Optical Technologies for very high throughput satellite communications

2019 Oberpfaffenhofen Workshop on High Throughput Coding

Institute of communications and navigation
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Global Connectivity with optical free-space communications

- Data retrieval from LEO satellites
  - Direct-downlinks

- Communications in Emergency situations
  - Aeronautical links

- Global Connectivity with GEO satellites
  - Optical high throughput links

- Exploration
  - Deep-Space communications

- Atmospheric Turbulence
  - Research through theory, simulations and demonstrations
  - Compensation methods: adaptive optics
Global connectivity with GEO satellites

- Motivation: Global Networking

- **Broadband Internet** everywhere
  - User access: internet with 50 Mbit/s and more
  - Data transport: optical infrastructure for space

- Internet availability for **Industry 4.0**
  - Towards a **versatile industry**: *Smart Service World*
  - **Adaptive Logistic**: world-wide networking of mobile sensors
  - Networking for a **cloud-based** business model
  - Requirements on security, availability and quality of service (reliability, data-rate, low latency requires LEO or HAPS constellations)

- Gaps in broadband access: e.g. 28% in European rural areas
  - Global provision of broadband connectivity using **satellite communications**
Motivation: satellite optical communications

- Few GEO satellites with worldwide coverage

- Currently: Ka-Band (user + feeder)
  - Ka-Sat (70 Gbps), ViaSat-1 (140 Gbps), ViaSat-2 (350 Gbps)

- GEO satellite communications
  - RF user-link with 50Mbit/s
  - Feeder Links with Terabits/s throughput
  - Number of required gateways increases linearly with throughput

- Approach: optical feeder link
  - every gateway provides full capacity
  - DWDM Technology from fiber communication

- Optical frequencies: several THz of bandwidth and no-regulation
Optical Communications: Atmospheric Channel

- Received signal fluctuations due to atmospheric turbulence
  - Scintillation: phase-distortions lead to Intensity fluctuations
  - Beam wander: uplink pointing errors
- Fading duration between 1 and 10 ms
  - 1 Gbit is lost each 1 ms of fading when transmitting 1 Terabit/s
Atmospheric channel

- SAT
  - Strong fluctuation
  - Almost perfect fibre coupling

- Ground station
  - Aperture averaging
  - More stable signal
Atmospheric channel

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Angle of Arrival
Fried parameter $r_0$

Downlink

Atmosphere ~20 km

DLR.de • Chart 7
Uplink channel

- # Fades increase with small divergences
- TX Diversity decreases deep fades
  - More fades at -3dB but shorter
  - More surges at +3dB

<table>
<thead>
<tr>
<th></th>
<th>20 April-23h B0210-1</th>
<th>25 April-23h B0140-1</th>
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</thead>
<tbody>
<tr>
<td>Mean -3dB</td>
<td>10.3 ms</td>
<td>10.6 ms</td>
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<tr>
<td>#Fades -3dB/s</td>
<td>45</td>
<td>29</td>
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<tr>
<td>Mean -10dB</td>
<td>2.9 ms</td>
<td>3.9 ms</td>
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<tr>
<td>#Fades -10dB/s</td>
<td>46</td>
<td>10</td>
</tr>
<tr>
<td>Mean +3dB</td>
<td>7.2 ms</td>
<td>7.2 ms</td>
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<tr>
<td>#Surges +3dB</td>
<td>22</td>
<td>15.5</td>
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</table>
Adaptive optics for phase-correction

- Technology from astronomy
- Phase distortions
  - Coupling losses
- Stronger turbulence conditions
  - Communications scenario
- Wave-front estimation
- Control-loop approaches
- Pre-distortion for uplink
Laser guide stars for communications

- Laser at 589 nm creates an „artificial star“
  - Sodium layer of the atmosphere at ~90 km

- Technique used in astronomy for adaptive optics
  - Imaging of astronomical objects

- Reference for the uplink direction
  - Use of adaptive optics in pre-correction

- „Tilt“ cannot be directly measured
  - Off-axis telescope
  - Challenge also for astronomy

- Collaboration with ESO, Durham University, INAF
Link budget comparison

- Advantage in distance is lost due to pointing stability
- ~2 dB margin gain for LEO compared to GEO
- It is assumed
  - Bigger telescopes for MEO and GEO
  - TX divergence is optimized for the transmitted power

