Packet Unloading Strategies for Buffer-Aided Multiuser Mixed RF/FSO Relaying

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***Abstract*—In this paper, a buffer-aided (BA) multiuser dual-hop mixed radio frequency (RF)/ free space optical (FSO) communication system is considered. For this setup, multiple RF users communicate with a single decode-and-forward (DF) relay with storage capabilities where the relay multiplexes the received packets along a FSO link. We analyze the scenario where the relay is equipped with multiple buffers and we propose different strategies for unloading these buffers for the sake of generating the multiplexed FSO packet. Through a Markov chain analysis, we highlight on the different levels of tradeoff between outage probability, queuing delay and quality-of-service (QoS) differentiation that can be achieved by the proposed schemes.**

***Index Terms*—Relaying, buffer, mixed RF/FSO, performance analysis, outage probability, average queuing delay.**

I. Introduction

Dual-hop mixed radio frequency (RF)/ free space optical (FSO) communications emerged as a practical solution for future wireless networks. The most common application corresponds to the scenario where a number of RF users communicate with a relay node that multiplexes the users' information into a single high-speed line-of-sight (LOS) FSO link [1]. The literature on mixed RF/FSO communications is extensive whether in the context of amplify-and-forward (AF) relaying [2]–[4] or decode-and-forward (DF) relaying [5]. The existing research revolves around studying the impact of the underlying FSO and RF channel models [2]–[5], channel state information availability [3] and RF interference [4].

While the scenario of buffer-free (BF) relaying was considered in [1]–[5], there has been a growing interest in buffer-aided (BA) relaying whether in the context of RF networks [6], [7] or FSO networks [8]. Equipping the relays with buffers contributes to reducing the outage probability (OP) of the network at the expense of introducing queuing delays [6]–[8]. A DF relay selection protocol with half-duplex RF relays was introduced in [6] and then enhanced in [7]. DF relaying protocols were also introduced and analyzed in [8] in the context of full-duplex FSO relaying. In addition to RF networks and FSO networks, BA relaying was also considered for networks comprising both RF and FSO links in [9]–[11]. In [9], a single-user mixed FSO/RF scenario was considered where the trajectory of the moving relay was optimized. Multiuser mixed RF and hybrid RF/FSO relaying was studied in [10] and [11] with infinite and finite buffer sizes, respectively.

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A common approach for conceiving BA multiuser mixed RF/FSO systems consists of equipping the relay with a single buffer in which the packets from all users are stored [10], [11]. In this context, no quality-of-service (QoS) differentiation is imposed among the users that all experience the same OP and same delay. In this work, we propose an alternative approach for designing BA multiuser mixed RF/FSO systems. This approach consists of equipping the relay with multiple finite size buffers where each one of these buffers is fully dedicated to a particular RF user. We also suggest and compare different packet unloading strategies corresponding to different solutions for selecting the packets (to be multiplexed) from the available buffers. This approach not only ensures different QoS levels to different classes of users, but it also offers more flexibility in the network design in the sense of achieving different levels of tradeoff between OP and delay.

The BA solution is not related to the popular caching technique in wireless networks. Caching reduces traffic load by exploiting the high degree of content reuse where, during off-peak periods, popular content is stored at wireless edges so that the peak hour demands can be met with reduced latency [12]. As such, wireless caching is an application-layer solution that is motivated by the fact that modern data traffic is dominated by videos with a large number of users requesting popular videos during peak hours. On the other hand, the considered BA approach is a physical-layer solution that is not specific to video applications. The BA solution targets enhancing the end-to-end outage performance of each user's dedicated traffic in the absence of content sharing. While the frequency of caching is in the order of hours [12], the shared queue in the BA system is loaded and unloaded several times every millisecond.

II. System Model and Relaying Strategy

Consider a dual-hop mixed RF/FSO network where K RF users (denoted by $\mathrm{S}_1,\dots,\mathrm{S}_K$) communicate with an optical destination (D) through a BA relay (R). We assume that an orthogonal RF multiple access scheme is implemented. A practical application corresponds to cellular setups where each RF user (source) is covered by a single base-station (R) as highlighted in Fig. 1. The base-station multiplexes the data from the mobile users for the sake of backhauling to a flying platform, FSO gateway or the core network. If a user is covered by more than one base-station (at the cell edges, for example), a relay selection protocol needs to be implemented prior to the suggested queuing scheme. This scenario is beyond the scope of this letter and must be addressed in future works. The main motivation behind using a FSO link between R

