Analysis of the performance of coded and un-coded mixed RF and multihop coherent OFDM-FSO systems for 5G-CRAN applications

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Abstract

The performance of coded and un-coded mixed single-hop RF links, as well as multihop FSO link systems, for the 5G centralized radio access network, is investigated in this paper using a coherent detection technique. A Generalized Nakagami-m fading channel is chosen for the RF link, and the Gamma-Gamma distribution channel is chosen for the FSO link. Both the RF and FSO links use M-quadrature amplitude modulated orthogonal frequency division multiplexing modulation for the coherent detection scheme. The Meijer-G function is used to calculate outage probability (OP) and average symbol error rate (ASER) for analyzing the performance of coded and un-coded systems. Reed solomon (RS) and bose-chaudhuri-hocquenghem codes are used in the coded system. In relays, the decode and forward method is used. For analysis, the effects of atmospheric turbulence, atmospheric loss, and pointing error are considered. The results show that the coding technique improves the system’s performance. When compared to RS codes, BCH codes improve system performance more at low SNR. At high SNR and higher order code-word lengths, RS codes outperforms BCH and un-coded system. A Monte-Carlo simulation is used to validate the analytical results.

Keywords

Average symbol error rate · Coherent · Multihop · Coding technique · Turbulence

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1 Introduction

1.1 Background and motivation

An increase in mobile and internet access usage leads the emerging 5G network to meet the demands like high data rate, less power consumption, and less latency (Iovanna, et al. 2016). The Cloud / Centralized Radio Access Network (C-RAN) architecture is incorporated in the 5G network to meet the requirements. C-RAN architecture consists of Baseband Unit (BBU) pool and Remote Radio Heads (RRH) (Zhang, Haijun, et al. 2016). The radio signal from the user equipment (UE) is received by RRH and forwards to the BBU pool, where the baseband signal processing takes place. BBU pool acts as a central processor that performs functions like modulation, coding, radio resource control, etc. 5G C-RAN requires reliable and high-speed links for front hauling between RRH and BBU pool (Ranaweera, et al. 2017). FSO is easy to deploy, which acts as a suitable front haul link for 5G networks (Ahmed et al. 2018). In C-RAN architecture, the signal from UE to RRH is a radio signal, and from RRH to BBU pool, it is the FSO front haul link. The structure of the architecture is like a dual-hop mixed RF-FSO system. Many works have been done in a dual-hop hybrid RF-FSO system.

In C-RAN architecture, under fixed BBU pool location, the link availability can be obtained by connecting serial relays between RRH and BBU pool so that long link distance can be covered by using short links using relays. RF link between UE and RRH cannot be increased as the RF link suffers from power loss due to its high frequency. Multihop relaying of the FSO system overcomes the problem of expanding the coverage area. The multihop FSO system is studied in many papers (Akella et al. 2005).

In (Akella et al. 2005) multihop FSO system with the DF technique is studied and compared with AF relaying technique. DF relaying performs better than AF relaying. In (Tang, et al. 2014), heterodyne detection with differential phase-shift keying (DPSK) modulation scheme with Gamma-Gamma distribution is investigated for different atmospheric turbulence and pointing error conditions. In (Bekkali, et al. 2010), a coherent multihop method with the DF technique is implemented to obtain a better spatial selectivity property. Though a coherent system is complex to implement, its advantages over non-coherent systems are distinct. The coherent system is considered in this paper. Orthogonal frequency division multiplexing (OFDM) is recently adopted in many types of research for its advantages like high transmission rates of data, inter-symbol interference suppression, random fading effect prevention. In (Bekkali, et al. 2010), OFDM modulation with IM/DD technique for Gamma-Gamma distribution, Multilevel DPSK modulated non-equalization OFDM system with coherent detection system (Chen et al. 2014), and in (Wang et al. 2015) quadrature amplitude modulated OFDM with tunable optical coherent detection is analyzed. Extension of (Wang et al. 2015) is given in (Wang et al. 2016), in which a multihop coherent OFDM FSO system is implemented with an M-QAM modulation scheme with DF relaying technique with Gamma-Gamma distribution.

Among many other mitigation techniques like diversity, modulation schemes, etc. coding technique is considered to improve the performance of the system. Reed Solomon (RS) and Bose-Chaudhuri-Hocquenghem (BCH) codes are taken as mitigation techniques for the system model presented in this paper. The effect of these codes on the proposed system is analyzed in terms of average symbol error (ASER). Forward Error Correction codes add redundant bits to the information bits to be sent to overcome the error rates (Gupta, et al. 2019). RS codes in high-speed, long-distance transmission are suitable for correcting burst
errors and random bit errors (Yu, et al. 2004). BCH codes correct multiple bit errors in a codeword (Nayak, 2014).

1.2 Contribution

Significant contributions in this paper are,

A coherent detection method is used to evaluate the performance of mixed RF and multihop FSO systems.
For the first time, RS and BCH coding techniques for mixed RF and multihop FSO systems are introduced, and performance is compared for both coded and un-coded cases.
For coherent detection, both RF and FSO links used M-QAM modulated OFDM modulation. The system’s performance is evaluated under various turbulence, weather, and pointing errors conditions.

In the proposed work, we consider a single RF link to be a Generalized Nakagami-m fading channel as it includes the Nakagami-m fading channel as a particular case that covers the line of sight (LOS) component (Zedini.Emna, Imran Shafique Ansari et al. 2015). Generalized Nakagami-m fading channel is modeled for fading effects like multipath and shadow (Zedini et al. 2016). In C-RAN architecture, the distance between the UE and RRH is less, which needs to consider LOS communication also. A multihop FSO link is regarded as a Gamma-Gamma distributed channel. Experimental and simulation data fits for all turbulence conditions for Gamma-Gamma distribution in case of point detectors than Log-Normal distribution (Wayne et al. 2010).

