FREE SPACE OPTICS BACKHAUL LINK FOR SMALL CELLS OF 5G CELLULAR NETWORKS

JAAFAR A. ALDHAIBANI*, NAEL A. AL-SHAREEFI

College of Engineering, University of Information Technology and Communications, Baghdad, Iraq
*Corresponding Author: dr.jaafaraldhaibani@uoitc.edu.iq

Abstract

One of the technologies that use modulated optical beams to transmit information through the atmosphere is Free Space Optics (FSO). In cellular networks, most of the users at the cell edge boundaries suffer frequent interruption of wireless services due to the long distance between them and the donor station. Small cells are introduced as Relay station (RS) by LTE-A cellular networks to help solve this problem and guarantee appropriate cellular link. This work proposed a new approach to increase the number of users and throughput and enhance the capacity of the user by using two links; the first is FSO links between distributed RSs while the second is radio link (RL) between donor eNB and RS. Based on SNR and outage probability, RS placements are mathematically derived to alleviate the interferences with increasing the coverage in 5G cellular networks. The experiments showed enhancements in the received signals from -84.2 dBm to 67.7 dBm by deploying the RSs at selected placements; moreover, there was an increase in the received power from -30 dBm to 0 dBm by using FSO link in compassion with RL.

Keywords: 5G, Cellular networks, Free space optics, Radio link, RSS.
1. Introduction

Fourth generation (4G) network introduced the multi-hop relay technology to increase the capacity and throughput of cellular networks. This technology has been gaining universal acceptance as one of the promising solutions in the next-generation of wireless cellular networks. Multi-hop relay technology means deployment of small cells as RS between donor eNB and the user to boost the received signal [1]. There are two types of relay; AF relay amplifies the received signal by a gain factor before forwarding to the destination, while the DF relay presses the signals via signal possessing techniques to remove noise and improve the security before forwarding to the destination. The main challenges facing this technology are the determination of the placement of RS within the cellular system in order to mitigate the interference in radio frequency, as well as optimizing the allocation of spectrum resources [1, 2].

Most of the mobile phone network users who are far from the donor base stations do suffer from wireless services outage due to environmental conditions. Under this condition, Radio Frequency (RF) link, which is one of the key techniques to addressing this problem, expends more of the user power to establish a connection with the base station [3]. The FSO technique contributes towards enhancing the link and alleviating frequent interruptions in wireless services [3, 4].

One of the important issues addressed by this article is to choose the right place for RS to provide maximum coverage while minimizing interference. In the recent past, free-space optical communication (FSO) evidence to be significant replacement to backhaul radio frequency.

The improvement of wireless services remains the most changing phenomena in the history of technology. The growth in the number of mobile users in the recent years and the need to provide high data throughput to keep pace with the development of mobile devices have all elicited studies into finding the appropriate solutions (Fig. 1). The provision of a reliable link with high-speed data services is one of the key methods to address these problems [1, 3].

![Fig. 1. One of FSO backhaul link scenarios.](image-url)
FSO refers to data transmission between two points through optical carriers using laser beams. It ensures high security and reduces interference at the unlicensed spectrum compared to radio link transmission [1, 4].

Since the FSO technology requires a line-of-sight between the optical transmitter and the optical receiver [3], in this work, the RS contains two links; the first is RF link for data exchange with the donor eNB and the second link is FSO for preparing a reliable link between the neighboring RSs. One feature of FSO is high security and inviolability to interference compared to traditional RF link [2]. The narrow laser beam transmission of FSO technology increases its degree of frequency reuse. FSO technology is cost-effective and easy to install [3, 5].

This study highlights a new topology for enhancing the wireless backhaul links between small cells deployed around the donor eNB stations in 5G cellular networks using FSO links. Using the FSO link solution prevents interference in the used frequencies [3, 5]. The rest of this article is organized as follows: Section 2 presents the related works to this topic while Sections 3 and 4 details the theoretical analysis and simulation results, respectively. Finally, the conclusion is given in Section 5.

2. Related works

Small cell distribution is one of the technologies that enable the efficient utilization of network resources by permitting the RSs to cooperate with each other in wireless services to enhance the cellular network coverage area and improve the quality of services for the current communication networks.

In recent years, the development of small cells, such as RS-based networks, has become an area of significant research interest in both industry and academia because it reduces the overall transmitted power without reliability loss; thus, extending the battery life.

Few researchers have discussed the relay-assisted mixed FSO/RF link [6]. RS deployment with the cellular network at the cell edge region is an efficient solution to broaden FSO coverage, improve systems’ performance, and fill the connectivity gap between FSO link and RF link [7].

To guarantee a reliable cellular link, the disjoint paths between the small cells must be made in the design phase. A study by [8] investigated a cost-effective solution in cellular backhaul using FSO links and mirror components. The study proposed the concept of link reliability based on the atmospheric turbulence factor in the network design.

