UAV-aided Cooperation for FSO Communication Systems

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***Abstract*—Relay-assisted Free Space Optical (FSO) systems were proposed as a means for remedying the effects of the various atmospheric impairments on the quality of the FSO signal. Conventional relay-assisted FSO systems are however designed around two basic assumptions: a) relays are buffer-free, and b) relays are stationary. This paper proposes to improve the performance of the existing relay-assisted FSO systems by relaxing both of these highly restrictive assumptions through the integration of Unmanned Aerial Vehicles (UAVs) as buffer-aided moving relays into the conventional relay-assisted FSO systems. Specifically, two possible simple integration scenarios are proposed and analyzed through simulation. The obtained simulation results demonstrate the great potential associated with the proposed highly promising, innovative, hybrid FSO architecture. Given that high performance gains are observed under small buffer sizes, it becomes conceivable to employ the buffer-aided moving relaying UAVs to serve a variety of other purposes. This includes, for instance, having these UAVs oversee the operation of amateur drones for potential misbehavior or wrongdoing within the area of their deployment.**

***Index Terms*—Unmanned aerial vehicle (UAV), free space optics (FSO), cooperative FSO systems, all-active cooperation strategy.**

I. INTRODUCTION

THE ever-increasing demand for bandwidth triggered by the contemporary data-rate hungry wireless applications is placing an enormous burden on the Radio Frequency (RF) spectrum. This phenomenon is widely referred to as the RF spectrum scarcity problem and is receiving a lot of attention in the 5G wireless communication framework [1]. One possible option to overcome the spectrum congestion problem consists of tapping into other parts of the spectrum (e.g., mmWave) or harnessing the great potential of optical technologies. This explains the growing interest in Optical Wireless Communication (OWC) as a complementary technology that can alleviate the RF spectrum crunch problem. This paper considers outdoor terrestrial point-to-point OWC systems, which operate in the infrared band. These systems are widely known as free space optical (FSO) systems and provide high data rate communication over distances of up to several kilometers.

Unlike RF links, FSO communication links are unlicensed, directional, immune to electromagnetic interference, and not easily interceptable [2]. Despite the many advantages that FSO links have over RF links, it is widely acknowledged that FSO links can be highly affected by the ambient atmospheric conditions. In particular, the FSO signal is extremely vulnerable to the so-called atmospheric turbulence-induced fading among others [2]. The random fluctuations of the received signal power increase dramatically with the propagation distance. The longer the source to destination distance is, the more pronounced this turbulence-induced scintillation would be. This led to the development of the relay-assisted FSO communication model, whereby a number of relays are placed between the distant source and destination to mitigate the effect of distance on the quality of the FSO link. Under such circumstances, the shorter FSO links, which would connect the source node to the relay nodes and then in turn the relay nodes to the destination node benefit, on average, from more favorable channel conditions. This increases the likelihood of successful data transmission by diversifying the paths along which the optical information signal propagates between the source and destination nodes. This has the advantage of improving the data throughput of the system as well as the availability of the source to destination connectivity.

Fig. 1 shows a parallel relay-assisted FSO system, where the source FSO transceiver deployed on top of the leftmost building is being assisted by two relays residing between the source and the destination. It is important to highlight in this regard that all of the relay-assisted FSO systems studied thus far have employed stationary buffer-free relays. In this context, stationary FSO transceivers often mounted on building rooftops and that have no buffering capabilities are often deployed to assist the source-to-destination communications. However, with the spike of interest in flying platforms such as Unmanned Aerial Vehicles (UAVs) in the communication sector, it becomes possible to envisage upgrading relay-assisted FSO systems with moving buffer-aided relays, which might take the form of UAVs.

Indeed, UAVs constitute a promising emerging technology that was initially developed for military applications. However, as time evolved, UAVs witnessed a significant expansion of their potential utility which includes other applications such as traffic monitoring, remote sensing, crop spraying, and so on. Clearly, a proper leveraging of the great potential of these flying platforms has the ability to revolutionize many of the well-explored existing network architectures, including relay-assisted FSO systems. This paper builds on this observation to explore the benefits that can be reaped from the deployment of UAVs as moving buffer-aided relays in the context of a relay-assisted FSO network like the one depicted in Fig. 1.