The rest of the paper is organized as follows. In Sect. 2, the system and channel model is discussed, in Sect. 3, Error Correcting Codes are presented, in Sect. 4, average symbol error rate (ASER) is derived for the un-coded and coded system, in Sect. 5, OP is derived for un-coded system, in Sect. 6 results and discussion is given, and finally, Sect. 7 concludes the paper.

2 System and channel model

2.1 System model

The system model of mixed RF and multihop FSO system for the C-RAN architecture is shown in Fig. 1. In Fig. 1, the source node is the user equipment (UE), it is denoted as Source, destination is the centralized baseband unit (BBU), it is represented as a Destination, and the intermediate relay nodes are designated as a Relay. The number of hops is L, and the number of links between source and destination is L-1. The first node from source to RRH unit, i.e., Relay 1, is connected using the RF link, and, from i+1 to L hops, communication occurs through the FSO link. The relays follow the decode and forward (DF) technique in which the signal from the transmitter is transmitted to the relays, which demodulates, decodes, and re-transmit the received signal after modulating it again to reduce the error, by this way, it defers from amplifying and forward technique in which the signal is amplified with noise and transmitted in each node. In a multihop transmission system, the occurrence of error is reduced using the DF technique, which helps in extending the transmission link distance of the system.
The signal from the Source is transmitted to the first relay node, Relay 1, through an RF link. The received signal from Source to Relay 1 is represented as $Y_1$ and is given in Eq. (1) as,

$$Y_1 = h_{R_{(1)}} X_1 + n_{R_{(1)}}$$  

where, $h_{R_{(1)}}$ denotes the channel gain of Generalized Nagakami-m distribution, $X_1$ is the signal transmitted from Source to Relay 1. $n_{R_{(1)}}$ is the additive white Gaussian noise added in the RF channel.

From the first relay Relay 1 to the Destination, the method adopted for detection is coherent. The coherent OFDM-FSO system is adapted from relay ‘i’ to a Destination where $i = 2 \ldots L$ nodes. The signal transmitted from Relay 1 to Destination is $X_i$ and the received signal at the Destination is denoted as $Y_i$,

$$Y_i = h_{R_{(i)}} e_i X_i + n_{R_{(i)}}$$

where, $e_i$ is the $i$th receiver sensitivity.

### 2.2 Channel model

#### 2.2.1 RF link

The RF link is established between Source and Relay 1. The Generalized Nakagami m fading channel is chosen as the RF link.

The instantaneous SNR PDF of the Generalized Nakagami-m fading function is given as (Zedini et al. 2015)

$$f_{\gamma_{RF}}(\gamma) = \frac{p}{\Gamma(m)} \left( \frac{d}{\gamma_{RF}} \right)^{mp} \gamma^{mp-1} e^{-\left( \frac{d}{\gamma_{RF}} \right)^{p}} \gamma^p,$$

where $m(m \geq 1/2)$ and $p(p > 0)$ are the fading figure and shaping parameters, respectively, $\gamma_{RF}$ is the average SNR, and $d = \Gamma(m + 1/p)/\Gamma(m)$. For the special cases, Generalized Nakagami m fading distribution tends to Nakagami-m, Rayleigh, Exponential, Gamma and Weibull when $(p = 1),(m = 1,p = 1),(m = 1,p = 1/2),(p = 1/2)$ and $(m = 1)$.
respectively. The PDF of Generalized Gamma distribution in terms of Meijer’s G function is given as (Zedini et al. 2015)

\[
f_{\gamma_{RF}}(\gamma) = \frac{p}{\Gamma(m)} G^{1,0}_{0,1} \left[ \left( \frac{d}{\gamma_{RF}} \right)^p \gamma^p | \bar{m} \right]
\] (4)

The CDF of the Generalized Gamma distribution is represented as (Zedini et al. 2015)

\[
F_{\gamma_{RF}}(\gamma) = 1 - \frac{1}{\Gamma(m)} G^{2,0}_{1,2} \left[ \left( \frac{d}{\gamma_{RF}} \right)^p | m, 0 \right]
\] (5)

### 2.2.2 FSO links

The FSO link is assumed Gamma-Gamma distributed. The combined channel state of Gamma-Gamma distribution includes three factors, atmospheric loss \( h_{li} \), pointing error \( h_{pi} \), and atmospheric turbulence \( h_{al} \) (Wang et al. 2016). The combined Channel state factor \( h = h_{li} h_{pi} h_{al} \).

Atmospheric loss is represented as

\[
h_{li}(z) = e^{-\sigma z}
\] (6)

where, \( h_{li}(z) \) is the loss due to attenuation when the signal propagates in path of length \( z \) Kms and \( \sigma \) is the attenuation coefficient. This loss is due to suspended particles present in the atmosphere, which affects the visibility of the optical light.

Pointing error is caused due to the misalignment of the transmitter and receiver. This misalignment occurs due to the vibration between the transceivers, wind speed change, and temperature change in the atmosphere (Anbarasi et al. 2017). In multihop systems, the alignment between the source, relays, and destination is affected mainly by jitter errors, which have to be considered when modeling the channel. Pointing errors depends on jitter error and the beamwidth.

The pointing error with a radial displacement of the beam that follows Gaussian distribution is represented in (Wang et al. 2016).

\[
h_{pi}(\delta) = A_0 e^{-\frac{\delta^2}{2w_{zeq}^2}}
\] (7)

where, \( w_{zeq}^2 = \frac{w_z^2 \text{erf}(v) \text{exp}(-v^2)}{2v} \) is the equivalent beam width, \( v = \sqrt{\pi r / \sqrt{2w_z}} \), \( r \) is the aperture radius of the receiver, \( w_z \) is the beam width at link length of \( z \), \( w_z / r \) is the normalized beam width, \( A_0 = \left[ \text{erf}(v) \right]^2 \) is the power received at \( \delta = 0 \). The pdf of \( h_{pi} \) is written as (Wang et al. 2016).

\[
f_{h_{pi}}(h_{pi}) = \frac{\gamma_i^2}{A_0^2} h_{pi}^{\gamma_i - 1}, 0 \leq h_{pi} \leq A_0
\] (8)

where, \( \gamma_i = w_{zeq}^2 / 2\delta_z \), \( \delta_z \) is the jitter and \( \delta_z / r \) is the normalized jitter error.

