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AVAILABILITY FOR LOW-PRIORITY TRAFFIC OF A HYBRID FREE SPACE OPTICAL AND RADIO FREQUENCY WIRELESS LINK

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To achieve reliable traffic delivery, wireless free space optical(FSO) links may be complemented by radio frequency(RF) links. We consider a hybrid FSO and RF link, which processes high-priority traffic by first sending it over the main (FSO) link, and by rerouting it to the backup link whenever the main link fails to send it. In addition, low-priority traffic is processed by the backup link when it processes no high-priority traffic. Given the parameters of high-priority traffic (Poisson in our case) we approximate the availability of the backup link for low-priority traffic and show how to provide probabilistic quality-of-service guarantees.

Keywords: hybrid links, probabilistic QoS guarantees, link diversity, optical links, wireless communication, real-time communication

1. Introduction

Data transmission over hybrid free space optical (FSO) and radio frequency (RF) links has been extensively studied in the recent past [1, 2, 3, 4, 5]. FSO links allow for high data rates and secure transmission, but are negatively affected by environmental conditions such as weather, in particular fog and snow. Millimeterwave RF links allow for reduced, yet comparable data transmission rates [3, 4] and are not affected by fog, and so it has been proposed that they be used in conjunction with FSO links. Proposed ways to send the data over hybrid links include using the hybrid link as one channel while splitting packets into parts that are sent synchronously over both links and reassembled at the receiver [1]. Alternatively, application- and network-layer mechanisms could allow for sending a percentage of the packets over one link and the rest over the other [3]. Finally, a link-layer protocol could be used to assign packets to each link [2]. A combination of the last two approaches is also possible.

We consider approaches where each data packet is assigned to one of the links, and no synchronization of the sending of the packets over the two links is attempted. The authors in [3] address long-term changes in the bit

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error rate of the FSO and RF link by monitoring the links to determine their availability. Depending on the current availability of each link, the percentage of traffic carried over each link is adapted appropriately. This is done if the capacity of one of the links decreases by a certain threshold below the amount of traffic sent over it, and it is expected that the change will last. Changing the percentage of traffic sent over each link is done at the network layer or above and requires rerouting and/or application reconfiguration. This is time-consuming and should only be done if the environment changes are likely to last. The study in [3] concludes that it is useful to trigger a reconfiguration only if the monitored bit error rate and other link parameters have been observed to be inadequate for a period of 5 minutes or more. For short-term changes in the environment, such as scintillation and small objects obstructing the line of sight of the optical link, acting at network layer or above is inappropriate, as it carries too much overhead. In such cases, link-layer protocols that can react on a per-packet basis are better suited to insure reliable and timely transmission of high-priority traffic [2]. The protocol we consider in this paper uses a modified acknowledgement-based retransmission scheme, where packets first sent over the main link are forwarded to the backup link after a fixed number of unsuccessful transmission attempts over the main link.

We assume that the environment induces a quasistationary error model of the main link, that is, the bit error rate for the main link behaves in a quasistationary manner. This is along the line of research of [6, 7, 8, 9], where wireless channels have been represented by quasistationary models. In recent literature FSO links have also been considered to obey the model of block fading channels [10]. In this contribution, the backup link is assumed to have a constant capacity.

In [2] a method to calculate a universal lower bound for the availability of the backup link for low-priority traffic for such situations was briefly described. This was done under the assumption that the main link is backlogged, i.e. there is always traffic for it to process. For this case the cumulative distribution function for the maximum amount of low-priority traffic that can be carried over the backup link is calculated. In this work, we provide a more accurate approximation of this availability for the situation when the high-priority traffic is Poisson. The next section introduces the model of the hybrid link and describes the load and the link diversity protocol used in this paper. In Section **3** we introduce a new method to assess the availability of the system for low-priority traffic when the high-priority traffic is Poisson. Then we show how our results can be used to provide probabilistic quality-of-service guarantees for low-priority traffic.

