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Abstract: The document provides a description of non-traditional solutions at the physical and link layers of ultra-broadband (bandwidth approaching or even in excess of 100 GHz) communication networks in the Terahertz band. More specifically, new dynamic bandwidth modulations and spread spectrum techniques as well as medium access control protocols and neighbor discovery techniques are presented and discussed.

Purpose: Information of IEEE 802.15 IG THz

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Exploiting 100 GHz of Bandwidth: Physical and Link Layer Solutions

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Conquering the Terahertz Band

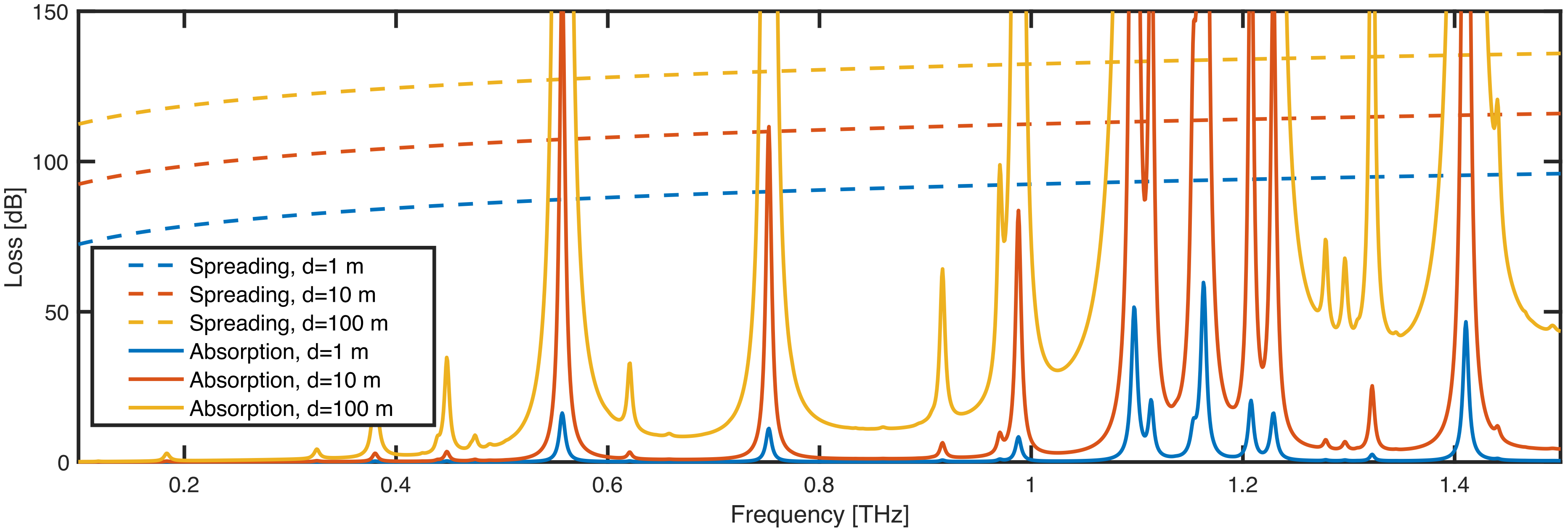
Standardization	Need to agree on how to better use the THz band
Regularization	Need to simplify the process to legally use the THz band
Networking	Bandwidth is no longer a constraint, but everything else is (MAC, neighbor discovery, relaying, …)
Communications and Signal Processing	Making the most out of the (huge) available bandwidth is a challenge (and we can do much better than with traditional systems…)
Propagation and Channel Modeling	THz signals propagate better than what many people think (for the good and for the bad)
Materials and Devices	The THz technology gap is almost closed

The Promise

- We are moving to the THz band, with the promise of larger bandwidths able to support
  - Higher peak data-rates for individual users
    → Above 1 Terabit-per-second (Tbps)
  - More simultaneously connected wireless devices
    → 100s to 1000s in close proximity

I. F. Akyildiz, J. M. Jornet and C. Han, **“Terahertz Band: Next Frontier for Wireless Communications,”** **Physical Communication**, vol. 12, pp. 16-32, September 2014.

The Bandwidth



- The THz channel provides nodes with very large transmission bandwidths
  - For distances below 1 meter: a few THz
  - For distances above 1 meter: several transmission windows, tens to hundreds of GHz each

J. M. Jornet and I. F. Akyildiz, **"Channel Modeling and Capacity Analysis of EM Wireless Nanonetworks in the Terahertz Band,"** **IEEE Transactions on Wireless Communications**, 2011.

Remember

- Maximum bandwidth in:
  - **5G New Radio (NR):**
    - FR1: 100 MHz
    - FR2: 400 MHz
  - **IEEE 802.11ax:** 160 MHz (8x20 MHz)
  - **IEEE 802.11ay:** 8.64 GHz (4x2.16 GHz)
  - **IEEE 802.15.3d:** 69.120 GHz (32x2.16 GHz)

Question

What do we do with 100 GHz of bandwidth (or more)?

Shall we just use the traditional communication solutions and networking solutions?

Let us revisit the physical and link layers

Terahertz Physical Layer

- To make the most out of the very large bandwidth provided by the THz band channel, new communication, and signal processing techniques are needed, including
  - **Time, frequency and phase synchronization**
    - When transmitting at Tbps and in the presence of phase noise
  - **Channel estimation and equalization**
    - Of tens to hundreds of GHz-wide bandwidths
  - **Modulation/demodulation**
    - Which can make the most out of the distance-dependent bandwidth of the THz channel

- All of these, while keeping mind that the **sampling frequency of the fastest digital to analog and analog to digital converters** is nowhere close to that defined as per Nyquist

THz Modulation

- **Option 0: Traditional modulations**
  – Easy, but will not make the most of the THz band
- **Option 1: Ultra-short-pulse-based Modulations**
  – For very short distances, where molecular absorption is almost negligible
- **Option 2: Dynamic Bandwidth Modulations**
  – To cope with the distance-dependent bandwidth resulting from absorption over long distances