Refai et al. [9] introduced the use of FSO to send modulated RF and also examined the key performance measures. The evaluation showed the occurrence of a minimal RF signal distortion over FSO. Lee et al. [10] presented an approach of frequency bands comparison with the RF link based on the SNR. The study also derived the outage probability of the RF/FSO relay links. The calculations of the capacity and outage probability of FSO mixed with relay-assisted transmission have been discussed in [11], while Amirabadi and Vakili [12] presented a dual-hop relay node-assisted hybrid FSO/RF communication in which the signal in the system accessed through multi-point within the building to the base station. These points are hybrid parallel FSO/RF links. A study on the end-to-end performance of multi-hop FSO has been introduced by Datsikas et al. [13], who discussed the
channel system over turbulence and fading; the study utilized AF relays with fixed-gain. The statistical analysis was performed based the outage probability and the bit error of the modulation schemes [14]. Sometimes, an RF or FSO link can be obtained as a backup between the transmitter and receiver stations [15, 16]. Prabu and Kumar [17] investigated the outage performance of a multi-hop relay-assisted FSO system. This system was examined over strong atmospheric turbulence.

The main contributions of this work are as follows:

● Proposing a new approach of using two different links in multi-hop techniques (the first is RF link and other is FSO link) to provide and optimize resource allocation in cellular networks.

● Elimination of the interferences at RF links by deriving the RS placement based on SNR and outage probability in order to increase the capacity and number of network users.

3. Proposed System Model

Figure 2 showed the model of the proposed system, where the main donor station eNB at the centre of the cell and RSs is the relay station deployed at a certain position from eNB; $i$ represents the number of RS and UE is the users attached with RS.

Therefore, the received signal through the direct link by the users is:

$$y_d(t) = \sqrt{P_t} h_d(t)x(t) + n(t)$$  \hspace{1cm} (1)$$

where $y_d(t)$ is the received signal via the direct link, $\sqrt{P_t}$ is the transmitted power from eNB, $h_d$ is the channel between eNB and RS, $n(t)$ is the additive white Gaussian noise (AWGN) at destination [12, 18].

To avoid self-interference and provide a low-cost system, this study proposed using half-duplex mode [19] where transmission and reception are not performed simultaneously. Therefore, the received RF signal at first time slot $t_1$ is:

$$y_{RS}(t_1) = \sqrt{P_t} h_{i(0,i)} x(t_1) + \sqrt{P_{RS}} h_{i(Nu)} x(t_2) + n(t)$$  \hspace{1cm} (2)$$
where $h_{(0,0)}$ is the channel between eNB and $i^{th}$ RS, $x(t)$ is the transmitted signal at any slot, $h_{(i,Nu)}$ is the channel between $i^{th}$ RS, and Nu is the number of users attached with RS [18].

In this system, the amplify and forward technology is proposed with RS because AF relay is lower in term of the cost than DF relay; so, the signal at the second slot $x_{RS}(t_2) = \psi y_{RS}(t_2)$ as shown in Fig. 3 [20], where $\psi$ is the gain factor for RS; so, to derive the $\psi$, instead of using Eq. (2), we get:

$$x_{RS}(t_1) = \psi(\sqrt{P_{t}}h_{(0,0)}x(t_1) + \sqrt{P_{UE}}h_{(i,Nu)}x(t_2)) + n(t) \quad (3)$$

where $\sqrt{P_{UE}}$ is the transmitted power by the user.

![Fig. 3. AF relay transmission.](image)

Taking the expectation from the two sides [18, 20]:

$$E|x_{RS}(t_1)|^2 = E|\psi(\sqrt{P_{t}}h_{(0,0)}x(t_1) + \sqrt{P_{UE}}h_{(i,Nu)}x(t_2)) + n(t)|^2 \quad (4)$$

Axiomatically that $E|x(t)|^2 = P$ (watt)

$$P_{RS} = \psi^2|\sqrt{P_{t}}h_{(0,0)}x(t_1) + \sqrt{P_{UE}}h_{(i,Nu)}x(t_2) + n(t)|^2 \quad (5)$$

$$\psi = \frac{P_{RS}}{\sqrt{P_{t}|h_{(0,0)}|^2 + \sqrt{P_{UE}}|h_{(i,Nu)}|^2 + n(t)}} \quad (6)$$

While the received signal by the user attached with RS is:

$$y_{UE}(t_2) = \psi \sqrt{P_{t}}h_{(0,0)}x_{RS}(t_1) + n(t) \quad (7)$$

Then,

$$y_{UE}(t_2) = \psi \sqrt{P_{t}}h_{(0,0)}(\psi \sqrt{P_{t}}h_{(0,0)}) + n(t) \quad (8)$$