2. Hybrid Link Model

We consider a wireless network that consists of a number of hybrid links, each of which connects two nodes. Each hybrid link is composed of a *main link*

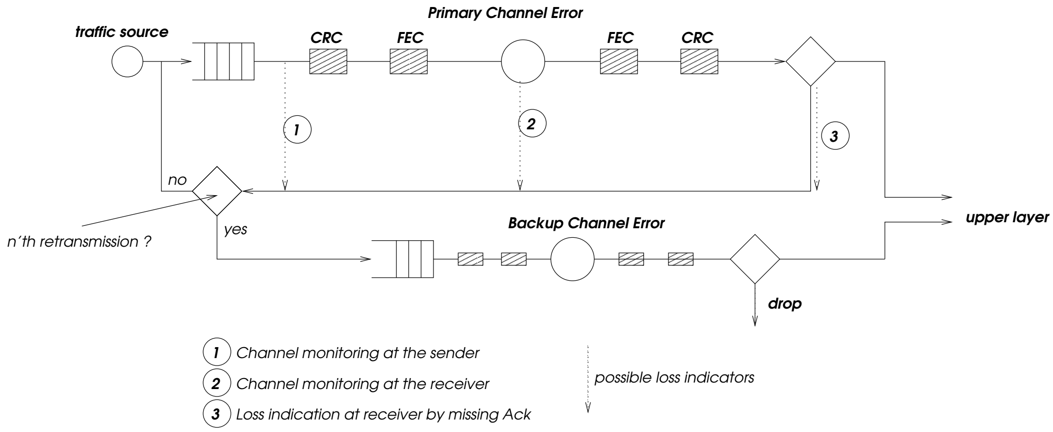

FIGURE 1. Link diversity model[2]

and a *backup link*. In order to assess the network's ability to meet the performance requirements of the applications, an accurate model of the underlying links is required. Such a model should describe the channel error statistics and its effect on the link's ability to carry the applications payload. Many such models exist for wireless channels, such as Rayleigh Fading [7, 12, 9] , or Rician [13, 14, 15, 16]. Finite-state Markov models are often used to represent time-varying channels, which was done for Rayleigh fading channels in [9]. In this paper such a model is used to describe the main link. We assume that the backup link processes traffic at a given constant rate.

In [6] Krunz and Kim developed a way to incorporate the effects of the forward error correction mechanism and a simple *stop-and-wait* ARQ scheme into the mathematical model of a wireless link described by a Rayleigh fading channel with two states. The authors of [8] generalize this method to be used for a channel with multiple states. We use the generalized method to more accurately describe the main link, while considering a model with $m + 1$ states.

2.1. **Single-Link Markov Model.** We next give a model for our main link. In general, channel models are determined by the bit error rates they exhibit. If the bit error rate is constant we have a *stationary channel*. Experience shows that wireless channels are not stationary over long periods of time, but can be considered stationary for short periods of time. So a non-stationary channel can be modeled by a set of states, each representing a stationary channel, with transitions between those states. The error rate of a wireless channel can be modeled as a *Markov modulated process*, whose states reflect channel states and whose transitions result from changes in the environment of the channel [9]. A simple quasistationary channel with two states is given by the Gilbert-Elliot model [17, 18].

In [6] a wireless channel is modeled using a finite-state Markov-modulated process model with two states. In [8] Wang *et al.* consider a more general model with m states. We consider the more general model which may have more than two states. In [8] the authors derive an average capacity C_i for each state i of the Markov model representing the link, while incorporating the effects of the use of forward error correction (FEC) and automatic repeat request (ARQ). The FEC error control mechanism includes cyclic redundancy check (CRC), which is applied to packets before they are sent over a link, and which is assumed to detect almost all bit errors in a packet. We next go over the calculations from [8].