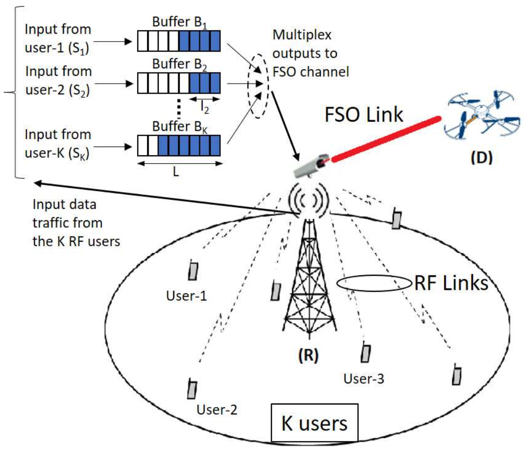

Fig. 1. Multiuser Mixed RF/FSO Relaying.

and D resides in the high data rates that can be realized along such optical links given the abundance of the optical spectrum (compared to the RF spectrum). Consequently, the data traffic from a large number of mobile users (K) can be multiplexed along a single FSO link. Moreover, the optical spectrum is license-free which constitutes an additional reason why FSO links constitute a viable alternative to RF links. Finally, FSO constitutes a cost-effective alternative to optical fibers overcoming expensive installation.

The destination is an intensity-modulation with direct-detection (IM/DD) receiver that is corrupted by additive white Gaussian noise (AWGN). The FSO link R-D is in outage if the signal-to-noise ratio (SNR) γ_{FSO} falls below a threshold level $\gamma_{\text{FSO,th}}$ needed to achieve the target bit rate R_{FSO}. We adopt a channel model that takes into account the combined effects of path loss, gamma-gamma turbulence-induced scintillation and misalignment-induced fading [13]. For this FSO channel model, the outage probability is given by [13]:

$$q = \frac{\xi^2}{\Gamma(\alpha)\Gamma(\beta)} G_{2,4}^{3,1}\left[\frac{\alpha\beta\xi^2}{(\xi^2+1)P_M}\middle| \begin{matrix} 1, \xi^2+1 \\ \xi^2, \alpha, \beta, 0 \end{matrix}\right], \tag{1}$$

where $P_M \triangleq \sqrt{\frac{\gamma_{\text{FSO}}}{\gamma_{\text{FSO,th}}}}$ is the power margin, $\Gamma(\cdot)$ is the Gamma function and $G_{p,q}^{m,n}[\cdot]$ is the Meijer G-function. The parameters α and β of the gamma-gamma distribution depend on the distance d between R and D and the refractive index structure parameter C_n^2 through the Rytov variance [13]. Finally:

$$\xi = \frac{\omega_z}{2\sigma_s}\left[\frac{\omega_z}{\sqrt{2}a}\text{erf}\left(\sqrt{\frac{\pi}{2}}\frac{a}{\omega_z}\right)\right]^{\frac{1}{2}} e^{\frac{\pi}{4}\frac{a^2}{\omega_z^2}}, \tag{2}$$

where a is the radius of the receiver, ω_z is the beam waist and σ_s is the pointing error displacement standard deviation.

We denote by h_k the channel coefficient of the RF link S_k-R. We adopt a Rayleigh block fading model where h_k is a circularly symmetric complex Gaussian random variable with zero mean and variance Ω_k for $k = 1, \ldots, K$. The RF link is in outage if the average SNR γ_{RF} falls below a threshold level $\gamma_{\text{RF,th}}$ needed to achieve the target bit rate R_{RF}. The outage probability along the link S_k-R can be determined from:

$$p_k = 1 - \exp\left(-\frac{\gamma_{\text{RF,th}}}{\Omega_k \gamma_{\text{RF}}}\right) \quad ; \quad k = 1, \ldots, K. \tag{3}$$

We assume that capacity-achieving channel codes are used along the constituent RF and FSO links. If a decoding error is detected at the receiver, an outage event is declared along the corresponding link and the received packet is dropped. We denote by M the quantity given by $M = \frac{R_{\text{FSO}}}{R_{\text{RF}}}$. Since higher data rates can be achieved along FSO links, then $M \geq 1$. In what follows, we assume that M is an integer.

