MOBILE AND SATELLITE LASER COMMUNICATION SYSTEMS

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Outline

1 Introduction (definition)
2 Satellite optical links
   2.1 Earth orbits
   2.2 Satellite optical link projects
3 Terrestrial mobile optical links
   3.1 Basic characteristics of the mobile optical links
   3.2 Mobile optical link projects
4 Conclusion
1 Introduction

Definition

Mobile and satellite optical link works as a Free-Space optical link (FSO link) which transmits an optical signal through the atmosphere or deep space.

Optical power is concentrated to one or more narrow beams.

Optical wave can be divided into several optical channels.

(Their application is suitable in situations where the use of optical cable is impossible and desired bit rate is too high for a microwave link.)
Regarding power budget of the link small divergence is required which means strict demands on APT (acquisition, pointing and tracking) system.

Optical transceivers with azimuthally and elevation assembly
Laser beam (without atmosphere)

Wave Helmholtz equation is starting point

Gaussian beam (laser beam) is one of its solutions

\[
\nabla^2 \dot{E}(x, y, z) + k^2 \dot{E}(x, y, z) = 0
\]

\[
\dot{E}(x, y, z) = E_0 \frac{w_0}{w(z)} e^{-j\frac{x^2 + y^2}{2q(z)}} e^{-j \left( kz + \varphi(z) - \frac{\pi}{2} \right)}
\]

Beam width vs. range

Radius curvature of wavefront vs. range

Johan Carl Friedrich Gauss (1777 – 1855)
Optical wave $\rightarrow$ Optical intensity $\rightarrow$ Optical power

$$P(z,t) = \int_{s} I(x,y,z,t) dx dy$$

Fast optical changes in time

$$\left\langle \vec{E}(\vec{r},t) \times \vec{H}(\vec{r},t) \right\rangle_{time} = I(\vec{r}) = I(x,y,z)$$

Optical intensity distribution in Gaussian beam

Slow (modulation) changes in time

$$I(x,y,z) = I_0 \left( \frac{w_0}{w(z)} \right)^2 e^{-2\frac{x^2+y^2}{w^2(z)}}$$
Laser beam

Optical intensity distribution in Gaussian beam

\[ I/I_0 \]

\[ \theta^2 \]

\[ x/w \]

laser diode

beam

Speckles in beam spot

Fresnel diffraction on lens socket
Basic characteristics of laser radiation

- high directivity – high concentration of **optical power**

![Laser diode diagram with TX and θ ≈ 10⁻³ rad]

- high monochromatic wave – high concentration of **information**

![Graph showing g(ν) with Δν and Δν/V < 10⁻³]

- possibility of transmission of quantum state of photons – leads to high degree of **security** during transmission
Advantages

- The narrow beams guarantee high spatial selectivity so there is no interference with other links.
- High bit rate enables them to be applied in all types of networks.
- Optical band lies outside the area of telecommunication offices, therefore, a license is not needed for operation.
- The utilization of quantum state transmission promises long-term security for high-value data.
- Short size and small weight corresponds to easy integration to the satellite body.
Disadvantages:
✓ availability of FSO link depends on the weather
✓ FSO link requires a line of site between transceivers
✓ birds and scintillation cause beam interruptions

For reliability improvement number of new methods is applied:

1. Photonic technology
2. Multi beam transmission
3. Wavelength and space division
4. Beam shaping
5. Auto-tracking system
6. Microwave backup
7. Adaptive optics
8. Polygonal (mesh) topology
Perspective of FSO communication

- The “last mile” solution (in the frame of access networks)
- Quantum states of photons transmission (long-term security transmission for high-value data)
- UV atmospheric communication
- Mobile optical communication
- Non-diffractive Bessel beams utilization
- Optical communication between satellites
- Utilization of LED for both illumination and communication
Optical wireless links division according to their location and work conditions.

