Performance Optimization of Cooperative Decode-and-forward Relaying Hysteresis Switching-based Hybrid FSO/RF Transmission

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Abstract*— In this study, we present a hybrid free-space optics (FSO)/ radio-frequency (RF) system with low complexity and high performance, switching between FSO and RF links is enabled by time hysteresis (TH). The hybrid system transmits data through an FSO link when the instantaneous signal-to-noise ratio (SNR) at the FSO receiver end is higher than the predefined threshold SNR. The transmission switches over the RF link if the SNR drops below the predetermined threshold value. We took into consideration multi-input-multi-output (MIMO) transmitter and receiver approach to make sure the proposed model would provide improved spatial diversity. We added cooperative communication employing the decode-and-forward (DF) relaying approach to increase the effectiveness of long-distance transmission. For receiver reconstruction, the majority logic combining (MLC) algorithm has been used due to its simplicity and vigorous signal detection capabilities. The outcomes of the proposed model under various atmospheric turbulence (AT) regimes as well as pointing errors (PE) values with a generalized Malaga (M) distribution are validated using the Monte-Carlo simulation. Average symbol error rate (SER), bit error rate (BER), outage probability, secrecy rate, ergodic channel capacity, and link quality are key performance indices (KPI) used to analyse the effectiveness of the proposed system. According to the results, the suggested switching strategy for DF hybrid systems significantly improves performance when compared to single-hop (SH) scheme assisted hybrid systems, single RF as well as single FSO systems. In the region with lower SNR, the proposed system attains an average SER of 10^{-7}.

Index Terms*— Free space optics (FSO), Malaga (M) distribution, Decode and Forward (DF) relaying, Multi-input-multi-output (MIMO), Majority logic combining (MLC).

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I. INTRODUCTION

Despite the significant growth in the number of handheld smart devices, high-speed and affordable communication protocols are essential. The global issue of spectrum congestion is addressed via the employment of RF systems. FSO is one of the effective alternatives to use in order to solve this problem. Future demands of information transmission can potentially be addressed by line-of-sight (LoS) optical wireless high-bandwidth transmission networks. Modified light signals are a simple way to communicate data over the air: a narrow laser beam is released from the transmitter end, carried through the atmosphere, and then collected at the receiver end. Due to its exceptionally high carrier frequency (20–375 THz), FSO can deliver communication at the fastest data rates. License-free communication, simple installation, suppression of electromagnetic emission, and wiretapping security are further benefits of FSO transmissions [1]. Additionally, FSO communication addresses concerns like first/last mile connectivity, internet access in rural locations, and disaster recovery, among other aspects. In the future generation of high-speed wireless networks, FSO links can be employed in optical multi-input multi-output (MIMO) and point-to-point topologies [2]. However, FSO transmission performances deteriorate from air turbulence (AT), misalignment error, fog, smoke, and haze. So in order to ensure link availability in such circumstances, a backup RF link is necessary. The hybrid system transmits

information over FSO links on priority when at the FSO receiver end the received instantaneous signal-to-noise ratio (SNR) is greater than the predefined threshold SNR value. If it drops down the predefined threshold SNR value, the system switches over RF links through TH-switching.

The rapid development of the technology has been held earlier due to reliability and availability issues related to weather influenced attenuations like fog, snow and rain [3]. Fog is the most important attenuating element, as it causes a huge attenuation for an extended period of time [4]. As a result FSO link falls short of the carrier-grade availability target of 99.999 percent. To cope-up with the weather-affected reduced availability of the FSO link, an alternative method is to employ a backup RF link [5]. When the main link is not entirely functioning, the concept behind having a blended network is to make link availability in all adverse conditions. However, the availability analysis in the presence of weather influenced attenuations can be helpful for selecting the optimum hybrid FSO-RF system.

Both RF and FSO systems have significant propagation characteristics [6]. While RF transmissions have been observed to be unaffected by fog, the FSO link propagation is susceptible to disruption [7]. On the other hand, excessive rainfall hampers high-frequency RF propagation while having less of an effect on FSO communication [8–9]. Combining these two approaches can thus make it simpler to develop high-capacity and high-network availability systems [10–11]. In addition, as noted in [12], the use of relay selection algorithms for parallel-hybrid systems can enhance coverage over longer distances by using both buffered and non-buffered relays. Additionally, combining a parallel dual-hop FSO network with a dual-hop full duplex (FD) RF relaying network results in extremely effective spectral utilization, incredibly high reliability, and enhanced wireless range. Network topologies with parallel hybrid FSO/RF links and multi - hop communication nodes have been examined so far in the study [12]. In [13], a source(S)-destination (D) hybrid FSO/millimeter-wave RF link has been reported. Single and dual FSO threshold implementations are employed in Log-normal and Nakagami-m fading channels, respectively, with the hard switching technique. In reference [11], a hybrid FSO-RF network with hard switching is investigated, and the performance is evaluated in terms of outage probability and bit-error-rate (BER) with considering the effects of AT and pointing errors as well as Rician fading factors. Maximum-ratio-combining (MRC) at the destination and a cooperative DF relaying method with hybrid FSO/RF links have been studied in [8]. Additionally, [14] proposes a selection combining (SC)-based DF relaying for a hybrid FSO/RF-millimeter-waves system that incorporates for Weibull fading as well as the Malaga distribution. A backhaul network with relay nodes connected by parallel hybrid FSO/RF lines was studied in Reference [10] with the purpose of reducing costs while maintaining transmission rate and reliability. A backhaul network with parallel hybrid FSO/RF links between the relay nodes, as well as transmitter power and optical beam-width adjustments, are also employed to meet quality of service requirements, such as throughput and end-to-end delay constraints [15].

However, earlier studies did not address the cooperative relaying operation for FSO systems or MIMO spatial diversity in hybrid FSO/RF. A MIMO cooperative hybrid FSO/RF system with Time-Hysteresis (TH)-switching and a Majority-Logic-Combining (MLC) approach has been implemented to increase the high throughput.

