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Ultra-low loss laser communications technique using smart beamforming optics

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Abstract

Theory and design is presented for a technique for ultra-low loss laser communication that uses a combination of strong and weak thin lens optics, hence obeying the paraxial approximation. As opposed to conventional laser communication systems, the Gaussian laser beam is prevented from diverging at the receiving station by using a weak thin lens that places the transmitted beam waist mid-way between a symmetrical transmitter–receiver link design. The weak lens can be a fixed optic for static link distances or programmable for mobile scenarios. The programmable weak optic can be a single pixel or multi-pixel lens made by liquid crystal or mirror technologies. The proposed link design is appropriate for low air turbulence links such as short-range or indoor links and space based links.

Keywords: Wireless; Laser communications; Freespace optics; Gaussian beam propagation; Liquid crystals; Variable focus lens; Low loss

1. Introduction

Laser communications has been around since the advent of the laser itself [1]. Laser communications scenarios include but are not limited to: short-range (indoor/a few meters) links [2], terrestrial short-hop building-to-building links (1–5 km), terrestrial (line of sight ~100 km) links [3,4], submarine-to-aircraft links, [5] submarine-to-satellite links [6], airborne links (~50–500 km) [7], mobile platform-to-airborne links, mobile platform-to-satellite links, ground-to-Low Earth Orbit (LEO) satellite links which range from several hundred km to a few thousand km [8,9],

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aircraft-to-satellite links [10], ground-to-Geostationary Earth Orbit (GEO) satellite links which range from 35,000 to ∼42,000 km, LEO-to-LEO satellite cross-links (∼3000 km), LEO-to-GEO satellite cross-links (∼40,000 km) [11–14], GEO-to-GEO satellite cross-links (∼80,000 km) [13], and ground-to-planetary probe links (>100,000 km to several millions of km) [15].

Of importance in these links is the communication medium which can sometimes degrade the communication link performance. In short-range or indoor links only physical obstruction in the line of sight link can disrupt the communication. In contrast, propagation effects on laser communications in the atmosphere need to be considered carefully [16]. The atmosphere is roughly a 20 km thick air blanket surrounding the earth. Due to temperature changes and wind flow, the index of refraction of the air randomly varies temporally. This causes the laser beam to both wander around the desired propagation direction and be spread as well along the propagation path in an indeterministic fashion, thus causing the loss of useful signal power.

The effect of the atmosphere is severe in links which involve a ground based station as the transmitter (TX) in a satellite uplink configuration because of the fact that the laser beam undergoes the atmospheric turbulence in the beginning of the communication link. This is true for example in a ground-to-LEO or a ground-to-GEO uplink where the ground terminal acts as the TX. Typical distances are in the range of ∼400 km to a few thousand km for a ground-to-LEO link while those for a ground-to-GEO link are ∼40,000 km. For example, in a ground-to-GEO uplink, the laser beam will encounter the atmospheric turbulence in the first 1% of the communication medium, resulting in large unwanted beam divergence and intensity variations (scintillation) at the satellite receiver (RX) terminal. Alternately, when the GEO satellite station acts as the TX in a satellite-to-ground link, the laser beam first travels for the 99% of the link length in space and in the last 1% comes across the atmosphere. Hence at the ground RX, the received beam properties are governed predominantly by the TX beam divergence. Moreover due to their limitations of prime-power, weight and volume, large size telescopes are not feasible in satellites resulting in a laser beam that diverges rapidly compared to a larger size transmit beam. As a result the ground terminal has to have a larger telescope in order to receive the TX beam from the satellite terminal resulting in an asymmetric laser communication link configuration. This configuration is feasible as the ground terminals can afford to incorporate the large telescope sizes required in asymmetric links. Ground terminals can also afford to use high power lasers and complex wavefront correction adaptive techniques in order to overcome undesirable beam spread and scintillation caused by the atmospheric turbulence. In effect, this makes the lasercom solution a better choice for satellite-to-ground links.

Since the satellite itself in most of the configurations such as imagery and reconnaissance is the data transmitting terminal, a high speed downlink is required as compared to a moderate speed uplink that is needed for satellite control and feedback purposes. Intersatellite cross-links involve space as the communication link medium, and hence atmospheric effects do not come into play making lasercom a preferred choice in these links. For example, the SILEX demonstration in November 2001 used a link between LEO satellite SPOT4 (832 km orbit, 25 cm TX telescope, 25 cm RX telescope, 60 mW GaAlAs laser diode at 847 nm and 50 Mbits/s NRZ modulation) and GEO satellite ARTEMIS (31,000 km orbit, 12.5 cm TX telescope, 25 cm RX telescope, 37 mW GaAlAs laser diode at 819 nm and 2 Mbits/s PPM) [12]. Image data was transferred from SPOT4 to ARTEMIS at a 50 Mbits/s rate for the first time using solely an optical link. The optical communication terminal onboard ARTEMIS was also tested before the actual inter-satellite link establishment using an earth based ground station as a mock-up LEO satellite [9]. The ground station had a 1 m Zeiss RX telescope and a 847 ± 5 nm Titanium–Sapphire laser with a peak power of 6 W that was pumped by an Argon ion laser. The ground station used four mutually incoherent TX beams with 4 cm diameters to counter far-field divergence caused by the atmospheric turbulence and scintillation. Due to the fast velocity relative to earth (∼7 km/s) [14], high speed track-