Gamma-Gamma distribution is modeled for atmospheric turbulence conditions like weak, moderate, and strong. The pdf of Gamma-Gamma distribution has two effective
number of optical wave intensity i.e., small scale eddies ($\alpha$) and large scale eddies ($\beta$) of the scattering process. It is given as (Wang et al. 2016)

$$f_{h_{ai}}(h_{ai}) = \frac{2(\alpha \beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} h_{ai}^{(\alpha+\beta-2)/2} K_{\alpha-\beta} \left( 2\sqrt{\alpha \beta h_{ai}} \right), h_{ai} > 0$$

(9)

where $h_{ai}$ is the scintillation intensity of the signal, $K_n(\cdot)$ denotes the modified Bessel function of the second kind of order $n$. $\Gamma(\cdot)$ is the Gamma function. The equations of $\alpha$ and $\beta$ are

$$\alpha = \exp \left[ \frac{0.49\sigma_i^2}{(1 + 1.11\sigma_i^{12/5})^{7/6}} \right] - 1$$

$$\beta = \exp \left[ \frac{0.51\sigma_i^2}{(1 + 0.69\sigma_i^{12/5})^{5/6}} \right] - 1$$

where $\sigma_i^2$ is the Rytov variance given as $\sigma_i^2 = 1.23C_n^2k^{7/6}L^{1/6}$, $k = 2\pi/\lambda$ is the wavenumber; L is the link length and $C_n^2$ is the refractive index structure coefficient.

The combined PDF, which includes path loss, atmospheric turbulence, and pointing errors, is given as (Tang et al. 2014)

$$f_{h_{i}|h_{ai}}(h_i/h_{ai}) f_{h_{ai}}(h_{ai}) dh_{ai}$$

(10)

$$f_{h_{i},h_{ai}}(h_i/h_{ai}) = \frac{\gamma_i^2}{A_0^2 h_{li} h_{ai}} \left( \frac{h_i}{h_{li} h_{ai}} \right)^{\gamma_i^2 - 1} 0 \leq h_i \leq A_0 h_{li} h_{ai}$$

(11)

By substituting Eqs. (7) and (9) into Eq. (10), we get (Wang et al. 2016)

$$f_{h_{i}}(h_i) = \frac{\alpha \beta \gamma_i^2}{A_0 h_{li} \Gamma(\alpha)\Gamma(\beta)} G^{3,0}_{1,3} \left[ \frac{\alpha \beta h_i}{A_0 h_{li}} \right] \frac{\gamma_i^2}{\gamma_i^2 - 1}, \alpha - 1, \beta - 1$$

(12)

### 3 Error-correcting codes

#### 3.1 Bose-chaudhri-hocquenghem (BCH)

BCH code is binary cyclic code in which the $n - k$ redundant bits are added to the $k$ information bits to form a codeword of length $n$ (Lin 2001; Moon 2020). A generator polynomial $g(x)$ is used to determine the characteristics of a codeword. Multiples of generator polynomial form codewords. The information bits are represented using polynomial $m(x)$, a codeword is formed by dividing $m(x)$ by $g(x)$, and the remainder is represented as check
bits $r(x)\cdot c(x)$ is the encoded data which is the summation of $m(x)$ and $r(x)$. BCH codes can correct up to $t$ independent error bits for $m \geq 3$. Possible BCH codes when $m \geq 3$ and $t < 2^m - 1$ are.

Block length $n = 2^m - 1$.
Check bits $n - k \leq mt$.
Minimum distance $d \geq 2t + 1$ (Hamming distance).

Decoding of BCH codes follows three steps.

- From the received code word, compute the syndrome.
- From the set of equations derived from the syndrome, find the error location polynomial.
- Identify the error bits and correct the error bits using the error location polynomial.

BCH codes are simple to encode and decode. Berklekamp Massey algorithm is used to decode the BCH coded bits.

### 3.2 Reed-solomon codes (RS)

Reed-Solomon codes are non-binary cyclic codes, which belong to the BCH codes family (Lin 2001; Moon 2020). It can correct burst errors since it corrects symbol errors; even if many bits in a symbol are erroneous, it is considered as one symbol error and corrected. ‘$n$’ is the total coded symbol consisting of ‘$m$’ bits per symbol, $k$ is the data symbols to be encoded and $n - k$ is the parity symbols and is equal to $2t$, where $t$ is the capability of correcting symbol error of the code.

Possible RS codes are

- Block length $n = m(2^m - 1)$ bits.
- Parity check bits $n - k = m \times 2t$.
- Minimum distance $d = 2t + 1$.

The RS code decoding process is more complex because of the found error weight determination i.e., the pattern of the error in the symbol has to be determined.

Reed Solomon code decoding process involves the following steps.

- Compute the syndrome from the received codeword.
- Determine the error location polynomial from the equations derived from the syndrome.
- Determine the weight of the error from the error location polynomial.
- Correct the error symbol using the weight of the error and error location polynomial.
4 Average symbol error rate

The influence of the atmospheric condition on the system is analyzed using a symbol error rate. As the number of relays increases, the system performance degrades. The symbol error rate of the system is derived for the M-QAM OFDM modulation technique, and the ASER is evaluated with RS and BCH codes, and the performance of un-coded and RS and BCH coded system is compared.

