Optics Communications 310 (2014) 12–18

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Link design of Moon-to-Earth optical communication based on telescope array receivers

Xiaorui Wang, Lei Guo *, Lincong Zhang, Yejun Liu

College of Information Science and Engineering, Northeastern University, Shenyang 110819, China

ARTICLE INFO

Article history:
Received 6 July 2013
Received in revised form
27 July 2013
Accepted 27 July 2013
Available online 3 August 2013

Keywords:
Moon-to-Earth optical communication
Telescope array
Link design
Antenna gain
Bit error ratio (BER)
Signal-to-noise ratio (SNR)

ABSTRACT

Optical communication technology shows promising prospects to fulfill the large bandwidth requirements of future deep-space exploration. This paper mainly studies the link design of Moon-to-Earth optical communication based on the telescope array receiver. Firstly, we analyze and design the telescope array model. An array of relatively small-sized telescope combined to form a larger synthesized aperture is a viable and efficient alternative to a large monolithic telescope. Moreover, this array structure also saves the total costs of the telescopes. In addition, we present an end-to-end system analysis to provide the expected signal and background photons as a function of the Moon–Earth distance. Then, we describe the work on the link design of the Moon-to-Earth optical communication. This primarily includes the received power, the antenna gain, the space loss, the atmospheric loss, and so on. We also provide an approximation calculation to the channel capacity, the data rate, the bit error ratio (BER) and signal-to-noise ratio (SNR). This demonstrates much theoretical significance on the actual Moon-to-Earth optical communication.

1. Introduction

Optical communication has many advantages as compared to microwave frequencies, such as high gain smaller diameter transmitter and receiver antennas (i.e., telescopes), a narrower beam width, a greater power density, a high center frequency for extremely fast modulation, and a large available spectrum [1]. Hence, the long distance of Moon-to-Earth communication should adopt optical communication, and the corresponding optical communication link is vulnerable to the impact of the space environment, so the link design is rather important.

The international scientific communities and various space agencies, such as National Aeronautics and Space Administration (NASA), European Space Agency (ESA), and Japanese Aerospace Exploration Agency (JAXA), continue to send discovery mission in space to unravel the mysteries of deep-space planets in the solar system, galaxies, and the universe. Future lunar missions demand a deep-space communication link with high bit rate to support high resolution image and even real-time video link from a satellite in space mission to earth. So far, NASA deep-space ventures have relied upon a global Radio Frequency (RF)-based deep-space network (DSN) using X-band, and more recently, Ka-band capabilities have been successfully tested [2]. The maximum achievable data rate from Mars using experimental Ka frequency in RF band is limited to 6 Mbits/s during Earth–Mars opposition phase and 500 Kbits/s during Earth–Mars conjunction phase. The maximum achievable data rate from Mars with optical frequency can reach 117 Mbits/s during Earth–Mars opposition phase and 32 Mbits/s during Earth–Mars conjunction phase [3]. It is believed that optical communication can outperform RF links in terms of lower transmitter power and reasonable telescope sizes. The ESA currently runs a worldwide network of reflector antennas in order to provide appropriately support to different satellites and probes, and three 35-m antennas are devoted to deep-space mission [4]. The cost of large aperture telescopes increases much faster than their photon collecting area. Furthermore, because of large size and huge mass, large aperture telescopes undergo a lot of gravitational and structural problems. Telescope arrays are proposed as an alternative to the large aperture telescopes [5]. An adaptive multiple-detector array receiver is also presented [6], which reduces the background noise by assigning higher confidence levels to detector elements that contain significant signal energy and suppressing those that do not. However, this terminal design is not flexible and convenient in the Moon-to-Earth optical communication.

Therefore, in this paper, we mainly use the telescope array at the receiver, and the number of the telescope is flexible. Telescopes act as the transmitting and receiving antennas in Moon-to-Earth optical communication system. In the receiver, a telescope can collect optical signals and concentrate them onto photo-detectors in the focal plane for optical to electrical signal conversion. The telescope

* Corresponding author. Tel./fax: +86 24 83684219.
E-mail address: haveball@hotmail.com (L. Guo).

0030-4018/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.optcom.2013.07.079

array is a collection of a multiple small-sized telescopes. According to current long term planning, by the year 2025, ESA intends to operate a number of scientific missions that place satellites in orbit around the Earth, the Moon, the Earth–Sun Lagrange points, Mars and Jupiter. The target is to provide a channel bandwidth of 100 Mbits/s at a range of 1 Astronomical Unit (AU), with the global communication channel availability greater than 95% [7]. In this paper, we will focus our attention on a communication link between Moon and Earth. A Moon-to-Earth optical communication link from a probe in Moon orbit is studied. Throughout in this paper, we assume that we are in the far-field, that the signal is intensity-modulated with pulse-position-modulation (PPM), and the received optical signal is direct-detected by a photo-detector. We choose this modulation and detection as it represents an efficient signaling over a Moon-to-Earth optical communication channel.

