Performance Analysis of RIS-Assisted Source Mixed RF/FSO Relay Networks

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Abstract—This letter proposes and evaluates the performance of reconfigurable intelligent surface (RIS)-assisted source multiuser mixed radio frequency (RF)/free space optical (FSO) relay network with opportunistic user scheduling. Closed-form analytical approximations are derived for the outage probability and average symbol error probability (ASEP) assuming Rayleigh and Gamma-Gamma fading models for the RF and FSO channels, respectively. Moreover, to gain more insight into the system behavior, the system is studied at the high signal-to-noise ratio (SNR) regime whereby the diversity order and coding gain are derived and analyzed. The results illustrate that the system performance is dominated by the worst hop and that the diversity order is equal to $G_d = \min(KN, \alpha, \beta, \zeta^2)$, where $K$ is the number of RF users, $N$ is the number of reflecting elements at each user, $\alpha$ and $\beta$ are the atmospheric turbulence parameters of the FSO link, and $\zeta^2$ is a measure for the alignment quality of the FSO link. In addition, findings show that for the same diversity order, $N$ is more impactful on the system performance than $K$ through the coding gain $G_c$.

Index Terms—Reconfigurable intelligent surface, opportunistic user scheduling, Rayleigh fading, Gamma-Gamma fading.

I. INTRODUCTION

Free space optical (FSO) communication has been recently proposed as an efficient means to deal with the “last-mile” problem in wireless networks [1]. In such systems, the data transmission takes place between an optical transmitter and a receiver located, for example, on high buildings, separated by several hundred meters.

Relay networks are also efficient in handling the multipath fading problem in wireless networks [2]. A mixture of relay and FSO networks has been introduced to increase the coverage distance of FSO networks, which is usually limited to a few hundred meters due to atmospheric turbulence conditions [3]. The mixed radio frequency (RF)/FSO relaying can be used to multiplex multiple users with only RF capability can be multiplexed into a single FSO link [4].

Owing to their excellent features, the reconfigurable intelligent surfaces (RISs) have recently attracted a noticeable attention as a promising technique for future wireless communication networks. An RIS is an artificial surface, made of electromagnetic material, that is capable of customizing the propagation of the radio waves impinging upon it [5]. It has been proposed as a new low-cost and less complicated solution to realize wireless communication with high energy and spectrum efficiencies [6].

In [7], it has been shown that RIS has better performance than conventional massive multiple-input multiple-output systems as well as better performance than multi-antenna amplify-and-forward relaying networks with smaller number of antennas, while reducing the system complexity and cost. Authors in [8] considered a dual-hop mixed FSO/RF network, where a RIS has been used on the second hop to forward the optical source message to destination.

There exists another important scenario, where the RIS is used as a transmitter along with the RF signal generator to help the source in sending its message to destination [9]. In this letter, we consider this scenario where multiple RIS-assisted sources or users are connected to a relay node via RF links and the relay is connected to a destination via a FSO link. Opportunistic user scheduling is used to select among users. Closed-form analytical approximations are derived for the outage probability and average symbol error probability (ASEP) assuming Rayleigh and Gamma-Gamma fading channels for the RF and FSO links, respectively. In addition, the system is studied at the high signal-to-noise ratio (SNR) regime, where the diversity order and coding gain are provided and discussed. Up to authors knowledge, the considered scenario and results are being provided for the first time in this work.