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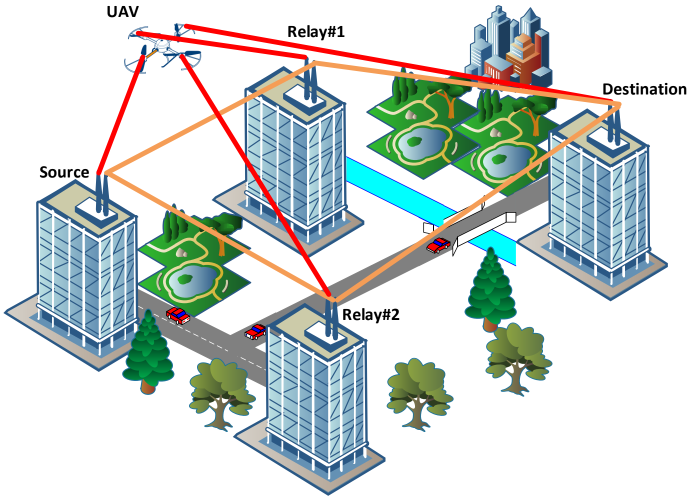


Fig. 1. A relay-assisted FSO system augmented with a moving buffer-aided aerial relay.

II. BACKGROUND

A. Relay-assisted FSO Systems

The concept of relay-assisted FSO communication came into being in [3], where the authors studied the performance of a mesh FSO network in terms of network capacity. However, the role that relay-assisted FSO communication can play in remedying fading effects was only highlighted a while later, namely in the seminal work [4]. The authors demonstrated therein that relay-assisted FSO system can benefit from shorter hop lengths to mitigate fading effects in a distributed manner. In addition to multi-hop relaying, parallel relaying was investigated in [5]. In [6], the notion of inter-relay communication was introduced and proven to be beneficial only under favorable Signal to Noise Ratio (SNR) conditions.

Relay-assisted communications have been investigated thus far exclusively in the context of all-terrestrial FSO-based Wireless LANs where all communication nodes are stationary. The main limitation of such network setups resides in the fact that the performance of each one of the end-to-end optical paths is governed by the link having the smallest path gain. In other words, the longest source-to-relay and relay-to-destination hops dictate the diversity gains that can be extracted though cooperation.

With moving UAVs as FSO relays, the anticipated variability in the link distances, and the potential reduction in the distance of the longest hop, advantageously impacts the network performance. On the other hand, all surveyed relay-assisted FSO systems assume relays with no storage capabilities. In other words, the relays retransmit the data packet even if the underlying channel conditions are not favorable, thus negatively impacting the system performance.

For the above reasons, this paper proposes to incorporate buffer-aided moving relay(s) into classical relay-assisted FSO systems. Such moving relay(s) can store data emanating from some stationary terrestrial nodes for possible future delivery to other nodes. The rationale driving this proposition is as follows. Due to the time-varying distance to ground nodes, buffer-aided moving relay(s) can exploit the favorable channel condition when it is closer to a ground node to either receive or deliver data.

B. UAVs in the Context of FSO Systems

1) Relationship of UAVs to FSO Systems: Some of the early studies were mainly concerned with investigating the feasibility of FSO communication with airborne terminals. Toward this end, successful FSO communications were demonstrated with Boeing 767-200, a BAC 1-11 aircraft, a tornado jet fighter, and an Altair unmanned aerial vehicle [7]. The era where Unmanned Aerial Vehicles (UAVs) will occupy the skies is fast approaching due to a surge of interest in employing such vehicles in numerous applications. [8] surveys a plethora of applications that might benefit from the deployment of UAVs or swarm of UAVs with an emphasis on the communication and networking aspects underlying such deployment. Interestingly, very few studies considered an integration of UAVs into FSO systems. Particularly, the authors in [9] introduced an FSO-enabled backhaul solution for 5G+ wireless networks that is based on UAVs. In this context, the authors proposed to employ UAVs for the purpose of relaying information from small cells to the wired core network. The advancement in aerial FSO communication has been remarkable in the past years especially with the commercialization of FSO transceivers for UAV systems such as the MLT-20 product from Vialight, which is ideal for flying platforms. This paper considers UAVs that are equipped with similar FSO transceivers. The technological advancement with respect to the air-to-ground and ground-to-air FSO communications motivates the crafting of UAV-based solutions that are adapted to the FSO systems. It is in this context that a solution such as the one proposed in this paper becomes necessary.

