Covert Photonics-Enabled Millimeter-Wave Transmitter

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Outline

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Millimeter wave bands have many 10s of GHz of bandwidth and are highly directional.

Ideally, military communications should have:
- Low probability of detection (LPD).
- Low probability of intercept (LPI).
- High-data rates.

Often, the degree of LPD and/or LPI is directly related to:
- The operating frequency limitations of the link.
- The directionality of the antennas.

The challenge is to design a long-distance W-band link with LPD/LPI and high-data rates, a feat made easier with photonics-enabled systems.
- LPD/LPI can be accomplished using spread-spectrum and/or frequency hopping.
Motivation

- The V-band (40–75 GHz) is ideally suited for LPD/LPI communications because of the large atmospheric attenuation.
  - Therefore, the V-band is suitable for short-distance links.

- The W-band (75–110 GHz) is more practical for long-distance point-to-point links where atmospheric attenuation can be as low as 0.4 dB/km.
Why Photonics-Enabled mmW?

Why Photonics?

- Photonic systems are naturally broadband (10s GHz BW).
- A single transceiver is frequency agile and can cover many RF bands.
- Photonics provides LO to signal isolation.
- Fiber has low-loss (~0.2 dB/km).
- Allows for antenna remoting.

Why mmW?

- Highly directional and narrow antenna beams.
- Small antenna arrays.
- Supports large data rates.
- More available contiguous spectrum.
- Good transmission through rain, clouds, dust, and other small particles.
Photonics-Enabled Systems

• A photonics-enabled system has:
  – Large BW.
  – Carrier frequency output/input flexibility.
  – The ability to modulate an optical carrier with an RF signal.
  – A photodiode to convert from optical to RF.
  – An electrical to optical converter.
  – A local oscillator (LO) input.

• $x(t)$ → Binary data sequence.
• $p(t)$ → PRN sequence.
• $\omega_{LO}$ → Local oscillator angular frequency.
• $\hat{T}$ → Estimated time delay at the Rx.
• $T$ → Actual time delay at the Rx.
• $A$ → Carrier power level.
Photonic Upconversion

- This stage requires the input of a low phase noise electronic LO at $f_c/n$ ($n$ is an integer).
  - $f_c/n$ is either used as a reference frequency or multiplied up to the desired LO frequency.

- An arbitrary waveform generator (AWG) is used to input the Tx waveform at $f_{IF}$ into the photonic upconverter.
  - A BPSK spread-spectrum waveform is constructed using MATLAB.

- The final mmW carrier frequency is then $f_c = f_{LO} + f_{IF}$ or $f_c = f_{LO} - f_{IF}$.
Photonic Downconversion

- The mmW signal is received by an antenna and modulated onto an optical carrier.
- The LO frequency is also modulated onto an optical carrier and combined with the mmW optical signal.
- Data is downconverted to microwave IF and output from a photodiode.
Spread Spectrum Systems

• Spread-spectrum signals use more BW than required to transmit data.
  – Ideal candidate for photonics-enabled systems.

• Spread signals are more resilient to:
  – Multi-path interference.
  – Intentional Jamming.
  – Multiple users.

Binary Data
\[ x(t) \]

PRN Code
\[ p(t) \]

\[ x(t) \oplus p(t) \]
By multiplying (or XOR-ing) the data with a pseudo-random noise (PRN) code, the transmitted signal is spread over a wide BW.

- Each data bit is “chipped” into multiple pulses.

The Tx Chips then get upconverted (using photonics) to the carrier frequency.

Definitions:
- **Data**: Binary data stream (quantified by the data rate).
- **PRN**: Random noise sequence.
- **Tx Chips**: The raw transmitted pulses after spreading (defined by the Chip Rate).
In general:
- PRN Rate > Data Rate.
- Each data bit is converted into \( n \) Tx chips.
- Chips/s > bits/s.
- Identical PRN codes can be generated in the Rx.

Tx signal appears as random noise to an observer.

