Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: Enhancements to the Physical Layer of IEEE 802.15.3d for Increased Data Rate and Coexistence

Date Submitted: 4 March 2022

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Re: TG3ma Call for Proposals IEEE P802.15-3ma/0071-01 | IEEE Standard for High Data Rate Wireless Multi-Media Networks IEEE 802.15.3d

Abstract: Three enhancements to IEEE 802.15.3d are proposed, namely higher order APSK constellations, a spread spectrum mode for coexistence with passive users, and hierarchical bandwidth modulations for single-transmitter multiple-receiver scenarios.

Purpose: For consideration to edit IEEE 80d.15.3d Standard

IEEE P802.15.3ma Proposal: Enhancements to the Physical Layer of IEEE 802.15.3d for Increased Data Rate and Coexistence

Motivations for Updating Std 802.15d-2017

- 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

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

Outline

- Propose 3 Physical Layer Solutions for 802.15.3d
  - Higher Order APSK Constellations
  - Spread Spectrum for Coexistence
  - Hierarchical Bandwidth Modulations

Solutions that have been experimentally verified to improve performance for THz communications

- Other Interesting Topics for Consideration for improving 802.15.3d
  - OFDM
  - MAC Protocols

Solutions that may be appropriate for this standard

- Discuss Future Considerations for 802.15.3d
  - MIMO
  - Joint Communications & Sensing

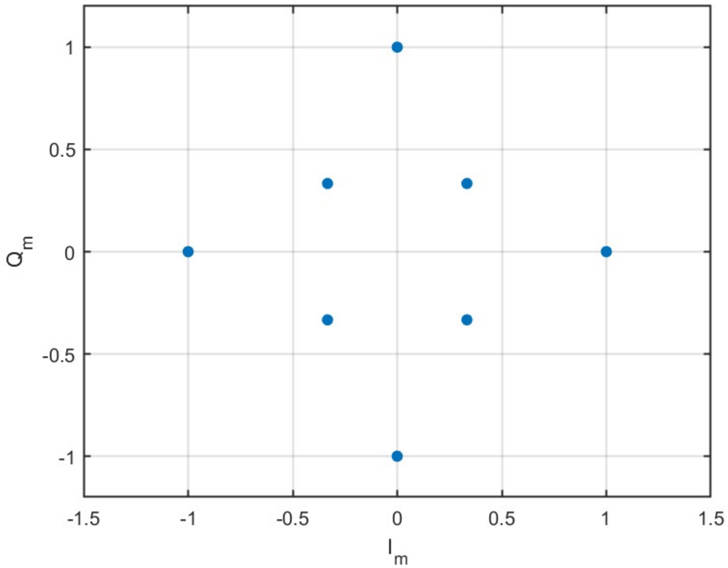
Solutions that are promising but are not yet ready for standardization

Proposals for IEEE 802.15.3d

1. Standardizing the **optimized 16-APSK and 32-APSK for THz-SC** Mode [Sec. 13.2.2.1]
2. Introducing a **new mode: THz-SS to implement spread spectrum solutions** for bands shared with passive devices and for communication over absorption lines [Sec. 13]
    1. Direct Sequence Spread Spectrum
    2. Chirp Spread Phase-Shift Keying
3. Introducing a **new mode: THz-HBM to facilitate single-transmitter multiple-receiver links** using hierarchical bandwidth modulations [Sec. 13]

