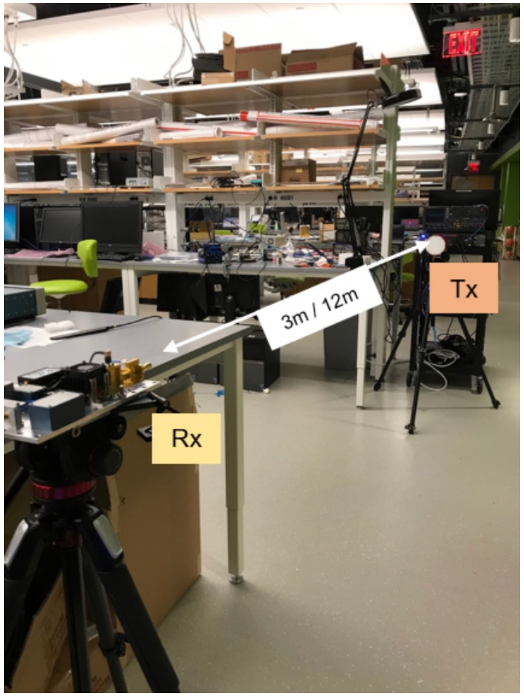

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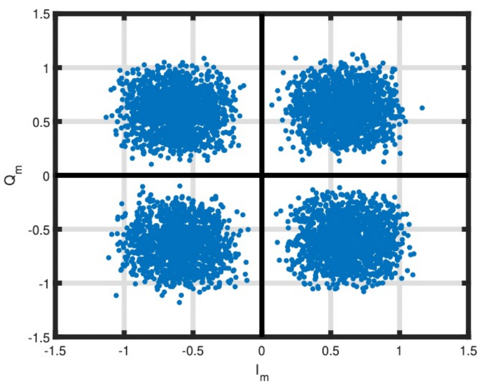
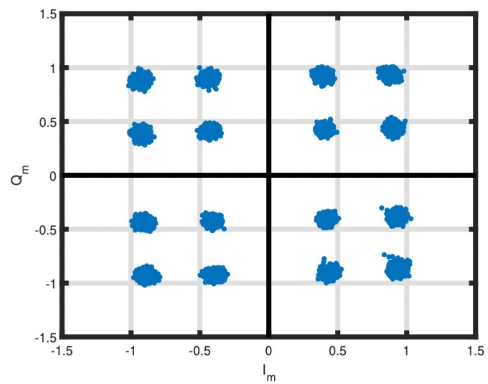


$Low\ Resolution\ \lambda = 0.6$



$High\ Resolution\ \lambda = 0.6$

Experimental Validation

λ	LR SER	HR SER
0.2	$1.25 * 10^{-4}$	$1.12 * 10^{-2}$
0.4	$< 8.3 * 10^{-5}$	$2.167 * 10^{-4}$
0.6	$6.667 * 10^{-4}$	$8.33 * 10^{-5}$
0.9	$3.8 * 10^{-3}$	$1.0 * 10^{-4}$

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Design Considerations for HBM

- Thresholds for switching resolutions at the receiver
  - Depends on how often system performs equalization
  - Depends on the speed of channel variations

Function of how quickly channel fluctuates, and frame duration (establishes a buffer)

Switching from Low to High

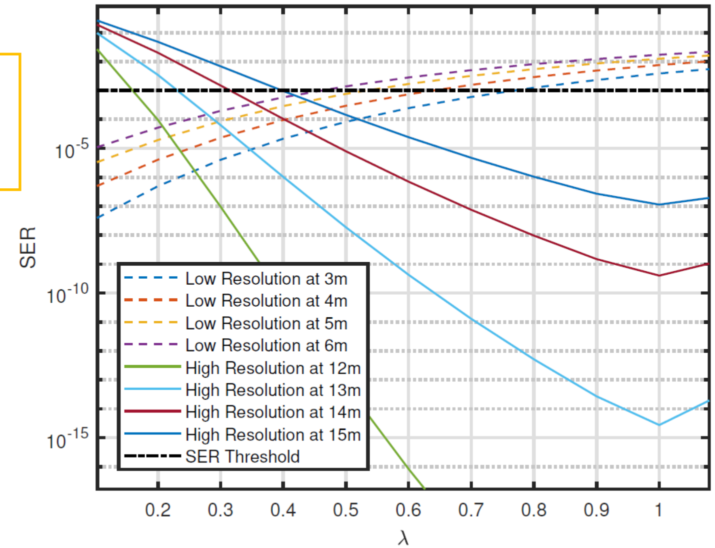
$$\frac{E_s}{N_0}_{LowHighTh}[dB] = \frac{E_s}{N_0}_{ThHigh}[dB] + \alpha[dB] + \beta[dB]$$

Switching from High to Low

$$\frac{E_s}{N_0}_{HighLowTh}[dB] = \frac{E_s}{N_0}_{ThHigh}[dB] + \alpha[dB]$$

Corresponds to SER Threshold (absolute threshold)

Function of how quickly channel fluctuates, frame duration, and number of consecutive frames that should demodulate with same resolution (establishes a transition region for less flip-flopping)



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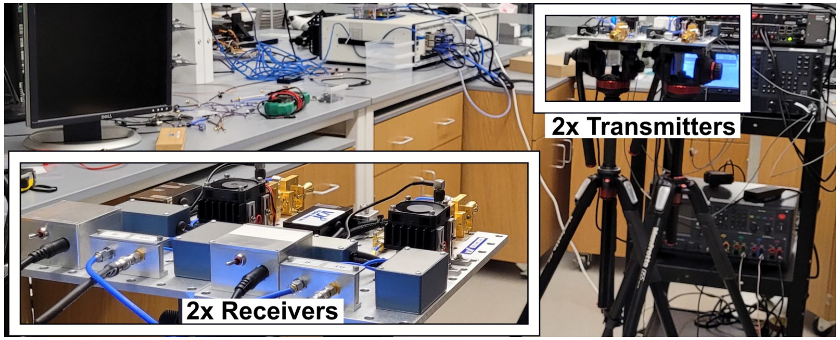
Hierarchical Bandwidth Modulations