II. PROPOSED METHODOLOGY OF BLENDED FSO/RF

In the proposed approach, we present a blended transmission of FSO/RF with switching. For a hybrid FSO-RF system to ensure continuous link availability under all connection circumstances, a quick changing mechanism incorporating both FSO and RF systems has been established. Time hysteresis (TH), which imposes a time delay before switching, is used to minimize transient fluctuations in the input signal. MLC's (Majority-Logic-Combining) algorithm is used in this work to integrate MIMO's spatial diversity. With the decode-and-forward method, this strategy employs cooperative relaying. Block model of the suggested design is presented in Figure 1.

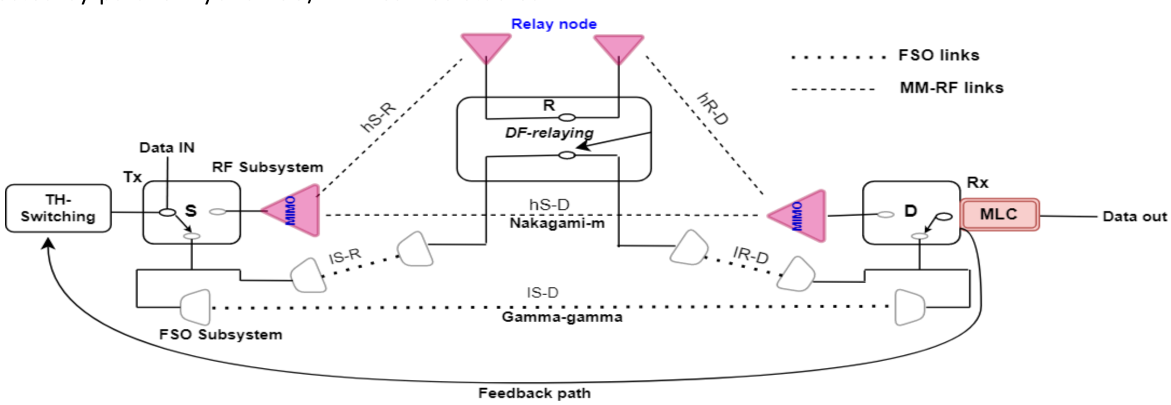
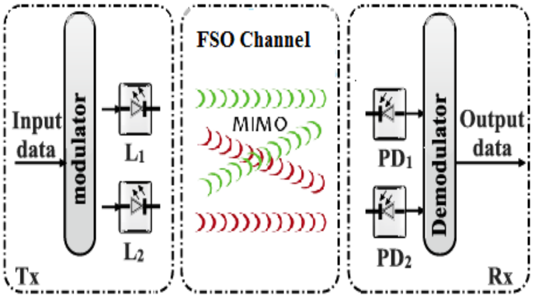


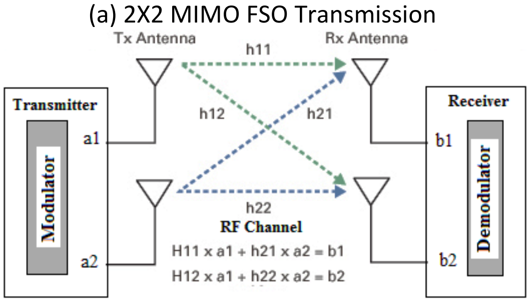
Fig.1. Block diagram of proposed Hybrid FSO/RF system model

A. *System Model*

Since no single wireless network can guarantee link availability at all times in all weather conditions. For the link to be accessible in all weather circumstances, a hybrid connection is required. The hybrid system is implemented using dual-hop cooperative transmission using the decode-and-forward (DF) approach when communication is established. We have taken into account the 2x2 MIMO antenna model in the proposed framework. In order to reconstruct the signal at the receiver end, we employ an MLC-based channel estimate approach. Malaga (M) distribution is used to model the FSO link, whereas additive white Gaussian noise (AWGN) is used to model the RF link.



(a) 2X2 MIMO FSO Transmission



(b) 2X2 MIMO RF Transmission

Fig.2. 2X2 MIMO Transmission model

The proposed design considers relaying system as multiple antenna sources, single antenna relay and multiple antenna destinations. The channel coefficients of source (S) to relay (R) node, relay (R) node to destination (D) for FSO and RF channel links are described as f_{sr}, f_{rd} and r_{sr}, r_{rd} respectively. Transmitter and receiver steps of FSO and RF link are depicted in Figure 2(a) and Figure 2(b) as 2X2 MIMO transmission, respectively. The source (S) information is transferred to the relay access point (R) and relay node act with decode-and-forward mechanism which forwards it to the destination (D) as shown in Figure (3).

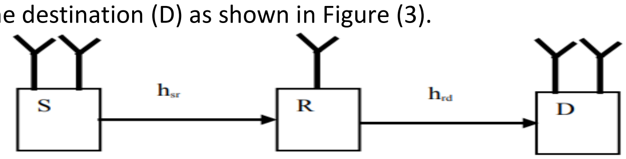


Fig.3. Dual hop (DH) MIMO

Let X be the transmitted signal of N symbols and modulated using BPSK in RF link and OOK in FSO link, defined as

$$M_r = \mathrm{bpsk}(X_i), i = 1,2, \dots\dots, N \quad (1)$$

$$M_f = \mathrm{ook}(X_i), i = 1,2, \dots\dots, N \quad (2)$$

The half-duplex method is used by the relay node R. Every broadcast timeframe is broken down into two slots. Source node S transfers data packets X to relay node R in slot 1. In slot 2, relay node R sends its decrypted character X to destination node D and Node D decodes the transmitted information. For each transmission, depends on the *M* transmit antennas, the beam-forming vector B is formed, hence the received signal at R is expressed as

