The DARPA 100Gb/s RF Backbone Program

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Objective: Capacity AND Mobility
• Fiber-like capacity with RF-like mobility
• Work in clouds, rain, and fog
• Size, weight, and power (SWaP) suitable for high-altitude (e.g. 60,000 ft.) platforms

Applications
• High capacity backbone (fiber extension, aggregation)
• High rate data transport
• 0.5 degree beam width permits spectral re-use
• Range ~100km air to ground, ~200km air to air

GOAL: High Capacity and Robust Mobility

Fiber
100 Gb/s per wavelength
100 wavelengths

Mobile SATCOM
Terrestrial Radio
Typical ~Mb/s
Best (roadmap): 9 Gb/s

High
Low
Fixed
On-the-move

100 Gb/s, ~200 km
100 Gb/s, ~100 km

BW = Bandwidth
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DARPA Phase 1
Tech Building Blks
Sept ‘13 - Apr ‘15

DARPA Phase 2
System Design / Integration
Oct’15 – Dec ‘17

DARPA Phase 3
Flight Testing
Jan’18 - Sep ‘18

 Demo Building Blocks
- Rate: 50 Gbps modem
  (25 Gbps * 2 polarizations)
- Range: 10 km
- Line of sight MIMO: 4 streams x 1 Gb/s
- Range: 20, 35 km

Technology Integration
- Rate: 100 Gbps (25 Gbps * 2 pol * 2 antennas)
- Range: 50 km Air-to-Ground
- Pointing, Acquisition, Tracking
- Phase 3 Flight Demo Planning
- Terrestrial Testing (Mountain to Ground Demo)

Flight Testing
- Rate: 100 Gb/s downlink, 10 Gb/s uplink
- Range: 100 km
- Demonstration aircraft
- PAT Validation

Phase 2 & 3 demonstrations are focused on operational transition

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Application spaces

Backbone Relay
- Fiber POP
- Wireless region
- 100G RF node(s)

Backhaul / Aggregator
- Fiber POP
- Multiple nodes

High Capacity Data Movement
- Single node
- Database

Local Relay
- Multiple nodes
- Interconnected network

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Technical Approach: Dimensions of Capacity

How we get 100 Gb/s
5 x 5 x 2 x 2 =
25 Gb/s x 4 strms = 100 Gb/s

\[ C \approx N_s N_p B \log_2(1 + SNR) \]

<table>
<thead>
<tr>
<th>B: Bandwidth</th>
<th>SNR (higher order modulation)</th>
<th>Np: Polarization</th>
<th>Ns: Spatial Combining</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 GHz</td>
<td>5 bits / sec / Hz</td>
<td>2 Polarizations</td>
<td>2 Separate Antennas</td>
</tr>
</tbody>
</table>

Millimeter Wave Bandwidth (B), (5 GHz)

- C ~ B
- 5 GHz in mmW
- Best balance of capacity & loss

SNR (Higher Order Modulation (x5))

- C ~ log₂ (SNR)
- Maximize information bits / symbol
- Limited by linearity and power

<table>
<thead>
<tr>
<th>States</th>
<th>2</th>
<th>4</th>
<th>8</th>
<th>16</th>
<th>32</th>
</tr>
</thead>
<tbody>
<tr>
<td>bits</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

Polarization Multiplexing (x2)

- C ~ Np
- 2 polarizations doubles data rate in same bandwidth
Phase 1 Accomplishments: High Order Modulation

- World record RF modulation rate and order over distance

![Phase 1 Link over downtown Los Angeles (19 km)](image1)

- Northrop Grumman’s Indium Phosphide (InP) modulator (3W)
- Raytheon’s efficient axially displaced ellipse adaptive focus antenna

- Objective: 5 GHz BW, 64 phase states, 2 polarizations
- Threshold: Battelle 30 Gb/s, Northrop Grumman 57 Gb/s, Raytheon 28 Gb/s

- Distance (km):
  - 0, 5, 10, 15, 20
  - Total Data Rate (Gb/s):
    - 0, 10, 20, 30, 40, 50, 60, 70
Phase 1 Accomplishments: Spatial Multiplexing

- Longest demonstrations of mmW line-of-sight multiple-input / multiple output (MIMO) link

\[ R_{Rayl} = \frac{d_1 d_2 N_R}{\lambda} \]

Goal

Typical d1, d2: 3 – 20 meters

R: 20, 35 km

TX Ant

RX Ant

R/ R_{Rayl} : Rayleigh Range Multiple

Silvus

4x

ACS

5.4x

Applied Communication Sciences (ACS)
New Jersey test range (2 antennas)

Silvus Los Angeles test range (2 or 4 antennas)
Phase 2 Overview: Putting It Together

Phase 2 Approach and Status

- Build integrated system using Phase 1* tech.
- Final design review complete; System integration ongoing; Ground tests this year

System technologies from Phase 1

- Single stream high rate radios (25 Gb/s)
- Multiple input / multiple output (MIMO) signal processing combines 4 streams

New in phase 2: Addressing mobility

- 18”–24” efficient adaptive focus dish antennas
- Pointing, acquisition, and tracking
- Ground adaptive antenna selection
- High power GaN power amplifier

SWaP budget (air, single data link)

- 1500 W / 200 lbs (approx. 400 W per transceiver)

*Northrop Grumman (lead), Raytheon, Silvus Technologies, Scaled Composites

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Testing and V/W Channel Measurements

Channel characterization essential to system design
- 4 months of terrestrial testing at 19 km and 44 km

Channel attenuation results
- Good correlation between ITU models and measurement
- Fog has little impact on link
- “Moderate” rain can cause high link attenuation

Scintillation models do not exist at these frequencies
- Measured markedly deeper fades at 44 km range vs. 19 km

Low elevation angle (1.5°) increases fades and more stressing than air-to-ground operation (>9°)

Atmospheric Attenuation @ 19 km

Testing Locations
- Northrop Grumman
- Mt. Lukens
- Westwood
- Weather Station
Capstone Test: 100G Airborne testing

60,000 feet

Phase 3:
- 100 km air-to-ground test

1. Adaptive Modulation (Ground/Air)
2. Antenna Switching
3. Adaptive Antenna and Pointing, Acquisition, and Tracking
Millimeter wave relieves spectral congestion through increased bandwidth allocations at the expense of increased rain loss and therefore availability.