II. SYSTEM AND CHANNEL MODELS

Consider a dual-hop mixed RF/FSO relay network consisted of $K$ RIS-assisted sources on the first hop $U_k$ ($k = 1, \ldots, K$), one decode-and-forward (DF) relay $R$, and one destination $D$. The sources are connected with the relay through RF links, and the relay is connected with a destination through a FSO link. It is assumed that each user is equipped with $N$ reflecting elements, the relay is equipped with a single antenna and a single photo-aperture transmitter, and the destination is equipped with a single antenna. The communication is assumed to operate in a half-duplex mode conducted over two phases: selected user $U_{sel} \rightarrow R$ and $R \rightarrow D$. The received signal at $R$ from the $k$th user can be expressed as

$$y_{k,r} = \sqrt{P_k} \sum_{i=1}^{N} h_{k,r,i} x_{k,r} + n_r,$$  \hspace{1cm} (1)

where $P_k$ is the transmit power of the $k$th user, $N$ is the number of reflecting elements, $h_{k,r,i}$ is the channel coefficient of the $i$th reflecting element at $U_k$ and $R$, $x_{k,r}$ is the transmitted symbol of $U_k$ with $\mathbb{E}\{|x_{k,r}|^2\} = 1$, and $n_r \sim \mathcal{N}(0, N_0, r)$ is an additive white Gaussian noise (AWGN) term, where $\mathbb{E}\{\cdot\}$ is the mathematical expectation. Using (1), the SNR at $R$ due to $U_k$ can be written as [6]

$$\gamma_{U_k,R} = \frac{P_k}{N_0, r} \left( \sum_{i=1}^{N-1} |h_{k,r,i}| \right)^2.$$ \hspace{1cm} (2)

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According to opportunistic user scheduling, the source selection takes place such that \( \gamma_{U_{k}, R} = \max_{k} \{ \gamma_{U_{k}, R} \} \). The subcarrier intensity modulation (SIM) scheme is employed at R, where a standard RF coherent/noncoherent modulator and demodulator can be used for transmitting and recovering the source data [10]. At R, after filtering by a bandpass filter, a direct current (DC) bias is added to the filtered RF signal to ensure that the optical signal is non-negative. Then the biased signal is sent to a continuous wave laser driver. The retransmitted optical signal at R is written as

\[
y_{r, \text{opt}} = \sqrt{P_{\text{opt}}(1 + M_{\text{Sel}, r})},
\]

where \( P_{\text{opt}} \) denotes the average transmitted optical power and it is related to the relay electrical power \( P_{r} \) by the electrical-to-optical conversion efficiency \( \eta_{r} = P_{\text{opt}} \), where the modulation index, and \( y_{\text{Sel}, r} \) is the RF received signal at R from the selected source. The optical signal at D received from R at the second phase of communication can be expressed as

\[
y_{r, d} = \sqrt{P_{\text{ele}} \left[ 1 + M_{\text{Sel}, r} \tfrac{g_{r}}{d_{r}^{2}} + n_{r} \right]} + n_{d}, \tag{4}
\]

where \( n_{r} \sim \mathcal{N}(0, N_{0, d}) \) is an AWGN term at D. Moreover, the channel coefficient of the R → D link, which is given by \( g_{r, d} \), is modelled as \( g_{r, d} = g_{a}g_{f} \), where \( g_{a} \) and \( g_{f} \) are the average gain and the fading gain of the FSO link, respectively [11]. When the DC component is filtered out at D and an optical-to-electrical conversion is performed and assuming \( M = 1 \), the received signal can be expressed as

\[
y_{r, d} = g_{r, d} \sqrt{P_{\text{ele}}} \left( \sqrt{P_{\text{Sel}} h_{\text{Sel}, r} x_{\text{Sel}, r} + n_{r}} \right) + n_{d}, \tag{5}
\]

where \( P_{\text{ele}} = \eta_{r} P_{r} \) is the electrical power received at D with \( \eta_{r} \) is the optical-to-electrical conversion efficiency and \( P_{r} \) is the transmit power at R. From [5], the end-to-end (e2e) SNR at D can be written using the standard approximation \( \gamma_{D} \equiv \min(\gamma_{U_{k}, R}, \gamma_{R, D}) \) as

\[
\gamma_{D} = \frac{\gamma_{U_{k}, R} \gamma_{R, D}}{\gamma_{R, D} + \gamma_{R, D}}. \tag{6}
\]