$$Y_{SR} = h_{sr} * B_{sr} * M_i + G \quad (3)$$

where Y_{SR} is received signal at relay node R and h_{sr} is channel coefficient of S-to-R link, M_i (for FSO and RF) is transmitted signal as from equation (1) and equation (2) for RF and FSO link respectively, G is AWGN noise with unit mean and variance. The beam-forming vector is represented as

$$B_{sr} = \frac{h_{sr}}{||h_{sr}||} \quad (4)$$

For single RF and FSO link the received signals are expressed as

$$Y_{SRr} = r_{sr} * B_{sr}^{R} * M_r + G_{r1} \quad (5)$$

$$Y_{SRf} = f_{sr} * B_{sr}^{F} * M_f + G_{f1} \quad (6)$$

where, G_{r1} is additive white Gaussian noise (AWGN) of S-to-R for RF link and G_{f1} is FSO channel noise of S-to-R, B_{sr}^{R} is beam-forming vector of RF link and B_{sr}^{F} is beamforming vector of FSO link which are expressed as

$$B_{sr}^{R} = \frac{r_{sr}}{||r_{sr}||} \quad (7)$$

$$B_{sr}^{F} = \frac{f_{sr}}{||f_{sr}||} \quad (8)$$

Hence the incoming signal at the destination D is represented as 189

$$Y_{RDr} = r_{rd} * B_{rd}^{R} * R_r + G_{r2} \quad (9)$$

$$Y_{RDf} = f_{rd} * B_{rd}^{F} * R_f + G_{f2} \quad (10)$$

where, G_{r2} is AWGN noise of R-to-D for RF link and G_{f2} is FSO channel noise of R-to-D, r_{rd} and f_{rd} are the channel coefficients of R-D link for RF and FSO, respectively and R_r and R_f are the decoded-and-forwarded information signal from relay R node to D for RF and FSO, respectively. Hence the received signal (SNR) at D with P_t transmit power is measured as

$$\gamma_{DR} = \left\|r_{rd}^{T} B_{rd}^{R}\right\|^2 P_t \quad (11)$$

$$\gamma_{DF} = \left\|f_{rd}^{T} B_{rd}^{F}\right\|^2 P_t \quad (12)$$

B. Time Hysteresis based Switching Module

In order to prevent abrupt changes in the transmitted signals, time hysteresis (TH) switching has been incorporated to the time delay. TH switching is used to reduce rapid randomness of the message data, which could result in an undesirable high proportion of switching between FSO and RF routes, and vice versa. For this work, the minimal temporal increment is 5 seconds. The channel status information (CSI) data has already been sent via a feedback mechanism and is accessible at both the transmitter and receiver terminals without any error and delay. Based on circumstances, Figure 4 illustrates the flowchart for the proposed switching TH-switching algorithm.

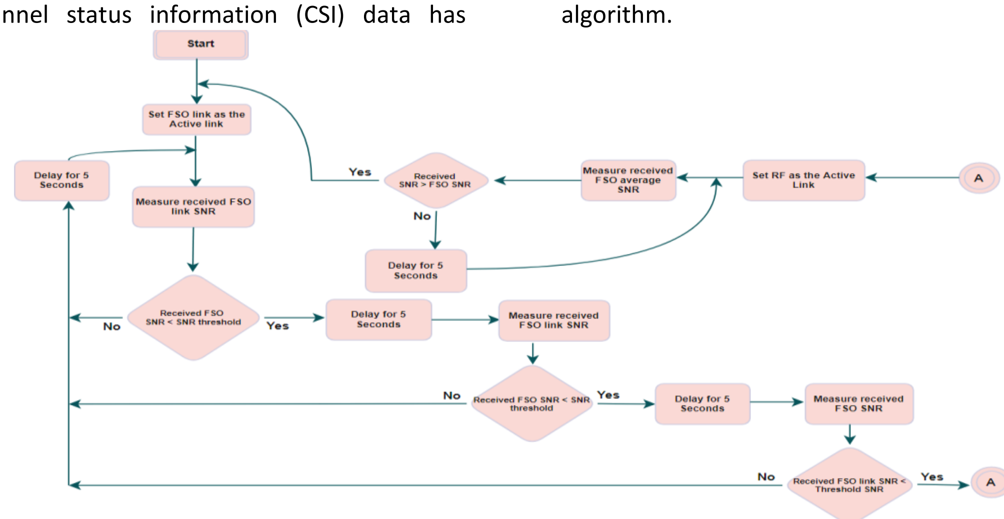


Fig.4. Flow chart of Time Hysteresis switching scheme

C. ***FSO Transmission***

For FSO transmission, On-Off keying (OOK) scheme has been used that has a balancing energy and spectrum performance in compare to other digital modulation schemes. The input symbols are modulated using OOK as ON for "1" bit and OFF for "0" bit. To convert the electrical signal of OOK to optical signal, upper and lower limit of power value for bit "1" and bit "0" bit, respectively has to be obtained as

$$P_u = \frac{2P_m}{1+\frac{1}{\xi}} \quad (13)$$

$$P_l = \frac{2P_m}{1+\xi} \quad (14)$$

$$\Delta_P = P_u - P_l \quad (15)$$

where, P_m is average optical output power, P_u is upper power limit of bit 1, P_l is lower power limit of bit 0, ξ is extinction ratio and Δ_P is power range of optical signal. From these measures, the converted optical signal is represented by reconstructing equation (2) as

$$M_f = \Delta_P * ook(X_i) + P_m \quad (16)$$

a) Channel Effects

FSO link performance is affected by fading because of turbulence and pointing errors as well as atmospheric attenuation factors such as fog, smoke, and haze.