Option 0: Traditional Modulations

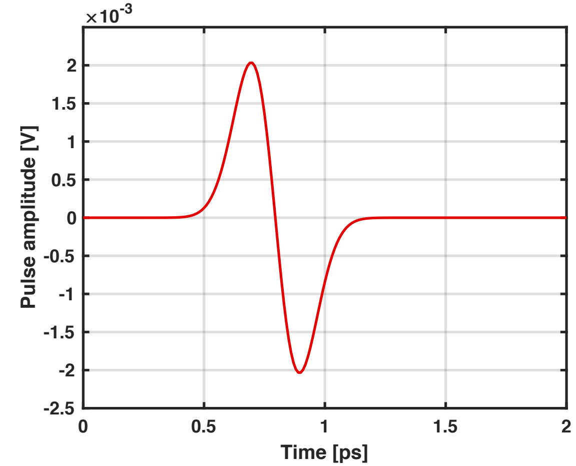
- For the time being, the few experimental works implement traditional modulations, including
  - Analog amplitude or frequency modulation (AM/FM)
  - Digital amplitude, phase and frequency modulation (M-ASK, M-PSK, M-FSK), even multi-carrier systems (OFDM)

- These modulations have been mainly designed for:
  - **Narrow-band systems:**
    - We are not narrowband at THz frequencies, specially over short distances, where absorption is negligible
  - **Fixed bandwidths:**
    - As we increase the communication distance, the absorption-defined bandwidth changes

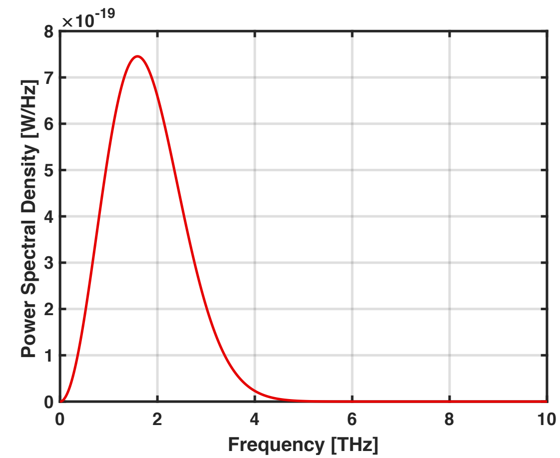
Result: these do not make the most of the THz band!

Option 1: THz Pulse-based Modulation

- We proposed a communication scheme based on the transmission of one-hundred-femtosecond-long pulses by following an asymmetric On-Off keying modulation spread in time
  - **TS-OOK (Time-Spread On-Off Keying)**



- We analyzed TS-OOK performance in terms of single-user and multi-user achievable information rates
  - We developed new **stochastic models of molecular absorption noise and multi-user interference**



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

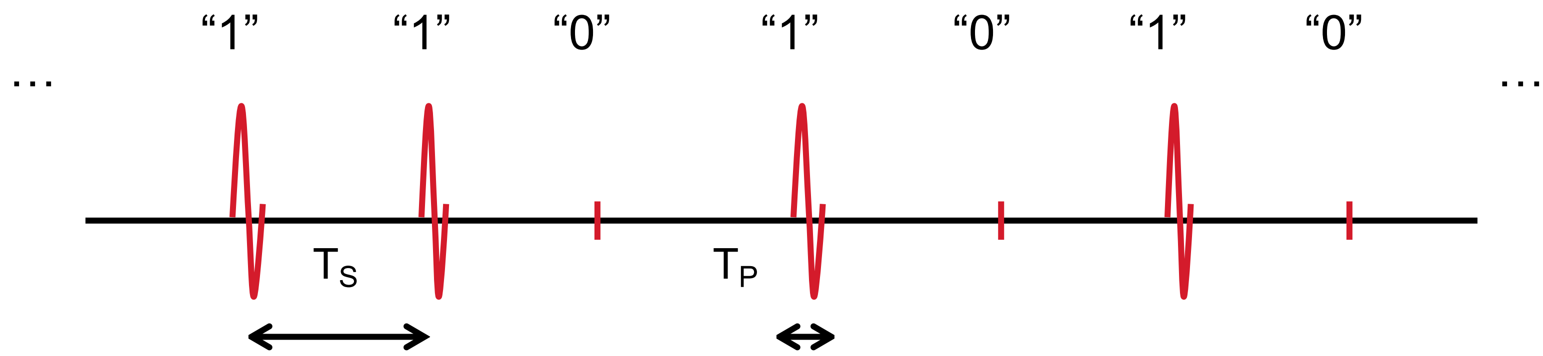
Time Spread On-Off Keying

"1" is transmitted as a pulse

- Pulse length: T_p = 100 fs
- Pulse energy: E_p <1 fJ

"0" is transmitted as silence

- Ideally no energy is consumed
- After an initialization preamble, silence is interpreted as 0s



Pulses are spread in time (T_S>>T_P)

- Relax the requirements on the transceiver architecture
- Exploit the molecular absorption noise behavior