**Available Bandwidth**

<table>
<thead>
<tr>
<th>BE-CDL Band Designator</th>
<th>Ku2</th>
<th>V1</th>
<th>V5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band</td>
<td>Frequency</td>
<td>Bandwidth</td>
<td></td>
</tr>
<tr>
<td></td>
<td>15.4-17.3</td>
<td>1.9 GHz</td>
<td></td>
</tr>
<tr>
<td></td>
<td>43.5-47.0</td>
<td>3.5 GHz</td>
<td></td>
</tr>
<tr>
<td></td>
<td>66.0-76.0</td>
<td>10 GHz</td>
<td></td>
</tr>
</tbody>
</table>

**Rain Loss vs Availability**

<table>
<thead>
<tr>
<th>Availability</th>
<th>Ku2</th>
<th>V1</th>
<th>V5</th>
</tr>
</thead>
<tbody>
<tr>
<td>99%</td>
<td>4</td>
<td>30</td>
<td>52</td>
</tr>
<tr>
<td>97%</td>
<td>2</td>
<td>14</td>
<td>26</td>
</tr>
<tr>
<td>95%</td>
<td>1</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>92%</td>
<td>0.3</td>
<td>3</td>
<td>7</td>
</tr>
</tbody>
</table>

Assumptions:
- Altitude: 60,000 feet
- Elevation Angle: 10 degrees
- Range: ~100 km
- Crane Region D2 (Wash, DC)

Significant increase in V/W Rain Loss for Availability > 95%
Air-to-Air Link, Rate vs Range (18” Apertures)

- Single polarization supports data rates of 25 Gbps at 360 Nmi
- Dual polarization antenna doubles data rate (50 Gbps @ 360 Nmi)
- Adding 2nd antenna for MIMO doubles peak data rate (100Gbps @ 150 Nmi)

Full 4x4 MIMO system can operate on any curve based on mission needs

Assumptions (in line with 100G design):
- Antenna Diameter: 18 inch
- Transmit Power: 40 Watt Psat
- Altitude: 60,000 feet
- Antenna Separation: 10 meter perpendicular to line of sight
- MIMO performance dependent on aircraft geometries

MIMO Enables x2 Data Rate for Bandwidth Constrained Systems

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Air-to-Ground Link Availability

- Millimeter wave relieves spectral congestion through increased bandwidth allocations at the expense of increased rain loss and therefore availability

100 km Target (54 Nmi)
(~90% availability for 100 Gbps)

Assumptions:
- Air-to-Ground Link
- Altitude: 60,000 feet
- Elevation Angle: 10 degrees
- Air Antenna Diameter: 18 inch
- Ground Antenna Diameter: 24 inch
- Crane Region D2 (Wash, DC)

~90% Availability for 100 Gbps, 100 km Air-to-Ground Link (for Crane Region D2)
# 100G “Firsts” -- Pushing State of the Art

<table>
<thead>
<tr>
<th>“First”</th>
<th>Uniqueness</th>
</tr>
</thead>
</table>
| 100 Gbps within 5 GHz Bandwidth  | • Extremely high spectral efficiency (20 b/s/Hz) over 5 GHz instantaneous bandwidth  
                          | • Commercial RF and optical systems typically < 5 b/s/Hz                      |
| 25 Gbps Modem                    | • Extremely high rate, high iteration channel decoding using strong low density parity check (LDPC) code |
| InP Single Chip Modulator        | • World record direct Digital-to-RF Conversion modulator (>30 Gbps)             
                          | • 256-APSK, up to 11 GHz symbol rates at low distortion (EVM < 5%)           |
| High Rate Line-of-Sight MIMO     | • Traditional MIMO relies on multi-path propagation effects and is data rate limited.  
                          | • Computationally efficient, high-rate line of sight MIMO                     |
| High efficiency E-band Antenna   | • >75% aperture efficient high gain mmW antennas with adjustable beamwidth   
                          | • Less than 0.002” RMS surface accuracy on 18” and 24” shaped Axial-Displaced Ellipse reflector antenna |
| E-band Power Amplifier           | • 10 – 20 dBW E-band power amplifier technology leveraging DARPA investments in Gallium Nitride materials and circuits |
| Airborne PAT                     | • High gain (<0.4° HPBW) antennas required advanced mobile mmW Pointing,  
                          | Acquisition, and Tracking system for air-to-ground and air-to-air links       |
| V/W Band Channel                 | • High scintillation and deep fades require adaptive coding and modulation at < 100 ms rates vs. seconds to minutes in conventional systems |

## Number of World First Required for an Operational 100G System
Conclusion

• DARPA 100G
  • Demonstrating fiber-like capacity with RF mobility
  • Exploiting and gaining understanding of all dimensions of channel capacity
  • Design can be adapted to different needs

• Status: System integration is underway
  • Underlying technologies demonstrated
  • Integrated 100 Gb/s design using four spatial streams at 25 Gb/s each is complete and being realized
  • Over-the-air outdoor system testing planned for this year
  • Airborne mobile demonstrations planned in 2018
  • Deployed systems adaptable to different platforms, payloads, and uses
Thank You