Fog as well as smoke gives the most foremost cause of absorption of laser beam in FSO link transmission [16], as these are made up of microscopic particles hanging in the air. The fog attenuation (q) is estimated based on the channel's visibility V in km using Kim model [17] that represented as

$$q = \begin{cases} 1.6, & V > 50 \\ 1.3, & 6 < V < 50 \\ 1.6 * V + 0.34, & 1 < V < 6 \\ V - 0.5, & 0.5 < V < 0.1 \\ 0, & V < 0.1 \end{cases} \quad (17)$$

Light beam ψ is defined as [17]

$$\psi = -\frac{\ln 0.02}{V}\left(\frac{\lambda}{550}\right)^{-q} \quad (18)$$

Hence, the attenuation of fog is computed finally from equation (18) and with link distance of L (km) as,

$$H_{fog} = e^{-\psi L} \quad (19)$$

b) Turbulence

Turbulence is instigated by the existence of gradient temperature in laser light path and air displacement in vertical direction to the laser beam. It varies the refractive index which varies the beam fading intensity. Based on the intensity of fading level it is categorized as Weak, Moderate and Strong turbulence [18]. In this work we use generalized Malaga (M) distribution model to model the turbulence fading effect.
Malaga distribution models their radiance fluctuations of an unbounded optical wave in homogeneous, isotropic turbulence [19]. Three components additionally included in this distribution are LOS component U_L, quasi forward scattered component U_{SQ} and off-axis eddy scattered component U_{SO}. Hence, the Malaga distribution (M) based fading function is described as

$$S_{fad}^{M} = \left|U_L + U_{SQ} + U_{SO}\right|^2 \tag{20}$$

$$L_{fad}^{M} = e^{2\chi} \tag{21}$$

$$f_{Msr/Mrd} = S_{fad}^{M} L_{fad}^{M} \tag{22}$$

where,

$$U_L = \sqrt{G}\sqrt{\omega}e^{j\phi_A} \tag{23}$$

$$U_{SQ} = \sqrt{G}\sqrt{\rho 2T_0}e^{j\phi_B} \tag{24}$$

$$U_{SO} = \frac{\sqrt{(1-\rho)2T_0}}{\sqrt{2}\chi} \tag{25}$$

where, χ is log normal random distribution variable, $2T_0$ is average energy of total scattering components, ρ is scaling factor from 0 - 1 for representing the scattering power linked to LOS component, ω is mean power of LOS component, G is gamma distribution real variable, ϕ_A and ϕ_B are direct LOS phase and coupled to LOS scatter phase, correspondingly.

c) Pointing Errors

Pointing error (PE) or misalignment error is one of the responsible factor that affects the FSO link performance. The intensity variation (or oscillation) of the transmitted signal in the transverse plan is caused by pointing errors, which contributes to the link's transmission loss [20]. PE is expressed as Log-normal Rician model that is expressed as

$$S_{fad}^{PE} = \mathcal{N}(\mu_{xPE}, \sigma_{PE}) \tag{26}$$

$$L_{fad}^{PE} = \mathcal{N}(\mu_{yPE}, \sigma_{PE}) \tag{27}$$

$$F_a = \sqrt{(S_{fad}^{PE})^2 + (L_{fad}^{PE})^2} \tag{28}$$

$$f_{Psr/Prd} = G_0 e^{-\frac{2F_a^2}{W_B^2}} \tag{29}$$

where, μ_{xPE}, μ_{yPE} are horizontal and vertical displacements, respectively, σ_{PE} is pointing error jitter, $\mathcal{N}$ denotes the normal distribution, G_0 is geometric loss and W_B is equivalent beam width.

D. RF Transmission

BPSK modulation is applied on RF communication in S to R and R to D link. Channel gain matrix is modeled using AWGN with unity variance. Channel impulse response is generated using Gaussian random function and it expressed as

$$r_{sr}(2x1) = \begin{bmatrix} h11 \\ h21 \end{bmatrix} \tag{30}$$

$$r_{rd}(1x2) = \begin{bmatrix} h12 \\ h12 \end{bmatrix} \tag{31}$$

E. Majority Logic Combining

The MLC framework employs a comparison-based aggregating mechanism in the rational realm and therefore is considered as a technique for multiple recipients. Figure (5) shows the basic notion of MLC to observe the output bits at every node and combining the corresponding output bit.

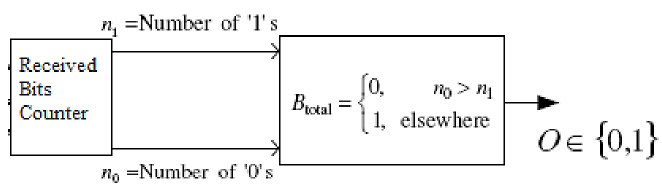


Fig.5. MLC based combining

III. RESULTS AND DISCUSSION

In the proposed implementation, the outcomes for proposed hybrid system are outperform the previous algorithms and design discussed in section I. In the performance analysis of proposed system we have considered in two situations - various turbulence regimes as well as different value of pointing errors (moderate and harsh).
The attributes configured for the simulation of proposed design is showed in Table I.

Table I. Simulation Attributes

Attributes	Specifications
MIMO	2x2

Optical Average Power	100mW
Extinction Ratio	20
Link Distance	500m
Fog/Smoke Visibility	1-50 km
Wavelength	1550 nm
Refractive Index (Strong Turbulence) (Weak Turbulence)	 $1x10^{-13}$ $1x10^{-16}$
Pointing Error σ_j	0.5, 1.5
Divergence Angle	10^{o}
Receiver Aperture Diameter	5mm
Angular FOV	1^{o}
Receiver aperture transmittance	90 %
Responsivity of photodiode	0.5 A/W
Trans-impedance amplifier gain	10 V/A
Noise equivalent power (NEP)	$1x10^{-12}$ W/sqrt (Hz)
Receiver load impedance	50 ohms
Time Delay threshold	5 seconds
Attenuation Threshold	5 dB
RF channel	AWGN distribution
FSO channel	Malaga (M) distribution

For two different pointing error (σ_j) values of 0.5 and 1.5 as well as constant values of RF SNR, we analyze the performance of BER, SER, Secrecy rate, Outage probability, Ergodic Capacity and Quality-factor for proposed hybrid system.

