

# Adaptive Transmission Algorithms for a Hard-Switched FSO/RF Link

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**Abstract**—Hybrid communication systems exploit channel diversity to improve network performance. One such example is hybrid Free Space Optical (FSO)/Radio Frequency (RF) systems. These networks aim to merge the high capacity of FSO links with the high availability of RF links to form resilient high-bandwidth communications. When used for wireless communications, the main challenge is the dynamic response to variations in the atmospheric channel in adverse weather conditions. In this paper we simulate adaptive hard-switched transmission algorithms on a practical prototype hybrid system. FSO channel scenarios are formed based on climate data, and are emulated on the prototype system to compare the performance of the hybrid system to each solo carrier respectively.

**Index Terms**—Communication systems, communication system control, hard-switching, hybrid FSO/RF channels, transmission algorithms.

## I. INTRODUCTION

FREE space optical (FSO) communication systems are a well investigated field of research and offer a vast number of advantages. FSO provides bandwidths into the gigahertz, high energy efficiency, high scalability and configurability, and license free communication. Additionally, FSO offers an increased level of security due to its invulnerability to electromagnetic interference and low probability of interception. However, FSO systems operate at the mercy of the environment and are strongly affected by atmospheric variations. Environmental limitations of FSO communication systems include fog, absorption, scattering, scintillation, and physical obstructions [1].

Channel diversity created with an RF backup channel can help to overcome these limitations. Radio frequency (RF) technologies are more robust and offer a higher tolerance to atmospheric conditions compared to FSO carriers. The downside is that RF typically provides an order of magnitude less channel capacity compared to optical communications. Additional challenges to RF include bandwidth scarcity due to licensing, susceptibility to interference, and vulnerabilities to detection and interception.

## II. HYBRID FSO/RF CONTROL

The distinct strengths/weaknesses exhibited by FSO and RF carriers make them good candidates for joint deployment. By

utilizing both channels in a cooperative manner, hybrid FSO/RF systems can combine the high data rates of FSO and the reliability of RF links through channel diversity. There have been several types of hybrid transmission schemes proposed and investigated in literature. Previous work on hybrid FSO/RF systems focus on hard-switched transmission schemes, soft-switched transmission schemes, or simultaneous redundant transmission on both links.

In the hard-switched configuration, the transmitter and receiver jointly switch between both the FSO and RF link for data transmission. Fig. 1 illustrates a simple schematic of a hard-switched hybrid FSO/RF system. The performance and viability of hard-switched hybrid systems was studied in [2-5].

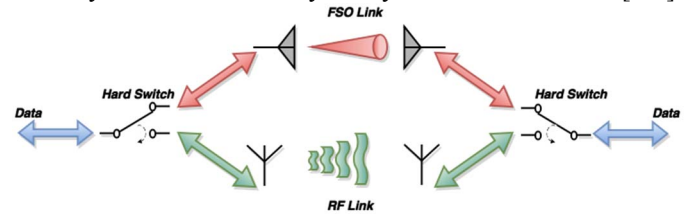


Fig. 1. Hard-switched hybrid FSO/RF communication system.

Specifically, [2] proposes a hard-switching system that analyzes the physical receive signal strength of the FSO channel using power hysteresis, time hysteresis, filtering, and a combination thereof. A hard-switching transmission scheme that monitors the system bit error rate (BER) was proposed and investigated in [3]. Furthermore, [4] studies a single and dual threshold hard-switching approach based on the BER and ergodic capacity of an FSO/millimeter wavelength RF system. In contrast, [5] uses a network monitoring approach through the use of echo request packets.

As an alternative, in the soft-switched configuration the system uses adaptive coding or adaptive modulation to balance the data transmission on both available links. Soft-switched methods with adaptive coding were studied in [6-8]. Non-uniform and rate-compatible low-density parity-check (LDPC) codes is studied in [6], and [7] proposes a system where the data is jointly encoded/decoded and each link is adjusted separately. Alternatively, [8] discusses using Raptor encoded packets to perform soft-switching between the FSO and RF links. Additionally, simultaneous redundant transmission was studied in [9]; a high capacity RF link and FSO link transmitted identical information with the same modulation scheme.

The efficiency, latency, and ease of design should all be considered when selecting a particular transmission method. Conventionally, FSO and RF channels will offer different data rates. While soft-switched schemes tend to offer higher capacity than hard-switched schemes, many complexities arise from the need for specialized encoders/decoders or networking devices to merge the two data rates. Additionally, if both carriers are continuously on it can result in wasted power and cause undesirable transmission and interference in times when one link is experiencing poor quality. Conversely, hard-switched systems offer less complexity because they do not have to compensate for various data rates. This leads to lower power consumption at the transmitter, and no adaptive modulation is required.