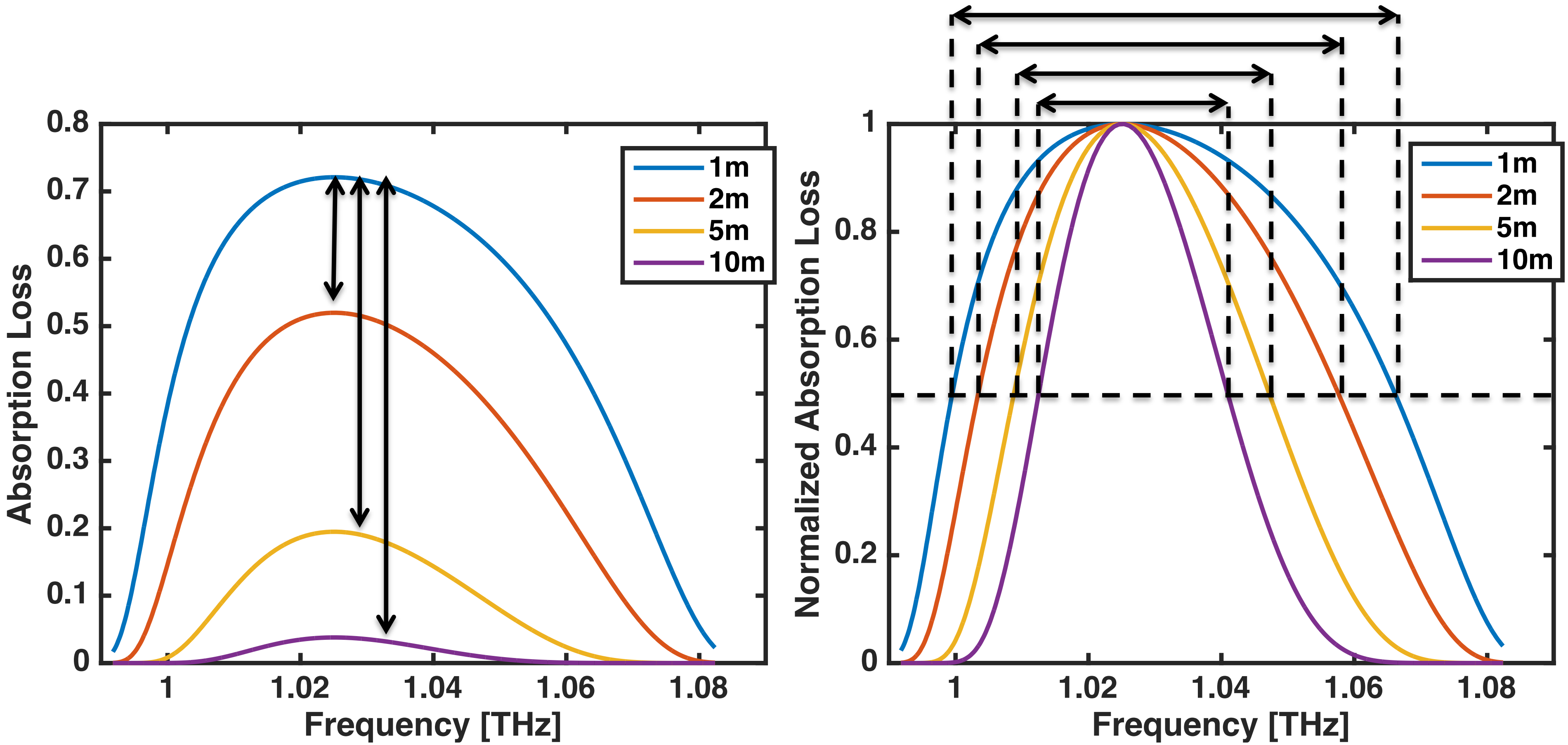
Remarks

- **This is not Impulse-Radio Ultra-Wide-Band (IR-UWB):**
  - Pulses are three orders of magnitude shorter in TS-OOK than in IR-UWB
    - Sub-picosecond vs sub-nanosecond pulses
  - In TS-OOK, information is encoded in the presence or absence of a pulse
    - A simple energy detection scheme will suffice
  - In IR-UWB, time-hopping pulse-position modulation (TH-PPM) was used
    - Challenging to implement, especially due to synchronization
- **This mostly works well for very short distances…**
  - …where molecular absorption does not "chop" the available spectrum

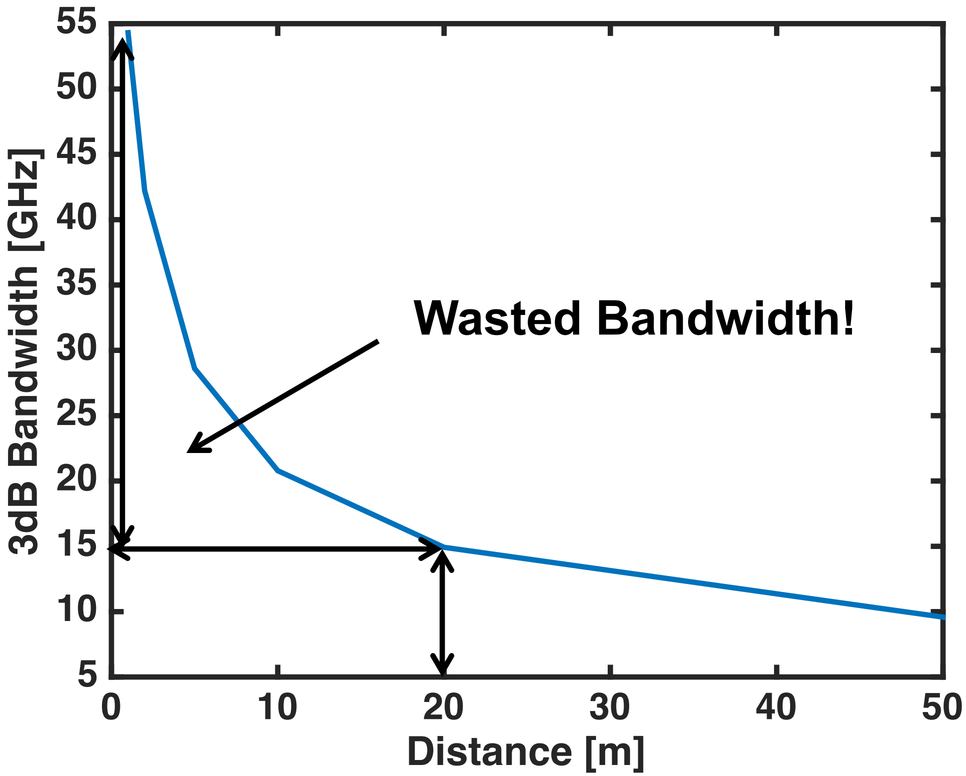
Moving to Longer Distances…

- Why "bandwidth-adaptive"? Can't we just use standard fixed-bandwidth QPSK, QAM, etc.?

A Closer Look at Bandwidth



Distance-varying Bandwidth



- For a given window, bandwidth changes drastically with distance
  - And so does the channel capacity and the achievable data-rate

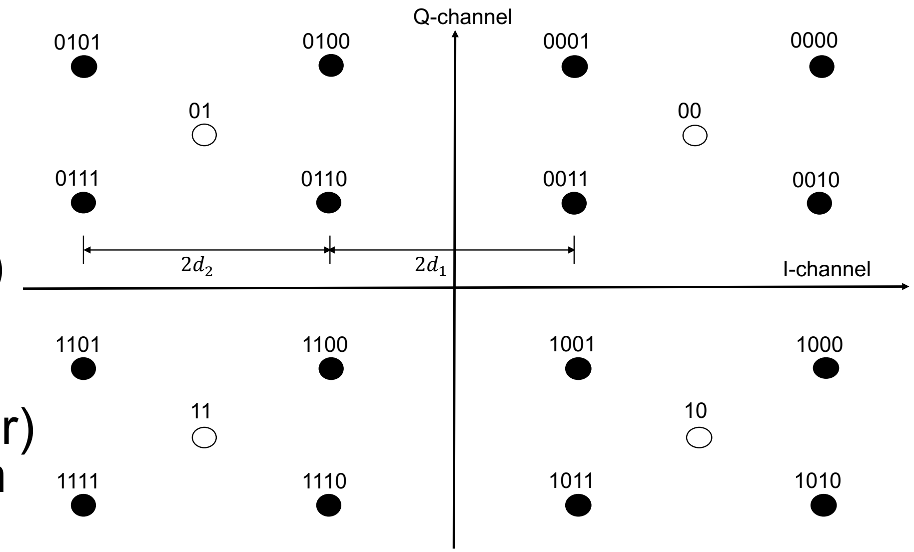
Hierarchical Bandwidth Modulation

- We propose **hierarchical bandwidth modulation (HBM)** to cope with the distance-dependent bandwidth of the THz channel
  - Partially related to the concept of hierarchical modulation (HM)
  - **Key idea: Symbol duration is adjusted based on available bandwidth**
- We analytically investigate the performance of the proposed scheme in terms of achievable data rate
- We derive the symbol error rate by starting from the new defined constellations
- We provide extensive numerical results to show that HBM can achieve higher data rate than HM and time sharing

