Free-Space Optical Communications for 6G-enabled Long-Range Wireless Networks: Challenges, Opportunities, and Prototype Validation

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Abstract—Numerous researchers have studied innovations in future sixth-generation (6G) wireless communications. Indeed, a critical issue that has emerged is to contend with society’s insatiable demand for high data rates and massive 6G connectivity. Some scholars consider one innovation to be a breakthrough—the application of free-space optical (FSO) communication. Owing to its exceedingly high carrier frequency/bandwidth and the potential of the unlicensed spectrum domain, FSO communication provides an excellent opportunity to develop ultrafast data links that can be applied in a variety of 6G applications, including heterogeneous networks with enormous connectivity and wireless backhauls for cellular systems. In this study, we perform video signal transmissions via an FPGA-based FSO communication prototype to investigate the feasibility of an FSO link with a distance of up to 20 km. We use a channel emulator to reliably model turbulence, scintillation, and power attenuation of the long-range FSO channel. We use the FPGA-based real-time SDR prototype to process the transmitted and received video signals. Our study also presents the channel-generation process of a given long-distance FSO link. To enhance the link quality, we apply spatial selective filtering to suppress the background noise generated by sunlight. To measure the misalignment of the transceiver, we use sampling-based pointing, acquisition, and tracking to compensate for it by improving the signal-to-noise ratio. For the main video signal transmission testbed, we consider various environments by changing the amount of turbulence and wind speeds. We demonstrate that the tested even permits the successful transmission of ultra-high-definition (UHD: 3840 × 2160 resolution) 60 fps videos under severe turbulence and high wind speeds.

I. INTRODUCTION

Recently, fifth-generation (5G) wireless communication systems have appeared in numerous countries, satisfying the demands of both industries and end users. However, today, researchers have focused on the concepts and applications of future wireless communication, that is sixth-generation (6G) wireless communications. As the roadmap of 6G becomes actualized, the data rates of 6G usage cases, such as streaming services and mobile augmented and virtual reality (AR/VR), are also required at a superior level, which exceeds one terabit per second (Tbit/s). In addition, an increasingly large number of such devices are being connected to the network, and they are communicating with one another. Such interactions are expected to exceed the connectivity of $10^7$ connections per km² [1], thereby surpassing the capacity of 5G (up from $10^6$) [1]. Moreover, severe problems arise from the scarcity of licensed spectrum resources. This problem cannot be resolved by existing radio-frequency (RF) communication systems, which are almost saturated by licensed spectrums. Although we find the available RF spectrum and utilize it for mobile access networks, it is difficult to satisfy the target data rate ($\approx$ Tbits/s) of 6G because of its relatively low bandwidth [1], [2]. An emerging solution is the free-space optical (FSO) communication system. FSO communication is a strong candidate for future wireless networks owing to several features, including high capacity and license-free characteristics, that can achieve the targets of 6G by utilizing hundreds of GHz or even THz of bandwidth scales [3]. For example, accompanied by unmanned aerial vehicles (UAVs), FSO communication can be used as a non-terrestrial wireless backhaul system. Generally, costly wired communication infrastructure (e.g., optical fiber) is necessary to provide reliable network services to rural areas. Many researchers believe that this problem can be solved by deploying FSO-communication-enabled UAVs to provide wireless backhaul connections [2]. Wireless backhauls can be easily developed by combining the mobility of UAVs with the high data rate and massive-connectivity properties of FSO links. Moreover, such backhaul connections can be expanded and reinstalled while adhering to the standards of the 6G network [1], [2].