SNR at the users via multi-hop link can be expressed as:

$$SNR = \frac{\psi^2 P_t |h_{(0,0)}|^2 |h_{(i,Nu)}|^2}{(\psi^2|h_{(i,Nu)}|^4+1)n(t)} \quad (9)$$

The capacity of the cell to cover Nu users can be written as:

$$C_{cell} = BW log \left(1 + \frac{\psi^2 P_t \sum_{i=0}^{Nu} |h_{(0,0)}|^2 |h_{(i,Nu)}|^2}{(\psi^2|h_{(i,Nu)}|^4+1)n(t)}\right) \quad (10)$$

Capacity divided by two because RS used half duplex mode technology.
3.1. RS placement

To provide maximum coverage, higher downlink capacity, and mitigate the interference between stations, the best placement of RS must be determined. The outage probability is one of the keys to achieve the target.

An outage is defined as a situation where the received signal-to-noise ratio (SNR) falls below a certain threshold $\gamma_{th}$ [21]. The received signal at the small cell, such as RS and access link, is expressed as follows:

$$\rho_{out} = p_r(SNR_{mh} < \gamma_{th}) \equiv \left(1 - e^{-\frac{\gamma_{th}}{SNR_{mh}}} \right)$$  \hspace{1cm} (11)

$$e^{-\frac{\gamma_{th}}{SNR_{mh}}} \equiv \left(1 - \frac{\gamma_{th}}{SNR_{mh}} \right)$$  \hspace{1cm} (12)

$$\rho_{out} = \frac{\gamma_{th}}{SNR_{mh}}$$  \hspace{1cm} (13)

$$\rho_{out} = \frac{\psi^2 p_f |h_{(0,0)}|^2 |h_{(l,N)}|^2}{\psi^2 |h_{(l,N)}|^2 + 1} n(t)$$  \hspace{1cm} (14)

The SNR is influenced by the quality of service (QoS) of the channel, the distance between the transmitter and receiver, the fading state of the channel, and noise and interference. Simply, the channel coefficient between the source and the destination can be defined as [22]:

$$|h|^2 = L(d)^{-\alpha}$$  \hspace{1cm} (15)

where $\alpha$ is the path-loss exponent which is dependent on the environment, and $R$ is the cell radius. $d_{rs}$ RS placement refers to eNB, and $L_r, L$ are the transceivers’ coefficients.

$$\rho_{out} = \frac{(\psi^2 L_{rs} P_{RS}(R-d_{rs})^{-\alpha+1} n(t)/\gamma_{th})}{\psi^2 p_f L(d_{rs})^{-\alpha} L_r (R-d_{rs})^{-\alpha}}$$  \hspace{1cm} (16)

Thus, the best placement of RS within a cell can be obtained by using the mathematics of convex optimization [23, 24]. Taking the first derivative of Eq. (16) with respect to $d_{rs}$:

$$\frac{d\rho_{out}}{d_{rs}} = \frac{(\psi^2 L_{rs} P_{RS}(R-d_{rs})^{-\alpha+1} n(t)/\gamma_{th})}{\psi^2 p_f L(d_{rs})^{-\alpha} L_r (R-d_{rs})^{-\alpha}}$$  \hspace{1cm} (17)

$$d_{rs} = \frac{R(L_P_{L})^{1/\alpha}}{\psi^2 P_{L} (d_{rs})^{-\alpha} L_r (R-d_{rs})^{-\alpha}}$$  \hspace{1cm} (18)

Transceivers coefficient $L = G_G d_{h} h \tau_n P_t$, $L_r = G_G d_{ue} h \tau_n$

$$d_{rs} = \frac{R(G_G d_{h} h \tau_n P_t)^{1/\alpha}}{(G_G d_{ue} h \tau_n P_t)^{1/\alpha}}$$  \hspace{1cm} (19)

Two antennas were proposed in the RS, one antenna is Omnidirectional and used to prove the connection between RS and the attached users. The other is the directional antenna used to guarantee the link between the eNB and RS [24, 25] as illustrated in Fig. 3.
3.2. Free space system

To beat fiber cables installation which requires continued maintenance, FSO is a free license communication technique. This technology provides a high data rate of up to 2.5 Gbps compared with RF communications which offer a few hundreds of Mbps [5]. FSO spreads very fast in various applications (such as links between multi-campus buildings); it also establishes quick temporary links and cellular backhaul communications.

Fog is one of the main factors that attenuate FSO links, especially during the scattering of fog particle which is identical to the wavelength of optical signals. FSO signal is not affected by rain but diminishes significantly in fog. Even though the RF signal is not influenced by fog, its performance is affected by rain [3, 19].