Current Physical Layer Design

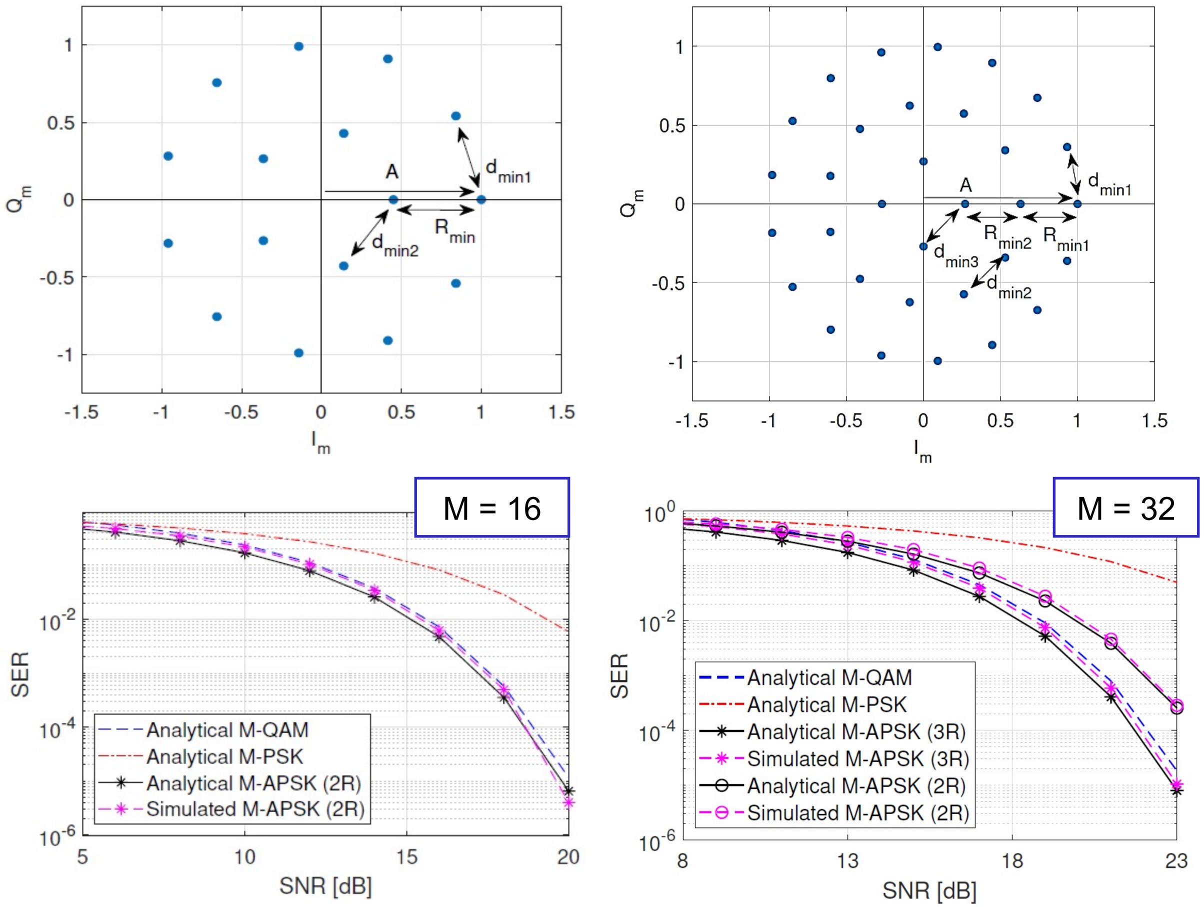
- Two modes of operation
  - THz-SC : BPSK, QPSK, 8PSK, 8APSK, 16QAM, 64QAM
  - THz-OOK
- We were excited to see the APSK constellation integrated into the standard IEEE 802.15.3d [Sec. 13.2.2.1]
  - Reduces Peak-to-Average-Power (PAPR) problem compared to M-QAM
  - Improved SER compared to M-PSK and M-QAM



Modulation	PAPR [dB]
8 PSK	0
8 QAM	7.78
8 APSK	3.98

Higher Order APSK Constellation

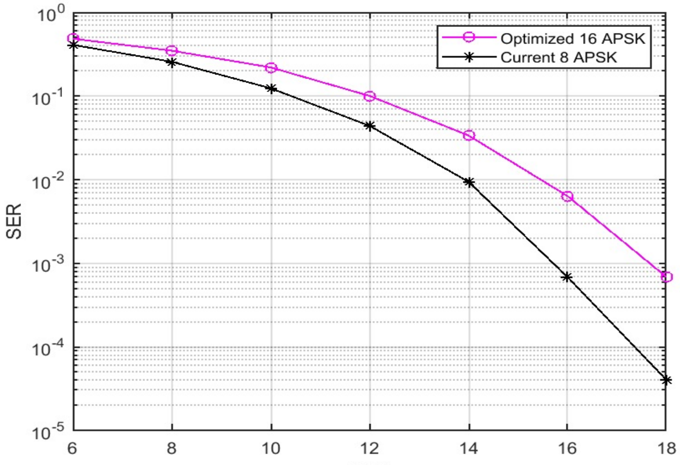
- The APSK constellation was optimized for a 2-Ring 16-APSK and a 3-Ring 32-APSK
  - Outperforms both QAM and PSK



P. Sen, V. Ariyarathna and J. M. Jornet, "An Optimized M-ary Amplitude Phase Shift Keying Scheme for Ultrabroadband Terahertz Communication," *2022 IEEE 19th Annual Consumer Communications & Networking Conference (CCNC)*, 2022, pp. 661-666, doi: 10.1109/CCNC49033.2022.9700581.

Higher Order APSK Constellation

- Reduces PAPR compared to current case
  - Also compared to M-QAM
- Improves SER performance compared to M-PSK and M-QAM
- Doubles or Quadruples the data rate of the standard for only ~2dB increase in SNR



Modulation	PAPR [dB]		
	M = 8 (standard)	M = 16 (optimized)	M = 32 (optimized)
PSK	0	0	0
QAM	2.22	2.5	3.2
APSK 2R	2.06	1.22	1.08
APSK 3R	-	-	1.73

We propose standardizing the optimized 2-Ring 16-APSK and 3-Ring 32-APSK for 802.15.3d