In this work, we consider a BA relay that is equipped with K buffers of size L each where the k-th buffer, denoted by B_k, is used to temporarily store the RF packets received from the k-th user for $k = 1, \ldots, K$. The relaying protocol is as follows. If the k-th buffer is not full, the k-th user proceeds with the transmission of a RF packet that, if decoded successfully, will be stored in this buffer. On the other hand, if B_k is full, the packet will not be transmitted to R and it will be stored at the head of the queue at S_k. In its turn, R merges M RF packets into a FSO packet that is transmitted to D along the optical link. Consequently, the relaying protocol does not require any prior knowledge of the outage probabilities in (1) and (3) and, hence, can be implemented in real-time. We denote by l_k the number of packets stored in the k-th buffer (with $0 \leq l_k \leq L$) for $k = 1, \ldots, K$. The packet unloading strategy corresponds to the method that is adopted for the selection of the M RF packets from the $\sum_{k=1}^{K} l_k$ packets stored in the K buffers. We assume that even if the number of stored packets is smaller than M, these packets can still be multiplexed into a FSO packet by adding some redundant packets. Consequently, the buffers will be completely emptied if $\sum_{k=1}^{K} l_k \leq M$ and the R-D link is not in outage. Finally, the adopted BA relaying scheme prioritizes transmission from R which contributes to reducing the number of full buffers and, hence, increases the availability of the S-R links.

III. Packet Unloading Strategies

We denote by $\mathbf{l} = (l_1, \ldots, l_K)$ and $\mathbf{l}' = (l'_1, \ldots, l'_K)$ the K-dimensional vectors containing the numbers of packets stored in the K buffers before and after the transmission attempt from R, respectively. The following cases arise. (i): If the transmission attempt from R is unsuccessful (i.e. the R-D link is in outage with probability q), then $\mathbf{l}' = \mathbf{l}$ since no packets can be unloaded in this case. (ii): If the R-D link is not in outage and $\sum_{k=1}^{K} l_k \leq M$, then $\mathbf{l}' = (0, \ldots, 0)$ since all stored packets can be unloaded in this case irrespective of the adopted packet unloading strategy. (iii): If the R-D link is not in outage and $\sum_{k=1}^{K} l_k > M$, then $\mathbf{l}'$ is determined according to the implemented unloading strategy with the following relation holding for all unloading techniques: $\sum_{k=1}^{K}(l'_k - l_k) = M$. In this section, we propose three packet unloading strategies and we focus on the case $\sum_{k=1}^{K} l_k > M$.

A. Strategy 1: Seq-B

The first strategy corresponds to spanning the non-empty buffers sequentially (*Seq-B*) and can be implemented as shown in Algorithm 1. For example, if $\mathbf{l} = (6, 0, 3, 5)$ and $M = 8$, then $\mathbf{l}' = (3, 0, 0, 3)$ implying that 3, 3 and 2 packets are unloaded from the heads of B_1, B_3 and B_4, respectively.

```
Data: l = (l_1, ..., l_K) and M;
Result: l' = (l'_1, ..., l'_K);
initialization: l' = l, M_sel = 0 and k = 0;
while M_sel < M do
    k = k mod K + 1;
    if l'_k > 0 then
        l'_k = l'_k - 1;
        M_sel = M_sel + 1;
    end
end
```

Algorithm 1: The *Seq-B* unloading strategy.

B. Strategy 2: Seq-U

This strategy spans the users sequentially resulting in the highest priority to S_1, followed by $S_2, \ldots$. In other words, the *Seq-U* strategy attempts to empty the buffer B_1 first followed by B_2 then $B_3, \ldots$. The flowchart of this strategy is shown in Algorithm 2. For example, if $\mathbf{l} = (6, 0, 3, 5)$ and $M = 8$, then $\mathbf{l}' = (0, 0, 1, 5)$ implying that 6 and 2 packets are unloaded from the heads of the buffers B_1 and B_3, respectively. In this case, no packets are unloaded from the buffer B_4 since $M = 8$ packets were already selected before reaching this buffer.

```
Data: l = (l_1, ..., l_K) and M;
Result: l' = (l'_1, ..., l'_K);
initialization: l' = l, M_sel = 0 and k = 1;
while M_sel < M do
    if l'_k > 0 then
        l'_k = l'_k - 1;
        M_sel = M_sel + 1;
    else
        k = k + 1;
    end
end
```

Algorithm 2: The *Seq-U* unloading strategy.