We assume that the channel coefficients between the users and the relay R \( \{ h_{k, r, i}, k = 1, ..., K; i = 1, ..., N \} \) are Rayleigh distributed with mean \( \mu \) and variance \( (\mu^{2} - 1) \). That is, their mean powers \( E[|h_{k, r, i}|^{2}] = 1 \). The cumulative distribution function (CDF) of \( \gamma_{U_{k}, R} \) assuming independent identically distributed (i.i.d.) channels \( \{ \gamma_{1, r}, \gamma_{2, r}, ..., \gamma_{K, r}, \gamma_{1, u}, ..., \gamma_{K, u} \} \) is given by

\[
F_{\gamma_{U_{k}, R}}(\gamma) = 1 - e^{-\frac{C}{\gamma}} \sum_{i=0}^{N-1} \frac{\gamma^{i}}{(C \gamma_{U_{k}, R})^{i+1}}, \tag{7}
\]

where \( C = 1 + (N - 1) \Gamma^{2} \left( \frac{3}{2} \right), \) with \( \Gamma(\cdot) \) is the Gamma function as defined in [12] Eq. (8.310)].

We assume that the FSO link experiences a unified Gamma-Gamma fading model with pointing errors effect whose SNR probability density function (PDF) is given by [4], [13]

\[
f_{\gamma_{D}}(\gamma) = \frac{C^{2}}{\gamma^{\alpha} \Gamma(\alpha) \Gamma(\beta)} \left[ \frac{\alpha}{\beta} \left( \frac{\gamma}{\gamma_{r, d}} \right)^{\beta} \right] \left( \gamma^{2} + 1 \right)^{-1} \left( \gamma^{2} \right)^{1/2}, \tag{8}
\]

where \( \zeta \) is the ratio between the equivalent beam radius at the receiver and the pointing error displacement standard deviation (jitter) at the receiver (i.e. when \( \zeta \to \infty \), we get the non-pointing error case) [4], \( r \) is the parameter defining the type of detection technique (i.e. \( r = 1 \) represents heterodyne detection and \( r = 2 \) represents intensity modulation (IM)/direct detection (DD)), \( \alpha \) and \( \beta \) are the fading parameters related to the atmospheric turbulence conditions, \( \gamma_{r, d} = \frac{P_{\text{ele}}}{N_{0, r}} E[|g_{r, d}|^{2}] \), \( \mu_{r, d} = \frac{P_{\text{ele}}}{N_{0, r}} E[|g_{r, d}|^{2}] \), and \( G(\cdot) \) is the Meijer G-function as defined in [12] Eq. (9.301)]. We assume plane wave propagation as assumed in [14].

III. PERFORMANCE ANALYSIS

A. Outage Probability

The outage probability is defined as the probability that the SNR at the selected destination goes below a predetermined outage threshold \( \gamma_{\text{out}} \), i.e. \( P_{\text{out}} = Pr(\gamma_{D} \leq \gamma_{\text{out}}) \), where \( Pr[\cdot] \) is the probability operation and \( \gamma_{\text{out}} \) is a predetermined outage threshold. The CDF of \( \gamma_{D} \) can be written as [10]

\[
F_{\gamma_{D}}(\gamma) = 1 - \left( 1 - F_{\gamma_{U_{k}, R}}(\gamma) \right) \left( 1 - F_{\gamma_{r, d}}(\gamma) \right), \tag{9}
\]

where \( F_{\gamma_{U_{k}, R}}(\gamma) \) and \( F_{\gamma_{r, d}}(\gamma) \) are the CDFs of first hop and second hop SNRs, respectively.