OWL

- indoor
- outdoor

atmospheric

stationary

mobile

working in near space (using Earth satellites)

working in deep space (using Moon, Mars satellites etc.)
Visualization of atmospheric layers and transceiver carriers

(min. 200km)
Atmospheric phenomena

Transmission of „clear“ atmosphere measured at sea level

\[ L_{12} = 1\text{km}; \Delta \lambda = 1,5\text{nm} \]
# Atmospheric phenomena

Components of $\alpha_{atm}$

- **1. Absorption, scattering and refraction on gas molecules and aerosols (fog, snow, rain)** *(slow variations)*

$(\lambda = 785 \text{ nm})$

<table>
<thead>
<tr>
<th>visibility [km]</th>
<th>attenuation [dB.km$^{-1}$]</th>
<th>State of the atmosphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.05</td>
<td>&gt; 340</td>
<td>Heavy fog</td>
</tr>
<tr>
<td>0.2 – 0.5</td>
<td>85 – 34</td>
<td>Middle fog</td>
</tr>
<tr>
<td>1.0 – 2.0</td>
<td>14 – 7.0</td>
<td>Weak fog or heavy rain</td>
</tr>
<tr>
<td>2.0 – 4.0</td>
<td>7.0 – 3.0</td>
<td>Haze</td>
</tr>
<tr>
<td>10 - 23</td>
<td>1.0 – 0.5</td>
<td>Clear</td>
</tr>
</tbody>
</table>
Atmospheric phenomena

Components of $\alpha_{atm}$

- 2. Beam deflection (*diurnal variations*)
  (temperature or mechanical deformation of consoles)
- 3. Short-term interruptions of the beam (*short pulses*)
  caused by birds, insect, ....

(7th floor, filmed from a distance of 750m)
Atmospheric phenomena

Components of $\alpha_{atm}$

- 4. Fluctuation of optical intensity (*noise-like*)

\[ f \text{ [Hz]} \]

<table>
<thead>
<tr>
<th>time of day</th>
</tr>
</thead>
<tbody>
<tr>
<td>00:00</td>
</tr>
<tr>
<td>06:00</td>
</tr>
<tr>
<td>12:00</td>
</tr>
<tr>
<td>18:00</td>
</tr>
<tr>
<td>00:00</td>
</tr>
</tbody>
</table>

- 5. Background radiation
Demonstration of integration of the optical wireless links into global communication network

(2.VIDEO_SatNetwork)
2. Satellite optical links

Earth orbits

GEO – Geostationary Earth Orbit (36 000 km; 24 hour)
MEO – Medium Earth Orbit (1 200 km – 35 000 km; 4x – 6x per day)
LEO – Low Earth Orbit (200 km – 1 200 km; 80 min – 130 min)
Satellite optical link projects

1. Project SILEX supported by ESA – European Space Agency
   (Semiconductor-laser Inter-satellite Link Experiment)

   November 2001
   Tx: LD GaAlAs (800 nm), Rx: APD;
   50 Mb/s @ 10^-9
   SPOT-4, LEO, 832 km
   (Satellite Pour l’Observation de la Terre)

ARTEMIS, GEO
(Advanced Relay and Technology Mission Satellite)
Satellite optical link projects

2. Project „Kirari“ OICETS supported by ESA and Japanese JAXA
   (Optical Inter-orbit Communication Engineering Test Satellite)

„Kirari“ OICETS
LEO, 610 km

December 2005
Parameters of experiment see SILEX

ARTEMIS
GEO, 36 000 km

JAXA – Japan Aerospace Exploration Agency
3. Common project Japanese institutions JAXA a NICT
(National Institute of Information and Communication Technology)

March 2006;
The first time in the world:
sat. LEO – Earth station

SATellite optical link projects

Terrestrial stationary station in Koganei, Tokio

„Kirari“ OICETS
LEO, 610 km

Laser beam

APT system confirmation

<table>
<thead>
<tr>
<th>Image</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td>Terrestrial stationary station in Koganei, Tokio</td>
</tr>
<tr>
<td><img src="image2.png" alt="Image" /></td>
<td>„Kirari“ OICETS LEO, 610 km</td>
</tr>
<tr>
<td><img src="image3.png" alt="Image" /></td>
<td>Laser beam</td>
</tr>
</tbody>
</table>

March 2006;
The first time in the world:
sat. LEO – Earth station
4. LOLA project
Optical communication between ARTEMIS (GEO) and airplane

(perfect system APT)

December 2006;
A world first:
satellite – airplane

French airplane Mystère 20; altitude 6 km and 10 km

ARTEMIS results as a whole:
ARTEMIS – stationary station,
ARTEMIS – satellite (LEO),
ARTEMIS – airplane.
Mobile optical link (M-FSO) works partly or totally in atmospheric conditions. Mutual position of transceivers changes during transmission.