Transmission schemes rely on the analysis of link performance and quality. Parameters for evaluating the channel health can be collected on the physical, network, or application layers. From the physical layer you can monitor the receive signal attenuation. The network layer parameters include bit error rates, or the performance of error correcting code, retransmission and replay, or the performance of network integrated quality of service. Alternatively the application layer parameters could be used to evaluate the performance of specific real-time/non real-time voice, video, or data streams. Each of these layers offer parameters for monitoring link performance attribute advantages and disadvantages. Some might be better suited for specific situations depending on the available equipment, practicality, and effectiveness.

It must also be considered that in hybrid systems path reconfiguration may inadvertently cause increased system delay and lower throughput as well as packet loss [10], thus the studies on path reconfiguration is of pronounced importance. In this paper, we consider a practical low-complexity hard-switched hybrid FSO/RF system where the hard-switched transmission scheme is driven by various algorithms monitoring the physical link layer. The validity of these hard-switched transmission schemes are compared in terms of average throughput performance, and persistent link availability.

### III. TRANSMISSION ALGORITHMS

In this section, the advantages and limitations of three particular transmission algorithms are discussed: single threshold comparison, trend-reactive switching, and trend-proactive switching. The switching decision is driven by the physical layer of the FSO link. In our work, the RF link is assumed to be always available. The outage threshold for the FSO receive signal power ( $\theta_{FSO}$ ) was designed as a function of the minimum achievable data rate. The derivation of the threshold requires a priori knowledge of the achievable data rate as a function of receive signal power. The threshold represents the receive signal power where the achievable data rate through the FSO link is equal to that offered by the RF link. This comparison highlights the trade-off between loss sensitivity, responsivity, and computational complexity.

#### A. Single Threshold Comparison

The easiest way to implement a hybrid transmission scheme is to use the instantaneous receive FSO receive signal power. In

this method, the optical receive signal power is rapidly monitored and compared against the threshold for loss ( $\theta_{FSO}$ ). The instantaneous receive signal power exclusively determines the switching operation. If the power is above the threshold the FSO link maintains priority, otherwise RF is used.

#### B. Trend-Reactive Algorithm

For this case, a technique that uses locally weighted scatter plot smoothing for local regression (LOESS) is used to alleviate undesired variations in the optical receive signal power. It was performed by using weighted linear least squares and a 2<sup>nd</sup> degree polynomial model to expose the trend. This method assumes that the instantaneous FSO receive signal power can be collected in series and divided into subsets of 5 second windows. A model is fit from this localized 5 second subset which builds a function that describes the deterministic part of the variation of the data. The majority of the function determines the switching operation. If the majority is dipping below the threshold for loss ( $\theta_{FSO}$ ), the RF link is used. Otherwise, the FSO remains active.

#### C. Trend-Proactive Algorithm

In this method the FSO receive signal power is treated as a time series scalar measurement. Prediction and estimation is performed using a Kalman filter (linear quadratic estimation) running recursively and updating in real time. The Kalman filter is widely used in the field of signal processing, and can be used to produce a statistical optimal estimate. It works as a two-step process: first producing an estimate of the current state, and then observing the error to refine that estimate. General Kalman filter state estimation, prediction, and correction is discussed in many excellent resources and won't be covered in this paper. In this case, a novel Kalman filter is used as a recursive estimator for the optical receive signal power.

A visual representation of the response of the aforementioned algorithms to a subset of FSO receive optical power is shown in Fig. 2 highlighting the obvious formation of trends in the trend-reactive and trend-proactive algorithms.

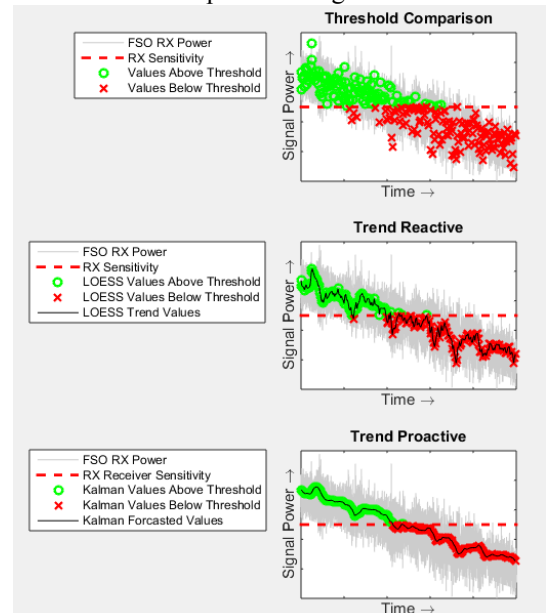


Fig. 2. The performance of the proposed algorithms to FSO received optical powers hovering about the cutoff level.