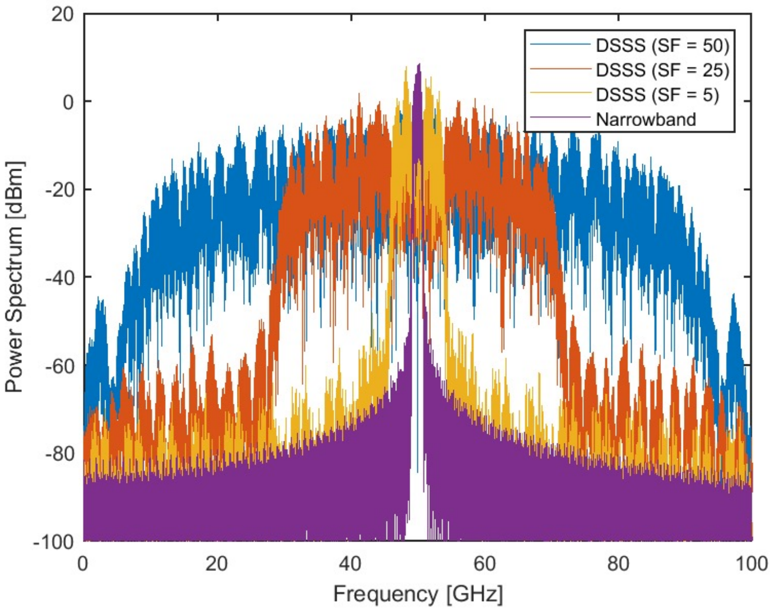
P. Sen, V. Ariyarathna and J. M. Jornet, "An Optimized M-ary Amplitude Phase Shift Keying Scheme for Ultrabroadband Terahertz Communication," *2022 IEEE 19th Annual Consumer Communications & Networking Conference (CCNC)*, 2022, pp. 661-666, doi: 10.1109/CCNC49033.2022.9700581.

Proposals for IEEE 802.15.3d

1. Standardizing the **optimized 16-APSK and 32-APSK for THz-SC** Mode [Sec. 13.2.2.1]
2. Introducing a **new mode: THz-SS to implement spread spectrum solutions** for bands shared with passive devices and for communication over absorption lines [Sec. 13]
    1. Direct Sequence Spread Spectrum
    2. Chirp Spread Phase-Shift Keying
3. Introducing a **new mode: THz-HBM to facilitate single-transmitter multiple-receiver links** using hierarchical bandwidth modulations [Sec. 13]

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)

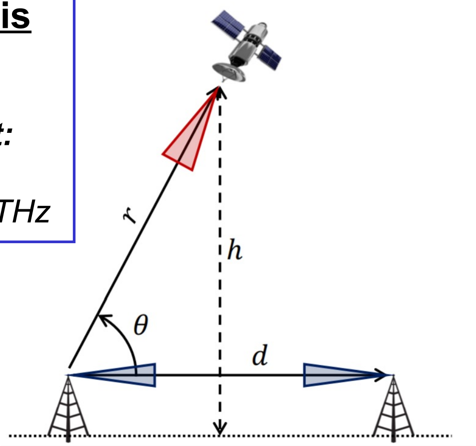


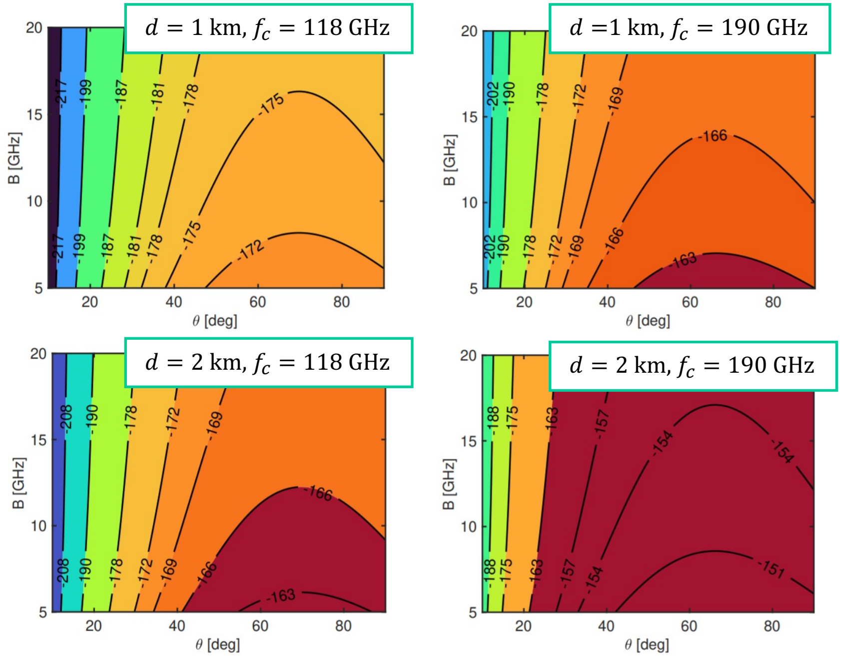
[1] Bosso, Christopher, et al. "Ultrabroadband Spread Spectrum Techniques for Secure Dynamic Spectrum Sharing Above 100 GHz Between Active and Passive Users." *2021 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*. IEEE, 2021.
[2] KrishneGowda, Karthik, et al. "Towards 100 Gbps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

<u>NASA's Aura Satellite Coexistence Analysis</u>
Sensitivity: *-166 dBW*
Height: *705 km*
Frequencies of Interest:
118 GHz, 190 GHz,
240 GHz, 640 GHz, 2.5 THz