1) First Hop Link: Using opportunistic user scheduling, the CDF \( F_{\gamma_{U_{k}, R}}(\gamma) \) can be written for i.i.d. users channels as

\[
F_{\gamma_{U_{k}, R}}(\gamma) = \left( F_{\gamma_{u}}(\gamma) \right)^{K}, \tag{10}
\]

where \( F_{\gamma_{u}}(\gamma) \) is the CDF provided by [7]. Upon substituting (7) in (10) and using the Binomial rule, we get

\[
F_{\gamma_{U_{k}, R}}(\gamma) = \sum_{k=0}^{K} \left( \frac{K}{k} \right)^{-1} e^{-\frac{x}{\left( \frac{\gamma_{\text{out}}}{\mu_{r, d}} \right)}} \sum_{j=0}^{N-1} \sum_{j_{0}=0}^{N-1} \left( \gamma_{U_{k}, R} \right)^{k} \left( \frac{\gamma_{r, d}}{\gamma_{\text{out}}} \right)^{j} \times \frac{1}{(C \gamma_{U_{k}, R})^{j} \prod_{n=1}^{j} n!}, \tag{11}
\]

2) Second Hop Link: The CDF \( F_{\gamma_{r, d}}(\gamma) \) can be obtained by integrating the PDF in (8) using \( \int_{0}^{\gamma_{\text{out}}} f_{\gamma_{r, d}}(\gamma) d\gamma \) to get

\[
F_{\gamma_{r, d}}(\gamma) = A G^{r+1}_{r+1, r+1} \left[ \frac{B}{\gamma_{r, d}} \right]^{-1} \left( \frac{1}{\gamma_{\text{out}}} \right) \chi_{2, 0}, \tag{12}
\]

where \( A = \frac{(\alpha \beta)^{\alpha \beta}}{(2\pi)^{\frac{r-2}{2}} \Gamma(\alpha) \Gamma(\beta)} \), \( B = \frac{\left( \gamma_{\text{out}} \right)^{(\alpha \beta)}}{(2\pi)^{\frac{r-2}{2}} \Gamma(\alpha) \Gamma(\beta)} \), \( \chi_{1} = \frac{\gamma_{\text{out}}^{2} + \gamma_{r, d}^{2}}{\gamma_{\text{out}}^{2} + \gamma_{\text{out}}^{2}}, \cdots, \frac{\gamma_{\text{out}}^{2} + \gamma_{r, d}^{2}}{\gamma_{\text{out}}^{2} + \gamma_{\text{out}}^{2}}, \) and \( \chi_{2} = \gamma_{\text{out}}^{2}, \gamma_{\text{out}}^{2}, \gamma_{\text{out}}^{2}, \gamma_{\text{out}}^{2}, \gamma_{\text{out}}^{2}, \gamma_{\text{out}}^{2}, \gamma_{\text{out}}^{2}, \) \( \gamma_{\text{out}}^{2}, \gamma_{\text{out}}^{2}, \gamma_{\text{out}}^{2}, \) and \( \gamma_{\text{out}}^{2} \) comprises of 3r terms. Upon substituting (11) and (12) in (9) and after some simplifications, we get (13). By replacing \( \gamma \) by \( \gamma_{\text{out}} \), the outage probability is obtained.
the asymptotic outage probability can be written as Eq. (3.38), we get (14).

\[
\text{ASEP} = \frac{a \sqrt{b}}{2 \sqrt{\pi}} \sum_{k=0}^{\infty} \frac{k!}{k^{\frac{3}{2}}} \sum_{j=0}^{N-1} \frac{\gamma^{N-j} \left( C_{\gamma_x} \right)^{\frac{1}{2}}}{\prod_{n=1}^{j} n!} \left( 1 - AG_{r+1,3r+1} \right) + \frac{B}{\gamma_{r,d}^{\frac{1}{2}}} 
\]

+ \frac{B}{\gamma_{r,d}^{\frac{1}{2}}} \left[ \frac{\gamma^{3r+2}}{\gamma_{r,d}^{\frac{1}{2}}} \right] \frac{B}{\gamma_{r,d}^{\frac{1}{2}}} \left[ \frac{\gamma^{1,\chi_1}}{\gamma_{r,d}^{\frac{1}{2}}} \right].
\]

\[\text{(13)}\]