The remainder of this paper is organized as follows. In Section 2, we describe the telescope array receiver. In Section 3, we analyze the received photons in the receiver. In Section 4, we present the link design of the Moon-to-Earth optical communication. Finally, we conclude this paper in Section 5.

2. The array receiver

2.1. The array model

The Moon-to-Earth optical communication system consists of lunar exploration system, optical ground station system and free space channel. Fig. 1 is the schematic diagram of the Moon-to-Earth optical communication system. The information from the lunar surface is mainly collected by the lunar exploration system, and then is transmitted to the optical ground station system through the free space channel.

The design of ground station communication terminal plays a key role in the signal receiving. The ground station traditionally uses a large diameter telescope as the ground receiver, where this telescope is cumbersome, high cost and hard to maintain. To overcome these disadvantages, in this paper, the receiver adopts telescope array structure in the Moon-to-Earth optical communication system, as shown in Fig. 2. This telescope array equals to a large telescope. The number of the telescope and diameter of a telescope in the array can be selected flexibly, and the telescope array has the advantages of lower cost of a single small telescope, flexible installation, and ease of maintenance. Since telescopes act as antennas, each telescope can be used as an independent receiver and it has its own clock, acquisition, and pointing. A closed loop tracking system is designed for each telescope in the array to cater for the tracking errors. The tracking system measures and corrects the tracking errors. We employ the tracking error sensor followed by photon counters in the focal plane of the telescope lens. The tracking error sensor converts the error photon count to the angular error, and then the loop filters are used to filter the noise and estimate the error signals. The output of the filters is used to correct the line of sight of the telescopes and eliminate the effects of tracking error. In addition, each telescope has the built-in detector which can detect the signals. The central combing unit combines the detected signals and counts from all the telescopes after delay compensation and synchronization. When the number of the telescope arrays is too large, these telescope arrays can be divided into several array clusters which can realize the group control of the telescope array. The central combining can directly combine the partial signals from the array clusters after delay compensation and synchronization, so that the

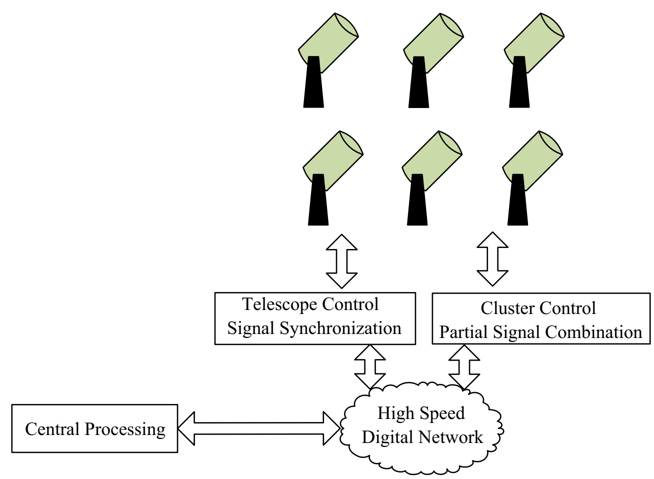

Fig. 2. Conceptual design of the telescope array receiver.

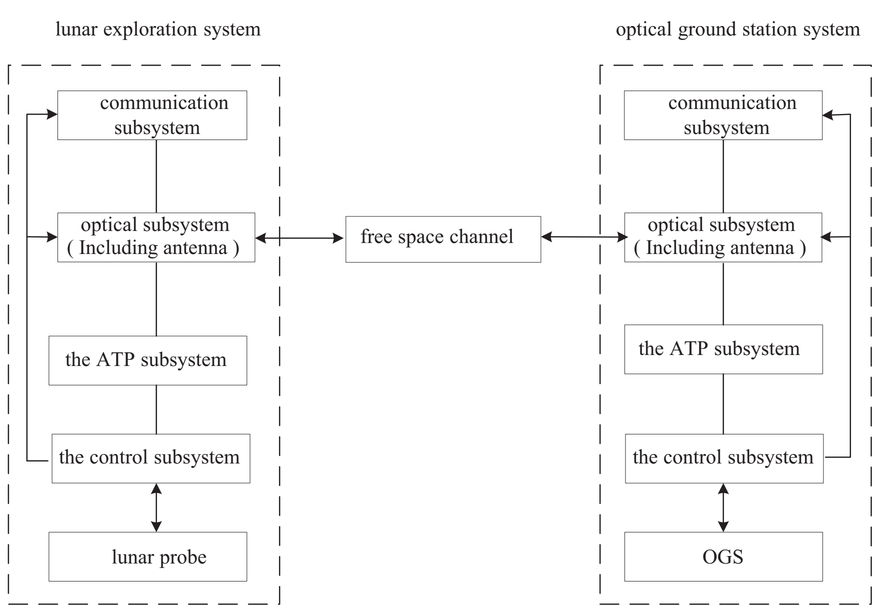

Fig. 1. Schematic diagram of the Moon-to-Earth optical communication system.