4.1 RF link

The RF link is defined by Generalized Gamma distribution. The system symbol error rate of the M-QAM-OFDM system can be written as (Proakis, 2001).

\[
P_{QAM-OFDM} = 4Q\left(\sqrt{\frac{3}{N(M-1)}}\right) \tag{13}
\]

where \( \gamma \) is the average SNR. \( N \) is the number of OFDM subcarriers, \( M \) is the constellation mapping coefficient of QAM.

The average symbol error probability in terms of PDF is given as (Liu, Xiaoxia, et al. 2017)

\[
P_{SER,i} = \int_{-\infty}^{\infty} P_{e/h_i} f_{h_i}(h_i) dh_i \tag{14}
\]

In terms of CDF (Liu, Xiaoxia, et al. 2017),

\[
P_{SER,i} = -\int_{0}^{\infty} \frac{dP_{e/h_i}}{dh_i} F_{h_i}(h_i) dh_i \tag{15}
\]

From Eq. (15),

\[
P_{SER,i} = -\int_{0}^{\infty} \frac{dP_{QAM-OFDM}}{d\gamma} F_{RF}(\gamma) d\gamma
\]

By differentiating Eq. (13), we get

\[
\frac{dP_{QAM-OFDM}}{d\gamma} = -\sqrt{\frac{6}{\pi N(M-1)\gamma}} e^{-\left(\frac{3}{2N(M-1)}\gamma\right)} \tag{16}
\]

By substituting Eqs. (16) and (5) in Eq. (15), the average symbol error rate of the RF link with 16-QAM OFDM system is obtained in the form of Generalized Gauss-Laguerre Quadrature function and it is given as

\[
P_{RF,1} = \int_{0}^{\infty} \sqrt{\frac{6}{\pi N(M-1)\gamma}} e^{-\left(\frac{3}{2N(M-1)}\gamma\right)} \times \left\{ 1 - \left\{ \left( \frac{1}{\Gamma(m)} \right)^{G,2,0} \left( \frac{d}{\gamma_{RF}} \right)^{p,1} \right\} \right\} d\gamma \tag{17}
\]

\[
P_{RF,1} = \int_{0}^{\infty} \sqrt{\frac{6}{\pi N(M-1)\gamma}} e^{-\left(\frac{3}{2N(M-1)}\gamma\right)} \times \left\{ 1 - \left\{ \left( \frac{1}{\Gamma(m)} \right)^{G,2,0} \left( \frac{d}{\gamma_{RF}} \right)^{p,1} \right\} \right\} d\gamma \tag{18}
\]
Assume, \( y = \frac{3}{2N(M-1)} \), then Eq. (18) becomes

\[
P_{\text{SER},1}^{\text{RF}} = \frac{2}{\sqrt{\pi}} \int_0^{\infty} y^{-\frac{1}{2}} e^{-y} \times \left\{ 1 - \left\{ \left( \frac{1}{\Gamma(m)} G_{2,0}^{1,2} \left( \frac{2N(M-1)y}{\frac{3\gamma_{RF}}{\mu_{RF}}} \right) \right) \right\} \right\} dy
\]

(19)

The above equation is of the form \( \int_0^{\infty} x^{-\frac{1}{2}} e^{-x} f(x)dx \), the mixed RF and multihop coherent FSO-OFDM system with the affecting factors like atmospheric turbulence, path loss and pointing error can be approximated using Generalized Gauss-Laguerre Quadrature function

\[
\int_0^{\infty} x^{-\frac{1}{2}} e^{-x} f(x)dx = \sum_{j=1}^{m_j} H_j f(x_j)
\]

(20)

where

\[
H_j = \frac{\Gamma\left(n + \frac{1}{2}\right) x_j}{n!(n+1)^2 \left[ \left( -\frac{1}{2} \right) \right] \left( \frac{1}{2} \right) \left( \frac{x_j}{n+1} \right) ^2}
\]

(21)

Considering, \( \mu_{RF} = \frac{3}{2N(M-1)} \), Eq. (19) can be written as

\[
P_{\text{SER},1}^{\text{RF}} = \frac{2}{\sqrt{\pi}} \sum_{j=1}^{m_j} H_j \left\{ 1 - \left\{ \left( \frac{1}{\Gamma(m)} G_{2,0}^{1,2} \left( \frac{\gamma_{RF}}{\mu_{RF}} \right) \right) \right\} \right\}
\]

(22)

4.2 FSO link

The system symbol error rate of the M-QAM-OFDM system can be written as (Wang et al. 2015, 2016).

\[
P_{\text{QAM-OFDM}} = 4Q \left( \sqrt{\frac{h_i^2 3TB}{2N(M-1)}} \right)
\]

(23)

where \( \overline{\text{SNR}} = \overline{\gamma} h_i^2 \). From (Wang et al. 2015, 2016), the SNR is given as

\[
\text{SNR} = \frac{4R^2 P_0 P_L h_i^2}{2q\rho (P_0 + P_L) R^2 + 4K_b T_{sys} R}
\]

(24)

In coherent optical communication system, SNR attains the shot noise limit when there is large local light power. Now, \( P_L \gg P_0 \) and the magnitude of the SNR is defined as \( \text{SNR} = \frac{2p_i h_i^2}{q\rho} \) and denoted as \( \overline{\gamma} = \frac{2p_i}{q\rho} \). \( p_i \) is the signal power, \( q \) is the electric charge, \( \rho \) is the detector efficiency, \( K_b \) is the Boltzmann constant, \( R \) is the equivalent load resistance and
\( T_{sys} \) is the relative kelvin temperature. OFDM parameters are bandwidth (B), number of subcarriers (N) and symbol period (T).