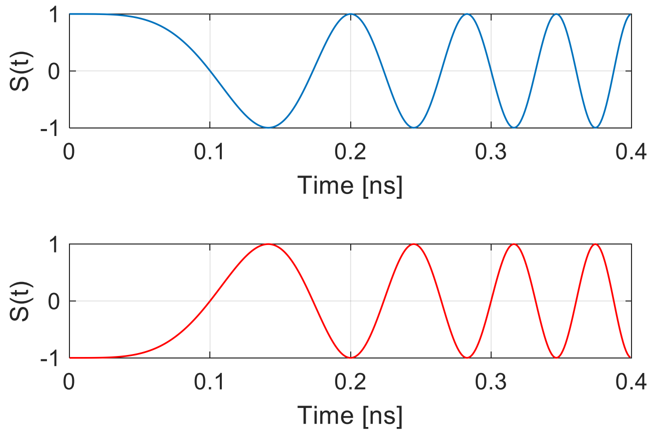


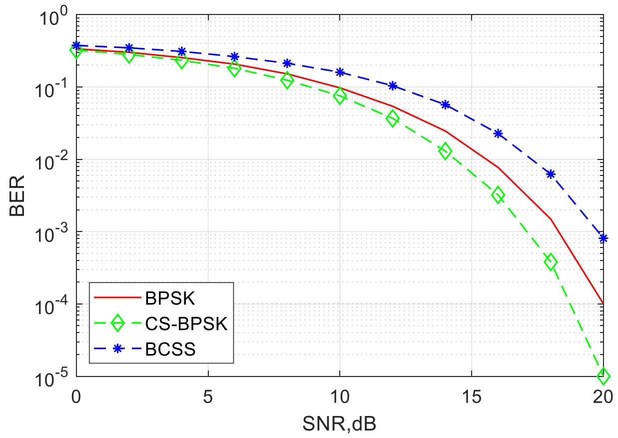
We propose standardizing DSSS for coexistence with passive sensing devices

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

We propose standardizing Chirp Spread Phase Shift Keying for communication over absorption lines

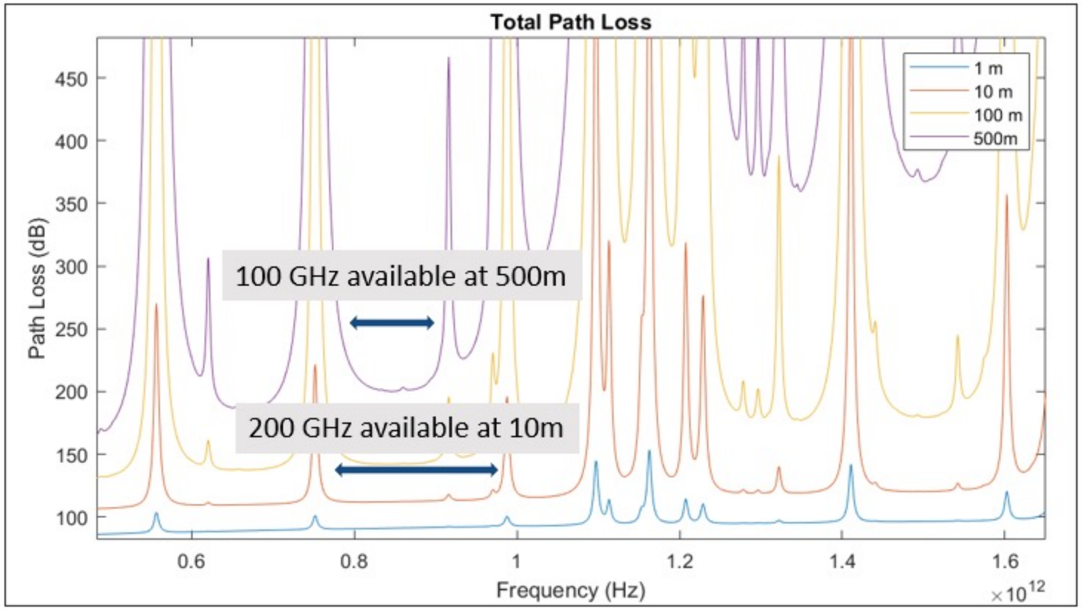
Sen, Priyangshu, Honey Pandey, and Josep M. Jornet. "Ultra-broadband chirp spread spectrum communication in the terahertz band." *Next-Generation Spectroscopic Technologies XIII*. Vol. 11390. International Society for Optics and Photonics, 2020.

Proposals for IEEE 802.15.3d

1. Standardizing the **optimized 16-APSK and 32-APSK for SC-THz** Mode [Sec. 13.2.2.1]
2. Introducing a **new mode: THz-SPR to implement spread spectrum solutions** for bands shared with passive devices and for communication over absorption lines [Sec. 13]
    1. Direct Sequence Spread Spectrum
    2. Chirp Spread Phase-Shift Keying
3. Introducing a **new mode: THz-HBM to facilitate single-transmitter multiple-receiver links** using hierarchical bandwidth modulations [Sec. 13]

Hierarchical Nature of Available Bandwidth in at THz Frequencies

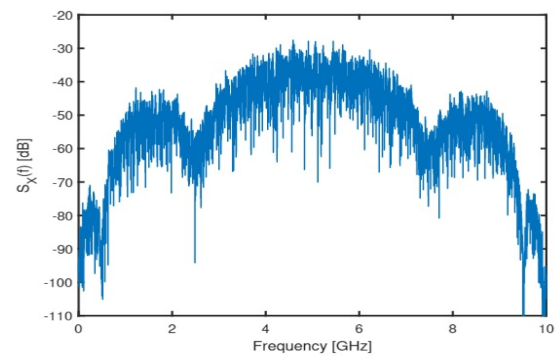
- Consider a single-transmitter multiple-receiver (STMR) system at ~850 GHz
  - Receivers closer to the transmitter will have a wider available bandwidth than receivers farther away from the transmitter...
  - Ideally, we would be able to service both these receivers at the maximum rate (with the maximum bandwidth) allowed by their perceived channel.