2) Types of UAVs/Adopted Types: In the context of the proposed solution, UAVs can operate in either a stationary manner or move along a well-defined trajectory to provide assistance for the ground FSO source, relay, and destination nodes. According to [10], UAVs range in cruise duration and action radius from mini drones to high-altitude long endurance ones. This paper considers UAVs having the ability to carry the somewhat heavy FSO transceivers and to move along a predetermined flight path. The UAVs that satisfy these requirements are the so-called Low Altitude Long Endurance (LALE) and Medium Altitude Long Endurance (MALE) UAVs.

3) Energy Consumption Constraints: Cruising duration is strongly affected by the energy consumption of UAVs, which is a major challenge that limits their flight time [11]. Therefore, it is essential that further insight be gained into the average power consumption of UAVs under different movement postures, such as hovering, moving, and circling. In addition, the impact of flight height under different weather conditions on the energy consumption of UAVs remains an interesting subject matter for any future study building on the present study. However, there is a silver lining when it comes to energy consumption and it is related to the following. Recent advances in battery technologies like enhanced lithium-ion batteries and hydrogen fuel cells augmented with the use of energy sources such as solar energy establish a strong foundation for potential extended UAV flight times [12]. It is worthwhile noting in this regard that recently, Titan Aerospace has introduced a solar-powered UAV, dubbed Solara 50, which can fly non-stop for a duration of 5 years.

C. Contributions

The contributions of this paper are threefold:

- The paper explores a novel way of integrating UAVs into relay-assisted FSO systems. The UAV-aided architecture is somewhat similar to the relay-assisted deep space communication architecture with the difference stemming from the different channel model in outer-space, the much larger delays, and the bigger buffer requirements therein [2].
- Even though buffer-aided relaying has been substantially covered in the context of RF wireless communication systems [13], no previous study has thus far considered the impact of buffer-aided relaying on the performance of FSO systems. The utilization of UAVs as buffer-aided relays opens the door widely for such analysis.
- To date, all of the existing relay-assisted FSO studies were built on top of the restrictive assumption that relays are stationary. This paper relaxes the assumption by looking into the advantage of deploying UAVs as buffer-aided moving relays in the context of relay-assisted FSO systems.

III. PROPOSED SYSTEM

A. Advantages of Integrating UAVs into Relay-assisted FSO Systems

Consider a relay-assisted FSO network where a source node S is communicating with a destination node D via K stationary relay nodes denoted by R_1,...,R_K. The number of relays is defined as the number of neighboring nodes that are fully assisting the source in its communication with the destination. Recall that such cooperation extracts spatial diversity gains in a distributed manner and this communication technique is perfectly adapted to the FSO fading channels that are subject to turbulence-induced scintillation [4], [5], [6].