- Enables multiple-receiver systems
- Enables higher aggregate data rates than traditional hierarchical or time-sharing techniques
- Flexible
  - Can be implemented with any hierarchical constellation
  - Allows for receiver flexibility based on experienced channel
- Still works when no absorption lines are present

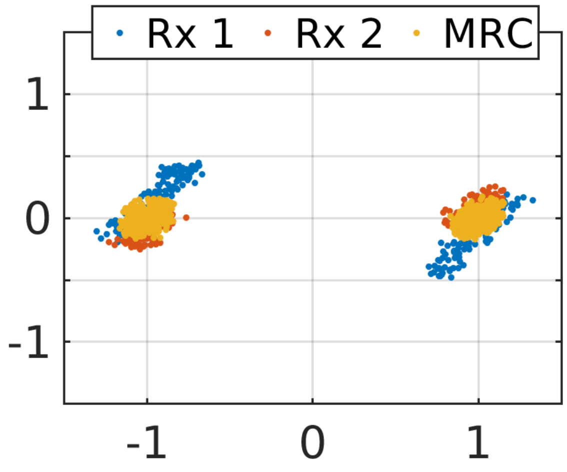
MIMO for THz Communications

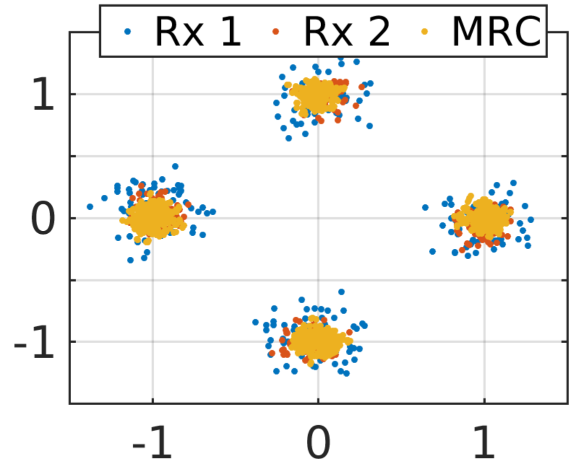
- There is a need to connect theoretical predictions with current hardware capabilities
  - UM-MIMO (1024 x 1024) [1]
  - Achievable Hardware (128 x 128) [2]
- Considering some practical challenges to bridging this divide [3]
  - Inter-Symbol Interference from back-and-forth reflections
  - Antenna element beamwidth effect on performance

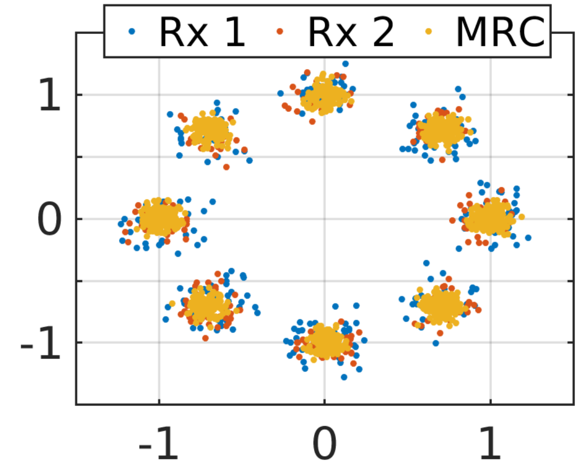


[1] Akyildiz, Ian F., and Josep Miquel Jornet. "Realizing ultra-massive MIMO (1024× 1024) communication in the (0.06–10) terahertz band." *Nano Communication Networks* 8 (2016): 46-54.
[2] Abu-Surra, Shadi, et al. "End-to-end 140 GHz Wireless Link Demonstration with Fully-Digital Beamformed System." *2021 IEEE International Conference on Communications Workshops (ICC Workshops)*. IEEE, 2021.
[3] Duschia Bodet and Josep Miquel Jornet. “Impact of Antenna Element Directivity and Reflection-Interference on Line-of-Sight Multiple Input Multiple Output Terahertz Systems” accepted by *URSI AT-AP-RASC February 2022.*

MIMO Experimental Results







Modulation	1x1 EVM	2x2 EVM		
	8° Antennas	1.6° Antennas	8° Antennas	ISI Mitigation
QPSK	20.2%	18.91%	16.4%	13.27%
8PSK	21.4%	16.27%	12.1%	11.47%

[1] D. Bodet and J. M. Jornet, *“Impact of Antenna Element Directivity and Reflection-Interference on Line-of-sight MIMO for Terahertz Systems,”* URSI AT-AP-RASC, May 2022.

J. Hall, D. Bodet, and J. M. Jornet, *“Experimental Demonstration of Multiple Input Multiple Output Communications above 100 GHz,”* to appear in Proc. of the IEEE International Conference on Computer Communications, May 2022.

Conclusion

- We have explored solutions for coexistence and for maximizing throughput of THz-band communications
  - Spread Spectrum
  - Hierarchical Bandwidth Modulations
  - MIMO
- There are other exciting areas where we can optimize the THz band that we will continue to explore
  - MAC protocols
  - Joint Communications & Sensing
  - Networking
  - Channel Sounding

Thank You

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