<table>
<thead>
<tr>
<th>Link budget</th>
<th>LEO</th>
<th>MEO</th>
<th>GEO</th>
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</thead>
<tbody>
<tr>
<td>Pointing strategy</td>
<td>Open-loop</td>
<td>Open-loop / DL-tracking</td>
<td>DL-Tracking</td>
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<tr>
<td>Spacecraft altitude [km]</td>
<td>1000.0</td>
<td>20000.0</td>
<td>36000.0</td>
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<tr>
<td>Elevation [º]</td>
<td>30.0</td>
<td>30.0</td>
<td>30.0</td>
</tr>
<tr>
<td>Transmitted divergence (e-2-radius) [µrad]</td>
<td>30.1</td>
<td>30.1 / 14.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Beam wander or pointing jitter [µrad]</td>
<td>11.2</td>
<td>11.2 / 4.9</td>
<td>1.7</td>
</tr>
<tr>
<td>Ground Antenna Gain [db]</td>
<td>99.5</td>
<td>99.5 / 106.1</td>
<td>113.4</td>
</tr>
<tr>
<td>Free-space loss [db]</td>
<td>-262.8</td>
<td>-285.3</td>
<td>-290.0</td>
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<tr>
<td>Margin w.r.t. GEO [db]</td>
<td>+27.2</td>
<td>+4.7</td>
<td>0</td>
</tr>
<tr>
<td>Mean pointing-loss [db]</td>
<td>-4.8</td>
<td>-4.8 / -4.3</td>
<td>-2.8</td>
</tr>
<tr>
<td>Scintillation margin for 99.99% availability</td>
<td>-6.6</td>
<td>-6.6 / -5.6</td>
<td>-3.7</td>
</tr>
<tr>
<td>Atmospheric attenuation + Cloud Margin</td>
<td>-2.0</td>
<td>-2.0</td>
<td>-2.0</td>
</tr>
<tr>
<td>Satellite Rx Antenna [cm]</td>
<td>15</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Satellite Rx Antenna Gain [db]</td>
<td>109.7</td>
<td>115.7</td>
<td>115.7</td>
</tr>
<tr>
<td>Margin w.r.t. GEO [db]</td>
<td>-6.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Tx and Rx efficiency</td>
<td>-4.0</td>
<td>-4.0</td>
<td>-4.0</td>
</tr>
<tr>
<td>Additional Margin (ancillary losses)</td>
<td>-2.0</td>
<td>-2.0</td>
<td>-2.0</td>
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<tr>
<td>Total Link loss [db]</td>
<td>-73.1</td>
<td>-89.5 / -81.3</td>
<td>-75.3</td>
</tr>
<tr>
<td>Margin w.r.t. GEO [db]</td>
<td>+2.3</td>
<td>-14.2 / -6.0</td>
<td>0</td>
</tr>
</tbody>
</table>
Uplink communications architecture

- Satellite has limited resources in power, mass and heat dissipation.
  - e.g. Alphabus offers 12-14kW payload power
Very high throughput satellite communications

- Optical Satellite Network, considering node connections between GEO and ground
- Dedicated platforms vs. application oriented
  - Higher number of platforms, smaller
- GEO as monitoring for the other orbits: higher visibility for traffic management.
Technology Challenges

- Space-qualification for satellite usage
  - DWDM technology, amplifiers, receivers

- Satellite on-board processing
  - **Communications architecture**
  - Terabit/s throughput on-board processing

- Multiple Terabit/s switching between gateways
  - Network of gateways: ~10 in Europe for 99,9% availability to avoid cloud coverage

- Atmospheric turbulence
  - **Mitigation of channel impairments**
  - **Optimization of the feeder-link**

First step: Demonstrate DWDM Technology in relevant environment
Free-space technology demonstration

- Ground link emulating the GEO feeder link
- Measurement of the communications performance with strong fluctuations
- Development of two terminals representing a satellite and a ground station
  - Single-mode fiber coupling

![C² profile graph and map showing DLR-Weilheim to DWD Hohenpeißenberg connection]

**C² profiles for Ground-GEO and THRUST Testbed**

- Close to ground

- Distance z along Line of Sight [m]
- Distance: 10.45 km
The optical terminals

- Ground station terminal with fiber coupling and adaptive optics
- Point-ahead emulation
  - lateral shift of downlink beacon in the satellite terminal
  - Point-ahead mirror in the ground station
- Atmospheric turbulence monitoring instruments
Hardware setup for fiber coupling

- Satellite terminal with single-mode fiber coupling

Optics
- Signal coupling

Electronics
- Sensor analysis
- Actuator control
Free Space Optical Communications AO Demonstrator

- AO System installed at OGS terminal
  - SH-WFS with 8x8 sub-apertures
  - InGaAs, Short Wave Infra-Red WFS detector, running between 500 – 3000Hz
  - 97 Actuator ALPAO DM
  - Transmitted and received beam projected from same DM, so pre-distortion AO can be demonstrated.
  - Focus Camera observes corrected spot
- Multiple measurement campaigns completed in 2018
AO Performance for fibre coupling and pre-distortion

Power and Scintillation received at OGS, alternating between AO on and off. Consistently higher power (+3.1dB) and lower scintillation (50% less) with AO

Power and Scintillation received at SAT alternating between AO on and off. Consistently higher power (+3.1dB) and lower scintillation (50% less)
Coherent Communications system

- Intradyne (digital homodyne) concept developed in 2016 tested for 30G BPSK [1]
  - Minimum lock-time after fading
  - SW complexity vs. HW complexity compared to OPLL
- Mid-2017 [2]
  - 40G receiver
  - More robust timing recovery (Lee algorithm)
  - Equalization
- Fall 2017 integration of I/Q Modulator -> 40G QPSK

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13,16 Tbit/s demonstration in 2017

- Collaboration with ADVA
- FSP 3000 Cloudconnect QuadFlexTM
  - DP-16QAM, DP-8QAM, DP-QPSK
- Channels swept with QF
- Power measurement
  - Full spectrum
  - At fixed channel
- DLR: Duplex operation
  - 80Gbps uplink / 20Gbps downlink
- BER evaluation (QF)
  - Post-FEC / Pre-FEC
  - Strong dependence on atmosphere
  - 3-days with various conditions
Summary

• GEO satellites can provide global coverage
  • Modeling the uplink channel in collaboration with Tesat

• WDM technology
  • Demonstrations under strong turbulence conditions
    • In 2016 1.72 Tbit/s with OOK
    • In 2017 13.16 Tbit/s with 16QAM, in collaboration with ADVA

• Coherent communications
  • Technology already space-proven
  • Digital homodyne have been demonstrated through strong turbulence conditions

• Adaptive Optics
  • For single-mode fiber coupling
  • Pre-distortion has been demonstrated

• Laser guide stars
  • Currently under test on the Canary Islands, in collaboration with the European Southern Observatory (ESO), European Space Agency (ESA), Durham University and Istituto Nazionale di AstroFisica – Osservatorio Astronomico di Roma (INAF-OAR)
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