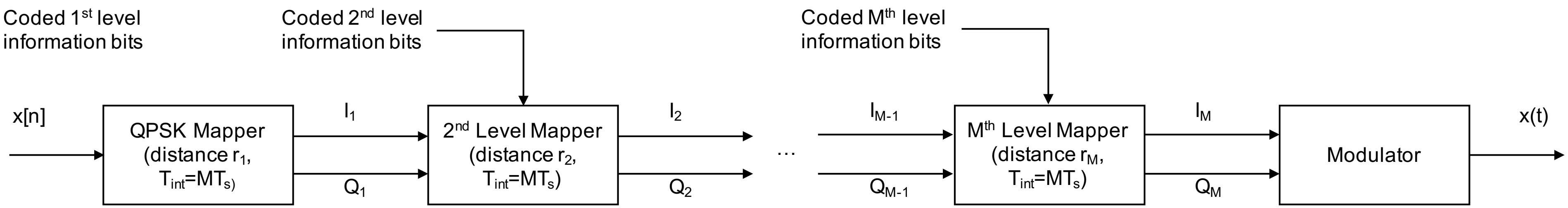
Z. Hossain and J. M. Jornet, **"Hierarchical Bandwidth Modulation for Ultra-broadband Terahertz Communication,"** **in Proc. of IEEE ICC, Shanghai,** China, 2019.

Classical Hierarchical Modulation

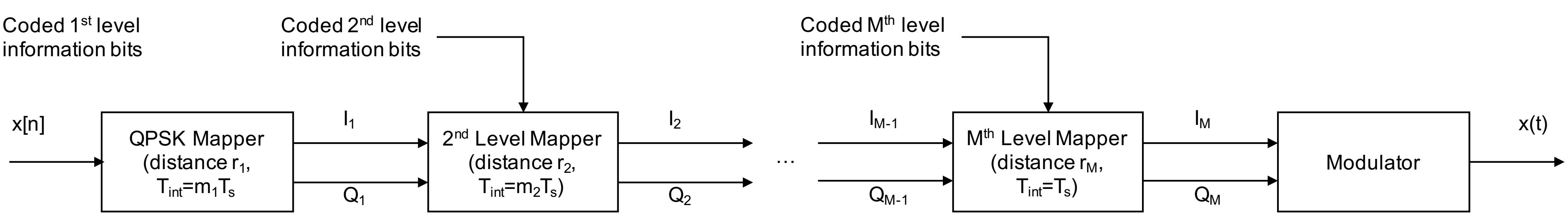
- Used to broadcast data to different receivers with different channel conditions
- Data is sent with two superposed layers
  - Receiver with good channel conditions (e.g., close receiver) can get both
  - Receiver with poor channel conditions (e.g., distant receiver) can get only low-quality version
- The parameter $\lambda = d_2/d_1$ characterizes the relative protection given to the two data streams



HM and HBM Block Diagram

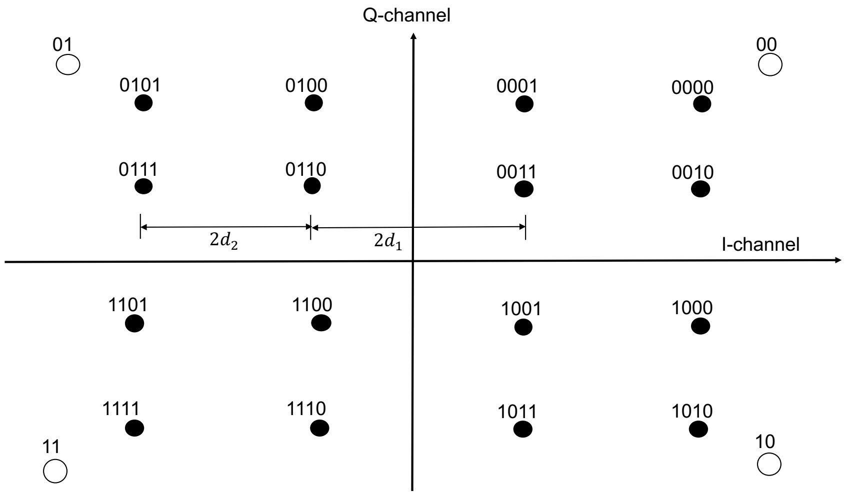


- $\frac{1}{T_s}$ is the bandwidth available at the closer receiver
  - In HM, all modulators operate at $T_s = MT_s$
  - In HBM, each modulator operates at a rate $T_s = m_i T_s$
    - $m_1 > m_2 > \cdots > 1$, where m_i is an integer multiple of m_{i+1}
    - Users are located at distance $r_1 > r_2 > \cdots$