From Eq. (15), \( P_{SER,i} = \int_{0}^{\infty} \frac{dP_{QAM-OFDM}}{dh_i} F_{h_i}(h_i) dh_i \)

\[
\frac{dP_{QAM-OFDM}}{dh_i} = -\sqrt{\frac{6TB\gamma}{\pi N(M-1)}} e^{-\left(\frac{6TB\gamma}{2N(M-1)}\right)} \tag{25}
\]

The CDF of Gamma-Gamma distribution is given as (Sandalidis, Harilaos et al. 2009)

\[
F_{h_i}(h_i) = \frac{\gamma_i^2}{\Gamma(\alpha)\Gamma(\beta)} \frac{\alpha \beta h_i^\gamma}{A_0 h_i^\delta} \left[ 1, \gamma_i^2, \alpha, \beta, 0 \right] \tag{26}
\]

Substituting Eqs. (25) and (26) in Eq. (15), we get

\[
P_{FSO, SER,i} = \frac{2\gamma_i^2}{\Gamma(\alpha)\Gamma(\beta)} \int_{0}^{\infty} \sqrt{\frac{6TB\gamma}{\pi N(M-1)}} e^{-\left(\frac{6TB\gamma}{2N(M-1)}\right)} \times \frac{\alpha \beta h_i^\gamma}{A_0 h_i^\delta} \left[ 1, \gamma_i^2, \alpha, \beta, 0 \right] dh_i \tag{27}
\]

Assume, \( y = \frac{h_i^2 TB\gamma}{2N(M-1)} \), then Eq. (27) becomes

\[
P_{FSO, SER,i} = \frac{2\gamma_i^2}{\Gamma(\alpha)\Gamma(\beta)} \sqrt{\pi} \int_{0}^{\infty} y^{-\frac{1}{2}} e^{-y} \times \frac{\alpha \beta}{A_0 h_i^\delta} \left[ \frac{2N(M-1)y}{3TB\gamma_{FSO}} \right]^{\frac{1}{2}} \left[ 1, \gamma_i^2, \alpha, \beta, 0 \right] dy \tag{28}
\]

Using Generalized Gauss-Laguerre quadrature function and considering, \( \mu = \frac{3TB}{2N(M-1)} \), Eq. (28) can be written as

\[
P_{FSO, SER,i} = \frac{2\gamma_i^2}{\sqrt{\pi} \Gamma(\alpha)\Gamma(\beta)} \sum_{j=1}^{m_i} H_j G_{2,4}^3 \left[ \frac{\alpha \beta}{A_0 h_i^\delta} \left( \frac{y_j}{\mu_{FSO}} \right) \right]^{\frac{1}{2}} \left[ 1, \gamma_i^2, \alpha, \beta, 0 \right] \tag{29}
\]

\( P_{FSO, SER,i} \) denotes the symbol error rate equation of the \( i \)th hop. For multihop, the average symbol error rate of \( L \) number of hops is given as (Wang et al. 2016)

\[
SER_{FSO, Total} = \sum_{i=2}^{L} P_{FSO, SER,i} \prod_{k=i+1}^{L} \left( 1 - 2P_{FSO, SER,k} \right) \tag{30}
\]

By substituting Eq. (29) in Eq. (30), the total average system symbol error rate of multihop coherent M-QAM OFDM-FSO link is obtained as

\[
SER_{FSO, Total} = \sum_{i=2}^{L} \left\{ \frac{2\gamma_i^2}{\sqrt{\pi} \Gamma(\alpha)\Gamma(\beta)} \sum_{j=1}^{m_i} H_j G_{2,4}^3 \left[ \frac{\alpha \beta}{A_0 h_i^\delta} \left( \frac{y_j}{\mu_{FSO}} \right) \right]^{\frac{1}{2}} \left[ 1, \gamma_i^2, \alpha, \beta, 0 \right] \right\} \prod_{k=i+1}^{L} \left( 1 - \frac{2\gamma_i^2}{\sqrt{\pi} \Gamma(\alpha)\Gamma(\beta)} \sum_{j=1}^{m_i} H_j G_{2,4}^3 \left[ \frac{\alpha \beta}{A_0 h_i^\delta} \left( \frac{y_j}{\mu_{FSO}} \right) \right]^{\frac{1}{2}} \left[ 1, \gamma_i^2, \alpha, \beta, 0 \right] \right) \tag{31}
\]
4.3 Mixed RF and multihop FSO system

I(Yi, Xiang et al. 2019), Eq. (30) gives the ASER of mixed RF and multihop FSO system

$$\text{ASER}_{\text{sys}} = \frac{1}{2} - (\frac{1}{2} - P_{\text{SER,1}}^\text{RF})(1 - 2\text{SER}_{\text{FSO}}^\text{Total})$$  \hspace{1cm}(32)$$

ASER of mixed RF and multihop coherent FSO with 16-QAM OFDM system is obtained from Eqs. (22) and (31) as

$$\text{ASER}_{\text{sys}} = -\frac{1}{2} \left( \frac{1}{2} - \frac{2}{\pi} \sum_{j=1}^{m_j} H_j \left\{ 1 - \left( \frac{1}{\Gamma(m)} G_{2,0}^{1,2} \left[ (d)^p \left( \frac{y_j}{\mu_{\text{RF}}^\gamma_{\text{RF}}} \right)^p \left| m, 0 \right] \right) \right\} \right)$$

$$\left( 1 - 2 \sum_{i=2}^{L} \frac{2y_i^2}{\pi \Gamma(\alpha) \Gamma(\beta)} \sum_{j=1}^{m_j} H_j G_{2,4}^{3,1} \left[ \alpha \beta A_0 h_{li} \left( \frac{y_j}{\mu_{\text{FSO}}^\gamma_{\text{FSO}}} \right)^{1/2} \left| 1, \gamma_i^2 + 1 \right. \right] \right)$$

$$\prod_{k=i+1}^{L} \left( 1 - \frac{4y_k^2}{\pi \Gamma(\alpha) \Gamma(\beta)} \sum_{j=1}^{m_j} H_j G_{2,4}^{3,1} \left[ \alpha \beta A_0 h_{li} \left( \frac{y_j}{\mu_{\text{FSO}}^\gamma_{\text{FSO}}} \right)^{1/2} \left| 1, \gamma_i^2 + 1 \right. \right] \right)$$  \hspace{1cm}(33)$$

Here $H_j$ and $y_j$ is the weight and nodes of the Gauss-Laguerre Quadrature function, $\alpha$ and $\beta$ values denotes the turbulence condition, $\gamma_i^2$ is the pointing error parameter, $h_{li}$ is the path loss, $\gamma_{\text{RF}}$ and $\gamma_{\text{FSO}}$ is the average SNR. $\mu_{\text{RF}}$ and $\mu$ are the constant values of RF and FSO system respectively.

