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RESEARCH ARTICLE

A novel multi-quality of service system design: Integration of hybrid free space optical/RF, cognitive hybrid and free space optical links

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Abstract

The proposed system design presents a novel configuration that is created by the integration of several standalone free space optical (FSO) links, a hybrid FSO/RF and some cognitive or pseudo hybrid links. The objective is to allow different quality-of-service (QoS) links within a system as a whole. In addition to individual QoS requirements, a constraint on the overall system QoS, in the form of minimum system outage, is also ensured. The design methodology aims at identifying the optimal number of standalone FSOs and cognitive hybrid links which can be supported by a single hybrid FSO/RF link. Atmospheric turbulence and pointing errors are considered for the analysis. Simulation results are used to corroborate the analytical findings.

KEYWORDS

hybrid FSO/RF, interweaved cognitive radio, resource utilization, shared-RF

Abbreviations: CDF, cumulative density function; FSO, free space optical; GG, gamma–gamma; PDF, probability density function; QoS, quality of service; RF, radio frequency

1 | INTRODUCTION

The vulnerability of optical signals to inherent channel degradations caused by atmospheric turbulence,[1,2] weather phenomenon as well as pointing error[3] between optical transreceivers hamper the carrier-class 99.999% availability. A suitable and practical approach for extending the link availability of free space optical (FSO) involve use of an RF link as a backup and such systems are commonly known as hybrid FSO/RF systems.[4,5] Some works have attempted to share a RF link among several FSOs in order to improve link availability of FSOs without deploying additional RF resources. Rakia et al.[6] presented a hard-switched point to multipoint system, wherein several remote users are connected to a central node via individual FSO links. A single RF resource, available at the central node, serves as a backup for any failing FSO link. All remote nodes have equal priority for using this backup RF; thus, they have identical link availability or Quality-of-Service (QoS). In Reference 7, shared-RF and on-demand architectures are proposed, which enable FSO links to share the RF resource associated with a hybrid FSO/RF link. The link outage of the FSOs is shown to improve as a result of this sharing. Cognitive radio principles offer a popular approach for implementing RF resource sharing.[8,9] In Reference 10, users of a secondary cognitive multicast network share the spectrum of a primary multicast network, with a limitation on the number of secondary users that may be supported for a given secondary transmission failure target. The authors of Reference 11 have implemented interweave cognitive radio and studied different data traffic conditions to reveal the existence of "FSO dependent" and "traffic dependent" temporal holes in the RF spectrum of a hybrid FSO/RF link. When data transmission in a hard switched hybrid link takes place via the FSO link, the RF spectrum remains idle, resulting in "temporal holes." Utilization of these temporal holes by solitary FSOs for backup purposes results in formation of cognitive hybrid FSO/RF link, which significantly improves link availability of the solitary FSOs. All such FSOs, which are permitted to operate as cognitive hybrid links are required to be equipped with energy sensing mechanism whereas the remaining FSOs need not be. The cognitive hybrid's link availability is known to be intermediary between that of a hybrid link and solitary FSO. Thus, the integration of all these three types of links, can offer users different link availabilities within a system. To the best of authors knowledge, the problem of designing such a multi-QoS system (multilink availability) using a combination of hybrid FSO/RF, cognitive or pseudo hybrid and solitary FSOs together with the dimensioning aspect have not been addressed in the existing literatures.

In this work, we propose a multi-QoS system and a novel flexible design methodology, which can support three different link availabilities or QoS within a system. The proposed system has a distributed architecture and comprises of (i) one hybrid FSO/RF offering the highest QoS, (ii) some cognitive or pseudo hybrid links for intermediate QoS fitted with energy detectors, and (iii) some solitary FSOs for the lowest QoS without energy detectors for reduced system complexity. The dimensioning of such a system is also addressed.

2 | PROPOSED SYSTEM MODEL AND DESIGN METHODOLOGY

2.1 | System model

The proposed system model shown in Figure 1C is obtained from an initial seed system model comprising of a set of N solitary FSO links as shown in Figure 1A. A prerequisite of this system model and the design methodology requires the initial seed system to be located in the RF footprint of a hybrid FSO/RF (FSO_H/RF_H) link. In order to form the multi-QoS system, N^* solitary FSOs, out of the total N FSOs, are permitted to operate as cognitive hybrid links subject to a given average system outage probability constraint. The final system size is denoted by (N, N^*). Thus, the proposed multi-QoS system as shown in Figure 1C consists of one hybrid FSO/RF link, N^* cognitive hybrid links and $N - N^*$ solitary FSO links. The proposed design methodology aims at obtaining the value of N^*.

Let S_o^H and S_r^H denote the instantaneous optical and RF SNRs of FSO_H and RF_H respectively. Predefined optical and RF thresholds are denoted by ϕ_o and ϕ_r respectively. Data transmission is hard switched from FSO_H to RF_H when $S_o^H < \phi_o$ provided $S_r^H \geq \phi_r$. If both $S_o^H < \phi_o$ and $S_r^H < \phi_r$, then the hybrid link is said to be in outage.[3] For all the times when $S_o^H > \phi_o$, data is transmitted via the FSO link and the RF spectrum remains idle. These idle periods of RF_H have been termed as "FSO dependent temporal holes"[11] and are shown in Figure 1B. Thus, the usage of RF_H in the hybrid link depends on FSO_H channel conditions.

