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All-optical two-way relaying free-space optical communications for HAP-based broadband backhaul networks

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ABSTRACT

High-altitude platforms (HAPs) are flexible, non-pollutant and cost-effective infrastructures compared to satellite or old terrestrial systems. They are being researched and developed widely in Europe, USA, Japan, Korea, and so on. However, the current limited data rates and the overload of radio frequency (RF) spectrum are problems which the developers for HAPs are confronting because most of them use RF links to communicate with the ground stations (GSs) or each other. In this paper, we propose an all-optical two-way half-duplex relaying free-space optical (FSO) communication for HAP-based backhaul networks, which connect the base transceiver station (BTS) to the core network (CN) via a single HAP. Our proposed backhaul solution can be deployed quickly and flexibly for disaster relief and for serving users in both urban environments and remote areas. The key subsystem of HAP is an optical regenerate-and-forward (ORF) equipped with an optical hard-limiter (OHL) and an optical XOR gate to perform all-optical processing and help mitigate the background noise. In addition, two-way half-duplex relaying can be provided thanks to the use of network coding scheme. The closed-form expression for the bit error rate (BER) of our proposed system under the effect of path loss, atmospheric turbulence, and noise induced by the background light is formulated. The numerical results are demonstrated to prove the feasibility of our proposed system with the verification by using Monte-Carlo (M-C) simulations.

1. Introduction

High-altitude platforms (HAPs) refer to the platforms that are able to keep a quasi-stationary position in the lower stratosphere. They are aircrafts or airships situated well above the clouds at typical heights of 17 to 25 km [1]. HAPs have the best features of both satellite and terrestrial communications [2]. For example, a HAP not only has larger coverage area than terrestrial systems, lower cost than launching a satellite or deploying a terrestrial network with a large number of base-stations, environmental friendliness by making use of solar energy but also can be upgraded or repaired more easily than satellite systems [3]. HAPs are recently receiving a lot of interests as promising candidates for the establishment of communication systems for disaster relief, new services and applications in urban environment, and for the provision of basic access to remote areas [4]. As a complementary solution to wireless technologies, HAP-based communication systems can be integrated into the future heterogeneous wireless access infrastructures. For example, links between the HAP and ground stations (GSs) will provide backhaul connections, where the HAP works as a data relay station [5].

Up to now, there are various HAP networks that have been deployed over the world. In 1980, SHARP, the first civil HAP station program of the world, was developed by Communications Research Centre in Canada by using an airplane at the height of 21 km [6]. To provide worldwide coverage, the Sky Station program given by Sky Station International supported a variety of wireless communication services with the rate of 2 Mbps uplink and 10 Mbps downlink across three cellular coverage zones. In Europe, the European Space Agency and the European Commission also paid attention to HAP by funding many research projects such as HALE, STRATOS, HeliNet, CAPANINA, HAPCOS and so on. Among them, HAP in the CAPANINA and HAPCOS projects use both radio and optical communication links to GSs [1,7]. SkyNet was a project deployed by National Institute of Information and Communication Technology in Japan. This project utilized a stratospheric balloon at the altitude of 20 km and had many functions such as communications, broadcasting and environmental observation [8]. In Korea, Electronics and Telecommunications Research Institute and Korean Aerospace Research Institute also planned to build a stratospheric airship and ground systems with a 10-year program [9]. In

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above-mentioned projects, because most of HAPs used radio frequency (RF)-links to communicate to the GSs, the supportable data-rates were limited.

1.1. Related works

Currently, many studies have investigated free-space optical (FSO) communications for the connections to/from HAPs [10–17]. The collimated laser beam is applied for FSO communications to transmit data at the high transfer rates up to several Gbps [10]. The advantages of FSO communications are lower weight- and power-impact and higher data rates than RF links. In addition, the FSO communication links have the license-free operation, the bandwidth scalability, the cost effectiveness and no interference with RF transmission. Fidler et al. provided an overview of the optical communications for HAPs in [10]. They introduced the structure of the laser communication terminal, the methods of modulation and detection, the impacts from the atmosphere and the background noise, and the summarization about the studies on a variety of HAP-based communication scenarios. Katimertzoglou et al. studied the BER performance for optical inter-platform links under multi-Gigabit regime without considering the atmospheric turbulence [11]. Besides, the authors provided some important concepts and technological requirements of optical links between HAPs and satellites. In [12–14], the authors also focused on researching the optical link between HAPs. Bit error rate (BER) and outage probability for optical inter-HAP link over the weak turbulence regime, which is modeled by log-normal distribution, are analyzed in [12,13], respectively.

In [15–17], optical communications between HAPs and GSs were studied. The system model that includes one HAP and two FSO transceivers situated at the ground level is considered in [15]. In this study, the authors only considered estimating FSO channel parameters included the divergence attenuation, the atmosphere attenuation, the turbulence attenuation, and the propagation delay. In [16], Giggenbach et al. deployed a stratospheric optical downlink experiment, which is a part of the CAPANINA project, to research the downlink from a stratospheric platform to a ground station. In [17], the authors proposed their system model which is based on multiple HAPs with two GSs. Considering the effects of path loss, atmospheric turbulence modeled by Gamma–Gamma distribution, and pointing errors, the authors derived the closed-form expression for the BER and the average capacity for multi-hop FSO communication links in the stratosphere.