B. Average Symbol Error Probability

The ASEP is expressed in terms of the CDF of $\gamma_d$ as

\[
\text{ASEP} = \frac{a \sqrt{b}}{2 \sqrt{\pi}} \sum_{k=0}^{\infty} \frac{k!}{k^{\frac{3}{2}}} \sum_{j=0}^{N-1} \frac{\gamma^{N-j} \left( C_{\gamma_x} \right)^{\frac{1}{2}}}{\prod_{n=1}^{j} n!} \left( 1 - AG_{r+1,3r+1} \right) + \frac{B}{\gamma_{r,d}^{\frac{1}{2}}} \left[ \frac{\gamma^{3r+2}}{\gamma_{r,d}^{\frac{1}{2}}} \right] \frac{B}{\gamma_{r,d}^{\frac{1}{2}}} \left[ \frac{\gamma^{1,\chi_1}}{\gamma_{r,d}^{\frac{1}{2}}} \right].
\]

\[\text{(14)}\]

IV. ASYMPTOTIC OUTAGE PERFORMANCE

The outage probability can be written at high SNR values as $P_{\text{out}} \simeq (G_{c} - \text{SNR})^{-G_{d}}$, where $G_{c}$ and $G_{d}$ are the coding gain and diversity order of the system, respectively. Here, the CDF in [12] becomes as follows

\[
F_{\gamma_d}(\gamma) \simeq F_{\gamma_{u,d}(\gamma)}(\gamma) + F_{\gamma_{r,d}(\gamma)}(\gamma).
\]

\[\text{(16)}\]

1) First Hop Link: At high average SNR values ($\gamma_{u,r} \rightarrow \infty$), the CDF of a user channel SNR is approximated by

\[
F_{\gamma_{u,r}}(\gamma) \simeq \frac{\gamma^N}{(C_{\gamma_{u},r})^N N!}.
\]

\[\text{(17)}\]

Now, upon substituting (17) in (10), we get

\[
F_{\gamma_{u,d},r}(\gamma) \simeq \frac{\gamma^N}{(C_{\gamma_{u},r})^N (N!)^K}.
\]

\[\text{(18)}\]

2) Second Hop Link: From [16 Eq. (07.34.06.006.01)], as $\gamma_{r,d} \rightarrow \infty$, or equivalently as $z \rightarrow 0$, the Meijer G-function can be approximated using the following series representation

\[
G_{p,q}^{m,n} \left[ \begin{array}{c}
\frac{a_1, \ldots, a_p}{b_1, \ldots, b_q}
\end{array} \right] = \sum_{k=1}^{m} \prod_{j=1, j \neq k}^{m} \Gamma(\delta_1) \prod_{j=1}^{p} \Gamma(\delta_2) \prod_{j=1}^{n} \Gamma(1 - \delta_2) \prod_{j=1}^{n} \Gamma(1 - \delta_2) \times z^{b_1} (1 + o(z)),
\]

\[\text{(19)}\]

where $\delta_1 = b_j - b_k$, $\delta_2 = a_j + b_k$, $\delta_3 = a_j - b_k$, $\delta_4 = b_j + b_k$, and $p \leq q$ is required. Defining $\nu = \min(\alpha, \beta, \zeta^2)$, then we have

\[
F_{\gamma_{r,d}}(\gamma) \simeq \frac{\gamma^N}{(C_{\gamma_{u},r})^N (N!)^K}.
\]

\[\text{(19)}\]

where $\gamma$ is constant. Upon substituting (19) and (19) in (16), the asymptotic outage probability can be written as

\[
P_{\text{out}}^\infty \left( \frac{C}{\gamma_{\text{out}}(N!)^N N!} \right)^{-G_{d}} \left( \frac{\gamma^{3r+2}}{\gamma_{r,d}^{\frac{1}{2}}} \right) \frac{B}{\gamma_{r,d}^{\frac{1}{2}}} \left[ \frac{\gamma^{1,\chi_1}}{\gamma_{r,d}^{\frac{1}{2}}} \right].
\]

\[\text{(20)}\]