#### IV. ATMOSPHERIC AND PHYSICAL OBSTRUCTION SCENARIOS

One limiting factor in FSO communication systems is intensity noise due to scintillation. Scintillation is described as the interference, both constructive and deconstructive, of an optical wave as it travels through a turbulent propagation path. This is due to the small temperature variations and velocities of eddies of air along the path. The atmospheric scintillation can be measured in terms of the scintillation index  $\sigma_I^2$ , given as:

$$\sigma_I^2 = (\langle I^2 \rangle) / (\langle I \rangle^2) - 1 \quad [\text{unit less}] \quad (1)$$

where  $I$  is the detected intensity of the optical wave and  $\langle \rangle$  denotes ensemble average.

The weak turbulence regime is characterized by the condition ( $\sigma_I^2 \ll 1$ ), which is the case for the scintillation data used in this experiment. In the weak turbulence regime, the scintillation index  $\sigma_I^2$  is proportional to the Rytov variance, so the relationship between the scintillation index  $\sigma_I^2$  and index of refraction  $C_n^2$ , with units of  $m^{-2/3}$ , can be expressed by the Rytov approximation shown in Equation 2 [11].

$$\sigma_I^2 = \alpha C_n^2 k^7 L^{11/6} \quad (2)$$

Solving for the index of refraction ( $C_n^2$ ) leads to Equation 3,

$$C_n^2 = (\sigma_I^2) / (\alpha k^7 L^{11/6}) \quad (3)$$

where  $\alpha = 1.23$  for a plane wave and  $\alpha = 0.5$  for a spherical wave,  $k$  is the wave number ( $k = 2\pi/\lambda$ ), and  $L$  is the propagation distance in meters.

Fig. 3 displays the scintillation of a climate collected 360 second optical signal that exhibits a scintillation index of 0.0096 and an index of refraction of 4.43E-16.

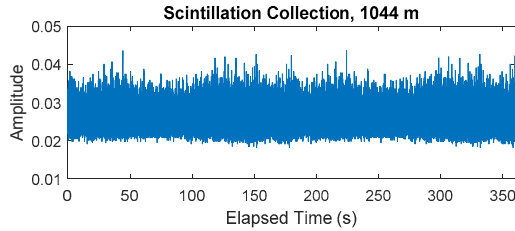


Fig. 3. Scintillation data of 360 second optical receive signal.

This collection was taken over terrestrial terrain in clear conditions representing a situation where there is no link loss. For the purpose of this paper additional link loss events are imposed onto this signal. The overall FSO link will emulate the scenario shown in Fig. 4.

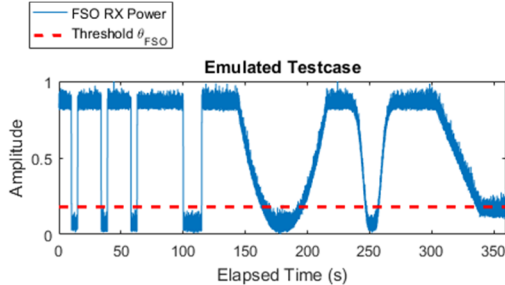


Fig. 4. Overall FSO test case encompassing fluctuations induced by scintillation with additional sudden and gradual attenuation scenarios.

Sudden drops in the optical receive signal can occur from misalignment of the laser beam, or in the event of physical obstructions in the propagation path. The overall test case emulates three periodic short losses lasting 5 seconds each, and one continuous loss lasting 15 seconds. The contrast in loss times is to highlight the effect of loss duration on the different transmission algorithms. A zoomed view of the sudden losses contained in the test case are shown in Fig. 5.

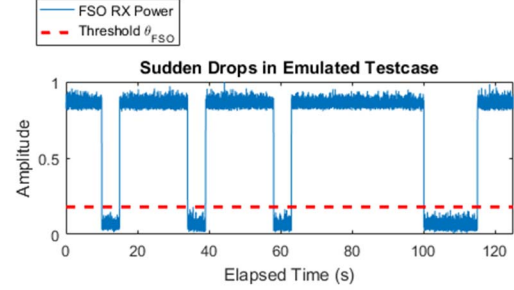


Fig. 5. Zoomed view of the sudden losses contained in overall FSO receive signal (Fig. 4.) to highlight the sudden threshold crossings of varying duration.