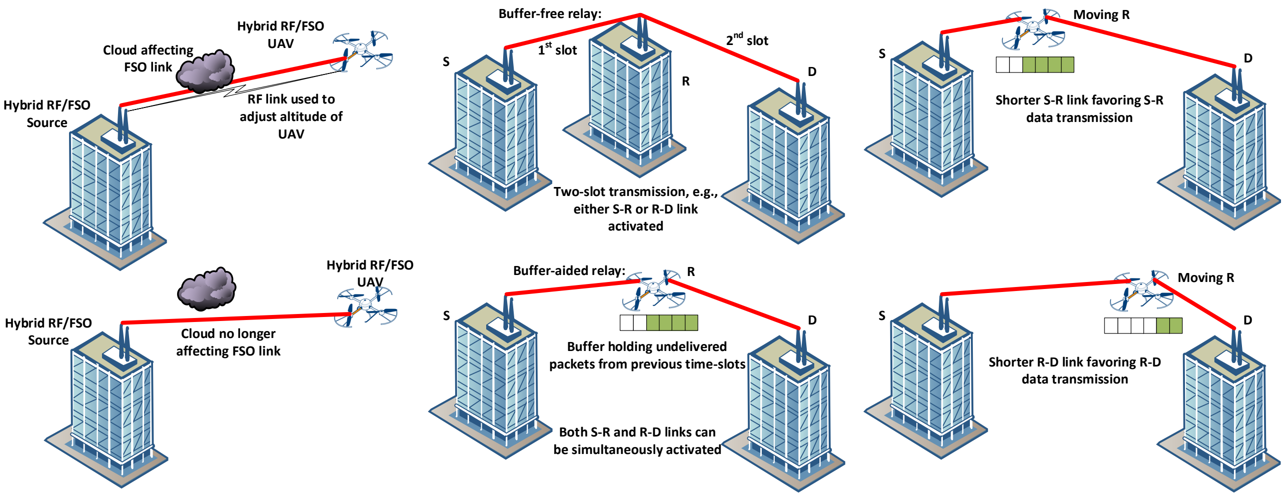
A graphical illustration of a possible instance of a relay-assisted FSO system is depicted in Fig. 1 where S is being assisted by two stationary relay nodes R_1 and R_2 in its communication with D. Assume that there is no direct FSO link between S and D due to geographical or environmental constraints. Under this condition and with conventional buffer-free relay assistance, data transmission between S and D occurs over two time slots. In the first time slot, S transmits a data packet to one or all the relays, which in turn would transfer the data packet in a second time slot to D. The number of relays involved in the communication depends on the adopted cooperation strategy. More specifically, two cooperation strategies were extensively studied in the literature, namely the all-active and selective relaying schemes [2]. All-active relaying requires the source to transmit its data packet to all the relays in the first time slot and the relays to subsequently transfer the packet to the destination in the second time slot. Selective relaying, on the other hand, ensures data transmission along the strongest end-to-end two-hop path from the source to destination. This guarantees an enhanced performance level but comes at the expense of an increased system complexity due to the channel state information acquisition.

Some of the main limitations of the conventional cooperative FSO systems are related to the fact that relays are assumed to have no storage capabilities and to be stationary. This paper proposes to relax these assumptions by investigating the advantages of utilizing UAVs as buffer-aided possibly moving relays on top of the existing buffer-free stationary relays. Full cooperation in terms of data relaying is guaranteed from UAVs since they are controlled and managed by the same network operator. Through the inclusion of UAVs, the proposed system model exhibits three main properties that are portrayed in Figs. 2(a) - 2(c).

Fig. 2(a) shows one of the advantages that emanate from the deployment of a moving relay (UAV); that is, adaptiveness. In other words, the figure considers the case where the FSO link between the source and the relay is smeared by an intervening cloud. However, owing to the typical existence of an RF signaling channel between the source and the relay and to the mobility of the relay, it can be envisaged to have the relay adjust its altitude in a way that would ultimately eliminate the cloud attenuation effect on the FSO link.

Fig. 2(b) explores another beneficial aspect resulting from the utilization of UAVs as buffer-aided relays. As illustrated in the upper portion of the figure, conventional relay-assisted FSO systems employ a two-slot transmission approach, in which transmission happens over two time slots as discussed earlier. In contrast, the buffer-aided relay introduced to the FSO system helps exploit one of the most important features of FSO systems, namely the directivity of FSO links. While RF links are broadcast by nature, FSO links are highly directional, which enables the simultaneous activation of multiple FSO links without any incurred interference. Therefore, unlike the buffer-free relay-assisted FSO system that is restricted to single node transmission in each time slot, the buffer-aided FSO system supports simultaneous activation of the $S-R$ and $R-D$ links in the same time slot. This observation significantly alters the dynamics of the system and has the potential of boosting the performance of the relay-assisted FSO system while preserving its diversity gains.