4.3.1 Coded SER analysis

Mixed RF and multihop 16-QAM modulated OFDM system, is coded with RS and BCH codes with the code rate 0.733. When a non-identical codeword from the transmitted codeword is received, error occurs. The probability of decoded error for $(n,k,t)$ RS and BCH codes with $t$ error correcting capability is given by (Ramavath Prasad Naik 2020a)

$$P_{\text{RS}} \leq \sum_{i=t+1}^{n} \binom{n}{i} p_i^j (1 - p)_i^{n-i}$$  \hspace{1cm}(34)$$

where $p$ is the symbol error probability. Here $p$ is the SER from Eq. (33), substituting it in Eq. (34) gives $P_{\text{RS}}$ of the system (Ramavath Prasad Naik 2020b).

$$P_{\text{BCH}} \leq \sum_{i=t+1}^{n} \binom{n}{i} p_i^j (1 - p)_i^{n-i}$$  \hspace{1cm}(35)$$

where $p_i = 1 - (1 - p_b)^{m_i}$. $p_b$ represents the system error probability. Substituting Eq. (33) in the place of $p_b$ gives $P_{\text{RS}}$.

5 Outage Probability

The outage probability $P_{\text{out}}$ of the multihop FSO system is given as (Wang et al. 2016)
The outage probability is given as (Yi, Xiang, et al. 2019)

\[ P_{\text{out}} = P_{\text{min}} \min \{ \mu \} \leq \mu_{\text{thr}} \]  

(36)

\[ = 1 - \prod_{i=1}^{L} (1 - P_{\text{out,FSO}}(\mu_{\text{thr}})) \]  

(37)

The \( P_{\text{out}} \) is given as (Yi, Xiang, et al. 2019)

\[ P_{\text{out}} = 1 - \left( (1 - P_{\text{out,RF}}) \times \prod_{i=1}^{L} (1 - P_{\text{out,FSO}}(\mu_{\text{thr}})) \right) \]  

(38)

For a multihop coherent OFDM system, the outage probability is given as (Wang et al. 2016)

\[ P_{\text{out,FSO}} = 1 - \prod_{i=1}^{L} \left( 1 - \frac{\alpha \beta \gamma_{2x}^2 \sqrt{N/2T}}{A_{0} h_{Li} \Gamma(\alpha) \Gamma(\beta)} G_{2,4}^{1.1} \left[ \frac{\alpha \beta x \sqrt{N/T}}{A_{0} h_{Li}} \right] 1, \gamma_{2x}^2 + 1 \right) \]  

(39)

The outage probability of mixed RF and multihop coherent FSO-OFDM system is obtained by substituting Eqs. (39) and (5) in Eq. (38) and we get,

\[ P_{\text{out}} = 1 - \left[ \left( \frac{1}{\Gamma(m)} \right)^{2.0} \left( \frac{d}{dM} \right)^{2.0} \left[ \frac{1}{m, 0} \right] \right] \times \left( 1 - \prod_{i=1}^{L} \left[ 1 - \frac{\alpha \beta \gamma_{2x}^2 \sqrt{N/2T}}{A_{0} h_{Li} \Gamma(\alpha) \Gamma(\beta)} G_{2,4}^{1.1} \left[ \frac{\alpha \beta x \sqrt{N/T}}{A_{0} h_{Li}} \right] 1, \gamma_{2x}^2 + 1 \right) \right] \]  

(40)

### 6 Results and discussions

In this section, the outage probability and the error performance of mixed RF and multihop coherent OFDM-FSO system is analyzed under the influence of atmospheric turbulence, various weather conditions, and pointing errors.

The error performance of the un-coded and coded mixed RF and multihop coherent OFDM-FSO system is compared. Both RF and multihop FSO systems follow M-QAM modulated OFDM system. The numerical results are validated using Monte Carlo Simulations. Numerical analysis is done for moderate and strong atmospheric turbulence conditions. The scintillation parameter values are given in Table 1. The attenuation values for different weather conditions is given in Table 2. For the OFDM system, the number of subcarriers is taken as \( N = 256 \). The number of hops considered in this work is two and five. For QAM modulation, \( M \) is taken as 16. For the analysis of the coded system, block length \( n = 15, 31, 255 \) and data length \( k = 11, 21, 239 \) is considered for both BCH

### Table 1 \( \alpha \) and \( \beta \) values of turbulence conditions (Wang et al. 2016)

| S.No | Turbulence | \( \alpha \) | \( \beta \) |
|------|------------|-------------|-------------|
| 1    | Weak       | 6.05        | 4.47        |
| 2    | Moderate   | 4.19        | 2.26        |
| 3    | Strong     | 4.34        | 1.31        |
Fig. 2 Mixed RF and multihop coherent FSO system with 16-QAM OFDM with MC simulation for path loss is 0.44, pointing error with $w/r = 25$ and $\delta/r = 3$ for $L = 2$ hops with coded system as BCH ($n = 15$, $k = 11$) and RS ($n = 15$, $k = 11$) code-word symbols.