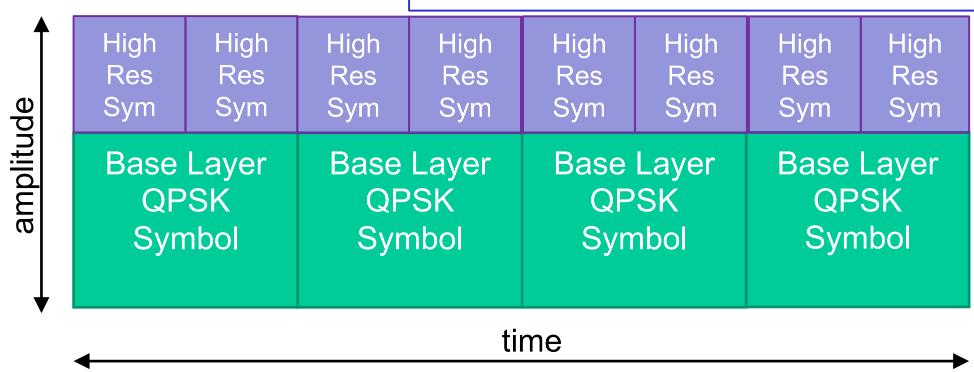
…HBM allows us to accomplish this by serving users at different symbol rates.

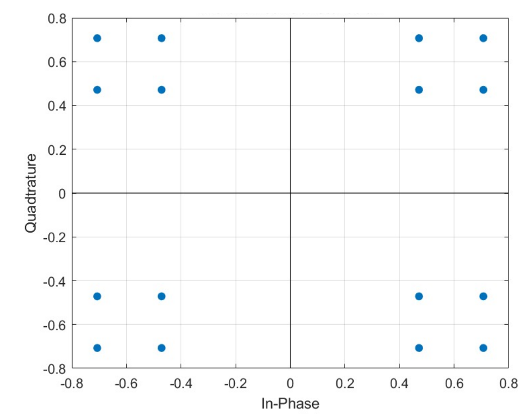
Coexistence Between Active Users via Hierarchical Bandwidth Modulations