For each state i an average capacity C_i is calculated such that the capacity losses due to the use of FEC and ARQ are taken into consideration. Given $e = k/l$ the ratio of useful bits in a packet (of size l), f_i the probability of a bit being received wrongly when the link is in state i, r the maximum number of bits that can be corrected upon inaccurate packet reception, and the number C of bits per second the channel can transmit, we can calculate the probability q_i that a packet needs retransmission,

$$q_i = \sum_{j=r+1}^{l} \binom{l}{j} f_i^j (1 - f_i)^{l-j}, \tag{1}$$

and

$$C_i = C \, \frac{k}{l} \, (1 - q_i). \tag{2}$$

Transitions between states can be model-led using an $m + 1$-state birth-death process as described in Figure 2.

In the following we describe the extension of this single-link model to the hybrid link model proposed in [2]. The availability of the backup link for low-priority traffic will be analyzed in Section **3**.

2.2. **Hybrid Transmission Protocol.** A packet is sent to the backup link if there have been n unsuccessful attempted transmissions over the main link. Here, n is a parameter of the model, which is selected to meet the requirements of the system. For example in order to have a higher throughput for the main link traffic one could choose $n = 1$. Similarly, in order to maintain a higher availability of the backup link, a higher value for n could be chosen. The detailed implementation (see Figure 1 for an overview of the hybrid link's transmission protocol) of this scheme depends on what mechanisms are available to detect packet losses, which then trigger retransmission. Loss indicators that may be used are (i) channel monitoring at the sender, (ii) channel monitoring and notification inside the network, and (iii) loss indication at CRC (cyclic redundancy check) decoder at the receiver. We assume that within the transmission time of one packet we know whether the packet needs to be retransmitted or not, which is true for stop-and-wait ARQ.

In [2] we gave an algorithm to calculate the probability p_i that a packet reaches the backup link if the main link is in state i when the first transmission attempt for the packet is made. In order to provide self-containment of this

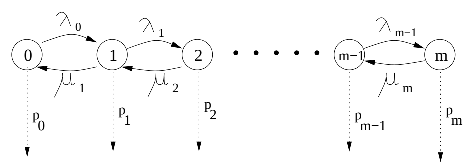

FIGURE 2. If a packet reaches the main link when it is in state i there is a probability p_i that it is sent to the backup link

paper we next describe this method. Let t_{tr} denote the time in which one attempt to transmit a packet takes place, and $BP(i,k)$ the probability that the packet reaches the backup link if its k^{th} transmission starts when the main link is in state i. The probability $p_i = BP(i,1)$ can be obtained using the recursive equation: $BP(i,k) = q_i[(1-\mu_i t_{tr} - \lambda_i t_{tr})BP(i,k+1) + \lambda_i t_{tr} BP(i+1,k+1) + \mu_i t_{tr} BP(i-1,k+1)]$, with $\lambda_m = 0$, $\mu_0 = 0$, and $BP(-1,k) = 0 = BP(m+1,k)$ for any k (also see Figure 2). Also, $BP(i,n+1) = 1$, since after n unsuccessful transmissions a packet is sent to the backup link.

Traffic arriving in this way at the backup link has priority over background traffic. Also, in the following we assume constant capacity of the backup link. This can happen when weather conditions affect the main link but do not affect the backup link.

We now can proceed with calculating the availability of the backup link for low-priority traffic in case the high-priority traffic is Poisson.

3. Availability for low-priority traffic

In this section, we assume arrivals of Poisson type. Initially we assume that the traffic produces no queuing at the entrance of the primary link, and approximate the maximum amount of low-priority traffic that can be serviced by the backup link for the case when the main link channel has two states. Then we show how the method can be generalized to more than two states. Afterwards we show that the no-queuing assumption leads to a conservative approximation.

3.1. Property of Poisson arrivals. Let N_t be a random variable corresponding to the number of arrivals until time t. The stationarity of the Poisson process implies $N_{t_1} + N_{t_2} = N_{t_1+t_2}$. Also, for disjoint intervals $i_1 = [s_1, s_1+t_1]$ and $i_2 = [s_2, s_2+t_2]$ we have $N(i_1) + N(i_2) = N_{t_1} + N_{t_2} = N_{t_1+t_2}$.