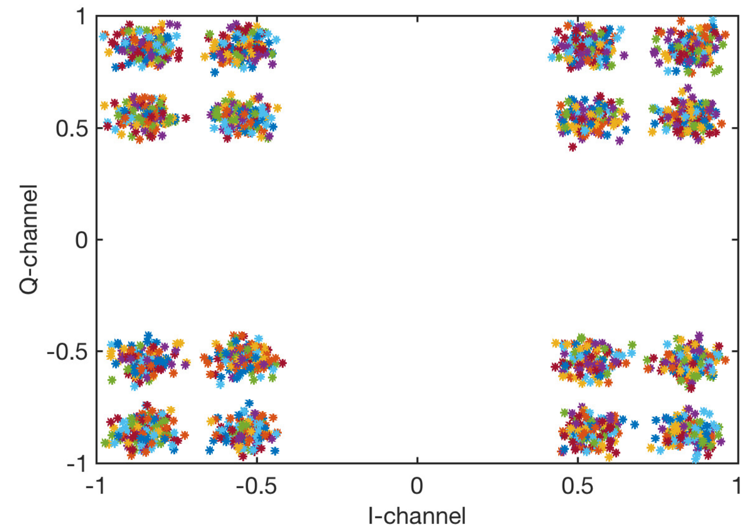


Constellations

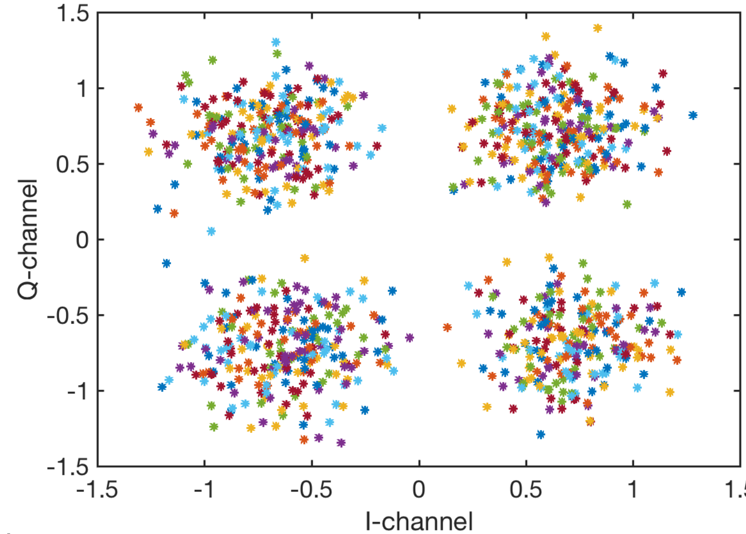
Transmitted Constellation



Closer receiver



Further receiver



Data Rates

Modulation scheme	SER [distance=1m]	SER [distance=30m]	BER [distance=1m]	BER [distance=30m]
QPSK	<1e-4	<1e-4	<1e-4	<1e-4
16QAM	<1e-4	0.01	<1e-4	2.5e-3
64QAM	<1e-4	0.30	<1e-4	0.05
256QAM	<1e-4	0.73	<1e-4	0.09
1025QAM	0.14	0.93	0.014	0.09
4/16HM, $\lambda = 0.25$	<1e-4	5.5e-4	<1e-4	2.75e-4
4/16HM, $\lambda = 0.2$	<1e-4	3e-4	<1e-4	1.5e-4
4/64HM, $\lambda = 0.125$	<1e-4	0.003	<1e-4	1.5e-3
4/64HM, $\lambda = 0.0625$	0.02	1e-3	3.3e-3	5e-4
4/64HM, $\lambda = 0.0825$	3e-4	0.0016	5e-5	8e-4
4/16BHM, $\lambda = 0.25$	<1e-4	1e-3	<1e-4	5e-4
4/16BHM, $\lambda = 0.2$	4e-4	6e-4	1e-4	3e-4

- **Unicast:** 256QAM for closer and 4QAM for farther receiver

$$R = \frac{8bits}{T_s} and \frac{2bits}{2T_s} = \frac{10bits}{3T_s} = 0.307\ Tbps$$

- **HM:** 4/64QAM

$$R = \frac{6bits}{2T_s} + \frac{2bits}{2T_s} = \frac{8bits}{2T_s} = 0.370\ Tbps$$

- **HBM:** 4/16QAM

$$R = \frac{4bits}{T_s} + \frac{2bits}{2T_s} = \frac{10bits}{2T_s} = 0.462\ Tbps$$

- **Beyond increasing the data-rate…**
  - **How else can we leverage such bandwidth?**

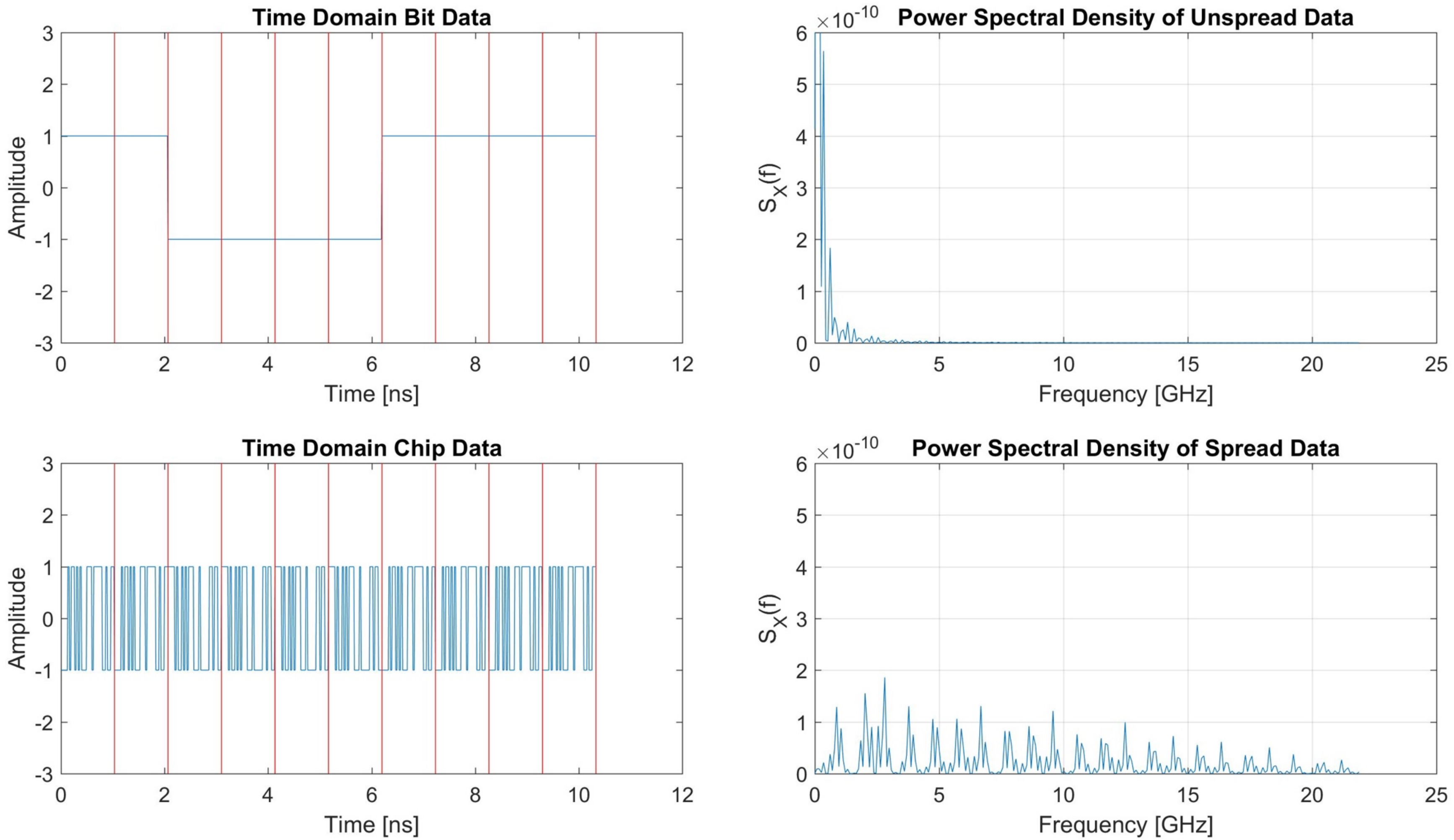
Opportunity

- The very large bandwidth available at THz frequencies can also be leveraged to enable **spread spectrum communication** techniques:
  - At lower frequencies, the limited available consecutive bandwidth results in very low data-rates for spread spectrum systems
  - At THz frequencies, Gbps links are possible while still ensuring large spreading factors
- Combined with the use of directional antennas at the transmitter and the receiver, simultaneously, this leads to **highly secure wireless communications**