- 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

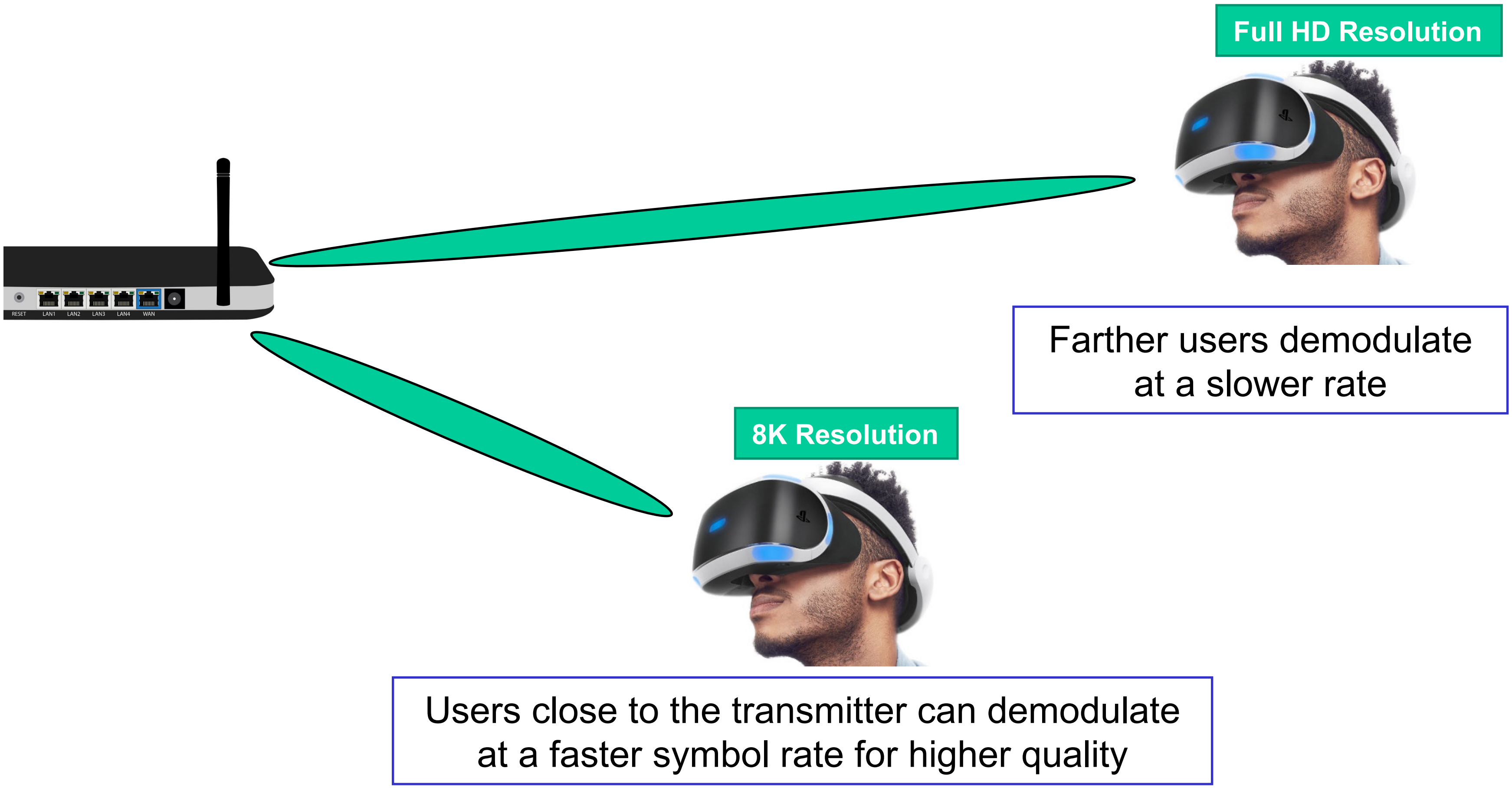




Hossain, Zahed, and Josep Miquel Jornet. "Hierarchical bandwidth modulation for ultra-broadband terahertz communications." *ICC 2019-2019 IEEE International Conference on Communications (ICC)*. IEEE, 2019.

Potential Application for HBM

- Video or Virtual Reality Streaming

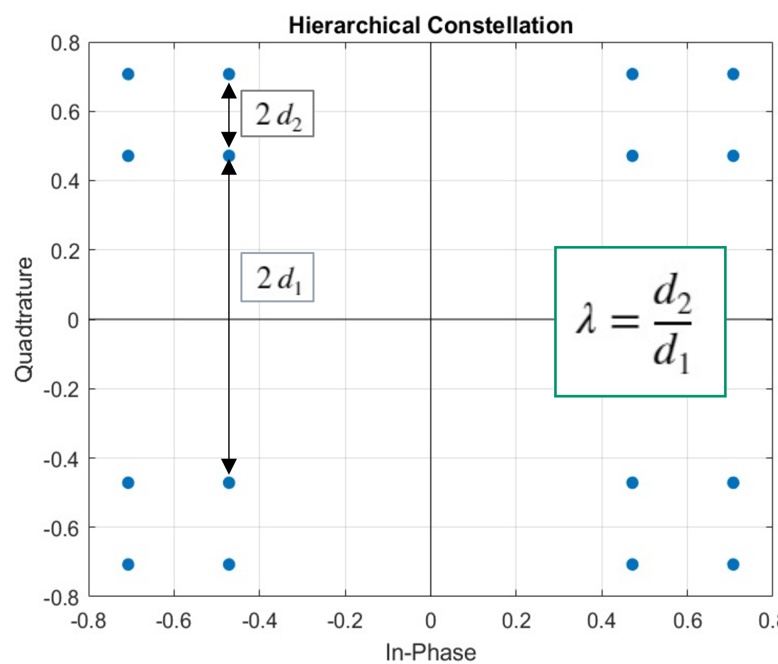


Design Considerations

- 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

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

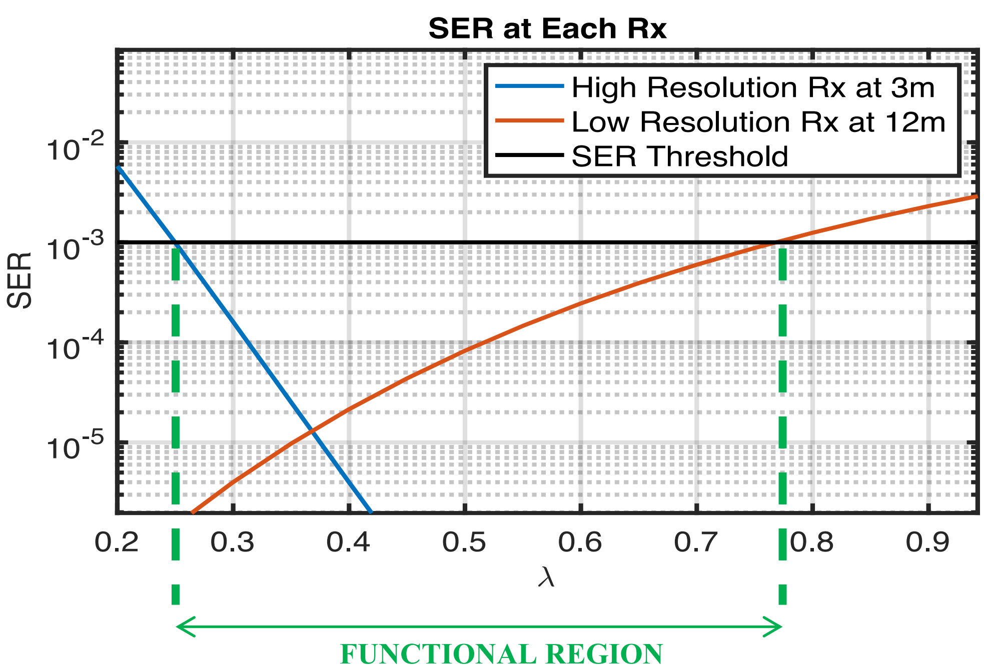
$$\mathrm{SER}_{\mathrm{HighRes}} = 2\,Q\left(\lambda\sqrt{\frac{\frac{E_s}{N_0}}{1+2\lambda+2\lambda^2}}\right) + Q\left(\sqrt{\frac{\frac{E_s}{N_0}}{1+2\lambda+2\lambda^2}}\right)$$