One of the most significant technical challenges of the FSO communication link is that the channel characteristics—atmospheric turbulence and scintillation—can easily fluctuate the signal by including [4]. To mitigate the effect of this phenomenon, researchers have investigated various methods to construct robust real-time transmission architectures with high bit rates. Most previous studies have developed high-level technologies for high-rate FSO signal transmission. These technologies have included a 3D video transmission with an

Note to Reviewers: Full demo video is also available for reviewers. Please check your manuscriptcentral account.
adaptive demodulation scheme and a robust channel coding strategy, and a robust UAV-trajectory optimization strategy for UAV-to-ground FSO signal transmission scenario under the turbulent correlated FSO channels [5], [6]. They also demonstrated end-to-end transmission of FSO signals with various modulation schemes and link distances of tens or hundreds of meters [7], [8]. However, these works solely focused on numerical simulation or short-distance-link prototyping, which cannot cover the actual feasibility of long-range FSO links, widely assumed in various scenarios (e.g., non-terrestrial cellular systems) for 6G wireless networks [2], [3].

In this study, we demonstrate a real-time FPGA-based high-resolution video signal transmission via the FSO channel emulator to verify the feasibility of the long-range FSO communication link for 6G. This transmission setup models the channel characteristics of the FSO channel, including turbulence, scintillation, and power attenuation. We processed the video signal via an electrical-to-optical (E/O) converter, optical-to-electrical (O/E) converter, and FPGA module. The solar background noise critically affects the FSO transceiver and the link quality. To minimize this effect, we applied a spatial selective filtering method that adaptively reduced the field-of-view (FoV) of the receiver and suppressed the background noise generated by sunlight. We applied the proposed sampling-based pointing, acquisition, and tracking (PAT) techniques to improve the signal-to-noise (SNR) ratio to enhance the accuracy of the FSO signal transmission. In the main video transmission testbed, we demonstrate that the proposed communication scheme transmits and processes the video signal, even under harsh channel conditions, such as high turbulence or wind speed. This study marks the world’s first integration of an FSO channel emulator and the FPGA-based software-defined-radio (SDR) platform and models the long-distance (up to 20 km) FSO link. The proposed testbed includes various techniques to enhance the robustness of the FSO link. These include the space-selective filtering technique, which suppresses the solar background noise, and the sampling-based PAT technique with SNR enhancement. 3) In Section III, we analyze the signal-transmission result using the proposed platform. 4) In Section IV, we present some concluding remarks.

II. LONG-RANGE FSO COMMUNICATION SYSTEM FOR 6G: CHALLENGES AND SOLUTION

In this section, we explain the confronted challenges to develop the proposed FSO link testbed, including the limitations of previous studies related to the feasibility of a long-range FSO network. Subsequently, we summarize the contribution of the proposed testbed in comparison with previous works.

A. Motivation for the Proposed Real-Time FSO Link Demonstration

1) Encountered Challenges of the Long-Distance FSO Link Utilization: To utilize the FSO communication which has a dominant position for obtaining a high data rate for 6G wireless networks, as illustrated in the left part of Fig. 1, we must overcome the vulnerability against atmospheric turbulence and other losses, such as penetration, pointing, or propagation losses. These effects become significantly stronger as the distance between the transmitter and receiver increases.
For instance, an FSO-communication-based wireless backhaul system with the assistance of UAVs is considered a novel service strategy for 6G, as illustrated on the right side of Fig. 1, assumes a ground-to-UAV link distance of up to 20 km [2]. Therefore, researchers have focused on modeling the turbulence of the FSO signal and developing transceiver techniques to enhance the link quality under various scenarios and reflect this in the link margin strategy [4], [5], [9].

2) Recent Works and Limitations: Owing to its potential in data rate and connectivity, several studies have been conducted to evaluate the actual performance and feasibility of an FSO link. Concurrently, researchers have been striving to develop related technologies for robust FSO communication, including its performance analysis by simulation. In [5], the authors analyzed the performance of 3D video transmission with \( N \)-orbital-angular-momentum-shift keying (\( N \)-OAM-SK) FSO system by applying deep-learning techniques. In [6], the authors assumed a UAV-mounted FSO communication system and maximized the flight time of the UAV by optimizing the trajectory based on various atmospheric environments and the channel and rate characteristics of FSO links. Both studies considered the distance of the FSO link up to approximately 1 km. In [9], the authors developed an RF lens-antenna-based PAT technique based on an accurate angle-of-arrival (AoA) estimation with a fast steering mirror (FSM) for hybrid RF/FSO communication systems with a maximum link distance of 3 km.