C. Strategy 3: Seq-W

The third strategy spans the users sequentially starting from the worst user and ending by the best user. In this context, user S_k is judged to be in a *worse* condition compared to user $S_{k'}$ if the buffer of the former is more congested than the buffer of the latter; that is if $l_k > l_{k'}$. This strategy can be implemented as shown in Algorithm 3 where the order of the users must be updated during each of the M iterations. In other words, the *Seq-W* strategy strives to minimize the maximum number of packets stored in the K buffers. For example, if $\mathbf{l} = (6, 0, 3, 5)$ and $M = 8$, then $\mathbf{l}' = (2, 0, 2, 2)$. In this case, $\max\{\mathbf{l}'\} = 2$ for the *Seq-W* strategy while $\max\{\mathbf{l}'\} = 3$ and $\max\{\mathbf{l}'\} = 5$ for the *Seq-B* and *Seq-U* strategies, respectively.

```
Data: l = (l_1, ..., l_K) and M;
Result: l' = (l'_1, ..., l'_K);
initialization: l' = l;
for M_sel = 1, ..., M do
    k̂ = arg max_{k=1,...,K} {l'_k};
    l'_k̂ = l'_k̂ - 1;
end
```

Algorithm 3: The *Seq-W* unloading strategy.

IV. Performance Analysis

A Markov chain analysis will be adopted for analyzing the BA system. A state of the Markov chain corresponds to the vector $\mathbf{l} = (l_1, \ldots, l_K)$ resulting in a total of $(L+1)^K$ states.

A. Transition Probabilities

We first derive the transition probability $t_{\mathbf{l_o},\mathbf{l_n}}$ of moving from the originating state $\mathbf{l_o}$ to the new state $\mathbf{l_n}$.

1) Case 1: Consider the case $\mathbf{l_o} = (0, \ldots, 0)$. Since all buffers are empty, no FSO packet can be generated. Consequently, the buffers will remain empty after the transmission attempt from R and the new occupancy of the buffers will be determined solely by the status of the K RF links. This results in the following 2^K possible transitions depending on whether the K links S_k-R (for $k = 1, \ldots, K$) are in outage or not:

$$\mathbf{l_o} = (0, \ldots, 0) \to \mathbf{l_n} = (d_1, \ldots, d_K), \tag{4}$$

where $d_k \in \{0, 1\}$ for $k = 1, \ldots, K$. The value $d_k = 0$ (resp. $d_k = 1$) indicates that a packet was not delivered (resp. delivered) along the RF link S_k-R. The probability of the transition in (4) is equal to $t_{\mathbf{l_o},\mathbf{l_n}} = \prod_{k=1}^{K} P_0(d_k)$ where:

$$P_0(d_k) = \begin{cases} p_k, & d_k = 0; \\ 1 - p_k, & d_k = 1. \end{cases} \; ; \; k = 1, \ldots, K. \tag{5}$$

2) Case 2: Consider the case $\mathbf{l_o} \neq (0, \ldots, 0)$ and the R-D link is in outage. Despite the availability of a FSO packet, this packet can not be delivered to D. Consequently, the buffer occupancy remains equal to $\mathbf{l_o}$ after the transmission attempt from R resulting in the following 2^K possible transitions:

$$\mathbf{l_o} = (l_1, \ldots, l_K) \to \mathbf{l_n} = (1_1, \ldots, 1_K) + (d_1, \ldots, d_K), \tag{6}$$

with the transition probability $t_{\mathbf{l_o},\mathbf{l_n}} = q \prod_{k=1}^{K} P_1(d_k)$ where:

$$P_1(d_k) = \begin{cases} \delta_{l_k,L} + (1 - \delta_{l_k,L}) p_k, & d_k = 0; \\ (1 - \delta_{l_k,L})(1 - p_k), & d_k = 1. \end{cases} , \tag{7}$$

where $\delta_{i,j}$ stands for the Kronecker delta function ($\delta_{i,j} = 1$ if $i = j$ and $\delta_{i,j} = 0$ otherwise). In fact, when the buffer B_k is not full ($l_k \neq L$), a packet transmitted from S_k can be accommodated in this buffer. In this case, $\delta_{l_k,L} = 0$ and $P_1(0) = p_k$ while $P_1(1) = 1 - p_k$ indicating that the number of packets in B_k will remain the same if the S_k-R link is in outage while this number will increase by 1 otherwise. On the other hand, when B_k is full ($l_k = L$), no additional packets can be stored in this buffer since the transmission along the R-D link was not successful. In this case, $\delta_{l_k,L} = 1$ and $d_k = 0$ with probability 1 indicating that the number of packets stored in B_k will remain the same ($l_k + d_k = l_k = L$).