Let FSO_i and CH_i denote the i^{th} solitary FSO and cognitive hybrid links respectively. When the instantaneous SNR (S_o^i) of any FSO_i, $i \in 1, \ldots, N$, falls below ϕ_o, the FSO_i has a tendency to go into outage. However, the solitary FSO_i can use the FSO dependent temporal holes of RF_H in an interweave manner to form a cognitive hybrid FSO/RF link, CH_i, to enhance its link availability. The RF spectrum utilization is depicted in Figure 1B. These FSO_i are considered to be equipped with energy detectors for the purpose of detecting temporal holes. By virtue of the inherent nature of hybrid FSO/RF systems, FSO_H has priority over the spectrum of RF_H and does not engage in energy sensing. In terms of cognitive radio terminology, RF_H is the primary user. The N^* CH_i are the secondary users, and are identical with equal priority for using the FSO dependent temporal

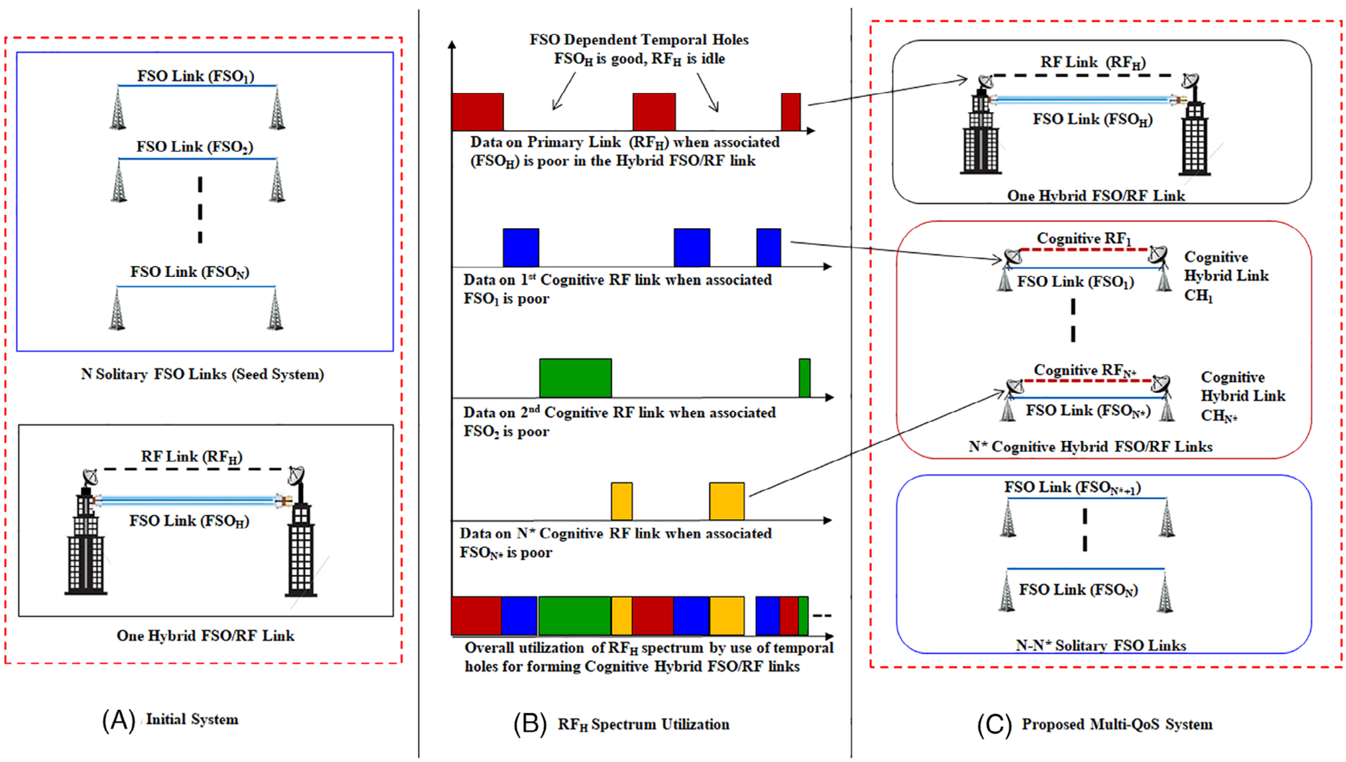

FIGURE 1 Proposed system model [Color figure can be viewed at wileyonlinelibrary.com]

holes of RF_H. These secondary users vie for the temporal holes in RF_H, thus, the important system design issue is to find out the number of such secondary users, which can be supported by RF_H. Thus, one of the major goals of this paper is to obtain the number of CH_i that can be supported by RF_H, while maintaining a desired overall average system link availability.