Gradual attenuation could be caused by atmospheric effects (fog, smoke, haze, or clouds), or mobile platforms breaching line-of-sight (LOS) distances. A zoomed view of three gradual attenuation cases is shown in Fig 6. This portion of the test case aims to expose the algorithms sensitivity to frequent threshold crossings.

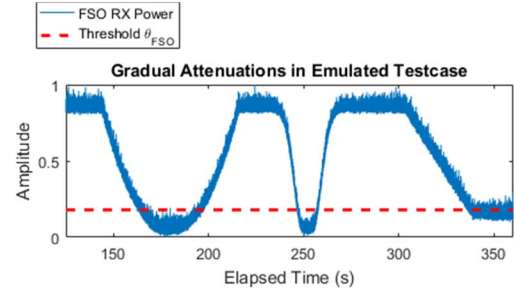


Fig. 6. Zoomed view of the frequent threshold crossings contained in overall FSO receive signal (Fig. 4.) to highlight the varying rates of attenuation.

#### V. EXPERIMENTAL SETUP

In this paper, we consider the low-complexity condition where the system uses a hard-switched scheme for hybrid FSO/RF transmission. The prototype system was composed of three main blocks: the FSO link, the RF link, and the monitor and control (M&C) block. The system operates as a FSO link and a RF link in parallel, thus the data transmitted will only either use the FSO link or the RF link at any time. The FSO link is considered the primary link due to its generally higher data rates, and the transmitted data will propagate on this link given the link quality is above a certain threshold.

The FSO link was simulated through the use of two Ethernet-optical converters, fiber cabling, an optical attenuator, and an acousto-optic amplitude modulator. Each Ethernet-optical converter operates at 1550 nm wavelength, and the optical attenuator was used to emulate the constant attenuation effects of the atmosphere. Additionally, the acousto-optic modulator was digitally controlled to impose varying levels of attenuation that

simulate effects from scintillation and the optical attenuation scenarios.

On the other hand, the RF link utilized two Comtech SDM-300 modems set to transmit at a lower frequency of 70.0 MHz at a rate of 5 Mbps through standard coaxial cables. The design of the RF link stemmed from the fact that lower frequency/lower data rate RF back-up channels are less susceptible to the atmospheric conditions and allow for highly reliable links.

The M&C block was composed of two laptop PC's, two Cisco routers, a data acquisition card, and a fiber optic splitter. A small fraction of the optical signal is split off for receive power analysis. The optical receive power is used as the performance metric in the FSO link. It is measured with the data acquisition card and transmitted back to PC1. The control program running on PC1 analyzes the optical receive power and controls the system switching operation. The Enhanced Interior Gateway Routing Protocol (EIGRP) was used to automatically route decisions and configuration between each router. The switching operation was performed by a command to modify the routing table of the routers. Thus, when the status of the routing table was switched from either link, the changes are sent to the second router automatically. The overall switching operation took less than 1 second. Concurrently, the actual data transmission and analysis is done with a program called Multi-Generator (MGEN), developed by the protocol Engineering Advanced Networking Research Group at the Naval Research Lab [12]. With this MGEN software, a steady stream of user datagram protocol (UDP) packets are transmitted at a rate of 20 Mbps, and the network traffic is monitored over time to measure the achievable data rates. The network map of the prototype system is shown in Fig. 7.

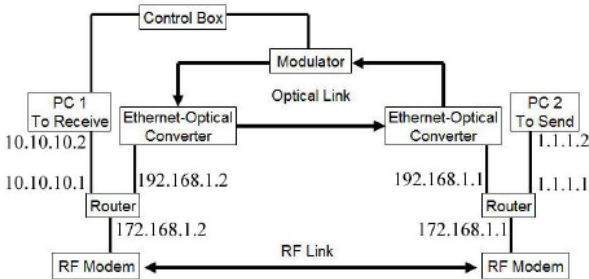


Fig. 7. Prototype system network map.

## VI. RESULTS AND ANALYSIS

The threshold comparison, trend-reactive, and trend-proactive hard-switching algorithms were simulated on the hybrid FSO/RF prototype system by means of emulating the control signal shown in Fig. 4 comprising FSO link degradation scenarios. The performance of each algorithm was studied in terms of overall system availability and throughput.