Spread Spectrum Communications

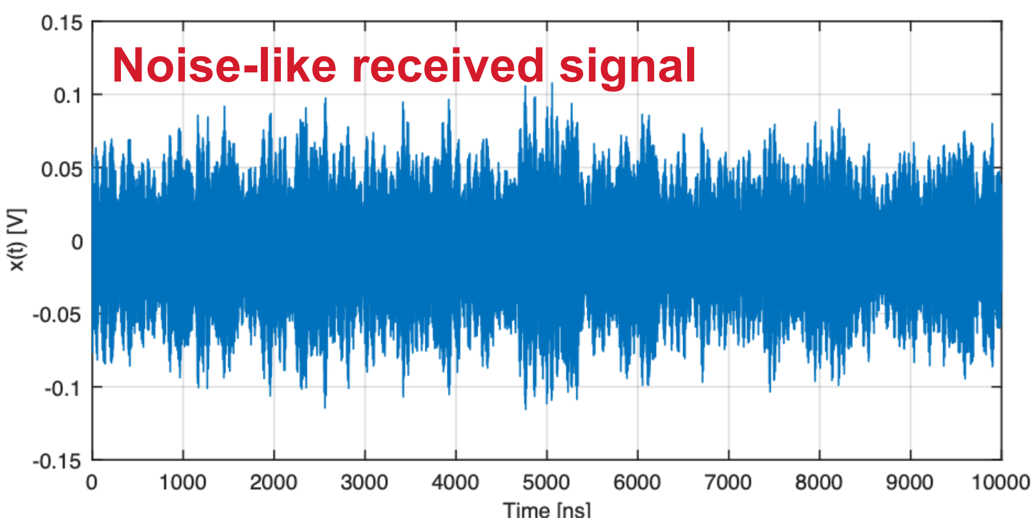
- **Frequency Hopping Spread Spectrum (FHSS)**
  - Signal rapidly switches between carrier frequencies based on a unique spreading sequence
  - Narrowband spectrum at specific time instant
- **Direct Sequence Spread Spectrum (DSSS)**
  - The information signal is multiplied by a unique spreading sequence largely increasing its bandwidth
  - Signal occupies a wideband spectrum at all times
- **Chirp Spread Spectrum (CSS)**
  - Information is encoded in the changes in carrier frequency across a large bandwidth
  - Signal occupies a wideband spectrum at all times

Direct Sequence Spread Spectrum



DSSS: Results

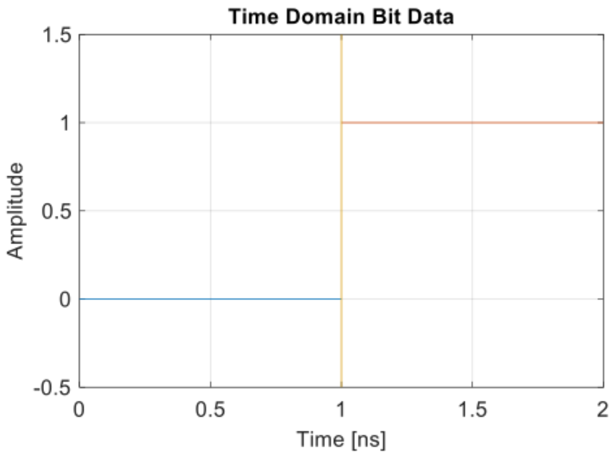
- **Test details:**
  - 1.02 THz carrier frequency
  - 20 GHz baseband / 40 GHz RF Bandwidth
  - Spreading length 31 (986 Mbps)
  - Effective radiated power < 30 μW
  - AWG sampling rate 90 GSa/s
  - DSO sampling rate 160 GSa/s
  - 26 dB gain horn antennas

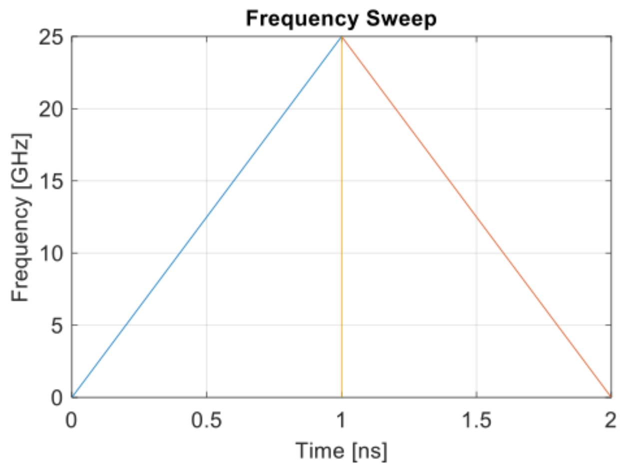


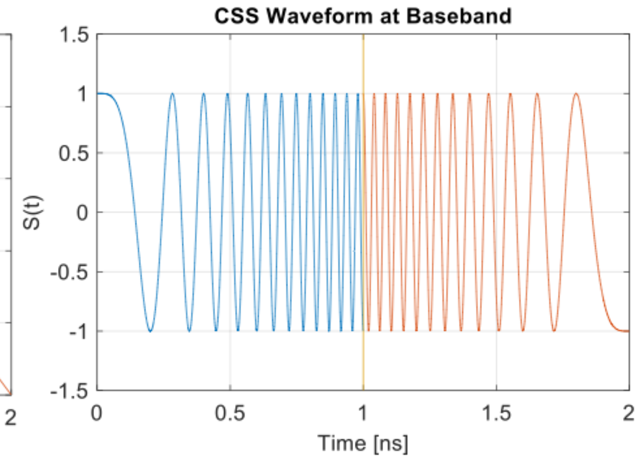
Number of bits	Distance	Average Number of Errors
2700	4 cm	1
2700	6 cm	2
2700	8 cm	3