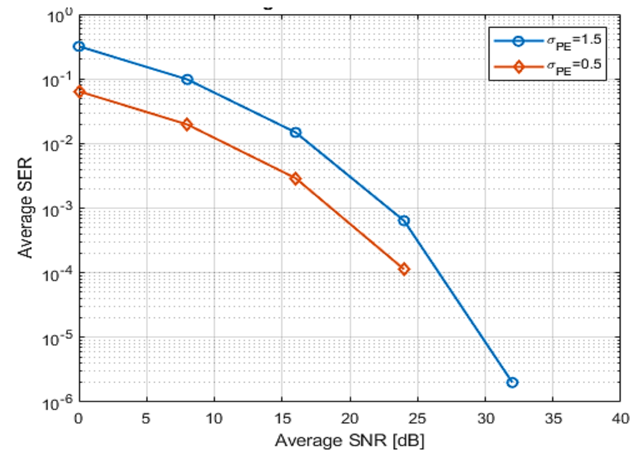


Fig. 6. Average SER Vs average SNR under different pointing errors

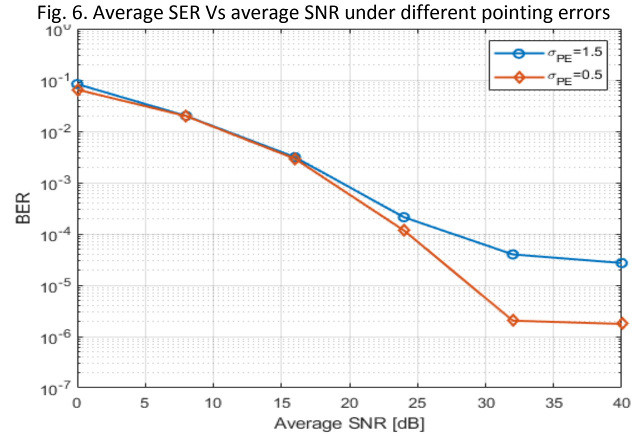


Fig. 7. BER Vs average SNR for different pointing error value

In Figure (6) and Figure (7), we illustrate the SER and BER curves for constant RF SNR value along-with two PE conditions. As FSO SNR increases the BER and SER both performing better and proposed system achieves upto 10^{-6} value for SER as well as BER. As from the graphical curves of above; as pointing error (σ_j) value increases the error performance of SER and BER getting decreases and vice-versa.

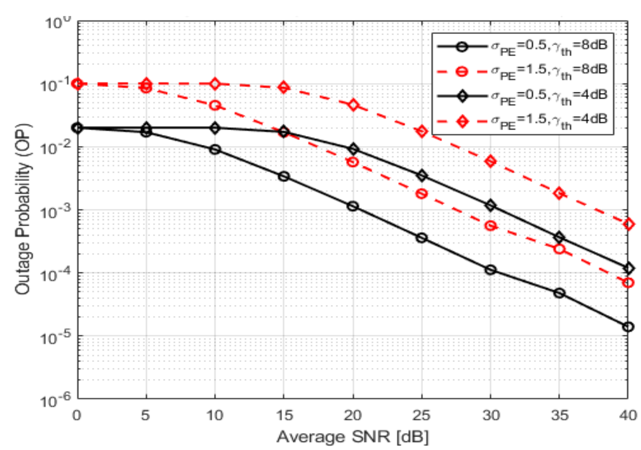


Fig. 8. Outage Probability Vs average SNR under different pointing errors

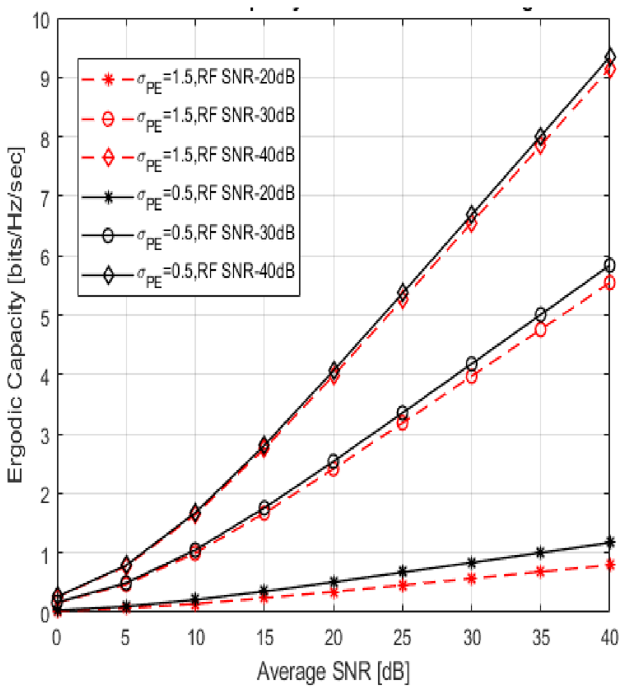


Fig. 9. Ergodic Capacity Vs average SNR under different pointing errors

Similarly, Figure (8) and Figure (9) show the outage-probability (OP) and ergodic-capacity of channel as a function of the average SNR of FSO link under different pointing error scenarios, respectively. The result as shown in Figure 8 is the outage-probability performance of hybrid FSO/RF system; proposed system achieves better OP performance upto 10^{-5} at PE of 0.5 and threshold SNR of 8dB.

Figure (10) and Figure (11) show the Secracy-rate Vs average SNR of FSO link and Quality-factor Vs FSO transmit power under different values of pointing error, respectively. As SNR is increasing, secrecy-rate reduced as BER. Quality-factor of proposed system is depicted in Figure 11 and it is observed that at lower value of PE link quality is better. There is approx 5% of quality performance gap between σ_j = 0.5 and σ_j = 1.5.

