A 666 GHz Demonstration Crosslink with 9.5 Gbps Data Rate

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Outline

• Motivation
• Electronic Capabilities at THz Frequencies
  – Receiver
  – Transmitter
  – Traveling Wave Tube Amplifier
• Link Calculations
  – Cross Link Calculations
  – Terrestrial Calculations
• 100G Modem
• Link Validation
• Conclusions
Motivation

**MM-WAVE Crosslink Benefit:**
- Robust, mature microwaves
- Well-understood pointing-and-tracking
- RF Comm infrastructure (backend, mod schemes)

**Disadvantage:**
- Large Aperture (6 ft for Satcom)
- Limited Bandwidth

**Laser Crosslink Benefit:**
- Smaller Aperture (wavelength)
- High instantaneous Bandwidth

**Disadvantage:**
- Maturity
- Modulation schemes
- Pointing-and-tracking
Motivation (continued)

Increasing frequency:
- Increases bandwidth
- Shrinks aperture
- Limited ground use above 100 GHz (atmospheric attenuation)

Other Facts:
- Output power decreases with frequency (~1/f^3)
  - Harder to close link
  - But lower DC power
- Receiver sensitivity degrades (~1/f)

Mathematical equation:
\[
\frac{P_{rec}}{P_{tran}} = G_{tran} \times G_{rec} \times \left(\frac{1}{4\pi r}\right)^2
\]
Motivation (continued)

- Significant RF technology advances over last 10 years
- Transistor-based receivers and transmitters to 850 GHz
- Traveling Wave Tube (TWT) Amplifiers to 1,000 GHz
- Spectrally efficient modems (100G)

### Friis Transmission Formula

\[
\frac{P_{rec}}{P_{tran}} = G_{tran} \times G_{rec} \times \left(\frac{1}{4\pi r}\right)^2
\]

#### Small Aperture!

\[G \propto \left(\frac{d}{\lambda}\right)^2\]

#### Sensitivity Degrades

\[T_{rec} \propto \frac{1}{f}\]

#### Power Drops Quickly

\[P_{trans} \propto \left(\frac{1}{f}\right)^3\]

What would it take to do a 670 GHz Link?
Link Calculations

- Terahertz high data rate communications now proven at short range in atmosphere
- Satellite crosslinks may be ideal application for this technology
  - Low probability of intercept
  - Supports high level modulation rates
  - Supports LEO-LEO links with 30 cm aperture

![Graph showing the relationship between Range (km) and Data Rate (Gbps) for different aperture sizes: 10 cm, 30 cm, 100 cm.]
Link Components

Exciter

TWT

Antenna

100G Mod

18.6 GHz

IF

RF

X18

LO

17.8 GHz

660 GHz

Antenna

Receiver

RF

LO

X18

IF

18 GHz

12.1 GHz

Oscilloscope

660 GHz

IEEE
Receiver (NGAS, Redondo Beach)

- ~25 dB Gain and 10 dB NF
- Bandwidth ~ 20 GHz
- Limited by IF mixer bandwidth

Measured Gain

Measured Noise Figure
Exciter (NGAS, Redondo Beach)

- Heterodyne up-converter
- 16 dB small signal gain
- 6 dBm saturated output power
TWT (NGMS, Rolling Meadows)

- Peak power of 200 mW
- >100 mW available at demo frequency (666 GHz)
- Tuneable with voltage
- Integrated with frequency converter (exciter and SSPA) and 10 cm reflector
100G Modulator

The 25Gbps ATCA form factor 100G modulator board processes internally generated PN11 payload data over a 5GHz wide bandwidth directly at 18.6GHz IF

- Custom DSP on two Virtex 7 FPGAs performs encoding, framing and pulse shaping (4.77Gsym/s upconverted to 7.2Gsamp/s)
- Parallel (low speed) to serial (high speed) 64:4 mux operation on custom designed SiGe mixed-signal ICs
- Direct modulation at 18.6GHz IF with 8bit I, 8 bit Q InP multiplying DAC IMA (Integrated Module Assembly)
THz Data Link Overview