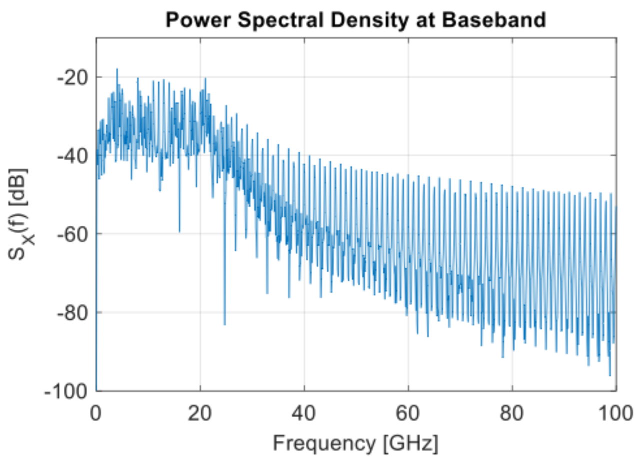
Distance limited by transmission power of current up-down converters, not by the channel

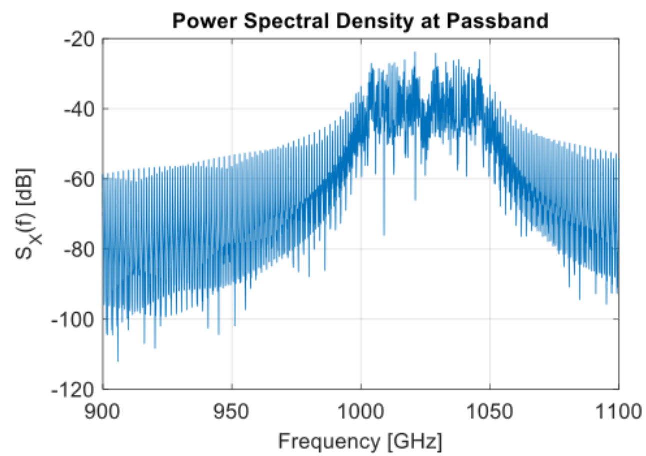
Chirp Spread Spectrum







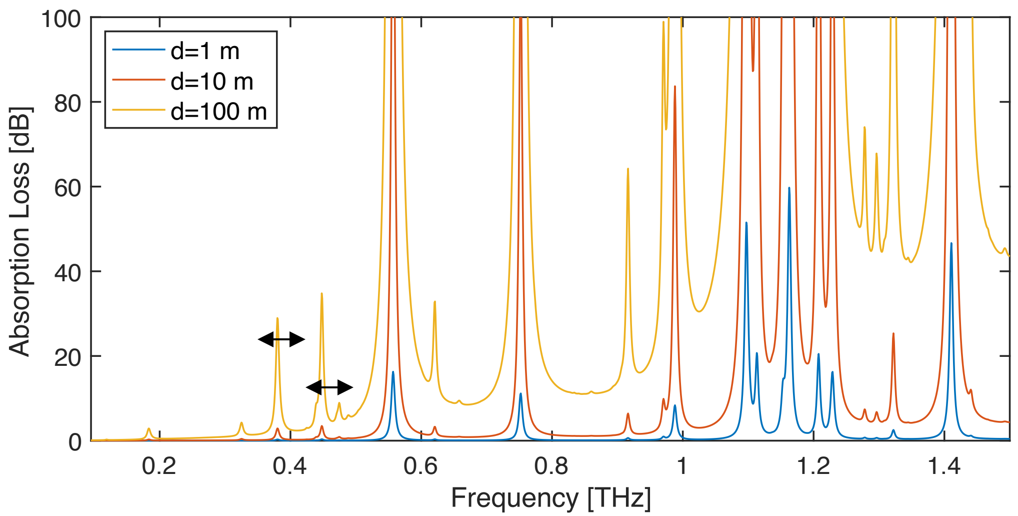




Opportunity

- CSS is particularly good with frequency selective channels:
  - Even if some frequencies are totally attenuated, a symbol can still be recovered
    - The information is encoded in the trending changes in frequency (e.g., going “up” or “down”)

- **Idea:** can we use CSS to communicate even when partially overlapped with absorption lines?
  - **Yes, we can!**



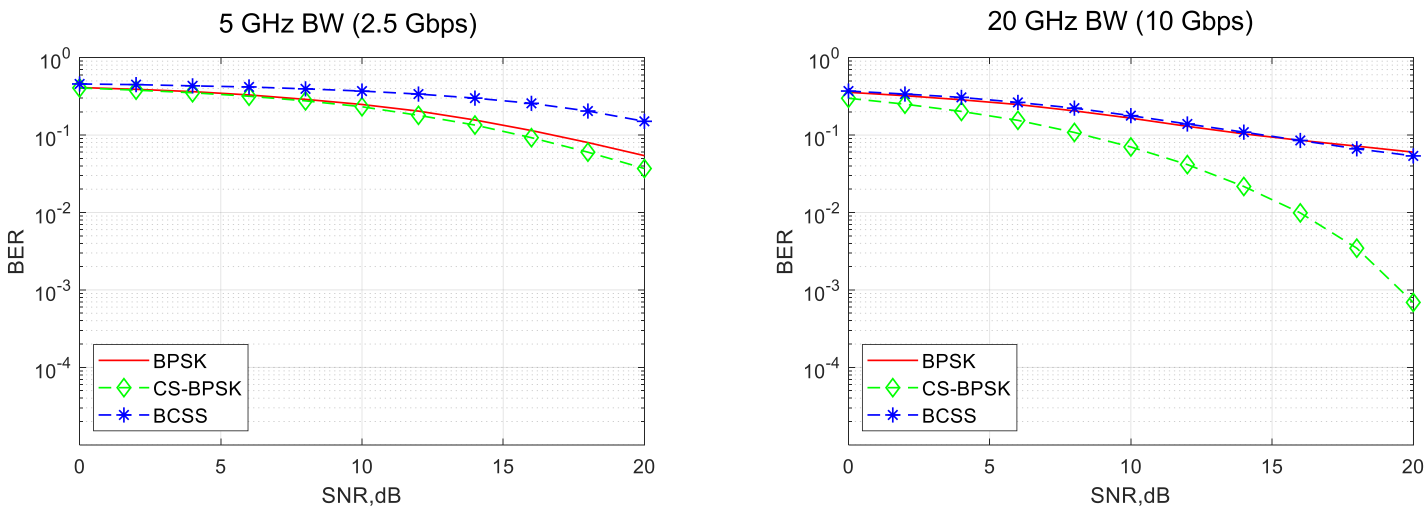
Chirp-Spread Binary Phase Shift Keying

- We proposed **chirp-spread binary shift keying (CS-BPSK) modulation** to enable communication across the absorption peaks
  - Partially related to the concept of Chirp Spread Spectrum (CSS)
  - **Key idea: power is spread over the whole bandwidth, which makes it robust against the frequency selective attenuation of the absorption band**
- We mathematically describe this modulation scheme and illustrate the waveform structures
- We investigate analytically the bit error rate (BER) of the proposed CS-BPSK scheme in contrast of binary chirp spread spectrum (BCSS)
- We experimentally validate the scheme and BER performance

P. Sen, H. Pandey and J. M. Jornet, **"Ultra-broadband Chirp Spread Spectrum Communication in the Terahertz Band,"** **to appear in Proc. of the SPIE Defense and Commercial Sensing Conference, 2020**.