2.2 | Design methodology

Let $Out_{N,fso}^{avg}$ denote average system outage for the seed system of N solitary FSOs and $Out_{N,n}^{avg}$ represent average system outage of the multi-QoS system in which n of the N solitary FSOs are allowed to operate as cognitive hybrid links. In this methodology, the N^* cognitive hybrid links are carved out of the seed system of N FSOs, thus, it is desired that the multi-QoS system should have a better or lower system outage over the seed system. In this respect, let $\mathcal{T}$ be the minimum desired improvement in average system outage of the multi-QoS system over the seed system, that is,

$$\frac{Out_{N,fso}^{avg} - Out_{N,n}^{avg}}{Out_{N,fso}^{avg}} \times 100 \geq \mathcal{T}\%. \tag{1}$$

The value of n, which satisfies Equation (1) gives the value of N^*, that is, the number of cognitive hybrid links which can be accommodated in the final multi-QoS system for a minimum desired improvement in average system outage. The remaining FSOs, that is, $N - N^*$ function as solitary FSOs. A design paradigm is proposed to obtain the value of N^* as defined above. The paradigm is based on the philosophy to allow "n" numbers of solitary FSOs to operate as cognitive hybrid links and compute the average system outage for an incrementing value of "n." The algorithm is terminated at the iteration when condition of (Equation (1)) is satisfied. The closed form expressions of the outage terms used at each iteration of the algorithm have been derived in Section 3 on Mathematical Analysis.

Step 1: Initially we calculate average outage for the seed system of N FSOs.

$$Out_{N,fso}^{avg} = \left(P_{out}^{FSO_1} + P_{out}^{FSO_2} + \ldots + P_{out}^{FSO_N}\right)/N,$$

where $P_{out}^{FSO_i}$ represents the outage of the i^{th} solitary FSO link, that is, FSO_i. Closed form expression of $P_{out}^{FSO_i}$ is given in Equation (5).

Step 2: Assuming that "n" FSOs have converted to cognitive hybrid links by using RF_H in interweave mode so that the intermediate system shall comprise of one hybrid FSO/RF link, $N - n$ solitary FSOs and n cognitive hybrid links. Here, $0 < n \leq N$, and n is an incremental counter determining the number of FSO_i converting to CH_i at each subsequent step. The average system outage of this intermediate system is defined as.

$Out_{N,n}^{avg} = \Big(P_{out}^{hyb} + P_{out,N}^{CH_1} + \ldots + P_{out,N}^{CH_n} + \ldots + P_{out}^{FSO_{n+1}} + \ldots + P_{out}^{FSO_N}\Big)/(N+1)$. Here P_{out}^{hyb} and $P_{out,N}^{CH_i}$ are outages of the hybrid and cognitive hybrid links respectively. The closed form expressions are given by Equations (6) and (12), respectively.

Step 3: Calculate $Out_{N,n}^{avg}$ when only any one of FSO_i, say, FSO_1 is converted to cognitive hybrid link $(n=1)$ in the intermediate system; thus,

$$Out_{N,1}^{avg} = \left(P_{out}^{hyb} + P_{out,N}^{CH_1} + P_{out}^{FSO_2} + P_{out}^{FSO_3} + \ldots + P_{out}^{FSO_N}\right) /(N+1).$$

Step 4: Repeat until all FSO_i, that is, FSO_1, $FSO_2 \ldots FSO_N$ are converted to cognitive hybrid links $(n=N)$:

$$Out_{N,N}^{avg} = \left(P_{out}^{hyb} + P_{out,N}^{CH_1} + P_{out,N}^{CH_2} + P_{out,N}^{CH_3} + \ldots + P_{out,N}^{CH_N}\right) /(N+1).$$

Step 5: Using the values of $Out_{N,fso}^{avg}$ from step 1 and $Out_{N,0}^{avg}, Out_{N,1}^{avg}, \ldots, Out_{N,N}^{avg}$ from steps 2–4, check, which values of $Out_{N,n}^{avg}$ satisfy the condition given in Equation (1).

Step 6: Assign the value of n which satisfies the condition in Equation (1) to N^*.

By this methodology, for a desired $Out_{N,n}^{avg}$ or equivalently $\mathcal{T}\%$ improvement in average system outage over the all-FSO system (seed system), all possible combinations of N,n which fulfill the desired $Out_{N,n}^{avg}$ are identified for different optical channel conditions at fixed $\overline{S}_o$ (Table 1). The above steps can be performed for any seed system of size N. It may be noted that any N^* number of FSOs out of N FSOs may be converted to cognitive hybrid links without violating the constraint on $Out_{N,n}^{avg}$. In this analysis, we have assumed an ideal situation of no-contention between FSOs vying to use the temporal holes.

3 | MATHEMATICAL ANALYSIS

The optical and RF channels in proposed system are modeled by gamma–gamma (GG) and Nakagami-m distribution respectively.

- Optical channel: When an optical signal propagates through turbulent channel, it gives rise to fluctuations in the received signal. For the GG channel, the strength of turbulence is expressed in terms of small and large scale eddies (α,β) or refractive index structure parameter $\left(C^2{}_n\right)$.[1,2] Using the pdf of intensity fluctuations for GG channel,[2,11] cumulative density functions (CDF) expressed in terms of instantaneous SNR, S_o and S_r, are given below. The symbols represent their usual meaning as in Reference 11, is given as:

i. Turbulence only, no misalignment error:

$$F_{S_o}(\phi_o)=\frac{1}{\Gamma(\alpha)\Gamma(\beta)}G_{1,3}^{2,1}\left(\alpha\beta\sqrt{\frac{\phi_o}{\overline{S}_o}}\middle|_{\alpha,\beta,0}^{1}\right). \quad (2)$$