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.

Design Considerations for HBM

- 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



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	$6.667 * 10^{-4}$	$8.33 * 10^{-5}$
0.8	$3.8 * 10^{-3}$	$1.0 * 10^{-4}$

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Design Considerations for HBM

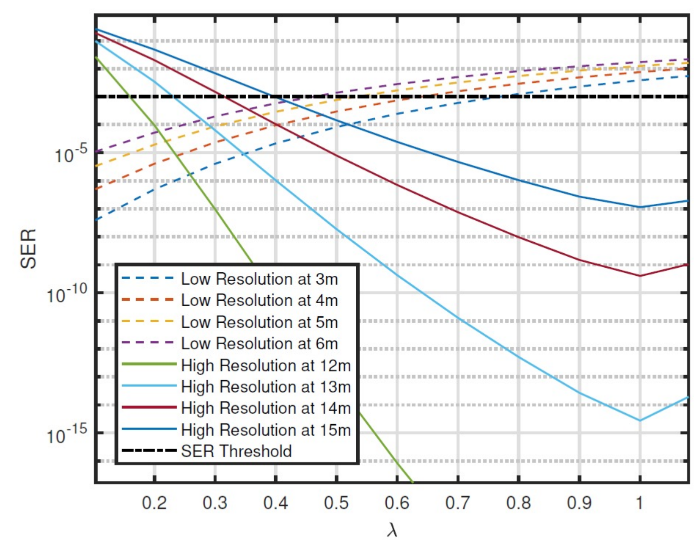
- Power allocated to each resolution
  - Depends heavily on transmission distances and observed Es/No values at the receivers
- Thresholds for switching resolutions at the receiver
  - Depends on how often system performs equalization
  - Depends on the speed of channel variations

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

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



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Coexistence Between Active Users via Hierarchical Bandwidth Modulations

- Enables user multiplexing at different distances
- Allows for flexibility on receiver side considering the channel conditions
- Enables higher aggregate data rates than traditional hierarchical or time-sharing techniques
- Can be implemented with any hierarchical constellation
- Still works when no absorption lines are present

We propose standardizing Hierarchical Bandwidth Modulations for single-transmitter multiple-receiver communications.

We are happy to provide more specific suggestions about HBM PHY Layer and MAC Layer design if there is interest.

Outline

- Propose 3 Physical Layer Solutions for 802.15.3d
  - Higher Order APSK Constellations
  - Spread Spectrum for Coexistence
  - Hierarchical Bandwidth Modulations

Solutions that have been experimentally verified to improve performance for THz communications

- **Other Interesting Topics for Consideration for improving 802.15.3d**
  - **MAC Protocols**
  - **OFDM**

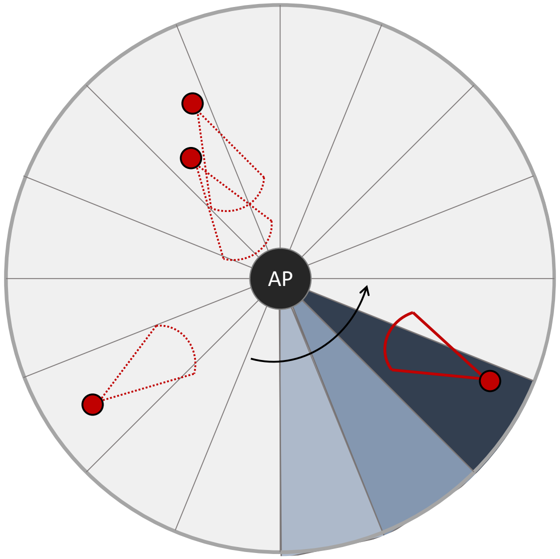
Solutions that may be appropriate for this standard

- Discuss Future Considerations for 802.15.3d
  - MIMO
  - Joint Communications & Sensing

Solutions that are promising but are not yet ready for standardization

MAC Protocols

- The different applications envisioned in IEEE 802.15.3d require very different type of MAC
- We have developed new synchronization and MAC protocols for THz-band communication networks
  - Based on a **receiver-initiated** or “one-way” handshake
  - Enabled by **high-speed turning directional antennas**
- We have analytically investigated the performance of the proposed protocol for the macro- and nano-scale scenarios
  - In terms of delay, throughput and successful packet delivery probability
    - Outperform “zero-way” handshake (Aloha-type) and “two-way handshake (CSMA/CA-type) protocols
- We validated our results by means of simulations with ns-3, where we have incorporated all our THz models → Next steps: experimental testing (then standardization?)