To measure the actual feasibility of FSO communications, research continues on how to develop an end-to-end FSO link prototype under various transmission and channel scenarios. The authors in [7] demonstrated an end-to-end link tested with a distance of 100 m and applied an FSO signal with a 25 GHz data rate and 32-quadrature amplitude modulation (QAM), which is sent by a 12 wavelength-division-multiplexing (WDM) channel. The authors in [8] presented an end-to-end demonstration of transmitting 4- and 64-QAM signals over an FSO channel under non-uniform turbulence, with a maximum distance of 500 m. Recently, the authors in [10] demonstrated a coherent 100 Gbps FSO link with a link distance of only 40 m by applying dual-polarization quadrature phase shift keying (DP-QPSK).

As indicated above, existing research works have focused on either overcoming the transmission environments or the link-quality enhancement strategies based on simulation and have assumed a relatively short FSO link of up to a few hundred meters for hardware validation. Nevertheless, formalizing the challenges and opportunities pertaining to a feasible long-distance FSO link is still considered an open problem. Indeed, it is difficult to measure the exact feasibility or properties of the FSO link for large distances of up to 20 km. This distance also restricts researchers from focusing on analytical expressions and computer simulations.

B. Contribution of the Proposed Real-Time FSO Link Demonstration

To solve these problems and evaluate the feasibility of the long-distance FSO link for 6G, we developed a real-time video signal transmission prototype. The prototype is an integration of an FSO channel emulator and an FPGA-based SDR platform. The channel emulator models the time-varying atmospheric channel with power attenuation by absorption and scattering, and it models turbulence with scintillation. An FPGA-based SDR platform was implemented for video signal generation and encoding/decoding. Moreover, we applied...
various link-quality-enhancement techniques to improve the quality of the received video signal.

This is the world’s first prototype that evaluates the feasibility of the long-distance FSO link by these two essential platforms for FSO and RF communications. Moreover, the novel sunlight noise mitigation and tracking algorithm are jointly included in the testbed for link-quality enhancement, which contributes to the robustness of the FSO signal against the long 20 km transmission distance. Therefore, it can solve the vulnerability issues of long-distance FSO links that occur under atmospheric conditions and transceiver misalignment. By combining these factors, we successfully transmitted an ultra-high-definition (UHD: 3840 × 2160) video signal over a 20 km FSO link under both clear and hazy atmospheric conditions, owing to the proposed hybrid FSO/RF hybrid platform and outage mitigation techniques. Accordingly, our demonstration significantly contributes to the reliable usage of long-range FSO communication in future wireless networks, including non-terrestrial FSO backhaul networks with a link distance of scale of tens of kilometers, as described in Section I and Fig. 1.

III. SYSTEM ARCHITECTURE OF FSO LINK PROTOTYPE

In this section, we present the proposed FSO link prototype, including the setup of the FSO channel model, hardware and data, and various techniques for increasing the robustness of up to 20 km in the FSO link. We then analyze the signal transmission results by varying the channel conditions of the experiment.

A. Path-loss Model of the FSO Communication Link

It is widely known that FSO signals undergo atmospheric attenuation, the degree of which depends on the scintillation and the size of the scattering particles. Pointing inaccuracy takes the center of the beam away from an air terminal, not to receive a maximum intensity, and optical loss occurs owing to the less-than-perfect FSO transceiver elements [9]. Consequently, the received power \( P_{r} \) is determined by \( L_1 \), \( L_p \) and \( L_o \), which indicate atmospheric attenuation, pointing, and optical loss, respectively, [2], [11].