Combined effect of turbulence and misalignment: Apart from turbulence, misalignment in the line of sight between the transmitter and receiver or pointing error occurs due to building sways, mechanical vibrations, minor earthquakes, and so on.[3] The CDF expressing their combined effect[11]

$$\begin{aligned}F_{S_o}(\phi_o)\ &=\frac{2^{\alpha+\beta-3}\zeta^2}{\pi\Gamma(\alpha)\Gamma(\beta)}\\ &\times G_{3,7}^{6,1}\left(\left(\frac{\alpha\beta}{4}\frac{\zeta^2}{\zeta^2+1}\right)^2\frac{\phi_o}{\overline{S}_o}\middle|_{\frac{\zeta^2}{2},\frac{\zeta^2+1}{2},\frac{\alpha}{2},\frac{\alpha+1}{2},\frac{\beta}{2},\frac{\beta+1}{2},0}^{1,\frac{\zeta^2+1}{2},\frac{\zeta^2+2}{2}}\right).\end{aligned} \quad (3)$$

- RF channel: Fading in the RF channel is governed by parameter "m" and the Nakagami-m CDF is

$$F_{S_r}(\phi_r)=\frac{\gamma\left(m,\frac{m}{\overline{S}_r}\phi_r\right)}{\Gamma(m)}. \quad (4)$$

3.1 | Outage analysis of proposed multi-QoS system

The overall system outage in the paradigm involves computation of three types of outages: $P_{out}^{FSO_i}, P_{out}^{hyb}$ and $P_{out,N}^{CH_i}$. For ease of understanding and representation, we derive and present the closed form expressions for these outages by considering a seed system of $N=3$. The calculation can be extended for any N. Following the design methodology, we have FSO_1, FSO_2 and FSO_3 as the three solitary FSOs and one hybrid FSO/RF link. Here, hard switching is assumed for hybrid and cognitive hybrid links.

- Outage of solitary FSO $\left(P_{out}^{FSO_i}\right)$: Any solitary FSO_i link shall go into outage when the instantaneous SNR S_o^i falls below the optical threshold ϕ_o,[12] thus,

$$P_{out}^{FSOi}=Prob\left(S_o^i<\phi_o\right)=\int_0^{\phi_o}f_{S_o^i}\left(S_o^i\right)dS_o^i=F_{S_o^i}(\phi_o)\,. \quad (5)$$

- Hybrid FSO/RF outage probability $\left(P_{out}^{hyb}\right)$: The hard switched hybrid FSO/RF system goes into outage when the instantaneous SNRs of FSO_H and RF_H fall below the respective thresholds, that is, $S_o^H<\phi_o$ and $S_r^H<\phi_r$.[12] Thus,

$$\begin{aligned}P_{out}^{hyb}&=Prob\left(S_o^H<\phi_o\right)\times Prob\left(S_r^H<\phi_r\right)\\ &=\int_0^{\phi_o}f_{S_o^H}\left(S_o^H\right)dS_o^H\times\int_0^{\phi_r}f_{S_r^H}\left(S_r^H\right)dS_r^H\\ &=F_{S_o^H}(\phi_o)F_{S_r^H}(\phi_r)\end{aligned} \quad (6)$$

Further, in the Hybrid FSO/RF link, RF_H is utilized by FSO_H as a backup when $S_o^H<\phi_o$ and $S_r^H\geq\phi_r$. "RF utilization factor" is used to define the usage probability of RF link by a FSO link. Thus, for the hybrid FSO/RF link, the RF utilization factor, PU can be computed as:

$$\begin{aligned}PU&=\int_0^{\phi_o}f_{S_o^H}\left(S_o^H\right)dS_o^H\int_{\phi_r}^{\infty}f_{S_r^H}\left(S_r^H\right)dS_r\\ &=F_{S_o^H}(\phi_o)\left(1-F_{S_r^H}(\phi_r)\right).\end{aligned} \quad (7)$$

It can be seen from Equation (7) that the spectrum of RF_H is available, that is, a temporal hole exists for use by the solitary FSO_i for $(1-PU)$ units. These temporal holes are identified by a nonideal detector with probability of detection of primary signal (p_d) and probability of false alarm (p_f). False alarm arises when the energy detector erroneously indicates the presence of primary signal when there is none, thus, probability of correct identification of primary signal's absence or alternately the presence of temporal holes is given by $1-p_f$. The RF^H utilization by any $FSO_i(i=1,2,3)$ now depends on the primary RF utilization PU, and it is utilization by the remaining $FSO_j^{'s}$, $j\neq i$. Let SU_N^i, denotes the RF utilization by FSO_i where N is the size of the seed system. The RF link shall be available for use by FSO_i for periods when it is not used by $FSO_j, j\neq i$, that is, $\left(1-PU-\sum_{j\neq i}^{N}SU_N^j\right)$. Thus, $SU_N^i=Pr\left(S_o^i<\phi_o\right).Pr\left(S_r^i\geq\phi_r\right)\left(1-PU-\sum_{j\neq i}^{N}SU_N^j\right)\left(1-p_f\right)$. Hence,

$$SU_3^1=F_{S_o^1}(\phi_o)\left(1-PU-SU_3^2-SU_3^3\right)\left(1-p_f\right)\left(1-F_{S_r^1}(\phi_r)\right). \quad (8)$$