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, 2019.

D. Morales and J. M. Jornet, “ADAPT: An Adaptive Directional Antenna Protocol for Medium Access Control in Terahertz Communication Networks,” Elsevier Ad Hoc Networks, p. 102540, May 2021.

OFDM

- Shown as potential candidate for indoor short-range ultrabroadband communications
  - Experimentally demonstrated 42 Gbps data rate using 64-subcarriers at 140 GHz
- We are curious why OFDM was not introduced in 802.15.3d-2017
- We hesitate to formally propose OFDM because more work needs to be done to consider if OFDM is the best option or if there are ways to improve or abstract it for THz-band communications
  - DFT-Spread-OFDM

OFDM works for THz-band communications, but given the uniqueness of this band, we think more work should be done to optimize OFDM for these higher frequency ranges and to explore other possible more innovative solutions.

Chakraborty, Shuvam, et al. "A case for OFDM in ultra-broadband terahertz communication: an experimental approach." *Proceedings of the 5th ACM Workshop on Millimeter-Wave and Terahertz Networks and Sensing Systems*. 2021.

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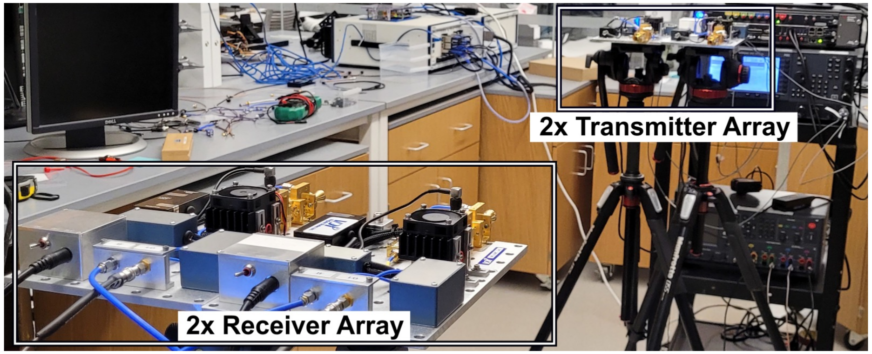
  - **MIMO**
  - **Joint Communications & Sensing**

Solutions that are promising but are not yet ready for standardization

MIMO for THz Communications

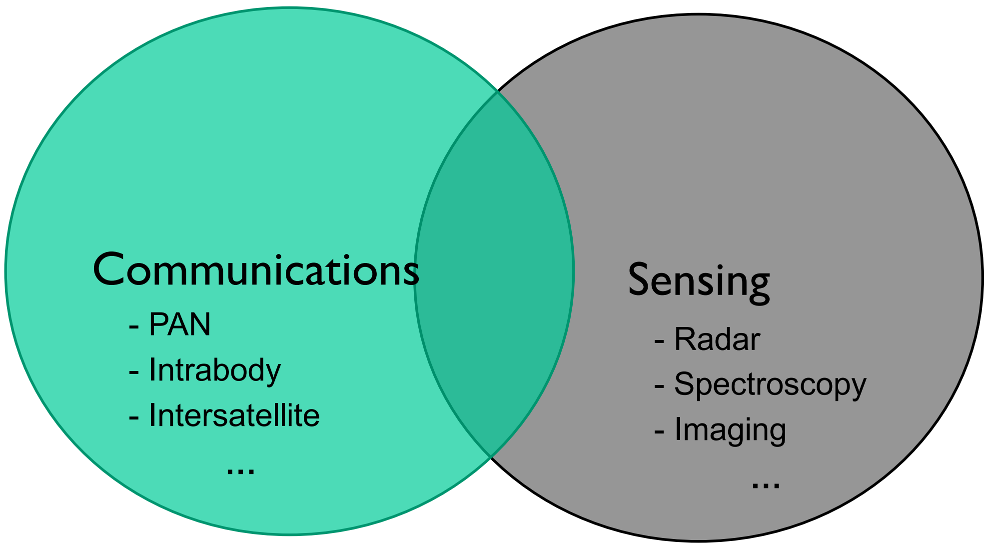
- There is a need to connect theoretical predictions with current hardware capabilities
  – UM-MIMO (1024 x 1024) [1]
  – Achievable Hardware (128 x 128) [2]
- Considering some practical challenges to bridging this divide [3]
  – Inter-Symbol Interference from back-and-forth reflections
  – Antenna element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

Joint Communications & Sensing for THz Systems

- Combining applications to optimize spectrum usage
  - Radar & Communications
  - Spectroscopy & Communications



Conclusion

- We Propose 3 Physical Layer Solutions for 802.15.3d
  - Higher Order APSK Constellations
  - Spread Spectrum for Coexistence
  - Hierarchical Bandwidth Modulations
- We discussed OFDM and MAC Protocols as other interesting topics for consideration for improving 802.15.3d
- We discussed future considerations for 802.15.3d
- We are excited to see how the standard evolves from here and are happy to help with the process if we can

Thank You

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