For the variation of transmit power we evaluate the performance and prove that as PE low as possible, we can get high quality in the system of flow.

Similarly, Figure 12 to Figure 17 show the performance of various KPI under difference scenario of atmospheric turbulence regimes-strong (C^2_n =1x10^{-13}) and weak (C^2_n =1x10^{-15}). From Figure (12) to Figure (17), it is observed that the impact of pointing error is greater than that in atmospheric-turbulence effect on proposed hybrid FSO/RF system.

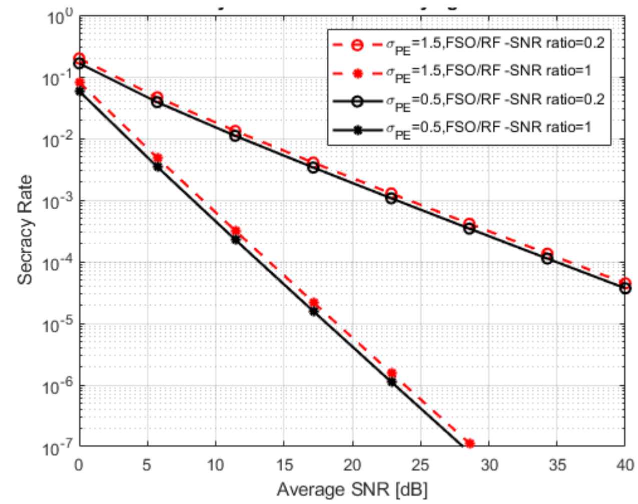


Fig. 10. Secrecy Rate Vs average SNR for different pointing errors

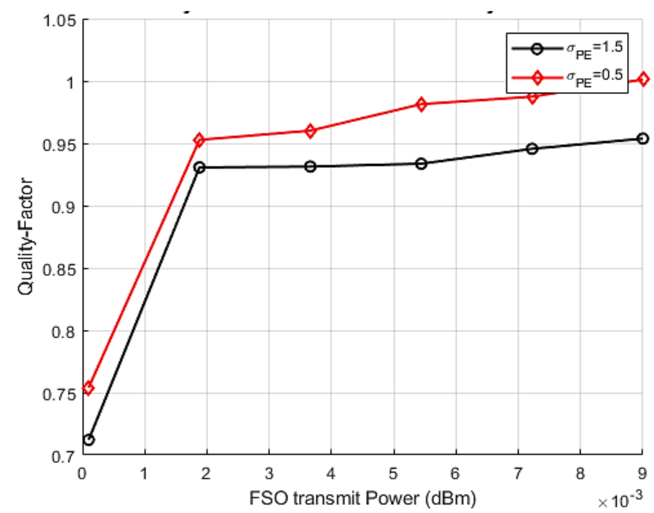


Fig. 11. Link Quality Vs Transmit Power under different pointing errors

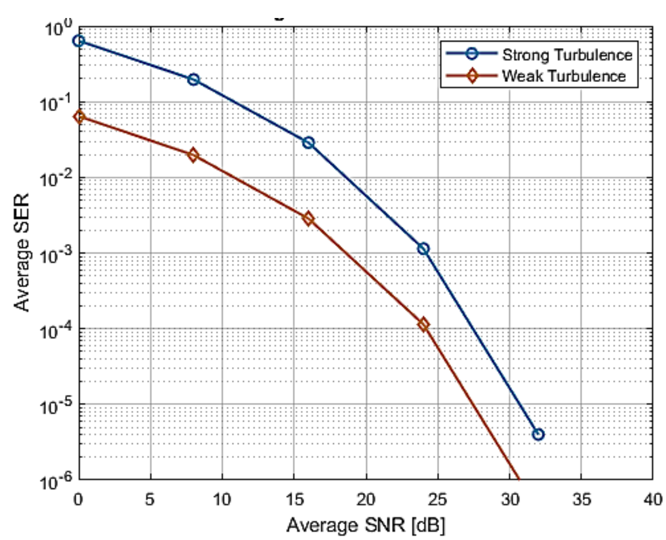


Fig. 12 ASER Vs average SNR under different turbulence regimes

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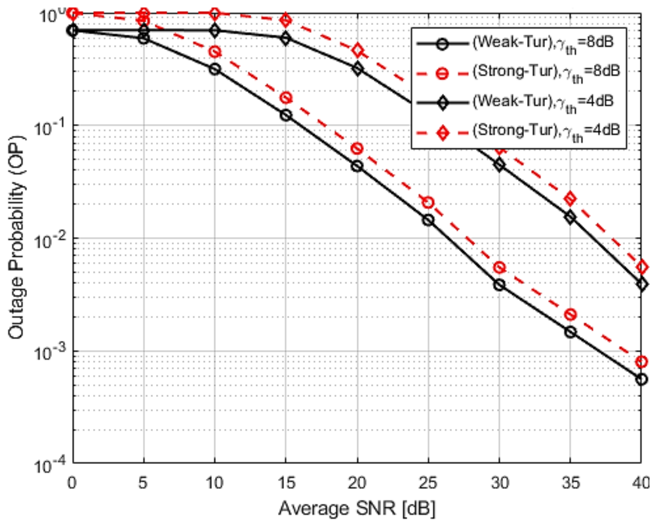