1) Atmospheric Attenuation: Scintillation: For \( L_1 \), we must consider the scintillation and scattering effects, which are key to the vulnerability of the long-distance FSO link. We employed the scintillation (turbulence) model \( L_{sca} \) for atmospheric channel modeling [4], [12]. It represents a function of the refractive index structure parameter \( C_n^2 \) modeled by the Hufnagel-Valley (H-V) model [4], which is a function of altitude \( h \) in meters and wind speed \( v \) in m/s.

2) Atmospheric Attenuation: Scattering: We consider the Mie scattering model to express the scattering loss \( L_{sca} \) in dB. This is induced by particles having a size similar to that of the wavelength \( \lambda \). As fog, rain, and clouds can cause a scattering effect [2], a scattering model must be considered for each scenario. For fog and rain, we employed the Kruse model to model the effects [4]. This is a function of the scattering coefficient \( \beta_{sca} \), which is a function of \( \lambda \), visibility range \( V \), and rainfall rate \( R_r \) in mm/h. In the proposed testbed, \( V = 10 \text{ km} \) and \( V = 3 \text{ km} \) are chosen to represent clear weather and hazy weather, respectively. These values are chosen to verify the transmission results based on two separate Kruse models corresponding to \( V \leq 6 \text{ km} \) [2], [13]. For cloudy conditions, we used the model in [14] to express the scattering loss by clouds. Therefore, the total loss \( L_1 \) in decibels is given by:

\[
L_1 = \sum \text{attenuation factors} \cdot L_{sca} + L_{sca}
\]

3) Pointing and Optical Loss: We set the pointing \( (L_p) \) and optical \( (L_o) \) losses equal to 2 dB, resulting from the misalignment and optical efficiency of the transceiver, respectively, [2]. The pointing loss is determined by each pointing loss factor of the transceiver, which is determined by the transceiver aperture, wavelength \( \lambda \), and pointing error angle [4]. We obtained data in our hardware setup (transceiver aperture and wavelength) and the proposed sampling-based PAT algorithm in Section III.C with low misalignment. The optical loss can be modeled as \( L_o = 10 \log_{10}(\eta_r \eta_t) \) for the optical efficiencies of the FSO transmitter \( (\eta_t) \) and receiver \( (\eta_r) \). The typical value of \( \eta_r \eta_f \) is in the range of \([0.2, 0.7]\) [2], [7], which depends on the optical components, and a value 0.65 is used in our demonstration, which approximates \( L_o \) by 2 dB.

B. Hardware and Data Setup

The prototype structure used to evaluate the feasibility of the FSO link is illustrated in Fig. 2 and the detailed parameters are listed in Table I. For video signal transmission, we transmitted a one-minute clip of the 2008 animated short Big Buck Bunny with 4 K UHD resolution. Since the transmission is demonstrated in an indoor environment, to induce the accurate signal transmission compared to an actual outdoor scenario with 20 km link distance, we used the Mach-Zehnder Modulator (MZM), which is widely applicable in high-speed optical systems owing to its dominant position on ease of fabrication and flexibility of pulse reputation [8], [15]. We employed the MZM in the proposed system to model the 2D atmospheric channel and perform error correction, including both line-of-sight (LoS) and pointing errors. Here, using the given atmospheric parameters, we generate the corresponding atmospheric channel with a distance of 20 km by the MZM, which is completed by the following procedure: we divide the transmitted FSO signal into two paths, determine the intensity and phase of the signal by driving voltages to each signal, which causes the variation of optical path length and merge them [15]. The channel emulator was connected between