Fig. 3 Mixed RF and multihop coherent FSO system with 16-QAM OFDM with MC simulation for path loss is 0.44, pointing error with $w/r = 25$ and $\delta/r = 3$ for $L = 5$ hops with coded system as BCH ($n = 15$, $k = 11$) and RS ($n = 15$, $k = 11$) code-word symbols.
and RS codes. Binary equivalent of the BCH parameters are taken for comparing with RS code-word symbols.

### 7 ASER of mixed RF and multihop coherent OFDM-FSO link

#### 7.1 Atmospheric turbulence effect

The effect of the atmospheric turbulence (moderate and strong) on the un-coded and coded system is analyzed under a constant path loss of 0.44, and the pointing error is considered constant with beamwidth and jitter error as \( \psi / r = 25 \) and \( \delta_s / r = 3 \). Figure 2 and Fig. 3, shows the ASER performance for different hop numbers. The atmospheric turbulence condition is varied as moderate and strong turbulence. From Fig. 2 and Fig. 3, it is clear that an increase in the intensity of the scintillation \( C_n^2 \) increases the symbol error rate, increase in the average signal to noise ratio decreases the average symbol error rate. The error performance of the system is affected when the number of relays is added Table.2. When the number of hops increases from \( L = 2 \) to \( L = 5 \), the system performance degrades due to system interruption.

From Fig. 2 and Fig. 3, it is shown that the performance of the system is improved when a coding technique is used. The advantages of a coherent OFDM system improve the performance of the system by reducing the error rate. At 20 dB, for strong turbulence condition, un-coded, BCH coded, and RS coded system attains SER of \( 10^{-4} \), \( 10^{-6} \) and \( 10^{-5} \) respectively for \( L = 2 \) hops. As the average SNR increases, system performance increases.

### Table 2

| S.No | Weather condition     | Attenuation (3 dB/Km) |
|------|-----------------------|------------------------|
| 1    | Very clear air        | 0.0647                 |
| 2    | Clear air/drizzle     | 0.2208                 |
| 3    | Haze                 | 0.7360                 |
| 4    | Light fog             | 4.2850                 |

### Table 3

| Un-coded and coded \((n, k, t)\) | Strong AT \(L = 2\) hops | Strong AT \(L = 5\) hops | Moderate AT \(L = 2\) hops | Moderate AT \(L = 5\) hops |
|-------------------------------|--------------------------|--------------------------|-----------------------------|-----------------------------|
| Un-coded                      | 7 × 10^{-5}              | 3 × 10^{-4}              | 3 × 10^{-7}                 | 1 × 10^{-6}                 |
| BCH coded \((15, 11, 1)\)     | 6 × 10^{-7}              | 9.7 × 10^{-6}            | 1.3 × 10^{-11}              | 2.1 × 10^{-10}              |
| RS coded \((15, 11, 2)\) symbols | 9.5 × 10^{-7}           | 5.8 × 10^{-5}           | 9.7 × 10^{-14}              | 6.2 × 10^{-12}              |
| BCH coded \((31, 21, 2)\)     | 1.9 × 10^{-9}            | 1 × 10^{-7}             | 2 × 10^{-16}                | 1 × 10^{-14}                |
| RS coded \((31, 21, 5)\) symbols | 5 × 10^{-11}           | 1 × 10^{-7}             | 5.4 × 10^{-25}              | 2 × 10^{-21}                |
| BCH coded \((255, 239, 2)\)   | 1 × 10^{-6}              | 7 × 10^{-5}             | 1.2 × 10^{-13}              | 7 × 10^{-12}                |
| RS coded \((255, 239, 8)\) symbols | 1.1 × 10^{-13}         | 1 × 10^{-8}             | 1 × 10^{-34}                | 3 × 10^{-29}                |
RS codes give better SNR gain than BCH codes for moderate turbulence condition. Table 3 shows the ASER comparison of the BCH codes and RS code-word symbols coded system with the un-coded system for \( L = 2 \) and 5 hops. Table 3 shows the performance enhancement of the RS and BCH coded system over the un-coded system at 20 dB SNR. RS coded system reduces the error rate more than BCH coded system for moderate turbulence condition, whereas for the strong turbulence condition BCH is efficient in correcting errors than RS coded system. The analysis is performed for the binary equivalent of BCH (15, 11) as RS (63, 39). As the number of hops increases, the error rate increases in the system. BCH coded system reduces the error rate of the uncoded system by \( 10^{-2} \) and \( 10^{-1} \) and RS code reduces the error rate by \( 10^{-1} \) for strong turbulence condition when the number of hops are 2 and 5. But as higher order code-word lengths are applied, RS codes outperforms BCH codes. Coding technique improves the system performance even when there is an increase in the hop numbers.

### 7.1.1 Effect of Weather condition

As it is known that weather conditions has adverse effect on the FSO system performance. Fog affects the FSO link as it hinders the line of sight. ASER performance is analyzed by varying the weather conditions for strong turbulence condition and pointing error with beam width and jitter error as \( w_\gamma / r = 25 \) and \( \delta s / r = 3 \).