Fig.13. Outage Vs average SNR under different turbulence regimes

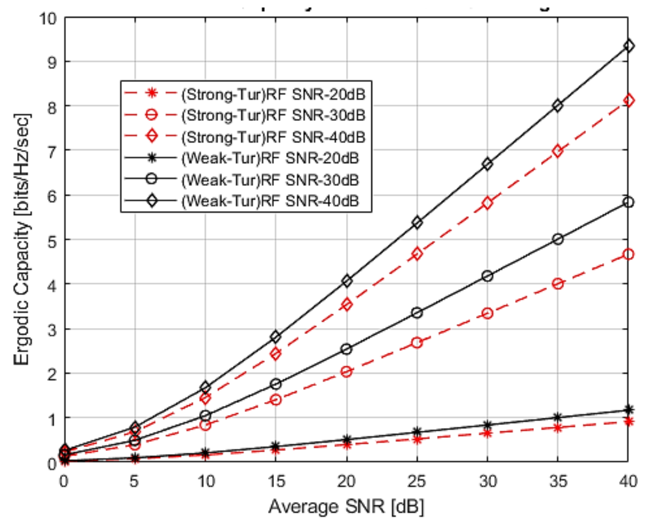

Fig.16. Channel Capacity Vs average SNR under different turbulence regimes`

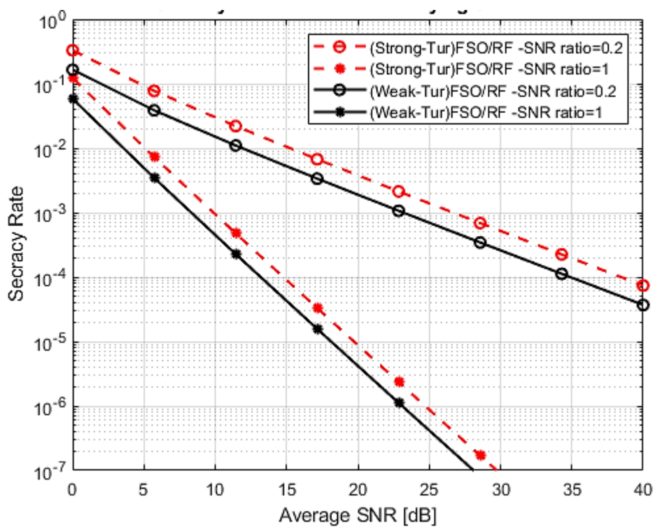

Fig.14. Secrecy Rate Vs average SNR under different turbulence regimes

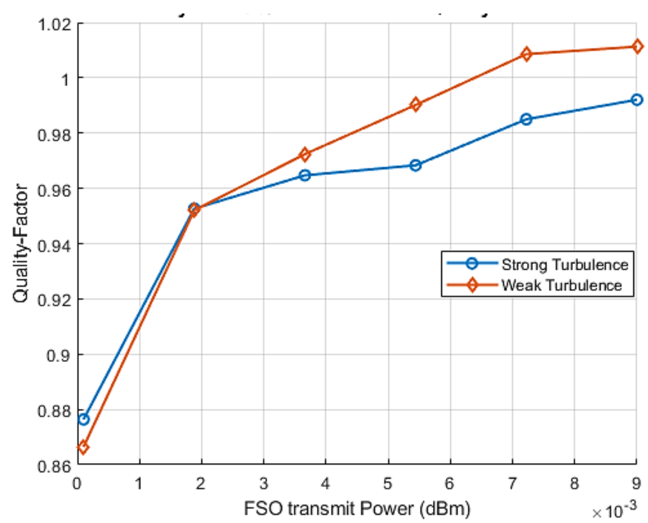

Fig.17. Link Quality Vs FSO transmit power

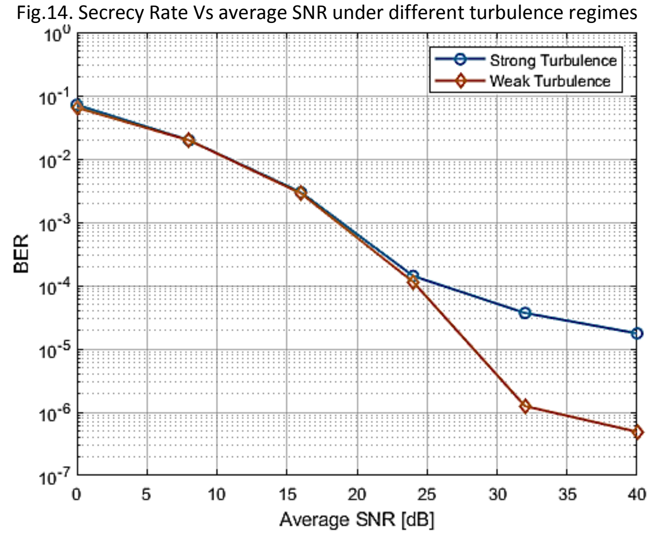

Fig.15. BER Vs average SNR under different turbulence regimes

IV. CONCLUSION

In the proposed study, an effective cooperative MIMO DF relaying hybrid FSO/RF system is modelled and analyzed. Hard switching to obtain high data rate with minimal complexity is made possible by time-hysteresis based switching. To examine the effectiveness of the proposed system under various turbulence regimes (strong-to-weak turbulence) and pointing errors (moderate-to-harsh), as well as to examine the impacts on FSO transmission performance, the generalized Malaga (M) distribution turbulence model is taken into consideration. Under various conditions, we evaluate the performance of the proposed MIMO-based DF relaying for the hybrid FSO/RF system. From the observations, it can be seen that SER performance outperforms that of the single-hop (SH) switching approach by a significant margin. The suggested design can achieve the best performance of link quality and SER for moderate

pointing error values. It has been found that the proposed hybrid FSO/RF system is more adversely influenced by pointing errors than by atmospheric turbulence.
To increase the data rate and facilitate quick computation, we can take into consideration the deep learning switching architecture in hybrid FSO/RF for future implementation.