Bit Error Rates

- To show the effect on BER with the increase of bandwidth, we considered communication across the 380 GHz absorption line at distance of 100 m



- Observations
  - CS-BPSK has the best performance among the three schemes in the case of the absorption band communication.
  - For CS-BPSK and BCSS, power is spread over the whole bandwidth, which makes them robust against the frequency selective attenuation of the absorption band.
  - For BPSK, the maximum power is centered near the carrier frequency, which makes it experience higher attenuation than other modulation schemes.
  - The results motivate and justify the use of chirp spread modulation schemes over single carrier modulation.

Let's Go up in the Protocol Stack

- The THz band provides devices with a very large bandwidth
  - These do not need to aggressively contend for the channel!
- Such very large bandwidth results in very high bit-rates and, thus, very short transmission times
  - Collisions are highly unlikely!

Do we need a MAC protocol after all?

- Link-layer synchronization is a problem:
  - The scarcest resource is not the channel bandwidth, but the receiver availability!
    - It might be pointing its antenna in any direction (perhaps not towards the transmitter)

Link-layer Synchronization and Medium Access Control Protocol

- We developed a new synchronization and MAC protocol for THz-band communication networks
  - Based on a **receiver-initiated** or “one-way” handshake
  - Enabled by high-speed turning directional antennas
- We 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
  - Compare it to that of “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

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.

Dual-band MAC Protocols: Synergistic Coexistence of THz and GHz Comms

- **Observation:** Terahertz communications are not going to replace existing wireless communication systems…
  - ... but enhance them in specific applications, by mainly adding a new option to the current pool of radio access technologies

- New synchronization and MAC protocols able to simultaneously exploit **the best properties of each frequency band** can be developed:
  - Nodes rely on the omnidirectional 2.4 GHz channel to exchange control information and coordinate data transmissions (Phase 1)
  - The actual data transfer occurs at THz frequencies only after the nodes have aligned their beams (Phase 2)

X. W. Yao and J. M. Jornet, **"TAB-MAC: Assisted Beamforming MAC Protocol for Terahertz Communication Networks,"** **Nano Communication Networks (Elsevier) Journal**, 2016.

Neighbor Discovery

- Neighbor discovery in directional communication networks (e.g., millimeter-wave networks) is a heavily researched topic.
- However, **existing solutions cannot be reutilized at THz frequencies**, mainly because they do not capture the peculiarities of the THz channel and THz devices:
  - Most existing solutions assume that communication can be established with at least one of the node pair utilizing omnidirectional/quasi-omnidirectional antenna
    → Not our case…
  - Solutions for fully directional communications take too long to complete the neighbor discovery process….
    → Defeat the original purpose of THz communications.

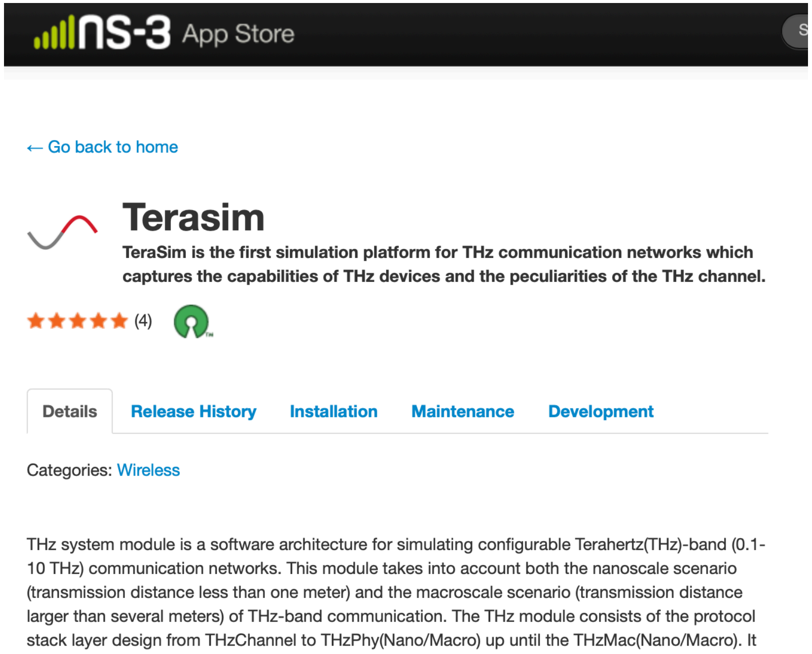
Our Solution

- We utilize the **full antenna radiation pattern** with **side-lobes** to expedite the neighbor discovery process.
  - We map the effectively received signal to a *universal detection standard*
    - Indicates the potential direction of the signal source
- We test and validate the proposed neighbor discovery protocol by using the **X60 testbed**
- We analytically and numerically show that the **neighbor discovery time can be significantly reduced** compared to utilizing the ideal antenna model without side-lobes(in *free space* & a *bounded area*)

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.**

Have New Networking Ideas… … but no Testbed to Try?

- **Terasim:**
  - An open source network simulation platform for THz networks
  - Captures
    - THz technology capabilities
    - Peculiarities of THz channel
  - Built as an extension for ns-3



Z. Hossain, Q. Xia, and J. M. Jornet, ***"TeraSim: An ns-3 extension to simulate Terahertz-band communication networks,"*** **Nano Communication Networks (Elsevier) Journal,** vol. 17, pp. 36-44, September 2018.

Conclusions

- The very large bandwidth available at THz frequencies opens the door to innovative communication and networking opportunities
- Some of the existing solutions at the physical and link layers will not work; some of them will, but won't make the most of the channel
- Let us not miss the opportunity and simply re-use what has been done for decades!

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Thank you

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