SPACE-BORNE OPTICAL COMMUNICATIONS – A CHALLENGING REALITY

Peter J. Winzer and Walter R. Leeb
Institut f. Nachrichtentechnik und Hochfrequenztechnik, Vienna University of Technology, Vienna, Austria
P. J. W. is presently at Bell Laboratories, Lucent Technologies, 791 Holmdel-Keyport Rd., Holmdel, NJ 07733 (USA)
peter.winzer@ieee.org

Abstract *Optical inter-satellite links (ISLs) have recently become operational reality. We outline potential commercial applications, focusing on broadband mobile communication networks with global coverage, and discuss some design issues and trade-offs for optical ISLs.*

Introduction

The mostly internet-driven, highly increasing bandwidth demand of our communication society in combination with the ever-growing desire for mobile data/voice communication services asks for mobile communication networks with truly global coverage. Networks making accessible remote locations on the ground and bringing high-speed internet onboard airplanes can only be realized using satellite constellations. To keep latencies and transmit power requirements within acceptable limits, and to allow for cellular architectures, satellites in low-earth orbit (LEO) are the method of choice.

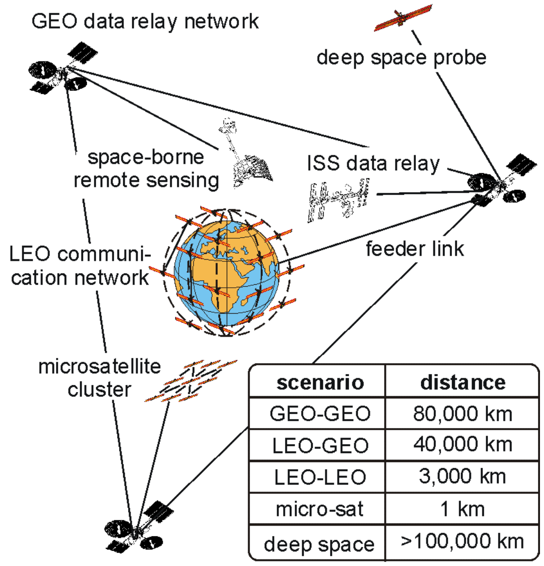
Application scenarios for optical ISLs

To carry the traffic within networks envisaged for systems like IRIDIUM, TELEDESIC, CELESTRI, or NELS [1,2], high-speed inter-satellite links (ISLs) are needed, which are best implemented optically [2-6]. Although the advantages of optical ISLs have been noticed several decades ago, commercial deployment has not yet taken place. This unfortunate fact can mainly be attributed to most investors' reluctant attitude towards newly emerging space technologies, which are hard to operationally validate and are viewed as being high-risk. However, this adverse frame of mind can be expected to change soon, since the first operational (non-military) optical ISL, spanning a link distance of ~30,000 km, has been successfully demonstrated by the European Space Agency (ESA) [7,8] in their project SILEX, and communication terminals for optical ISLs are in their final development phases [9-11].

Apart from LEO networks supporting terrestrial mobile communications, satellites in geostationary orbits (GEO) are used as data relays for space platforms (such as the International Space Station, ISS) or earth observation satellites in LEO: Since LEO orbits do not allow for continuous visibility to a single ground station, they have to either store data, or relay it to GEO satellites, which either send them directly to Earth, or route them on to other GEO or LEO platforms. NASA's Tracking and Data Relay Satellite System (TDRSS) is an example for a GEO data relay network [5,10]. Due to the increasing data flow from remote sensing and imaging satellites, optical ISLs will be the optimum choice here. Other applications for optical ISLs include data communication with deep space probes [10,12], optical feeder-links between GEO data relays and receiving stations on Earth [13], optical interconnections between high-altitude platforms [14], and optical links within micro-satellite clusters [15,16]. Figure 1 summarizes the potential application scenarios for optical ISLs, and lists typical link distances.