Finally, it is worth noting that some of the transitions in (6) occur with probability 0 for $(l_k, d_k) = (L, 1)$ indicating that the corresponding transition can not take place.

3) Case 3: Consider the case $\mathbf{l_o} \neq (0, \ldots, 0)$ and the R-D link is not in outage. In this case, the possibility of generating a FSO packet and the availability of the FSO link will imply that the buffers will be unloaded during the transmission attempt from R. Consequently, the following transitions are possible:

$$\mathbf{l_o} = (l_1, \ldots, l_K) \to \mathbf{l_n} = (1'_1, \ldots, 1'_K) + (d_1, \ldots, d_K), \tag{8}$$

where the value of the vector $\mathbf{l}' = (1'_1, \ldots, 1'_K)$ is determined according to the adopted unloading strategy. In fact, the packet unloading strategies discussed in Section III imply a one-to-one relation between $(l_1, \ldots, l_K)$ and $(l'_1, \ldots, l'_K)$ where $(l'_1, \ldots, l'_K) = (0, \ldots, 0)$ if $\sum_{k=1}^{K} l_k \leq M$ while $(l'_1, \ldots, l'_K)$ can be determined from algorithm 1, algorithm 2 or algorithm 3 if $\sum_{k=1}^{K} l_k > M$. The probability of the transition in (8) is equal to $t_{\mathbf{l_o},\mathbf{l_n}} = (1-q)\prod_{k=1}^{K} P_2(d_k)$ where $P_2(d_k)$ can be determined from (7) by replacing l_k with l'_k.

B. Steady-State Probability Distribution

The transition probabilities will be stacked to form the $(L+1)^K \times (L+1)^K$ state transition matrix $\mathbf{A}$ as follows:

$$\mathbf{A}_{\psi(\mathbf{l}'),\psi(\mathbf{l})} = t_{\mathbf{l},\mathbf{l}'}, \tag{9}$$

where the function $\psi(\cdot)$ is used to number the states and defines a one-to-one relation between the set of all possible states $\{0, \ldots, L\}^K$ and the set of integers $\{1, \ldots, (L+1)^K\}$:

$$\psi(\mathbf{l}) = \psi\left((l_1, \ldots, l_K)\right) = 1 + \sum_{k=1}^{K} l_k (L+1)^{K-k}. \tag{10}$$

The matrix $\mathbf{A}$ is used to evaluate the steady-state probability distribution vector π as follows [6]–[8]:

$$\pi = \left(\mathbf{A} - \mathbf{I} + \mathbf{B}\right)^{-1} \mathbf{b}, \tag{11}$$

where $\mathbf{I}$ and $\mathbf{B}$ are $(L+1)^K \times (L+1)^K$ matrices denoting the identity matrix and all-one matrix, respectively. Vector $\mathbf{b}$ is the $(L+1)^K$ vector whose elements are all equal to 1. The i-th element of the vector π stands for the probability of having l_k packets stored in B_k at steady-state for $k = 1, \ldots, K$ where $\psi\left((l_1, \ldots, l_K)\right) = i$.

Following from the joint distribution in (11), the marginal distribution of having l packets stored in B_k at steady-state can be determined as follows:

$$\pi_l^{(k)} = \sum_{i=1}^{(L+1)^K} \pi_i \mid \psi\left((l_1, \ldots, l_{k-1}, l, l_{k+1}, \ldots, l_K)\right) = i. \tag{12}$$

C. Outage Probability and Average Packet Delay

We denote by $P^{(k)}$ and $D^{(k)}$ the outage probability (OP) and average packet delay (APD) experienced by the k-th user S_k. These quantities will be determined from the probability distribution derived in (12).