- Demo took place in Rolling Meadows, Illinois
- Week of March 33rd 2017
- Two Demos:
  - “Short Range”: 250 M
  - “Long Range”: 600 M
## Ground Based Link Predictions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmit Frequency</td>
<td>666 GHz</td>
<td></td>
</tr>
<tr>
<td>Modulation &amp; Coding</td>
<td>16-APS Kor=7/8</td>
<td></td>
</tr>
<tr>
<td>Data Rate</td>
<td>25 Gb/s</td>
<td></td>
</tr>
<tr>
<td>Net Transmit Power</td>
<td>20 dBm</td>
<td></td>
</tr>
<tr>
<td>Backoff</td>
<td>-1.8 dB</td>
<td></td>
</tr>
<tr>
<td>Losses</td>
<td>-1 dB</td>
<td></td>
</tr>
<tr>
<td>Net Transmit Gain</td>
<td>55.9 dBi</td>
<td></td>
</tr>
<tr>
<td>Aperture Diameter</td>
<td>10.00 cm</td>
<td></td>
</tr>
<tr>
<td>Pointing Loss</td>
<td>-0.5 dB</td>
<td></td>
</tr>
<tr>
<td><strong>EIRP</strong></td>
<td>75.6 dBmi</td>
<td></td>
</tr>
<tr>
<td>Path Loss</td>
<td>-144.5 dB</td>
<td></td>
</tr>
<tr>
<td><strong>Range</strong></td>
<td>600.0 m</td>
<td>Long range test</td>
</tr>
<tr>
<td>Atm Loss</td>
<td>-5.8 dB</td>
<td>15% humidity</td>
</tr>
<tr>
<td>Total Channel Losses</td>
<td>-150 dB</td>
<td></td>
</tr>
<tr>
<td><strong>RSSI</strong></td>
<td>-74.6 dBmi</td>
<td></td>
</tr>
<tr>
<td>Net Receive Gain</td>
<td>54.9 dBi</td>
<td></td>
</tr>
<tr>
<td>Aperture Diameter</td>
<td>10.00 cm</td>
<td></td>
</tr>
<tr>
<td>Pointing Loss</td>
<td>-0.5 dB</td>
<td></td>
</tr>
<tr>
<td>Circuit Loss</td>
<td>-1 dB</td>
<td></td>
</tr>
<tr>
<td>Received Signal Power</td>
<td>-20.2 dBm</td>
<td></td>
</tr>
<tr>
<td>Noise Temperature</td>
<td>3238.3 K</td>
<td></td>
</tr>
<tr>
<td>LNA NF</td>
<td>10.5 dB</td>
<td></td>
</tr>
<tr>
<td>Earth+Sky Contribution</td>
<td>191.0 K</td>
<td></td>
</tr>
<tr>
<td>LNA+Backend Rx</td>
<td>2975.7 K</td>
<td></td>
</tr>
<tr>
<td><strong>Net G/T</strong></td>
<td>19.8 dB/K</td>
<td></td>
</tr>
<tr>
<td>Available Eb/No</td>
<td>41.3 dB</td>
<td></td>
</tr>
<tr>
<td>Net Req’d Eb/No</td>
<td>11.4 dB</td>
<td></td>
</tr>
<tr>
<td>Ideal Req’d Avg Eb/No</td>
<td>6.4 dB</td>
<td></td>
</tr>
<tr>
<td>Implementation Loss</td>
<td>-5 dB</td>
<td></td>
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<tr>
<td><strong>Link Margin</strong></td>
<td>30.0 dB</td>
<td></td>
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</tbody>
</table>

- Original link budget booked -61 dB/km for gaseous atmospheric losses based on ITU reference standard atmosphere
- Weather measurements taken during testing predicted a loss of -9.6 dB/km due to favorably low humidity
  - 22% during demo, 15% during long range testing
Demo Overview: Short Range

Link Details:
- 234 M Range
- Receiver initially saturated
- Rotated receive horn by 90 degrees to receive Cross-Polarization and reduce receive power

CW Mode Receiver Output*

*Note that TWT is operated in pulsed mode
Results: Short Range

- Successfully received and demodulated QPSK and 16-APSK
Results: Short Range

Const. # 2: 29789 sym EVM\textsubscript{RMS/RMS} = 17.6\%
Results: Short Range

Const. # 2: 29789 sym EVM_{RMS/RMS} = 19.1%
Results: Long Range

Link Details:
- 600 M Range
- Receive and Transmit each deployed in a trailer
- Received power ~ 20 dB lower after flipping polarization of horn to Co-Polarization
- Note transmit mixer was swapped after power outage due to component failure

CW Mode Receiver Output*

*Note that TWT is operated in pulsed mode
Results: Long Range

- Successfully received and demodulated QPSK
- Error rate on 16-APSK is higher
- May be at least partially attributed to swapped mixer with higher LO leakage in band

**QPSK**

![QPSK Scatter Plot]

EVM: 19%

**16-APSK**

![16-APSK Scatter Plot]

EVM: 26.6%
Results: Long Range

Const. # 2: 29789 sym EVM_{RMS/RMS} = 19.0%
Results: Long Range

Const. # 2: 29789 sym \( \text{EVM}_{\text{RMS/RMS}} = 26.6\% \)
Outcomes and Insights

• Data passed over-the-air at 666 GHz and 600 M range with good link margin in atmosphere
• Both QPSK and 16-APSK transmitted and demodulated
• Careful Size, Weight and Power (SWaP) trades may show THz links are a viable alternate to millimeter and optical cross links
Ongoing Northrop Grumman “THz” Activities

• First Air-to-Air THz Demo currently being prepared at Northrop Grumman
• CloudSat Radar at 239 GHz in development (NASA)
• “Optically Thin” Contrail Cumulus Cloud demonstration in development (NASA)
• “THz” Technology wafer fabrication now offered as a foundry service.
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• The views, opinions and/or findings expressed are those of the authors and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government.