Why and when to favour optical over RF links

The main difference between *optical* ISLs and well-proven *radio-frequency* (RF) communication links is the electromagnetic carrier frequency, which is on the order of several ten GHz (typ. 60 GHz) for the highest-frequency RF links, and on the order of several hundred THz (typ. 300 THz) for optical links [5,6,16]. This difference in carrier frequencies by a factor of ~5000 explains the two major advantages of free-space optical communications: First, a vast absolute bandwidth range is opened up at optical frequencies, while strict narrow-



scenario	distance
GEO-GEO	80,000 km
LEO-GEO	40,000 km
LEO-LEO	3,000 km
micro-sat	1 km
deep space	>100,000 km

Fig. 1: Potential application scenarios for optical ISLs.

band characteristics of the signal are maintained. Second, since the gain of an antenna is proportional to the carrier frequency squared, optical antennas have about 74dB more gain than RF antennas of the same size, which directly translates into the link budget. The high directivity of optical beams thus allows for communication over huge distances (e.g., GEO-GEO, cf. Fig. 1), but, on the other hand, necessitates highly accurate beam pointing. In fact, the pointing, acquisition, and tracking (PAT) subsystem constitutes a major portion of optical space communication terminals [5,6,9]. An additional advantage of optics over RF, which follows from the low optical beam divergence, is the immunity to multi-user interference, and, consequently, the absence of regulations for the electromagnetic spectrum at optical frequencies. – In short, optical ISLs have the edge whenever *high data rates*, *long link distances*, or *low interference* are required.

Main technologies and trade-offs for optical ISLs

As the requirements for different classes of optical ISLs vary widely, we will focus on the two most important applications, which are LEO networks and GEO data relays. We will sketch the most relevant system parameters and outline some design trade-offs [5,6,10].

The quadratic increase of antenna gain with frequency inherently favours short *optical wavelengths*. On the other hand, the input power requirements to optical receivers decrease linearly with wavelength, resulting in a net linear link-budget improvement with increasing wavelength. Tighter manufacturing tolerances for diffraction-limited optics together with higher *pointing requirements* of the narrower beams at shorter wavelengths (and thus more complex PAT subsystems) further reduce the advantage of short wavelengths. The PAT subsystem usually employs separate beacon lasers or some portion of the information-carrying laser beam to illuminate a position-sensitive detector (e.g., a quadrant detector or a CCD array) at the counter-terminal. Active control loops for beam pointing compensate for satellite motion and spacecraft micro-vibrations [5] by means of electro-mechanical beam deflectors, optical phased arrays [17], or liquid-crystal devices [18]. At the receive terminal, high *receiver sensitivity* is desired: The most sensitive optical receivers use homodyne detection and phase-shift keying (PSK) modulation. This rather complex communication technique employs a local oscillator laser (typically a narrow-linewidth Nd:YAG laser at 1064 nm) that has to be actively phase-locked to the received light [9,11]. Another promising receiver type is optically preamplified direct detection, using either on/off keying (OOK) or differential phase shift keying (DPSK) [5,19]. Being significantly simpler to implement, optically preamplified DPSK systems are theoretically 3 dB less sensitive than those based on homodyne PSK. However, the best experimental results reported for DPSK at 10 Gbit/s [20] are only 1.5 dB worse than the best reported homodyne PSK results at 565 Mbit/s [21]. Further, commercially available and mature opto-electronic components developed by the terrestrial fiber communications industry for operation in the 1550-nm band can be advantageously deployed for preamplified DPSK, which potentially allows for significant cost savings once *space-qualification* of all components, particularly of Erbium-doped fiber amplifiers, is achieved. The recent interest in phase-coded formats for fiber communications [22,23] can be expected to further advance the commercial availability of DPSK receiver components. Nevertheless, due to limited *power resources* onboard a spacecraft, as well as due to stringent constraints on *antenna size (and weight)*, the sensitivity advantage of homodyne PSK might still justify the higher technological effort for, e.g., ultra-long distance GEO-GEO ISLs.

Conclusion

Operational optical inter-satellite links have become reality, and are expected to soon enter the commercial stage. A variety of system tradeoffs allows for cost-optimization of the entire space-borne network solution.

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