V. ACKNOWLEDGMENT

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APPENDIX A: SER AND BER OF HYBRID FSO/RF SYSTEM

The proposed hybrid FSO/RF system with N symbols and $N_b$bits, SER and BER is evaluated as,

$$P_{SER} = \frac{1}{2}(P_{SER}^{RF} + P_{SER}^{F}) \qquad (A_1)$$

$$P_{SER}^{RF/FSO} = \frac{(T_s \neq R_s)}{N} \qquad (A_2)$$

$$P_{BER} = \frac{1}{2}(P_{BER}^{RF} + P_{BER}^{F}) \qquad (A_3)$$

$$P_{BER}^{RF/FSO} = \frac{(T_b \neq R_b)}{N_b} \qquad (A_4)$$

where, T_s is transmitted symbols, T_b is transmitted bits, R_s is received symbols and $R_b$is received bits.

APPENDIX B: OUTAGE PROBABILITY OF HYBRID FSO/RF SYSTEM

Outage probability of the proposed hybrid FSO/RF system is defined by the received SNR less than predefined threshold. When the received SNR of FSO after the MLC combining is greater than predefined threshold, then it is switching to the RF link and vice versa for RF link [21]. The outage probability is described from the CDF computation of both RF and FSO links as below,

$$P_o = O_{\Upsilon}^{F} O_{\Upsilon}^{R} \qquad (B_1)$$

where, O_{Υ}^{F} is outage CDF of FSO with MLC transmission and O_{Υ}^{R} is Outage CDF of RF with MLC transmission and are given by,

$$O_{\Upsilon}^{R} = \frac{\Psi_x^{m_x} \Upsilon_{m_x-1}^{r}}{\Gamma(m_x)} e^{-\Psi_x \Upsilon^{r}} \qquad (B_2)$$

$$\Psi_x^{m_x} = m_x(\overline{\Upsilon_x^r})^{-1} \qquad (B_3)$$

The received SNR of RF Υ_x^r is given as,

$$\Upsilon_x^r = \overline{\Upsilon_x^r} |r_{rd}|^2 \qquad (B_4)$$

The average SNR of RF,

$$\overline{\Upsilon_x^r} = \frac{P_x C_{gx}^r}{\sigma_{rx}^2} * \frac{E_s}{2} \qquad (B_5)$$

where, $\Gamma(.)$ is gamma integral function, r_{rd} is RF channel coefficient with m-fading severity, P_x is transmit power, E_s is energy of shaping pulse, σ_{rx}^2 is noise variance of RF transmission, $x \epsilon (SR, RD)$ and C_{gx}^r is RF channel gain. It is derived as,

$$C_{gx}^r = C_t + C_r - 20 \log_{10} \frac{4\pi L}{\lambda} - (\alpha_o + \alpha_r)L \qquad (B_6)$$

where, C_t, C_r are the transmit and receive antenna gain respectively, λ is wavelength, L is link distance and α_o, α_r are the attenuation coefficients due to oxygen and rain atmosphere respectively.

$$O_{\Upsilon}^{F} = T^x (\Upsilon_x^f)^{-1} M_{0,2}^{2,0} \left(S_{fad} L_{fad} \sqrt{\Upsilon^f \left(\Upsilon_x^f\right)^{-1}} \middle| \overline{Z^x} \right) \qquad (B_7)$$

$$T^x = \frac{1}{2\Gamma(S_{fad})\Gamma(L_{fad})} \qquad (B_8)$$

$$\overline{Z^x} = \frac{\sum_{i=1}^{x} [S_{i,fad}, L_{i,fad}]}{x} \qquad (B_9)$$

The received SNR of FSO Υ_x^f is derived as,

$$\Upsilon_x^f = \overline{\Upsilon_x^f} |f_{rd}|^2 \qquad (B_{10})$$

The average SNR of FSO,

$$\overline{\Upsilon_x^f} = \frac{P_x^2 \eta^2}{\sigma_{fx}^2} * \frac{E_s (C_{gx}^f)^2}{2} \qquad (B_{11})$$

where, $M_{p.q}^{i,j}(.)$ is Meijer G-function, f_{rd} is FSO channel coefficient, η is optical to electrical conversion coefficient.
The term C_{gx}^f is channel gain of FSO is defined as,

$$C_{gx}^f = e^{-(S_{fad} + L_{fad})L} \qquad (B_{12})$$

APPENDIX C: SECRECY RATE OF HYBRID FSO/RF SYSTEM

To consider the system with highly security, it has to be attaining the high secrecy rate [22]. It is defined as with predefined achievable rate of $R_S$and satisfying the secrecy rate of $S_r > R_s$, which is described as,

$$S_r = \log_2(1 + \gamma_A) \qquad (C_1)$$

The term γ_A is overall SNR of hybrid FSO/ RF system and is given by,

$$\gamma_A = \min(\Upsilon_x^f, \Upsilon_x^r) \qquad (C_2)$$

APPENDIX D: ERGODIC CAPACITYOF HYBRID FSO SYSTEM

Ergodic Capacity is the topmost value of capacity of the hybrid FSO/RF system and also named as upper bound of the capacity [23]. For cooperative system it is averaged to obtain the overall capacity as below,

$$C_E = C_o + (C_1 + C_o)P_{BER} \qquad (D_1)$$

where C_o is capacity of bits correctly received is given by,

$$C_o = \frac{B}{2\log 2}\log_2(1+\gamma_o) \qquad (D_2)$$

The term C_1 is capacity of bits erroneously received is given by,

$$C_1 = \frac{B}{2\log 2}\log_2(1+\gamma_1) \qquad (D_3)$$

The received SNR of correct bits and inaccurate bits are described by,

$$\gamma_o = \frac{\gamma}{2}(H_{SD}+2H_{RD})^2 \qquad (D_4)$$

$$\gamma_1 = \frac{\gamma}{2}(H_{SD}-2H_{RD})^2 \qquad (D_5)$$

where, $H_{SD} = f_{SD} + r_{SD}$ and $H_{RD} = f_{RD} + r_{RD}$ and B is bandwidth of the transmitted signal.

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