Fig. 2(c) tackles yet another important consequence of the incorporation of UAVs into relay-assisted FSO systems. The inherent mobility feature of UAVs makes it possible for the relay to roam between S and D. In this case, the strengths of the $S-R$ and $R-D$ links evolve over time as a function of the $S-R$ and $R-D$ distances. When the relay is closer to S, the $S-R$ link would have a superior quality relative to the $R-D$ link enabling thus the transfer of a large number of packets from S to the relay. With these packets stored in the buffer of the relay and given that the relay is navigating towards D, the UAV would reach a point where the $R-D$ link becomes better than the $S-R$ link securing as such the transfer of the buffered packets to D.



(a) (b) (c)

Fig. 2. a) Adaptive; b) Buffer-aided; c) On the move relaying for relay-assisted FSO systems.

B. Possible Relay Configurations

In a bid to leverage the properties delineated in the previous subsection, the present subsection defines some possible relay configurations that are suitable for the proposed system model. Two different use-cases are distinguished. In the first, UAVs are deployed as quasi-stationary buffer-aided relays that move only in the vertical direction to achieve the adaptiveness requirement introduced earlier. In the second use case, UAVs are utilized as moving buffer-aided relays to contribute to the communication between S and D.

The first use case is given in Fig. 3(a) where a conventional relay-assisted FSO system augmented with two quasi-stationary UAV relay nodes is considered. The figure shows two stationary relays denoted by R_1 and R_2, which are overlaid by two UAVs hovering over S and the stationary relay nodes areas, respectively. Under this condition, the following cooperation strategy can be adopted. S transmits data to D on a two time-slot basis via R_1 and R_2. However, given that the UAVs are equipped with buffers, communication through the UAVs is performed on a non-predefined manner, where both the $S-UAV$ and $UAV-D$ links can be concurrently activated in each individual time slot.

The second use-case is illustrated in Fig. 3(b) where a moving buffer-aided UAV navigates back and forth between S and D along a *linear* trajectory. In this case, communication between S and D through R_1 and R_2 still spans two time slots per packet, whereas the communication via the moving buffer-aided UAV is realized such that both the $S-UAV$ and $UAV-D$ FSO links are simultaneously active at any given time slot.

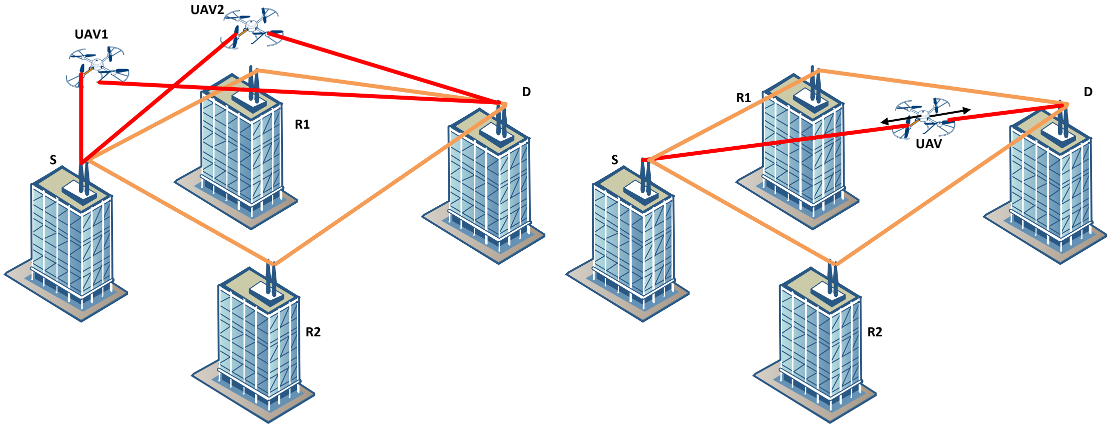
It is clear that more complicated mobility and relaying strategies can be envisaged either for one UAV or for more UAVs with or without inter-UAV communication. But, this paper aims at examining these simple yet illustrative scenarios to emphasize the added-value brought by mobility and buffering to the conventional relay-assisted FSO systems. For completeness, it is worthwhile noting that the performance of the two scenarios considered in this subsection will be evaluated in the simulation study section.