It is clear from (21) that the performance of the considered system is dominated by the worst hop, which depends on the parameters of these two hops. Therefore, the diversity order $G_{d}$ is equal to $\min(KN, 2)$ and based on this value, the system performance could be dominated by either: 1) the first hop (i.e. $K$ and $N$) when it is the worst hop, 2) and the second hop (i.e. $\alpha$, $\beta$, $\zeta^2$, and $r$) when it is the worst hop.

V. SIMULATION AND NUMERICAL RESULTS

A good matching between the derived results against simulations is clear in Fig. [1]. It is clear that as $K$ increases, the diversity order $G_{d}$ increases and better the achieved performance. This is expected as when the first hop dominates the performance, $G_{d} = KN$. As $\gamma_{r,d}$ is kept constant, a noise floor appears in the results when $\gamma_{u,r}$ becomes close to or larger than $\gamma_{r,d}$. This is because in this region, the second hop becomes dominant and no gain is achieved in the performance when $\gamma_{u,r}$ keeps increasing. All the curves converge to the same performance in this region as they have no effect here.

Fig. [2] again validates the derived results against simulations. We can see that as $N$ increases, $G_{d}$ increases and better the achieved performance. To study the impact of $N$, $\gamma_{r,d}$ is kept constant here. This also results in a noise floor in the results, where when $\gamma_{u,r}$ becomes close to or larger than $\gamma_{r,d}$, no gain is achieved in the performance as the second hop becomes dominant. Accordingly, all the curves converge to the same performance in this region as they have no effect here.

Fig. [3] compares the performance under different values of $K$ and $N$. It is obvious that when $(K = N = 1)$, $G_{d} = 1$. For the cases where $(K = 2, N = 1)$ and $(K = 1, N = 2)$, $G_{d} = 2$, but the later gives better results in terms of coding.
gain $G_c$. This informs us that one user with two reflecting elements outperforms two users each of one reflecting element. When $(K = N = 2)$, $G_d = 4$ and the best performance is achieved. A noise floor appears as $\gamma_{r,d}$ is kept constant here.

The ASEP is studied in Fig. 3 for BPSK modulation scheme ($p = q = 1$), $\gamma_{u,r}$ is kept constant and $r = 1$. Clearly, when the FSO link minimum parameter is increased $\gamma$, $G_d$ is increased and the performance is more enhanced. Increasing $\gamma^2$ reduces the alignment error. On the other hand, when $\gamma^2 = 0.9$ is kept constant and $\alpha$ and $\beta$ are increased, only $G_c$ is enhanced. This is because $G_d$, when the FSO link is dominant, $G_d = \min(\alpha, \beta, \gamma^2)$. Again, as $\gamma_{u,r}$ is kept constant here, a noise floor appears in the results when $\gamma_{u,c}$ becomes close to or larger than $\gamma_{r,d}$, as expected.

The ASEP is portrayed in Fig. 3 for two modulation schemes: BPSK ($p = q = 1$) and QPSK ($p = 1, q = 0.5$). We can see that the QPSK is outperforming the BPSK, as expected. This impact comes in terms $G_c$. In addition, the impact of increasing $K$ on the performance is clear here through increasing $G_d$. Again, a noise floor appears in the results as $\gamma_{r,d}$ is kept constant in this figure.

VI. CONCLUSION

Closed-form analytical approximations were derived for the outage probability and ASEP of RIS-assisted sources mixed RF/FSO relay network. Moreover, the system was studied at the SNR regime whereby $G_d$ and $G_c$ were provided. The results illustrated that the system performance is dominated by the worst hop and that $G_d$ is equal to $\min(KN, \alpha, \beta, \gamma^2)$. In addition, findings showed that for the same $G_d$, $N$ is more impactful on the system performance than $K$ through $G_c$.