The Tx signal is \( s(t) = \sqrt{2Ax(t)p(t)}\cos(\omega_c t) \):
- \( A \) is the carrier power level.
- \( x(t) \) is the binary data sequence.
- \( p(t) \) is the binary PRN sequence.
- \( \omega_c \) is the angular carrier frequency.
At the Rx, the incoming signal $r(t)$ is:

$$r(t) = G\sqrt{2A}x(t - T)p(t - T)\cos[\omega_c(t - T) + \phi]$$

In the correlator, the correct time delay is found by multiplying $r(t)$ by a locally generated copy of the PRN sequence and filtering. The output of the correlator is:

$$h(t) = G\sqrt{2A}x(t - T)p(t - T)p(t - \hat{T})\cos[\omega_c(t - T) + \phi]$$

When $\hat{T} = T$, the correct time delay is found and the product $p(t - T)p(t - \hat{T}) = 1$.

Afterwards, traditional BPSK demodulation can proceed.

- $T \rightarrow$ Actual time delay.
- $\hat{T} \rightarrow$ Estimated time delay at the Rx
- $G \rightarrow$ System Gain.
• The antenna is replaced with a spectrum analyzer for the experimental setup.

• The 80 GHz LO is generated by the combination of:
  – An optical C-band external cavity laser (ECL) with linewidth < 5 kHz.
  – An intensity modulator is driven by an RF source $f_{LO}/2 = 40 \text{ GHz}$.  
    • This suppresses the optical carrier and produces two sidebands 80 GHz apart.

• An AWG (12 GSa/s, not shown) is programmed with a BPSK spread spectrum signal at $f_{1F} = 3 \text{ GHz}$ and input into an optical modulator.
After optical amplification with an EDFA, a demultiplexer (DEMUX) filters the optical sidebands.

An optical phase modulator driven by the IF signal modulates one of the optical sidebands.

A multiplexer (MUX) combines the modulated and unmodulated sidebands which then get converted to RF through a photodiode.

- PD specs: $f_{3dB} > 100$ GHz, 0.43 A/W responsivity.

The result is a mmW BPSK spread-spectrum signal with a carrier of $f_{IF} + f_{LO} = 83$ GHz.
• The same data rate was used for all simulations and measurements while the chip rate was varied.

• BPSK Spread Spectrum Signal Parameters:
  \[-f_{sym} = 4 \, MHz\]
  \[-f_{chip} = 4 - 2000 \, MHz\]
  \[-f_c = 83 \, GHz\]
Results

Measured and simulated results agree with each other. Bandwidth continues to increase while peak power decreases for larger chip rates. The peak at 82.4 GHz is caused by a combination of mixing spurs and quantization errors in the AWG.
Results

Measured and simulated results agree with each other. Bandwidth continues to increase while peak power decreases for larger chip rates. Additional peaks beyond the fundamental peak are observed because square pulses are used.
## Results

<table>
<thead>
<tr>
<th>Chip Ratio (chips/bit)</th>
<th>Data Rate (Mbps)</th>
<th>Chip Rate (Mcps)</th>
<th>Bandwidth (MHz)</th>
<th>Carrier Frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>4</td>
<td>8</td>
<td>83</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>20</td>
<td>40</td>
<td>83</td>
</tr>
<tr>
<td>50</td>
<td>4</td>
<td>200</td>
<td>400</td>
<td>83</td>
</tr>
<tr>
<td>500</td>
<td>4</td>
<td>2000</td>
<td>4000</td>
<td>83</td>
</tr>
</tbody>
</table>

- As the chip rate of the signals increase, the peak power level decreases and the signal dives closer to the noise floor.

- The data rate remains the same in all cases but LPD/LPI becomes better as the chip rate is increased.

- The main BW limitation is the AWG, the photonic system has a much wider BW.
Conclusion and Future Work

• A photonics-enabled architecture for mmW point-to-point links has been developed.
  – Allows for wide BW and frequency agility.

• This architecture successfully demonstrated a W-band link with favorable LPD/LPI.
  – A spread-spectrum BPSK signal was used.

• In future work we plan to implement:
  – Frequency hopping.
  – A photonics-enabled receiver.
  – A point-to-point link with high gain antennas.
Questions