The block diagram of the system is shown in Fig. 4 where the modulated RF signal was received by RS1 from the base station eNB via relay link with the frequency of 2.3GHz to achieve the 4G requirements. This signal will follow it to the optical system in order to be converted to optics signal. An optical modulator is a unit used to modulate the RF signal with a new optical frequency. The optical signal with a new frequency will transmit to space via FSO unit, while RS2 will receive the RF signal after demodulation in the FSO receiver unit as shown in Fig. 4.

In an FSO communication system, the optical signal propagates through the atmosphere; so, the received signal here is limited by several factors when it passes through the atmosphere link. Among these factors are the optical depth ($\tau$) which connects with power at the receiver $P_R$, and the transmitted power $P_T$ [24, 26] given as:

$$ P_R = P_T e^{(-\tau)} \quad (20) $$

On the other hand, there are losses during propagation through the atmosphere and these losses can be calculated thus [19]:

$$ P_R = P_T e^{(-\tau)} \quad (20) $$
\[ \text{Loss}_{\text{prop}} = 10 \log_{10} \left( \frac{P_{R}}{P_{T}} \right) \] (21)

The power received by the FSO link depends on the transmitted signal and the length of the link between the FSO host points and the atmospheric attenuation factor [3].

![Fig. 4. The proposed FSO system.](image)

4. Results and Discussion

Figure 5 showed the practical test of the received signal without using RS. The received signal was -84.1 dBm with a transmitted frequency of 2.3 GHz and a distance of 250 m between the donor eNB and the mobile phone. This received signal is very weak and causes frequent interruptions in wireless services. This test was done using a spectrum analyzer and omnidirectional antenna within the range of 500MHz - 4GHz as shown in Fig. 5.

The determination of RS placement within the network is the first challenge that faces the enhancement of the capacity at the cell boundaries. This work introduced the practical and mathematical solutions to solve these challenges by selecting the best RS positions that will ensure the maximum improvement and lowest interferences from the neighboring cells. Fig. 6 shows the increase in the received signal (from -84.1 dBm to -55.56 dBm) after using the RS technology. Although the RS technology increased the coverage and enhanced the capacity, this solution requires extra spectrum to alleviate the interferences between neighboring RSs. The FSO link was proposed as an alternative solution to address these challenges instead of the links between RSs as shown in Fig. 1. A comparison of the practical results between radio link through RS and FSO link was done in Fig. 7; the received signal was observed to improve from -55.56 dBm to 5 dBm via FSO.

To test the simulation and practical results, we calculated the received signals via the FSO link using Eqs (20) and (21). The comparison of these simulated results with the experimental results was aimed at measuring the signal received by the Optical Spectrum Analyzer (OSA) at a frequency of 2.3 GHz as demonstrated in Fig. 7. The proposed distance between two RSs was 500 m; the simulation results matched the experimental results to some extent. The received power was improved despite the small differences observed in the measurements due to the effects of the atmosphere and some other factors like temperature, humidity, etc. It was also observed that for FSO link, the reliability was ameliorated while the received power was increased by using FSO link rather than RF link.
Small cell technology is a promising approach towards enhancement of the quality of radio links between eNB donor station and UE. The experiments in this study, as presented in Fig. 8, showed that FSO guaranteed a high-quality link to data exchange between the distributed RSs in the network. This figure showed the comparison between the experimental and simulated results of the received signal relative to the distance between the transmitter and the receiver. As mentioned, the simulation results have been collected based on Eqs 20 and 21. The proposed distance between the two RSs is 500 m, so, from Fig. 8, the simulation result was -12 dBm while the experimental result was -15 dBm. Thus, the observed error percentage between the two results is negligible. For two tests, the received signal is higher near the transmitter (5 dBm), this signal decreases away from the source because of the increase in the propagation loss. It is worth mentioning here that these experiments were conducted during sunny weather (temperature of 27°C); it should also be noted that the proposed model provides little power consumption; hence, the battery life of the mobile phone was extended.
Fig. 7. Experimental test of proposed model (a) received signal over FSO (b) Comparison of the experimental received signal over FSO and RF links.

Fig. 8. The comparison of the FSO links between the experimental and simulation results over different distances.
5. Conclusion

In this paper, a new model to enhance the links between small cells deployed around the donor eNB stations in 5G cellular networks was proposed. Instead of using RF links, FSO links were used to prevent frequent interruptions in wireless services. Besides that, appropriate placement of the RSs has been derived based on SNR and outage probability. This will allow wireless sites planners to install the small cells without the need for expensive simulators. Using the solution of the FSO link prevents interference in the used frequencies; moreover, it increases the number of users through the exploitation of the spectrum frequency. The proposed model was evaluated using practical (experimental) tests of the system and simulation studies. The results of the field tests showed that the received power was improved from -30 dBm to 0 dBm using FSO compared to RF link.

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