From Figs. 4 and 5, it is clear that the influence of fog is high when compared with other weather conditions like clear air, drizzle, and haze. At 10 dB SNR, ASER is below \( 10^{-3} \) for all weather conditions except fog. For fog, when \( L = 5 \) hops, as the SNR increases above 30 dB, ASER reaches \( 10^{-1} \), and for haze at 20 dB SNR, ASER

![Fig. 4](image-url)

**Fig. 4** Different weather condition with Strong turbulence condition and pointing error with beam width and jitter error as \( w_\gamma / r = 25 \) and \( \delta s / r = 3 \) for \( L = 5 \) hops with as BCH \((n = 31, k = 21)\) and RS \((n = 31, k = 21)\) code-word symbols.
The performance of the system depends on the FSO link. FSO link is less affected by clear air and drizzle, whereas system performance deteriorates for adverse weather conditions like haze and fog. Compared to the un-coded system, the coded system improves the system performance. In the coding system, RS codes performs better than BCH after 20 dB. For low SNR and for lower order code-word lengths, BCH is efficient than RS codes. But for high SNR value and higher order code-word lengths, RS performance is better than BCH as it can correct burst errors with OFDM. Table 4 shows the

![Fig. 5](image_url) Different weather condition with Strong turbulence condition and pointing error with beam width and jitter error as \( w/r = 25 \) and \( \delta/r = 3 \) for \( L = 2 \) hops with as BCH \((n = 31, k = 21)\) and RS \((n = 31, k = 21)\) code-word symbols

| Weather condition     | ASER for \( L = 2 \) hops | ASER for \( L = 5 \) hops |
|-----------------------|-----------------------------|-----------------------------|
|                       | Un-coded | BCH coded | RS coded | Un-coded | BCH coded | RS coded |
| Clear air             | \( 4.6 \times 10^{-5} \) | \( 2 \times 10^{-7} \) | \( 2.7 \times 10^{-12} \) | \( 1.8 \times 10^{-4} \) | \( 2 \times 10^{-6} \) | \( 1 \times 10^{-8} \) |
| Drizzle               | \( 5.7 \times 10^{-5} \) | \( 3 \times 10^{-7} \) | \( 9.2 \times 10^{-12} \) | \( 2.2 \times 10^{-4} \) | \( 5 \times 10^{-6} \) | \( 3 \times 10^{-8} \) |
| Haze                  | \( 1 \times 10^{-4} \) | \( 1.3 \times 10^{-6} \) | \( 5 \times 10^{-10} \) | \( 4.4 \times 10^{-4} \) | \( 2 \times 10^{-5} \) | \( 5 \times 10^{-7} \) |
| Fog                   | 0.01     | 0.3949    | 1         | 0.04     | 0.1274    | 0.8       |

of the un-coded system is \( 10^{-4} \), BCH coded system is \( 10^{-5} \) and RS coded system is \( 10^{-10} \). From, Figs. 4 and 5, as the relay increases, system interruption increases, and SER increases.
comparative analysis of ASER performance of the multihop system when the number of hop numbers increases from $L = 2$ to $L = 5$. Un-coded system performance deteriorate when the hops increases and when the weather condition is adverse. ASER of BCH and RS coded system is reduced by $10^{-2}$ and $10^{-6}$ respectively than the un-coded system at 20 dB SNR under clear, drizzle and haze weather condition, when the hop number is 2. When the hop number is 5, at 20 dB SNR value, except fog and haze for all the other weather conditions the ASER of the un-coded system is improved by $10^{-2}$ when introducing BCH codes and above $10^{-4}$ after the implementation of RS codes.

### 7.1.2 Effect of Pointing error

The effect of pointing error is analyzed by varying the normalized beam width and jitter error. Beamwidth $w_z/r$ is increased from 2 to 5, and jitter error $\delta_z/r$ is increased from 2 to 5. The analysis is performed for strong turbulence and path loss as 0.44 with average SNR of 35 dB.

From Fig. 6, it is shown that increases in beam width decrease the SER of the system, whereas an increase in jitter error increases the SER. An increase in beam width from 2 to 3 decreases the SER by 0.0072 for $L = 2$ hops, and for $L = 5$ hops, SER falls by 0.017. When the width of the beam is increased, it leads to better SER performance than narrow beamwidth under the condition of misalignment (Wang, Ping, et al. 2015). SER performance degradation due to an increase in the number of hops can be reduced by increasing the beamwidth. An increase in jitter error from 4 to 5 for beam width 5 increases the SER by 0.0213 and 0.069 for $L = 2$ and five hops, respectively. The lower value of jitter does not have much impact on system performance when the strength of the jitter increases; alignment between the transmitter and receiver is worsening, which leads to degradation in the performance of the multihop system.

### 7.1.3 Outage Probability

Outage Probability and the system cost increases with the increase in the number of relays. Outage probability is measured under different atmospheric turbulence conditions with fixed path loss, weather, and pointing error. The beam width and jitter error are taken as $w_z/r = 25$ and $\delta_z/r = 3$, respectively (Wang et al. 2016). The outage performance of the
single RF link and serial relaying FSO system is analyzed for the different number of hops. For the RF link, the fading figure and the shape parameter value is taken as \( m = 2.5 \) and \( p = 1.15 \), respectively (Zedini et al. 2016) for the Generalized Gamma fading channel. The outage probability of the system decreases with the decrease in the normalized threshold value. As the normalized threshold value increases, the Outage probability increases and reaches 1 for more than \(-10\) dB. As the number of relays increases, the outage probability increases since the system’s outage increases as the number of hops increases. From Fig. 7, for the normalized threshold value of \(-15\) dB, as the number of hops rises from \( L = 2 \) to \( L = 5 \), outage probability increases by 0.005 for moderate turbulence and 0.007 for strong turbulence. Along with the increase in the hop numbers, an increase in scintillation intensity increases the system’s outage.

8 Conclusion

OP and ASER of the single RF and multihop coherent OFDM-FSO system are derived for RF link with Generalized Nakagami-m fading channel and FSO with Gamma-Gamma distribution. Performance analysis is done for coherent OFDM-FSO system, which follows DF relaying scheme. The influence of different atmospheric turbulence conditions, weather conditions, and pointing error on both uncoded and coded system are shown. The analytical results show that in both uncoded and coded system, an increase in hop numbers increases the system interruption in case of extending the coverage area. FSO link performance is severely affected by fog in both detection schemes. But the coded system improves the performance of the un-coded system. In a coded system, usage of RS codes improves the performance of the system efficiently than BCH codes for
high SNR values and for higher order code-word lengths. At low SNR values, BCH coded system performs better than RS coded system and un-coded system.

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