Even though this paper does not consider the possibility of inter-UAV communication, the deployment of a group of communicating UAVs can considerably improve the performance of the cooperative FSO system. However, this comes at the expense of a greater cost for the UAV-aided relay-assisted FSO system. Consequently, the targeted level of compromise between performance and cost can be used to determine the practical number of relays in realistic systems. A thorough investigation of the stability of UAV groups would also be required in that context [14]. Although not considered in this paper, another performance enhancing opportunity manifests itself through the support of relay-to-UAV communication. In this way, stationary relays can offload their data packets to UAVs so as to maximize the chances of data packet delivery to the destination.

C. Channel Model

The FSO signal is subject to both atmospheric attenuation as well as other types of losses such as pointing, geometrical, and optical losses. Details about the aforementioned impairments can be found in [9]. As per the guidelines presented therein as well, it is assumed that the Doppler effect resulting from the motion of UAVs can be fully mitigated and as such can be ignored. Furthermore, with the emergence of tracking-enabled electro-optic and acousto-optic FSO transceivers, the effect of pointing losses can be compensated for. It is obvious that a quantitative characterization of the numerous impairments that influence the reliability of the FSO communication link is an absolute necessity. This is particularly true since the various impairment factors may have a detrimental effect on the availability of the sender to receiver FSO link, leading ultimately to the loss of received power at the receiver. In this context, the failure of all activated FSO links at a given time slot is viewed as an outage of the entire FSO system.

A multitude of statistical models have been investigated over the years to capture the main characteristics of the atmospheric channel. This paper adopts the widely acknowledged channel



(a) (b)

Fig. 3. Possible use-cases for relay-assisted FSO systems using: a) quasi-stationary buffer-aided UAVs; b) moving buffer-aided UAVs.

model derived in [15]. The nitty-gritty details pertaining to the model in question are omitted in this paper to maintain a streamlined intuitive discussion throughout the paper. Interested readers are referred to [15] for a thorough technical description of this channel model, which is considered in the simulation study section of this paper.