REFERENCES

[1] D. Kedar and S. Arnon, “Urban optical wireless communications networks: The main challenges and possible solutions,” IEEE Commun. Mag., vol. 42, no. 5, pp. 2–7, 2003.

[2] J. N. Laneman, D. N. C. Tse and G. W. Wornell, “Cooperative diversity in wireless networks: efficient protocols and outage behavior,” IEEE Trans. Info. Theory, vol. 50, no. 12, pp. 3062–3080, 2004.

[3] E. Lee, J. Park, D. Han, and G. Yoon, “Performance analysis of the asymmetric dual-hop relay transmission with mixed RF/FSO links,” IEEE Photon. Technol. Lett., vol. 23, no. 21, pp. 1642–1644, 2011.

[4] J. S. Ansari, F. Yilmaz, and M.-S. Alouini, “Impact of pointing errors on the performance of mixed RF/FSO dual-hop transmission systems,” IEEE Wireless Commun. Lett., vol. 2, no. 3, pp. 351–354, 2013.

[5] M. D. Renzo et al., “Reconfigurable intelligent surfaces vs. relaying: Differences, similarities, and performance comparison,” IEEE Access, vol. 1, pp. 798–807, 2020.

[6] E. Basar, M. D. Renzo, J. D. Rosny, M. Debahb, M.-S. Alouini, and R. Zhang, “Wireless communications through reconfigurable intelligent surfaces,” IEEE Access, vol. 7, pp. 116753–116773, 2019.

[7] Q. Wu, and R. Zhang, “Intelligent reflecting surface enhanced wireless network via joint active and passive beamforming,” IEEE Trans. Wireless Commun., vol. 18, no. 11, pp. 5394–5409, 2019.

[8] L. Yang, W. Guo, and I. S. Ansari, “Mixed dual-hop FSO-RF communication systems through reconfigurable intelligent surface,” IEEE Commun. Lett., vol. 24, no. 7, pp. 1558–1562, 2020.

[9] L. Yang, F. Meng, Q. Wu, D. B. Costa, and M.-S. Alouini, “Accurate closed-form approximations to channel distributions of RIS-aided wireless systems,” IEEE Commun. Lett., Early Access, DOI 10.1109/LWC.2020.3010512.

[10] A. M. Salhab, F. Al-Qahtani, R. M. Radaydeh, S. A. Zummo, and H. Alnuweiri, “Power allocation and performance of multuser mixed RF/FSO relay networks with opportunistic scheduling and outdated channel information,” accepted in IEEE/OSA J. Lightwave Technol., 2016.

[11] W. Zhang, S. Hranilovic, and C. Shi, “Soft-switching hybrid FSO/RF links using short-length raptor codes: Design and implementation,” IEEE J. Sel. Areas Commun., vol. 27, no. 9, pp. 1698–1708, 2009.

[12] I. S. Gradshteyn and I. M. Ryzhik, Tables of Integrals, Series and Products, 6th ed., San Diego: Academic Press, 2000.

[13] I. S. Ansari, F. Yilmaz, and M.-S. Alouini, "Performance analysis of free-space optical links over Malaga (M) turbulence channels with pointing errors," IEEE Trans. Wireless Commun., vol. 15, no. 1, pp. 91–102, 2016.

[14] A. M. Salhab, "A new scenario of triple-hop mixed RF/FSO/RF relay network with generalized order user scheduling and power allocation," J. on Wireless Commun. and Netw., (2016) 2016:260, 2016.

[15] M. R. McKay, A. L. Grant, and I. B. Collings, "Performance analysis of MIMO-MRC in double-correlated Rayleigh environments," IEEE Trans. Wireless Commun., vol. 55, pp. 497–507, 2007.

[16] Wolfram, “The Wolfram functions site,” Available: http://functions.wolfram.com 2013.