Since all FSO_i are identical and independent in nature, the expressions for SU_3^2 and SU_3^3 can be written as:

$$\begin{aligned}SU_3^2&=F_{S_o^2}(\phi_o)\left(1-PU-SU_3^1-SU_3^3\right)\left(1-p_f\right)\left(1-F_{S_r^2}(\phi_r)\right),\\ SU_3^3&=F_{S_o^3}(\phi_o)\left(1-PU-SU_3^1-SU_3^2\right)\left(1-p_f\right)\left(1-F_{S_r^3}(\phi_r)\right).\end{aligned} \quad (9)$$

Denoting $k_1=F_{S_o^1}(\phi_o)\left(1-p_f\right)\left(1-F_{S_r^1}(\phi_r)\right), k_2=F_{S_o^2}(\phi_o)\left(1-p_f\right)\left(1-F_{S_r^2}(\phi_r)\right)$ and $k_3=F_{S_o^3}(\phi_o)\left(1-p_f\right)\left(1-F_{S_r^3}(\phi_r)\right)$,

Equations (8) and (9) are rewritten in matrix form as:

$$\begin{bmatrix}1 & k_1 & k_1\\ k_2 & 1 & k_2\\ k_3 & k_3 & 1\end{bmatrix}\begin{bmatrix}SU_3^1\\ SU_3^2\\ SU_3^3\end{bmatrix}=\begin{bmatrix}k_1(1-PU)\\ k_2(1-PU)\\ k_3(1-PU)\end{bmatrix}. \quad (10)$$

Solving the above equations results in the following closed form expressions for SU_3^1, SU_3^2, and SU_3^3:

$$SU_3^1 = \frac{(1-PU)[k_1(k_2k_3-1)+k_1k_2(1-k_3)+k_1k_3(1-k_2)]}{k_1k_2+k_1k_3+k_2k_3-2k_1k_2k_3-1},$$
$$SU_3^2 = \frac{(1-PU)[k_2(k_1k_3-1)+k_1k_2(1-k_3)+k_2k_3(1-k_1)]}{k_1k_2+k_1k_3+k_2k_3-2k_1k_2k_3-1},$$
$$SU_3^3 = \frac{(1-PU)[k_3(k_1k_2-1)+k_1k_3(1-k_2)+k_2k_3(1-k_1)]}{k_1k_2+k_1k_3+k_2k_3-2k_1k_2k_3-1}. \quad (11)$$

- Outage probability of cognitive hybrid link: It is possible for any, FSO_i (e.g., FSO_1), which forms a cognitive hybrid link to still go in outage. This is largely dependent on the interpretation of RF_H status by the energy detector as follows:
- Status of RF_H correctly identified as busy with probability p_d shall result in outage P_1:

$$P_1 = F_{S_o^1}(\phi_o)p_d\left(PU+SU_3^2+SU_3^3\right).$$

Here, FSO_1 is degraded with probability $F_{S_o^1}(\phi_o)$ and it wishes to use the RF spectrum. The RF spectrum may be in use by FSO^H, FSO_2 or FSO_3 with utilization factors PU, SU_3^2 and SU_3^3 respectively. Thus, FSO_1 is unable to use the RF spectrum, resulting in link outage.

- The energy detector suffers from false alarm, thus, the free RF_H is not utilized by FSO_1, hence outage P_2:

$$P_2 = F_{S_o^1}(\phi_o)p_f\left(1-PU-SU_3^2-SU_3^3\right).$$

- The energy detector misses RF_H transmission, and RF_H is incorrectly declared as free, but the quality of the RF spectrum is deemed to be poor: Thus, outage P_3 :

$$P_3 = F_{S_o^1}(\phi_o)(1-p_d)\left(1-PU-SU_3^2-SU_3^3\right)F_{S_r^1}(\phi_r).$$

- The RF_H is free and correctly interpreted as "temporal hole" by the energy detector, however, the quality of RF channel is poor to serve as a backup for FSO_i, hence outage P_4:

$$P_4 = F_{S_o^1}(\phi_o)\left(PU+SU_3^2+SU_3^3\right)\left(1-p_f\right)F_{S_r^1}(\phi_r).$$

The link outage for any cognitive hybrid link, here $\left(P_{out,3}^{CH_i}\right)$ for CH_1, is obtained by considering all the above cases and is given by Equation (12).

$$\begin{aligned}P_{out,3}^{CH_1} &= P_1+P_2+P_3+P_4\\ &= F_{S_o^1}(\phi_o)p_d\left(PU+SU_3^2+SU_3^3\right)+F_{S_o^1}(\phi_o)p_f\left(1-PU-SU_3^2-SU_3^3\right)\\ &\quad +F_{S_o^1}(\phi_o)(1-p_d)\left(1-PU-SU_3^2-SU_3^3\right)F_{S_r^1}(\phi_r)+F_{S_o^1}(\phi_o)\left(PU+SU_3^2+SU_3^3\right)\left(1-p_f\right)F_{S_r^1}(\phi_r)\end{aligned}. \quad (12)$$

Following the steps 4–6 described earlier in Section 2, the resulting expressions of $P_{out,3}^{CH_1}, P_{out,3}^{CH_2}$ and $P_{out,3}^{CH_3}$ are then used for the calculation of average system outage probability, $Out_{3,n}^{avg}$ as below,