User S_k suffers from outage if none of its packets can be transmitted along the S_k-R and R-D links. The following three cases arise. (i): B_k is empty ($l_k = 0$). In this case, no packets of S_k can be transmitted along the FSO link R-D and this user will suffer from outage if the link S_k-R is in outage with probability p_k. (ii): B_k is neither empty nor full ($l_k = 1, \ldots, L-1$). In this case, S_k will suffer from outage if the link S_k-R is in outage and the link R-D is not available. This latter scenario arises either if the packet at the head of B_k is not selected to be unloaded or if this packet was selected but the R-D link is in outage. Consequently, the corresponding outage probability can be expressed as $p_k[\delta_{l_k,l'_k} + (1-\delta_{l_k,l'_k})q]$ where $(l'_1, \ldots, l'_K)$ is determined from $(l_1, \ldots, l_K)$ following from any of the unloading strategies discussed in Section III. In this case, $l'_k = l_k$ (and $\delta_{l_k,l'_k} = 1$) implies that B_k was not involved in the packet unloading phase. (iii): B_k is full ($l_k = L$). As in the previous case, no packet of S_k is transmitted along the R-D link with probability $\delta_{l_k,l'_k} + (1-\delta_{l_k,l'_k})q$. In this case, B_k remains full and, hence, no packet can be accommodated from S_k regardless of the state of the RF link S_k-R. Therefore, the OP of user S_k can be determined from:

$$P^{(k)} = \pi_0^{(k)} p_k + \sum_{l=1}^{L-1} \pi_l^{(k)} p_k [\delta_{l_k,l'_k} + (1-\delta_{l_k,l'_k})q] + \pi_L^{(k)} [\delta_{l_k,l'_k} + (1-\delta_{l_k,l'_k})q]. \tag{13}$$

Following from the analysis presented in [7], the APD of user S_k can be calculated as follows:

$$D^{(k)} = 1 + \frac{2\bar{L}^{(k)}}{1 - P^{(k)}}, \tag{14}$$

where $P^{(k)}$ is given in (13) and $\bar{L}^{(k)} = \sum_{l=0}^{L} l\pi_l^{(k)}$ is the average queue length of buffer B_k. (14) follows from Little's law [7] where $\bar{L}^{(k)}$ is the average number of stored packets while $1-P^{(k)}$ is the effective arrival rate (in packets/sec). The ratio between these latter quantities yields a delay in seconds.

Finally, following from (13) and (14), the average OP and average APD of the unloading schemes can be determined from $P_{\text{av}} = \frac{1}{K}\sum_{k=1}^{K} P^{(k)}$ and $D_{\text{av}} = \frac{1}{K}\sum_{k=1}^{K} D^{(k)}$, respectively. Moreover, we define $P_{\text{b}} = \min_{k=1,\ldots,K}\{P^{(k)}\}$ and $P_{\text{w}} = \max_{k=1,\ldots,K}\{P^{(k)}\}$ as the OP of the best user and worst user, respectively. Similarly, $D_{\text{b}} = \min_{k=1,\ldots,K}\{D^{(k)}\}$ and $D_{\text{w}} = \max_{k=1,\ldots,K}\{D^{(k)}\}$. For the *Seq-B* and *Seq-U* strategies, $(P_{\text{b}}, P_{\text{w}}) = (P^{(1)}, P^{(K)})$ and $(D_{\text{b}}, D_{\text{w}}) = (D^{(1)}, D^{(K)})$ since the first packet to be unloaded is selected from buffer B_1 following from algorithm 1 and algorithm 2. For the *Seq-W* scheme, anyone of the K users can manifest the best or worst performance depending on the states of the RF links.

V. Numerical Results

Regarding the RF hop, we consider $K = 4$ users with $\Omega_k = 1$ for $k = 1, \ldots, 4$. On the other hand, the FSO link R-D has a length of 4 km. For this link, we fix $C_n^2 = 1.7 \times 10^{-14}$ $\mathrm{m}^{-2/3}$, $\sigma_s/a = 3$ and $\omega_z/a = 10$ reflecting the scenario of average scintillation with average pointing errors. Finally, we fix $M = 5$ and $P_M = 10$ dB in (1) while we plot the OP and APD as a function of the RF SNR γ_{RF} in (3). The buffers at R are assumed to have a size $L = 5$. We also show the performance of the single-relay scheme in [11] with a buffer size of $KL = 20$. In practice, while M is fixed by the implemented RF and FSO technologies, the number of users K might vary from one time to another. On the other hand, increasing L reduces the OP at the expense of increasing the APD.