- M-FSO links use space, air and terrestrial platform for communication.
- Terrestrial station can be placed on a moving vehicle or on a ship.
- Satellites of Earth, stratospheric HAPs (High Altitude Platform), UAV (unmanned aerial vehicle), classical airplanes and terrestrial stationary or mobile stations can be used as carriers of transceivers.
Mobile optical link projects

1. EU-FP6 project CAPANINA (13 partners including 2 Japanese) (Communications from Aerial Platforms Providing High Bandwidth Communications for All)

August 2005

Optical power of 100 mW (Tx on the HAP);
Altitude of 22 km, range of 60 km;
Bit rate of 622Mb/s, bandwidth of 1,25 Gb/s;
Modulation used is IM/DD, OOK;
Bit error rate of 10^-9;
Wavelength of 1550 nm.

Laser beacon: 986 nm; 200 mW

Base ESRANGE (European Space Range), in Kiruna, Sveden
Arrangement of CAPANINA experiment

TOGS, Transportable Optical Ground Station (DLR)

FELT, Freespace Experiment Laser Terminal (DLR)
Overview of the APT system

(CAPANINA project)
APT system on the stratospheric balloon in details
(CAPANINA project)

APT system (DLR)
Resolution: 9 μrad
Mobile optical link projects

2. Common project JAXA and DLR: KIODO
(Kirari Optical Downlink to Oberpfaffenhofen)

June 2006
Duplex communication
50 Mb/s @ BER=10^-6

"Kirari" OICETS
LEO, 610 km

Mobile OGS, Optical Ground Station Wessling, Germany
3. Common project DLR (Wessling) and Carl-Zeiss Optronics (Oberkochen): MOND (Mobile Optical Near-Ground Demonstrator)  

Moving vehicle was equipped by inertial navigation sensor (supported by GPS) providing APT system by needed information. Wavelength of 1550 nm was used and video signal in HDTV quality was transmitted with bit rate of 1.5 Gb/s. A special canal coding ARQ and FEC ensuring immunity of transmission quality against beam interruption by accidental obstructions was used.

Eye diagram and laser beam transmitted by stationary terrestrial station

February 2007

Terminal placed on moving vehicle
Mobile optical link projects

4. Project Terra-SAR-X
(German satellite LEO, altitude 510 km)

Coherent optical link works with bandwidth of 7 GHz at the wavelength of 1064 nm. Signal from the satellite is received by two stationary terrestrial stations in Spain. Investigation of influence of turbulent atmosphere on coherent transmission from the satellite is the goal of this experiment.

June 2007

Space terminal for coherent optical communication was developed by DLR in conjunction with Tesat-Spacecom
Activity in the area of terrestrial FSO links

ORCAVE – FSO link of the Czech company
Miracle Group

- 2 laser beams
- auto-tracking system
- range 2.0 km @ BER = 10^{-9}
- wavelength 1550 nm
- management system
- monitoring system etc.
Monitoring of atmospheric phenomena in selected sites

Selected sites:
- Prague (750m)
- Brno (950m)
- Milesovka hill (Donnersberg)

Czech Republic

- Long-term monitoring of optical power and BER
- Meteorological sensors
4. Conclusion

FSO technology is ready for utilization as terrestrial links, mobile links and satellite links.

- Importance of high bit rate and security for high-value data.
- Possibility of integration in global wireless communication network.
- Optical communication in deep space between Mars satellite and Earth station is in preparation (MTO, Mars Telecommunication Orbiter).
- Terrestrial links are a suitable technology for the ”last mile” solution in the frame of access network.
- The utilization of the FSO links is requested namely in situations where the use of an optical cable is impossible and desired bit rate is too high for a microwave links.
- FSO links are flexible, simple and full-value (in terms of quality of transmission) license-free instrument of network communication technologies.
References