| Parameter                     | Value (hazy, clear weather) |
|-------------------------------|-------------------------------|
| Wind speed (height: 0 km) (v) | model in [12] (6, 1 m/s)     |
| Visibility (V)                | 3, 10 km                      |
| Fog layer thickness (d_{fog}) | 50, 0 m                       |
| Rain layer thickness (d_{rain})| 1, 0 km                       |
| Cloud attenuation (L_{sca,cloud}) | model in [14]   |
| Wavelength (\lambda)          | 1550 nm                       |
| Link distance (d)             | 20 km                         |
| Bit rate of video signal      | 35 Mbps                       |
| Resolution and frame rate     | UHD 60 fps (H.264)            |
the transceiver FPGA modules. The transmitter and receiver included a laser diode (LD) with an E/O converter and a photodiode (PD) with an O/E converter, respectively, to ensure long-term video signal transmission. After receiving an oversampled data stream using a digital sampling oscilloscope (DSO) on the receiver side, we derived the bit-error-rate (BER) performance by using the average and standard deviations of the received ones and zeros [7]. The diodes were connected to an FPGA-based PXie SDR platform for real-time video signal processing. This involves the encoding and modulation of the bitstream of the video signal. The SDR platform at each transceiver side comprises a PXie chassis (PXie-1082) and FPGA controller modules (NI-7976, 5791, PXie-8880, 8374, and 2953R for the transmitter and receiver sides).

C. Proposed Techniques for Link-Quality Enhancement

Since we consider a link distance of up to 20 km, the vulnerability becomes even greater. Hence, we applied several link-quality-enhancing strategies to ensure the reliability of video signal transmission.

1) Suppressing Solar Background Noise by Spatial Selective Filtering: In this section, we present the testbed structure for suppressing the solar background noise. The FSO signal is known to be vulnerable to solar noise [3], where SNR degradation is approximately 5 dB, resulting in more than 50 dB when sunlight becomes direct [11]. Hence, in the proposed test bed, we suppress this solar background noise compared to the signal power using the proposed spatial selective filtering technique. We assume that the amount of solar noise is given by (20) in [3], where the amount of noise is proportional to the receiver FoV, and hence the amount of noise proportionally decays by the selected portion of the receiver aperture. Here, we spatially divide the given area into specific partitions (e.g., $2 \times 2$, $3 \times 3$, ···) and filter the area where the signal intensity is greater than that of the others. This leads to the result that the signal power of the selected region is, assuming $2 \times 2$ division, for example, greater than the average signal power $P_{s}$ for the total signal power of aperture $P_{s}$. However, the noise power of the selected area was suppressed by $P_{n}$ for the total noise power through the total aperture $P_{n}$. Hence, the optical SNR becomes greater than $P_{s}/P_{n}$, which is the SNR of the conventional method without spatial filtering. To measure the performance of the proposed spatial selection technique, we performed a point-to-point test and realized the algorithm. We split the transmitted FSO link by the beam splitter and determined by our high frames-per-second (fps) image sensor, the amount of reduction of the receiver FoV, and feedback to the receiver. Using the proposed spatial selective filtering method (shown in Fig. 3), we can reduce the BER from an order of $10^{-3}$ to $10^{-4}$, which positively contributes to the accuracy of the long-distance video signal transmission.

2) Link-Quality Enhancement by SNR-Improving PAT Technique: It is widely known that when the FSO transmitter and receiver are misaligned, the link quality is highly degraded, and the outage of the FSO link is increased [9]. Therefore, we need to apply the proposed multiple-sampling-based PAT technique to our testbed, as illustrated in Fig. 4. To improve the SNR performance, we measured the received $m$ signals $Y_{m} = HX_{m} + n_{m}$ for the static channel $H$, transmitted signal $\{X_{i}\}_{i=1}^{m}$ and noise $\{n_{i}\}_{i=1}^{m}$ for each sampling and acquisition time with the control of the quadrant-detector (QD) receiver, and measured the concatenated optical SNR $\text{SNR}_{c}$ for $m$ samples. Here, the QD receiver detects optical signals from its photoreceiver divided into quarters, estimating the beam displacement by comparing the received signal power of each quadrant $V_{1}, \cdots, V_{4}$ [3]. The concatenated SNR is given by $\text{SNR}_{c} = \frac{mH_{ average X}}{\sqrt{\frac{1}{n_{1}+\cdots+n_{m}}}} \approx \frac{mH_{X}}{n\sqrt{m}} = \sqrt{m} \frac{H_{X}}{n}$, which implies that we can obtain an SNR gain of $\sqrt{m}$ for $m$ sampling
Fig. 4. Proposed multiple-sampling-based PAT technique through SNR improving and 3D acquisition and the misalignment result along the x-axis. By enhancing SNR through sampling gain of $\sqrt{m}$, we can achieve far less tracking error compared to the size of QD.