IV. Simulation Study

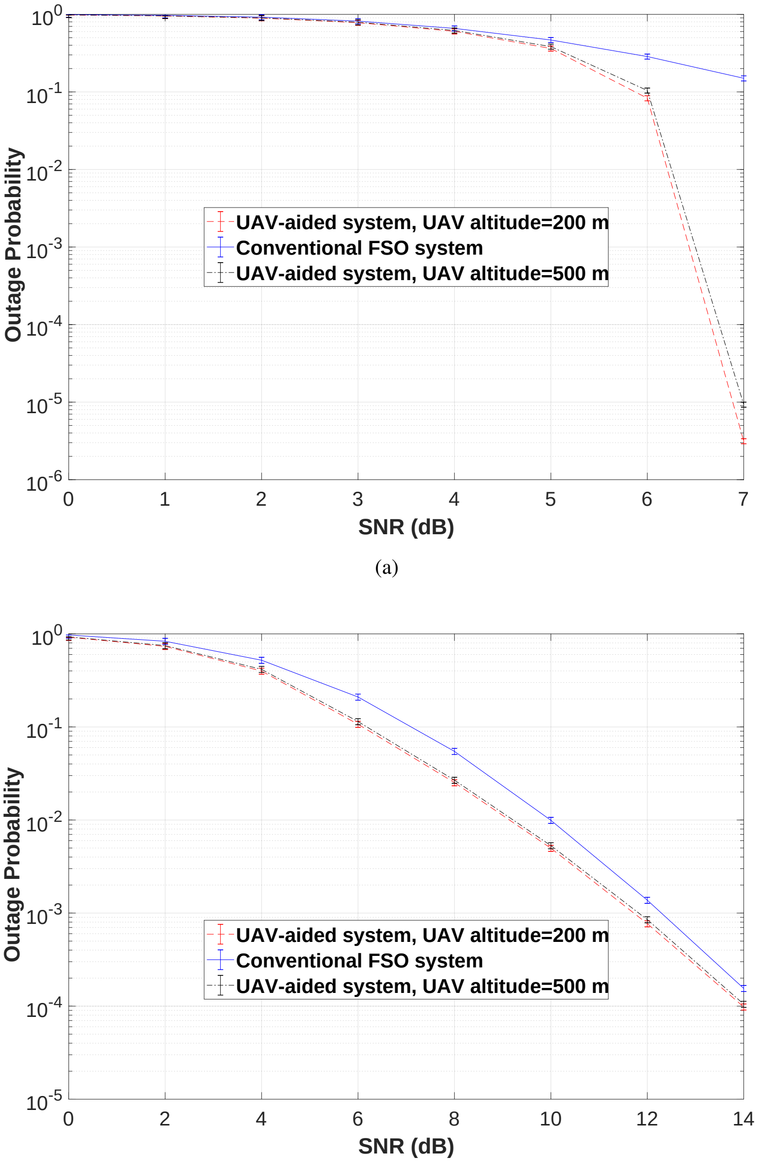
A. *Outage Probability*

Outage probability is a critical performance measure for relay-assisted FSO systems. An FSO link is considered to be available when its SNR exceeds a certain threshold value. Under this condition, a signal propagating through the link can be decoded at the receiving side with an arbitrarily small probability of error. An outage of the relay-assisted FSO system occurs when the system is unable to deliver data to the destination. For example, consider a conventional relay-assisted FSO system composed of a single source S communicating with a single destination D via 2 stationary relays, R_1 and R_2, through an all-active cooperation strategy. In this case, the same data packet is transmitted from S to both R_1 and R_2 in a first time slot and then in a second time slot, the data packet travels from R_1 and R_2 to D. So, an outage of both of the $S - R_1 - D$ and the $S - R_2 - D$ paths results in a packet delivery failure and hence an outage of the overall FSO system. This situation can be improved through the deployment of buffer-aided moving relays. As a matter of fact, unlike conventional relays, which are stationary and deprived of storage capabilities, buffer-aided moving relays can guarantee the delivery of a received packet since the latter is stored in the relay's buffer until the channel quality becomes favorable. This has the advantage of increasing the number of successful packet deliveries and consequently, decreasing the outage probability of the overall FSO system.

B. *Simulation Setup*

A discrete event simulator was developed for the purpose of gauging the benefits that can be reaped from the integration of buffer-aided moving UAVs into conventional relay-assisted FSO systems. The performance of the use-cases given in Figs. 3(a) and 3(b), which will be referred to as scenarios 1 and 2 in what follows, is compared to that of conventional relay-assisted FSO systems in terms of outage probability. In particular, the outage probability of scenario 1 depicted in Fig. 3(a) is contrasted with that of a conventional relay-assisted FSO system employing 4 buffer-free stationary relays. Moreover, the outage probability of scenario 2 presented in Fig. 3(b) is compared to that of a conventional relay-assisted FSO system utilizing 3 buffer-free stationary relays. Symmetrical conventional relay-assisted FSO systems are considered where the stationary relays are assumed to be at a distance $d_1 = 1.5$ km from the source and $d_2 = 2.25$ km from the destination. S is assumed to be separated from D by a distance of $d_{SD} = 3$ km. For scenario 1, the two quasi-stationary buffer-aided UAVs are assumed to be hovering at an altitude of either 200 m or 500 m above rooftop and to be equipped with individual buffers that can hold up to 15 packets. A packet duration is assumed to extend over the coherence time of the FSO channel so as to capture its quasi-static fading nature. For example, for a coherence time of 1 msec and a data rate of 1 Gbits/s, a buffer size of 1 packet translates in practice into a memory unit with a storage capability of 0.12 MBytes, which is within the practical limits.