An inductive argument leads to the conclusion that for countable disjoint intervals $i_1,\ i_2, \ldots, i_p, \ldots$ that have durations $t_1, \ldots, t_p, \ldots$, the number of all arrivals in these intervals is given by

$$N_{ints} = N_{t_1} + N_{t_2} + \ \ldots \ + N_{t_p} + \ \ldots \ = N_{t_1+t_2+ \ \ldots \ +t_p+\ldots}. \qquad (3)$$

This means that for a countable number of disjoint intervals the random variable corresponding to the sum of the arrivals in the intervals is stochastically the same as the random variable corresponding to arrivals until the time given by the sum of the durations of the intervals. Here we also used the fact that Poisson arrivals are memoryless.

3.2. **Arrival and Service Curves.** To describe the traffic arriving at a link and the service provided by the latter, *arrival* and *service curves* are typically used [11]. Deterministic arrival curves describe for each time moment t the amount of traffic $A(t)$ that arrived or is expected to arrive at the link until time t. A service curve of a link gives for each time moment t the maximum amount of traffic $S(t)$ that could have been serviced by the link until time t. Also, $S(t) = \int_0^t C(\tau)d\tau$, where $C(\tau)$ is the capacity of the link at time τ. To denote a service curve that is not known in advance the term *stochastic* service curve was used in [8]. In the following we calculate the cumulative probability distribution F_{SB} of the service curve S_B provided by the backup link to the low-priority traffic. We have $F_{SB}(t,x) = P(S_B(t) \le x)$. This function depends on the total service curve of the backup link and on the high-priority traffic that is rerouted by the hybrid transmission protocol to the backup link.

3.3. **Rerouted High-Priority Traffic.** Let $A(t)$ be the amount of high-priority traffic that arrives until time t. This amount must be an integer multiple of the packet size l. Since the arrivals are Poisson, their cumulative distribution function is for each integer value $q \ge 0$:

$$F_A(t,ql) = P(A(t) \le ql) = \sum_{k=0}^{q} P(A(t) = kl) = \sum_{k=0}^{q} \frac{e^{-\lambda t}(\lambda t)^k}{k!}. \qquad (4)$$

We derive a method to obtain $F_{SB}(t,x)$, the cumulative distribution function (CDF) of the maximum amount of low-priority traffic that can be serviced by the backup link until time t. F_{SB} is also the cumulative probability distribution of the stochastic service curve S_B of the backup link for low-priority traffic. We have $S_B(t) = \int_0^t C_{BL}(\tau)d\tau$ where $C_{BL}(\tau)$ is the capacity that the backup link offers at time τ for low-priority traffic.

First, we characterize the *sojourn time* of the system in each state i, i.e. the time amounts $t_i(t)$ the system spends in state i until time t. To do this, we compute the CDF $T_j(t,x)$ of $t_j(t)$, i.e. $T_j(t,x) = P(t_j(t) \le x)$. For this, we use the method given in [8] to calculate the cumulative probability distribution of the service curve of a wireless link with minimal adjustment (instantiation of some parameters) multiple times. Let $G_{i,j}(t,x)$ be the probability that $t_i \le x$ if the system is in state j at time t. Let $r_{i,j} = 0$ if $i \ne j$, and $r_{i,j} = 1$ if $i = j$. Assuming that the state of the primary link changes only once in the time interval $[t, t+\Delta t]$ and does that at the end of the time interval, we have for all $j \in \{1, 2, \dots m\}$:

$$G_{i,j}(t+\Delta t, x) = \lambda_{j-1}\Delta t G_{i,j-1}(t, x - r_{i,j-1}\Delta t) + [1-(\lambda_j+\mu_j)\Delta t]G_{i,j}(t, x - r_{i,j}\Delta t) + \\ + \mu_{j+1}\Delta t G_{i,j+1}(t, x - r_{i,j+1}\Delta t) \qquad (5)$$

Equation (5) is valid because a time Δt was spent in state i in the time interval $[t, t+\Delta t)$ if and only if the primary link was in state i at time t, and otherwise no time was spent in state i during that time interval. Here, we consider $\lambda_m = \mu_0 = 0$.