compared to a single-signal-reception scenario. Moreover, by our precise control of the QD receiver with angle resolution of sub-$\mu$ rad scale and compensation frequency of up to 1 kHz, the misalignment along the x-axis is reduced by 0.19 mm for ten samplings ($m = 10$), which is negligible compared to the size of the QD given by order of 1 mm [3].

D. Video Signal Transmission under Various Channel Conditions

By implementing the proposed testbed using the various link-quality-enhancing techniques described above, we conducted video signal transmission through the emulated FSO channel. We assumed a four-level pulse-amplitude-modulated (PAM-4) signal for video signal transmission, which achieves superior computational complexity and power consumption for long-distance FSO signal transmission compared to other higher modulation schemes (e.g., n-QAM or orthogonal-frequency-division-multiplexing (OFDM)-QAM) that require a complex system architecture and enormous transmit power. The upper part of Fig. 5 illustrates the verification procedure for data reliability by measuring. As shown in the figure, by transmitting a 4-Gbps PAM-4 signal under a weak turbulence channel with a 20-km link distance, our proposed technique can achieve a BER of $10^{-4}$ order. This guarantees the reliability of data transmitted through the 2D channel model.

The lower part of Fig. 5 shows snapshots of the video transmission results under the channel conditions. In an environment with low turbulence and slow wind speed, the original clip can be transmitted with almost zero distortion. Even under harsh conditions of high turbulence and fast wind speed, the clip can be sent with negligible distortion. Therefore, we can conclude that, with our prototype of a realistic FSO channel model, researchers can confirm the feasibility of the long-distance FSO link under several channel conditions.

IV. Conclusion

In this article, we highlighted the utility of long-range FSO communication links for 6G networks by investigating their high-data-rate, unlicensed, and narrow-beam properties. We also emphasize that the vulnerability of the FSO communication link depends heavily on atmospheric conditions, the harshness of which increases as the link distance increases. To measure the link-level feasibility of the long-distance FSO link, we developed the first novel technique to model a real FSO channel with an MZM emulator and a point-to-point transceiver realized by FPGA modules. We considered the FSO channel with both low- and high-turbulence scenarios and adopted various link-quality enhancement strategies, including solar-noise suppression by selective filtering and SNR-improving PAT. To verify the performance of the strategies, we independently conducted a point-to-point FSO signal transmission experiment and demonstrated how our techniques lowered the BER and misalignment results. For the main feasibility measurement, we demonstrated that even a video signal with UHD 60 fps could be received without distortion (or less) using the proposed SDR-platform-based prototype. We believe that through the description of the challenges and opportunities and the proposed demonstration in this article, we have conveyed a promising insight into the benefits of implementing long-distance FSO links in future wireless networks. Furthermore, we believe that more accurate video transmission techniques, which hold up in practice, can be modeled and tested using the proposed testbed.

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Fig. 5. Data-reliability validation process under $\ell = 20$ km scenario and snapshots of video transmission in clear (low turbulence, 1 m/s wind speed, ...) and hazy (high turbulence, 6 m/s wind speed, ...) weathers. The denoted wind speed is based on the height of 0 km [12].

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