In the case of scenario 2, the moving buffer-aided UAV is supposed to be navigating at a speed of 100 m/s at an altitude of either 200 m or 500 m above rooftop between S and D and to be equipped with a buffer that can accommodate up to 15 packets. In both scenarios 1 and 2, the stationary relays are assumed to be located at distances d_1 and d_2 from S and D, respectively. In all performed simulations, the adopted performance metric is evaluated over a total of 10^9 time slots with a view to achieving the highest degree of accuracy in terms of reported results. It is important to highlight that the channel model discussed earlier was implemented within the simulator and that data is relayed from S to D according to an all-active cooperation strategy. Without loss of generality, the source node is assumed to have an infinite supply of data meaning that there is always a packet ready to be transmitted from the source at each time



(a)

(b)

Fig. 4. Outage probability of: a) scenario 1 vs. conventional relay-assisted FSO system with 4 stationary relays, and b) scenario 2 vs. conventional relay-assisted FSO system with 3 relays.

slot. Finally, the communication taking place between any two nodes in the network is complemented with an ACK/NACK mechanism whereby the receiving node notifies the sending node about successful/unsuccessful receipt of a data packet. For the system under consideration, the backup RF link, that often complements the FSO links in practical transceivers, is perfectly adapted to establish a low-rate highly-reliable signaling channel. This high reliability emanates from the fact that the dependence of the path gains on the link distance is less pronounced for RF links as compared to the FSO links.

C. Numerical Results

Fig. 4(a) plots the outage probability relating to two variants of scenario 1 and a conventional relay-assisted FSO system with 4 stationary relays as a function of SNR. The two variants of scenario 1 correspond to the two cases where the quasi-stationary UAVs are hovering at an altitude of 200 m and 500 m above rooftop, respectively. The reported results show clearly the tremendous ability of the buffer-aided relays to enhance the outage probability performance, notably in both medium to high SNR regimes. For example, an outage probability of approximately 10^{-6} is observed for scenario 1 at an SNR of 7 dB as opposed to 10^{-1} for the conventional system. These results are indeed expected since an acceptable channel quality would enable the transmission of a relatively large number of packets from the UAVs' buffers to D. As a result, this contributes to the enhancement of the outage probability of the overall FSO system. A slight increase in terms of outage probability is observed in the variant of scenario 1 where the UAV is hovering at a higher altitude owing to the increased fading variance in this case. Fig. 4(b) compares the outage probability of two variants of scenario 2 to that of a conventional relay-assisted FSO system with 3 stationary relays. The results are a clear evidence of the superiority of a moving buffer-aided relay as opposed to stationary buffer-free relays when it comes to packet delivery. Indeed, both variants of scenario 2 exhibit a consistent improvement over the conventional FSO system in terms of outage probability. This observation holds even for low SNR regimes, as expected. In fact, the presence of buffer augmented with the continuous mobility of the UAV between S and D contributes to a great extent to increasing the number of successful packet deliveries to D and as such to boosting the outage probability of the overall FSO system. The performance gain is realized despite both the small buffer size and the simple to-and-fro linear mobility between S and D assumed for the UAV in the simulation study. This underscores the great value associated with the coupling of buffer-aided moving UAVs with conventional relay-assisted FSO systems.

V. CONCLUSION

For many state-of-the-art network architectures, communication through UAVs represents an additional degree of freedom that can be exploited to enhance performance levels. In the same spirit, this paper proposed to leverage buffer-aided quasi-stationary/moving UAVs as relays in the context of cooperative FSO systems. An empirical study of two simple scenarios illustrating possible ways of integrating buffer-aided UAVs into relay-assisted FSO systems revealed the benefits of the resulting hybrid architecture. However, special consideration should be given for the engineering of such novel systems to ensure a proper deployment of the buffer-aided quasi-stationary/moving UAVs. This is particularly true since only through appropriate utilization of these relaying entities can performance gains be maximized.

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