- No FSO_i is converted to cognitive hybrid:

$$Out_{3,0}^{avg} = \left(P_{out}^{hyb}+P_{out}^{FSO_1}+P_{out}^{FSO_2}+P_{out}^{FSO_3}\right)/4.$$

- Only FSO_1 is converted to cognitive hybrid link:

$$Out_{3,1}^{avg} = \left(P_{out}^{hyb}+P_{out,3}^{CH1}+P_{out}^{FSO_2}+P_{out}^{FSO_3}\right)/4.$$

- FSO_1 and FSO_2 are converted to cognitive hybrid links:

$$Out_{3,2}^{avg} = \left(P_{out}^{hyb}+P_{out,3}^{CH1}+P_{out,3}^{CH2}+P_{out}^{FSO_3}\right)/4.$$

- All, that is, FSO_1, FSO_2 and FSO_3 are converted to cognitive hybrid links:

$$Out_{3,3}^{avg} = \left(P_{out}^{hyb}+P_{out,3}^{CH1}+P_{out,3}^{CH2}+P_{out,3}^{CH3}\right)/4.$$

We have derived the closed form expressions of $Out_{N,n}^{avg}$ for $N=1-15$; however, due to paucity of space, expressions for $N=3$ only are presented.

4 | NUMERICAL RESULTS AND DISCUSSIONS

To obtain the multi-Qos system dimensions, $Out_{N,n}^{avg}$ is computed numerically for a fixed value of $\overline{S}_o$. All possible combinations of (N,n) which fulfill the desired $Out_{N,n}^{avg}$ or $\mathcal{T}\%$ improvement in average system outage are compiled. We present results for seed system size $N=1$ to 15 for (i) weak turbulence, no misalignment, (ii) strong turbulence, no misalignment, and (iii) strong turbulence and significant misalignment. Standard parameters are used: optical wavelength = 1550 nm, link length = 1 km, weak turbulence $(\alpha=2.902, \beta=2.51)$, strong turbulence $(\alpha=2.064, \beta=1.342)$ and significant misalignment or pointing error $(\zeta=0.8509)$.[4,13] Here Equation (2) is used for cases (i) and (ii) and Equation (3) for case (iii).

TABLE 1 Valid combinations of N and N^* for a fixed $Out_{N,n}^{avg}$; $\overline{S}_o$=12 dB, $\phi_o = 10$ dB, $\phi_r = 10$ dB

	Weak Turb and no misalignment ($Out_{N,fso}^{avg} = 0.5072$)		Strong Turb and no misalignment ($Out_{N,fso}^{avg} = 0.602$)		Strong Turb and significant misalignment ($Out_{N,fso}^{avg} = 0.6633$)	
$Out_{N,n}^{avg}$	$\mathcal{T}\%$	Seed system: multi-QoS $N : (N, N^*)$	$\mathcal{T}\%$	Seed system: multi-QoS $N : (N, N^*)$	$\mathcal{T}\%$	Seed system: multi-QoS $N : (N, N^*)$
0.35	31%	**4: (4, 4)** 3: (3, 1), (3, 2), (3, 3) 2: (2, 1), (2, 2) N = 1, degenerate case	41.86%	**2: (2, 1), (2, 2)** N = 1, degenerate case	47.23%	**2: (2, 2)** N = 1, degenerate case
0.4	21.14%	**6: (6, 5),(6, 6)** 5: (5, 2) till (5, 5) 4: (4, 1) till (4, 4) 3: (3, 1) till (3, 3) N = 1, 2, degenerate cases	33.55%	**4: (4, 4)** 3: (3, 1), (3, 2), (3, 3) 2: (2, 1), (2, 2) N = 1, degenerate case	39.69%	**2: (2, 1), (2, 2)** $N = 1$, degenerate case
0.45	11.28%	**11: (11, 9)–(11, 11)** 10: (10, 5) till (10, 10) 9: (9, 3) till (9, 9) 8: (8, 2) till (8, 8) 7: (7, 1) till (7, 7) 6: (6, 1) till (6, 6) 5: (5, 1) till (5, 5) N = 1–4, degenerate cases	25%	**6: (6, 6)** 5: (5, 2) till (5, 5) 4: (4, 1) till (4, 4) 3: (3, 1) till (3, 3) N = 1, 2, degenerate cases	32.16%	**3: (3, 1), (3, 2), (3, 3)** $N = 1,2$ degenerate cases
0.5	1.42%	**15: (15, 1) till (15, 15)** 14: (14, 1) till (14, 14) 13: (13, 1) till (13, 13) $N = 1 - 12$ degenerate cases	16.90%	**10: (10, 9), (10, 10)** 9: (9, 5) till (9, 9) 8: (8, 2) till (8, 8) 7: (7, 1) till (7, 7) 6: (6, 1) till (6, 6) 5: (5, 1) till (5, 5) N = 1–4, degenerate cases	24.62%	**5: (5, 2), (5, 3), (5, 4), (5, 5)** 4: (4, 1), (4, 2), (4, 3), (4, 4) $N = 1,2,3$ degenerate cases

Note: The largest possible configurations are highlighted in bold.