The OP and APD are shown in Fig. 2 and Fig. 3, respectively. The results highlight on the benefit of using K buffers of size L at R rather than using a single buffer of size KL. While [11] manifests a slight OP enhancement at low SNR, the three proposed schemes outperform [11] in terms of OP and APD in the remaining SNR range. It is worth noting that

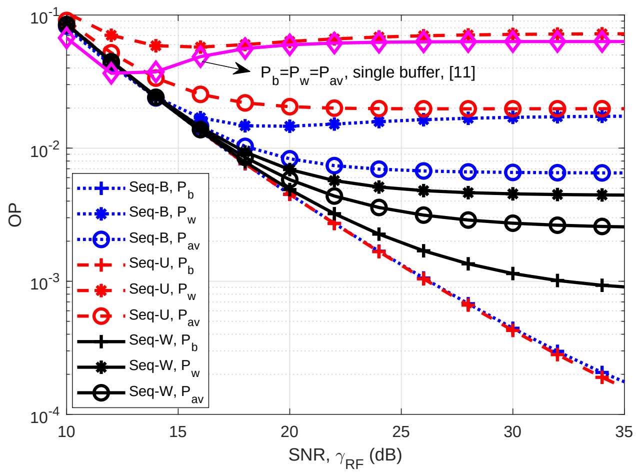

Fig. 2. Outage Probability with $K = 4$ users.

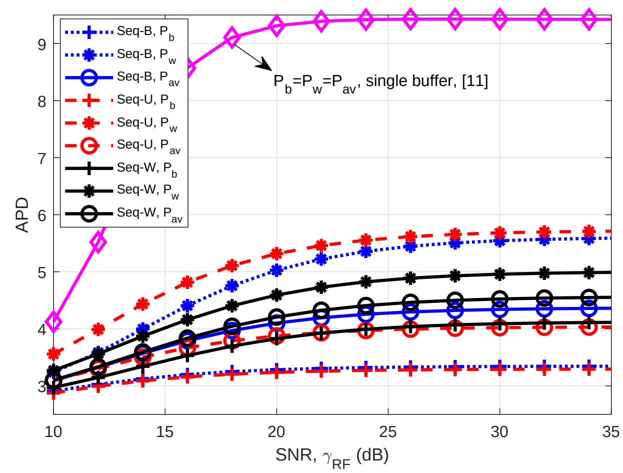

Fig. 3. Average Packet Delay with $K = 4$ users.

the APD increases with $\gamma_{\rm RF}$ in Fig. 3 since larger values of $\gamma_{\rm RF}$ increase the arrival rate of packets at R, hence, increasing the number of stored packets and the queuing delays. On the other hand, OP floors can be observed in Fig. 2. This follows since, above a certain value of $\gamma_{\rm RF}$, the buffers tend to be full and hence the system outage will be dominated by the FSO link since no packets can be communicated along the RF hop.

Comparing the *Seq-B*, *Seq-U* and *Seq-W* schemes shows that *Seq-U* ensures the smallest values of $P_{\rm b}$ and $D_{\rm b}$ while it suffers from the largest values of $P_{\rm w}$ and $D_{\rm w}$. In other words, the best QoS is guaranteed to user $\rm S_1$ at the expense of other users, especially user $\rm S_4$. For practical applications, $\rm S_1$ can correspond to an ultra-reliable low-latency application. At the other extreme, *Seq-W* results in the smallest values of $P_{\rm w}$ and $D_{\rm w}$ at the expense of the largest values of $P_{\rm b}$ and $D_{\rm b}$. In other words, the *Seq-W* strategy attempts to equalize the occupancies of the K buffers in order to guarantee the best QoS to the worst user. In this context, the OP and APD gaps between the best and worst users are the smallest among all three unloading strategies. Consequently, for practical applications, *Seq-W* is preferred if fairness is to be maintained among the K users if they possess comparable QoS requirements. Comparing the average network performance shows that *Seq-W* manifests the smallest OP while *Seq-U* manifests the smallest APD. In this context, *Seq-B* emerges as a compromise between *Seq-W* and *Seq-U* with a smaller average OP compared to *Seq-U* and a smaller average APD compared to *Seq-W*.

VI. Conclusion

For multiuser mixed RF/FSO communications, equipping the relay with multiple dedicated-buffers provides an additional degree of freedom compared to buffer-free relays and relays equipped with a single shared-buffer. This degree of freedom revolves around the packet unloading protocol whose design significantly impacts the best-user, worst-user and average-network performance for practical network requirements. Three protocols were proposed, analyzed and compared in this work highlighting on their capability of achieving different performance tradeoffs.

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