The performance of the hybrid prototype system was dependent upon the accurate selection of the FSO receive sensitivity threshold ( $\theta_{FSO}$ ). This threshold determined the number of hard-switching operations called. Due to the nature of the system, a hard-switch operation requires a certain amount of time which can result in undesirable link loss. The system aimed to maintain a steady link throughput of 20 Mbps. The FSO link (un-attenuated) could effortlessly handle this

capacity. For the purposes of this work, the RF link is assumed to offer 100% availability with an overall throughput capability of 25%. The throughput of the RF link was derived based on the max capacity, 5 Mbps, relative to the FSO link capacity of 20 Mbps.

The results of the simulation are shown in Fig. 8 exposing the system performance to sudden optical RX power drops as well as intermittent frequent outages. The hard-switch to the RF link during FSO link outage is obvious as the throughput drops to the RF max capacity of 5 Mbps. The first hard-switching technique studied was the threshold comparison method. It is clear that the threshold comparison method performed better when the sudden outage lasted longer than the switching time. This method was the quickest to switch to the backup RF in the occurrence of long term blockages. On the other hand, the repetitious threshold crossing caused by the gradual attenuation scenarios show the detrimental effect of repetitious intermittent outages. Due to the nature of the system, the overactive switching results in instances of full link loss. Resultantly, the threshold comparison method offered the lowest reliability rate of the three algorithms studied.

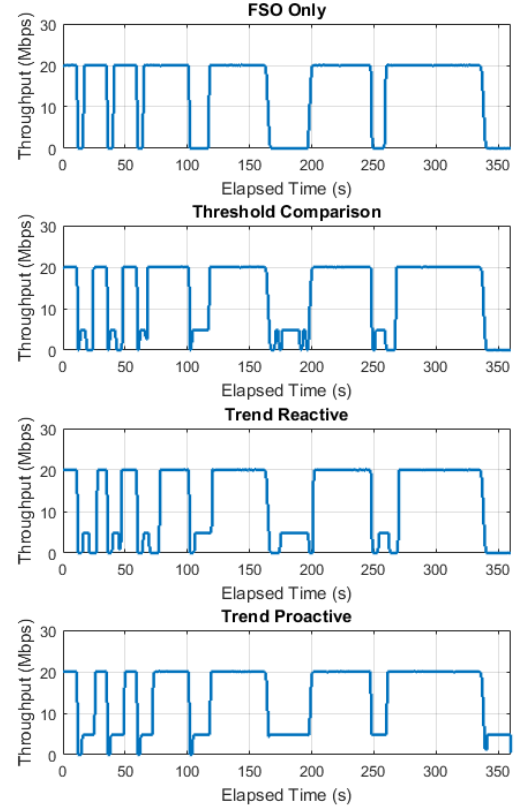


Fig. 8. Transmission results of the hybrid system using both a FSO and RF link.

Both the trend-reactive and trend-proactive cases employ an observation window that aims to strike the balance to allow for fast reactions while providing some insensitivity to minor drops. These methods were often able to increase the system reliability over the threshold comparison method. Furthermore, the trend-proactive method outperformed the trend-reactive method. The trend-proactive method was able to find when there is a decreasing trend in the optical receive power and



preemptively switch. Also, it was able to switch slightly faster in the event of sudden drops.

TABLE I. COMPARISON OF TRANSMISSION ALGORITHM PERFORMANCE

Link Control	Average Throughput (Mbps)	Average Reliability (%)
FSO Only	14.6115	80.56
Threshold Comparison	13.9552	89.72
Trend-Reactive	12.8914	84.72
Trend-Proactive	14.4915	97.50

Table 1 reveals the throughput and reliability corresponding to the transmission algorithm response plots in Fig. 8 with respect to the FSO only case. The results reflect that the different transmission algorithms influence on the throughput and availability rates of the system as a whole. The three transmission algorithms result in a decreased throughput caused by the loss during the switching operation, yet each yield an improvement for overall link availability. Furthermore, the trend-proactive method performs best, as it provides the best balance in throughput and link availability.

## VII. CONCLUSION

In this paper, an array of hard-switching schemes were explored and tested on a hybrid FSO/RF communication system. The performance of the system in the presence of atmospheric and physical obstructions was demonstrated through an experimental study of attenuation scenarios. By utilizing a hybrid transmission scheme, the availability and throughput of the system was improved. The threshold comparison method proved that switching at every instance of link loss may not be the optimal solution. Trend-reactive and trend-proactive hard-switching methods were able to smooth temporary drops, as well as determine the overall trend of link degradation. The reaction times of these algorithms expose the trade-off between system availability and throughput; the more reliable system often results in less achievable throughput.

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