- System design and impact on dimensioning: The average outage analysis depends upon the individual link outage calculation for FSO_i and CH_i, as given in Equation (12), thus, extensive Monte Carlo simulations have been used to verify these closed form expressions for the worst case of combined strong turbulence and strong pointing error as presented in Figure 2. Simulations validate the theoretical results. Improvement obtained in individual link outage for the medium QoS (CH_i) users as compared to those of lowest QoS (FSO_i) is noted. In Figure 3, $Out_{N,n}^{avg}$ is plotted as n FSO_i are progressively converted to cognitive hybrid link for seed system sizes varying from $N = 1$ to 15. We consider strong atmospheric turbulence and significant pointing error for a given average optical SNR $(\overline{S}_o = 12$ dB). It can be observed that for a desired $Out_{N,n}^{avg} \leq 0.5$, seed systems of $N = 4$ and $N = 5$ fulfill the criteria of Equation (1), when atleast one, two FSO links respectively, are converted to cognitive hybrid links. However, the criteria are never satisfied for $N > 5$. For $N = 4$, there are four possible multi-QoS configurations, namely (4, 1), (4, 2), (4, 3), and (4, 4); however, (4, 4) means all FSOs are converted to cognitive hybrid link. Thus, with this proposed multi-Qos system design, for seed size 4, the engineer has a flexibility to choose from the configurations (4, 1), (4, 2), (4, 3), and (4, 4) by trading off between average system outage and the number of energy sensors that

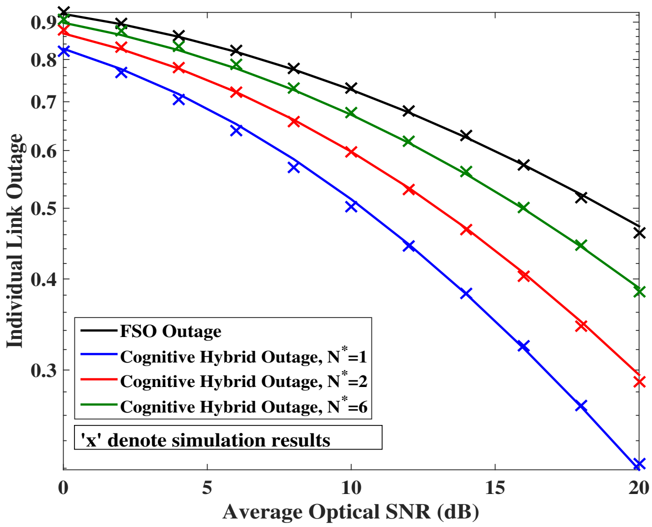

FIGURE 2 Individual link outage ($P_{out,N}^{CHi}$) comparison for solitary FSO and cognitive hybrid link for various $N = N^*$ under combined effect of strong turbulence and significant pointing error. FSO, free space optical [Color figure can be viewed at wileyonlinelibrary.com]

can be deployed. It may be noted that seed systems for $N = 1$, 2, and 3, also meet the desired the average system outage constraint of ≤ 0.5. However, these system sizes satisfy the constraint when none of the FSOs are converted to cognitive hybrid links and hence, may be considered as degenerate cases for the given constraint.

- Impact of optical channel conditions: The possible multi-QoS system dimensions (as discussed above) for different seed system sizes N have been tabulated using Figure 3 to construct Table 1 for different values of $Out_{N,n}^{avg}$ and various channel conditions. The largest possible system configurations are highlighted in bold. Several such graphs and corresponding tables similar to Table 1 were generated using $N = 1 - 15$ for above-mentioned three types of channel conditions for various $\overline{S}_o$. It can be seen from Table 1 that for fixed SNR, $\overline{S}_o = 12$ dB, and for desired $Out_{N,n}^{avg} = 0.45$ many system dimensions are possible for all the three cases of channel conditions. However, the largest possible system size for weak turbulence and strong turbulence with pointing errors are (11, 11) and (3, 3) respectively. By comparing the largest system dimensions for all channel conditions, for any desired $Out_{N,n}^{avg}$, it can be observed that the system dimension decreases as the channel impairments increase. To be more precise, a single hybrid link can support significantly more number of FSOs, hence, more number of users, in weak turbulence conditions as compared to when the channel suffers from strong turbulence and pointing error. This highlights the detrimental effect of turbulence and pointing error on multi-QoS system dimensions.
- Impact of optical SNR: Table 2 is formed by compiling the largest multi-QoS system dimensions as obtained from several tables generated in a manner similar to Table 1, for $20\% - 40\%$ minimum average system outage advantage as defined in Equation (1). From Table 2, we see that out of an overall system size N, N^* users can be upgraded from the poorest QoS to medium QoS by virtue of conversion from solitary FSO to cognitive hybrid links. Thus, the number of users at the lowest QoS is reduced from the original N to $N - N^*$. The table gives the trade-off between $\overline{S}_o, N, N^*$ and desired advantage in system outage. It can be clearly seen from Table 2 for any given optical channel impairments, larger multi-QoS system dimensions can be accommodated by increasing $\overline{S}_o$. It can thus be inferred that the RF link of the hybrid FSO/RF link can support more number of solitary FSO links as the optical SNR increases. This result can be justified since for larger SNR, the FSO of the hybrid link shall have a lesser requirement for its RF resource, which in turn is used by the solitary FSOs to form cognitive hybrid

