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

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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 coexistence between devices and optimize THz-band communications.
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)


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

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

Phase-Modulated Chirp Signals

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

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).

### Phase-Modulated Chirp Signals

**Experimental Results**

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

<table>
<thead>
<tr>
<th>BPSK</th>
<th>Data rate (Gbps)</th>
<th>Dist. (cm)</th>
<th>SNR (dB)</th>
<th>BER</th>
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<td>1.6 × 10^{-3}</td>
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<td>0.8</td>
<td>7 × 10^{-2}</td>
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<td>2.5</td>
<td>2.5 × 10^{-2}</td>
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<tr>
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<td>-0.5</td>
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<td>10</td>
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<tr>
<td></td>
<td>30</td>
<td>-1.5</td>
<td>2.4 × 10^{-1}</td>
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</table>

<table>
<thead>
<tr>
<th>CS-BPSK</th>
<th>Data rate (Gbps)</th>
<th>Dist. (cm)</th>
<th>SNR (dB)</th>
<th>BER</th>
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<tbody>
<tr>
<td>2.5</td>
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<td>7.5</td>
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<td></td>
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<td>1.4 × 10^{-2}</td>
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<td>30</td>
<td>-1.9</td>
<td>1.6 × 10^{-1}</td>
<td></td>
</tr>
</tbody>
</table>

Outline

• Solutions for Coexistence
  – 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 bandwidth.
  - 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

Potential Applications for HBM

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

Users close to the transmitter can demodulate at a faster symbol rate for higher quality.

When channel is stronger, the receiver demodulates at a faster symbol rate for high resolution.

When channel is weaker, the receiver demodulates at a slower symbol rate for pertinent information.

Farther users demodulate at a slower rate.

- Full HD Resolution
- 8K Resolution
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

\[
\text{SER}_{\text{LowRes}} = Q\left(\sqrt{\frac{E_s}{N_0}} \left(1 + 2\lambda + 2\lambda^2\right)\right) + Q\left(\sqrt{\frac{E_s}{N_0}} \left(1 + 2\lambda + 2\lambda^2\right)\right)
\]

\[
\text{SER}_{\text{HighRes}} = 2Q\left(\lambda \left(1 + 2\lambda + 2\lambda^2\right)\right) + Q\left(\sqrt{\frac{E_s}{N_0}} \left(1 + 2\lambda + 2\lambda^2\right)\right)
\]

Design Considerations for HBM

• Power allocated to each resolution
  – Depends heavily on transmission distances and observed Es/No values at the receiver

Design Considerations for HBM

• Power allocated to each resolution
  – Depends heavily on transmission distances and observed Es/No values at the receivers

Experimental Validation

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>LR SER</th>
<th>HR SER</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>$1.25 \times 10^{-4}$</td>
<td>$1.12 \times 10^{-2}$</td>
</tr>
<tr>
<td>0.4</td>
<td>$&lt; 8.3 \times 10^{-5}$</td>
<td>$2.167 \times 10^{-4}$</td>
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<tr>
<td>0.6</td>
<td>$6.667 \times 10^{-4}$</td>
<td>$8.33 \times 10^{-5}$</td>
</tr>
<tr>
<td>0.9</td>
<td>$3.8 \times 10^{-3}$</td>
<td>$1.0 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
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

\[
\frac{E_s}{N_0_{Low\text{HighTh}}} [dB] = \frac{E_s}{N_0_{ThHigh}} [dB] + \alpha [dB] + \beta [dB]
\]

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

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)

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

MIMO Experimental Results

![MIMO Experiment Results Diagram]

<table>
<thead>
<tr>
<th>Modulation</th>
<th>1x1 EVM</th>
<th>2x2 EVM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8° Antennas</td>
<td>1.6° Antennas</td>
</tr>
<tr>
<td>QPSK</td>
<td>20.2%</td>
<td>18.91%</td>
</tr>
<tr>
<td>8PSK</td>
<td>21.4%</td>
<td>16.27%</td>
</tr>
</tbody>
</table>


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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