Generally, HAPs play a role as a relay node, where the signal is amplified or regenerated before being sent to the next node. Electrical relaying and all-optical relaying techniques are two types of relaying techniques that are studied widely. When the electrical relaying technique is used at HAPs, the optical signal needs to be converted into the electrical one, handled in the electrical domain, and then converted back to optical domain [18–21]. This limited the processing speed of HAPs and required additional components for optical/electrical/optical conversion. This relaying technique has been used by Sharma et al. to study HAP-based relaying FSO systems [17]. It is desirable that the optical signal received at HAP-based relay node could be processed directly in optical domain by using all-optical relaying technique [22,23]. This technique gives the high data-rate without the need of complex optoelectronics and electronics processing components. There are two common all-optical relaying techniques which are optical amplify-and-forward (OAF) and optical regenerate-and-forward (ORF). In OAF, the received signal is amplified by an optical amplifier and continued to transmit to the next node [22–24]. Although OAF is a simple technique in terms of execution, the accumulation of background noise through many nodes can affect the system performance seriously. In order to get over this problem, ORF, where the received signal is regenerated and forwarded to the next node after being amplified, is a better choice. In ORF relaying, an optical hard-limiter (OHL) which situated in front of an optical amplifier can be used to eliminate the effect of background noise at each relay [23].

In addition, relaying techniques can be classified into one-way relaying and two-way relaying. Using one-way relaying cannot satisfy the demand on exchanging the bidirectional data transmission and reception such as in communication networks. The disadvantage of the one-way relaying has been analyzed in [25]. Two-way relaying which can make use of throughput and spectra efficiently has been considered in [19–21]. There are two kinds of two-way relaying including two-way full-duplex and two-way half-duplex techniques. The two-way full-duplex technique needs only one-time slot to transmit data, nevertheless thus its performance is degraded by self-interference which leaks from the transmitter and the receiver [26]. With two-way half-duplex technique, there are four-time slots to transmit data but relaying architecture is simpler than that of two-way full-duplex one. Network coding schemes can be applied to narrow down the number of time slots to three-time slots and improve the efficiency of data transmission and security [26,27].

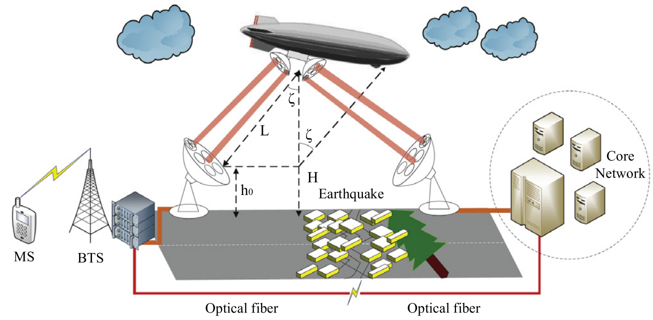

Fig. 1. The model of two-way relaying FSO communications for HAP-based broadband backhaul networks.

1.2. Motivation and contributions

In this paper, we consider a broadband backhaul network, which provides high data-rate connections between base transceiver stations (BTSs) and core network (CN) of next-generation cellular networks. Normally, optical fibers are used for backhaul networks [28]. Nevertheless, if disasters such as earthquakes, floods, and so on, happen, optical fibers can be broken and the communications will be interrupted. It is difficult and takes time to repair broken fibers when many obstructions will appear from collapsed buildings, trees, etc. Hence, to deal with these difficult situations and inherit the advantages of ORF relaying, we propose an all-optical two-way relaying FSO for HAP-based broadband backhaul networks, where two GSs located near BTS and CN play a role in transmitting the signal from BTS to CN via a HAP and vice versa. The model of two-way relaying FSO for HAP-based broadband backhaul networks is shown in Fig. 1.

The data exchanged between two GSs is relayed via a HAP, which has a role as an all-optical relay node. We propose to equip an optical hard limiter and an optical amplifier at HAP to retrieve the data in the manner of ORF, whose feasibility has been proved in [23]. In addition, we apply network coding scheme by using an optical XOR gate at HAP and an electrical XOR gate at each GS to provide two-way half-duplex relaying. It is worth noting that, in [29], we have implemented two-way half-duplex relaying based on all-optical XOR gates for the *terrestrial* FSO system. In that work, the relay node is, however, located at the ground level, not at HAP. Therefore, the channel model used in this study and that of our previous work [29] will be different in terms of turbulence strength, which varies with the height. Also, several physical layer impairments such as receiver noise, which is ignored in [29], will be taken into account in this paper.

The contributions of this paper could be summarized as follows

- We propose a model of an all-optical two-way half-duplex relaying FSO system with the architecture (in terms of a block diagram, see Fig. 2) of HAP and two GSs based on ORF relaying technique and network coding scheme.