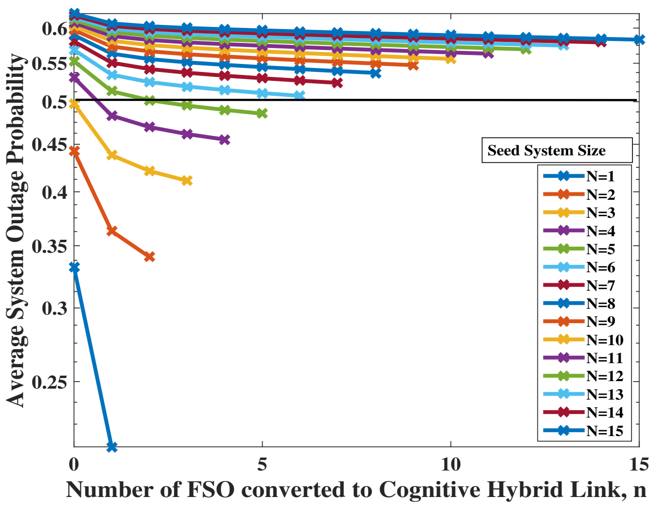

FIGURE 3 Variation in $Out_{N,n}^{avg}$ as n number of FSOs are converted to cognitive hybrid link under combined effect of strong turbulence and significant pointing error (PE) for fixed $\overline{S}_o$=12 dB [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Largest multi-QoS system dimensions, that is, maximum N with corresponding N^* for desired minimum $\mathcal{T}\%$ advantage of $Out_{N,n}^{avg}$ over $Out_{N,fso}^{avg}$

	Weak turbulence and no pointing error		**Strong turbulence and no pointing error**		**Strong turbulence significant pointing error**	
	$\mathcal{T} = 20\%$	$\mathcal{T} = 40\%$	$\mathcal{T} = 20\%$	$\mathcal{T} = 40\%$	$\mathcal{T} = 20\%$	$\mathcal{T} = 40\%$
Average optical SNR ($\overline{S}_o$)	(N,N^*)	(N,N^*)	(N,N^*)	(N,N^*)	(N,N^*)	(N,N^*)
8 db	(3, 1)–(4, 1)	(#, #)	(5, 2)–(5, 5)	(#, #)	(4, 2)–(4, 4)	(2, 1), (2, 2)
10 db	(4, 1)–(6, 3)	(2, 1)	(5, 4), (5, 5)	(2, 1), (2, 2)	(5, 2)–(5, 5)	(2, 2)
12 db	(3, 1)–(6, 5)	(2, 1)	(6, 6)	(2, 1), (2, 2)	(5, 2)–(5, 5)	(2, 2)
14 db	(6, 1)–(8, 7)	(2, 1)–(3, 2)	(7, 6), (7, 7)	(3, 3)	(5, 3)–(5, 5)	(2, 1), (2, 2)
16 db	(4, 1)–(10, 9)	(2, 1)–(4, 3)	(8, 5)–(8, 8)	(3, 3)	(5, 3)–(5, 5)	(2, 1), (2, 2)
18 db	(3, 1)–(12, 10)	(2, 1)–(5, 5)	(10, 9), (10, 10)	(#, #)	(7, 2)–(7, 7)	(3, 2), (3, 3)
20 db	(3, 1)–(15, 11)	(1, 1)–(5, 5)	(10, 5)–(10, 10)	(#, #)	(9, 7)–(9, 9)	(3, 2), (3, 3)

Note: # represents combination of (N,N^*) does not exist as constraint in Equation (1) is not met. N^* : no. of medium QoS link (cognitive hybrid), $N - N^*$: no. of least QoS (solitary FSO).

links. Further, it may be noted that as $\mathcal{T}$ increase from 20% to 40%, the requirement of average system outage becomes stricter, which results in smaller system dimensions. This can be understood by the fact that as the requirement of outage decreases, the utilization of RF_H increases, so its availability for standalone FSOs decreases.

It may be noted that for the sake of completeness, we report combinations satisfying the outage constraint in which $N = N^*$. However, all such combinations necessarily require every FSO to be equipped with energy detectors and leads to increased system complexity and cost. Thus, these configurations may be ignored for practical deployment purposes since they do not fulfill the essence of the proposed multi-QoS structure.

5 | CONCLUSIONS

In this article, we have proposed a novel system design methodology, which can cater to three different types of QoS expressed in terms of link availability or probability of link outage within the system. The proposed multi-QoS system can simultaneously accommodate one high priority user who is assigned the Hybrid FSO/RF link, N^* medium priority users who were originally solitary FSO links but have been upgraded as cognitive hybrid links which guarantees better link availability than the earlier FSO link and remaining $N - N^*$ lowest priority users who continue to operate as solitary FSO links without any RF backup, and thus, have the lowest link availability in the system. The specialty of this design methodology is finding the number of medium QoS links such that the system outage constraint is met through the efficient use of a single RF resource. The results reveal the flexibility of the design methodology, which can provide multiple multi-QoS configurations satisfying a given constraint on overall system outage. This is an important feature of this methodology as the system designer has more freedom to choose which configuration among the possible options is most suitable. Analysis for different optical channel impairments reveal the multi-QoS system dimensions to be influenced by turbulence and pointing error, with pointing error being majorly responsible for degradation in multi-QoS system size. The impact of optical SNR, on the multi-QoS system dimensions has also been examined. We see that, for a given requirement of system outage, the system dimension increases as the SNR increases. Also at a fixed optical SNR, a better requirement of average system outage results in smaller system dimensions.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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