Dividing by Δt and letting $\Delta t \to 0$ we obtain for each state i a system of partial differential equations from which the desired cumulative distribution T_i can be calculated. We have for $j \neq i$:

$$\frac{\partial G_{i,j}(t,x)}{\partial t} = \lambda_{j-1} G_{i,j-1}(t,x) - (\lambda_j + \mu_j) G_{i,j}(t,x) + \mu_{j+1} G_{i,j+1}(t,x), \tag{6}$$

and

$$\frac{\partial G_{i,i}(t,x)}{\partial t} + \frac{\partial G_{i,i}(t,x)}{\partial x} = \lambda_{i-1} G_{i,i-1}(t,x) - (\lambda_i + \mu_i) G_{i,i}(t,x) + \mu_{i+1} G_{i,i+1}(t,x). \tag{7}$$

The functions $G_{i,q}(t)$, where $q \in \{0, 1, \ldots m\}$, represent the cumulative distribution of the time the system spent in state i until time t given that at time t the main link is in state q. Let $t_i(t)$ or t_i be the time the system spent in state i until time t. We have:

$$T_i(t,x) = \sum_{j=0}^{m} \pi_j G_{i,j}(t,x) = P(t_i(t) \leq x), \tag{8}$$

where π_j is the probability that at any time the main link is in state j. Thus, solving numerically these $m+1$ systems of equations (for $i \in \{0, 1, \ldots m\}$), the cumulative distributions $T_i(t)$ of the amount of time the system spends in state i up to some time t can be determined.

The time spent in state i can consist of many intervals. By Equation (3) the random variable corresponding to the number of arrivals during the time spent in state i is stochastically equal to N_{t_i}, the random variable representing the number of arrivals in one time interval of length t_i. WLOG, in the following we will therefore calculate the amount of traffic that arrived while the main link was in a state i until a time t as if the whole time spent until time t in state i by the system were one contiguous interval. We start by calculating the cumulative distribution of the amount of traffic rerouted to the backup link for the case that there are only two states.

Suppose there are only two main link states, say states 1 and 2. We have the probability p_i that packets are rerouted to the backup link if they arrive while the main link is in state i. Also, from the assumption that the arrival is Poisson, the CDF of the arrival is $F_A(t,x) = P(A(t) \leq x) = \sum_{k=0}^{\lfloor x/l \rfloor} \frac{e^{-\lambda t}(\lambda t)^k}{k!}$.

We use the notation $P_A(t,k) = P(A(t) = kl) = \frac{e^{-\lambda t}(\lambda t)^k}{k!}$. For each positive integer q we have for $x \in [ql, q(l+1))$ that $F_B(t,x) = F_B(t, ql)$. Thus, the function $F_B(t,x)$ is determined for all positive numbers x if $F_B(t, ql)$ is known for all $q \in \mathbb{N}$. The probability that at most q high-priority packets are rerouted to the backup link until a time t is

$$F_B(t,ql) = \int_0^{t-nt_{tr}} P(t_1(t-nt_{tr})=\tau) \sum_{k_1+k_2\leq q} P_{B1}(\tau,k_1)P_{B2}(t-nt_{tr}-\tau,k_2)\, d\tau, \tag{9}$$

where $P_{Bi}(t,q)$ denotes the probability that q high-priority packets are resent to the backup link, which arrive in a time interval of length t during which the system is in state i. Here, t_{tr} denotes the transmission time of a packet, including ACK or loss notification. All high-priority packets which are resent to the backup link arrive there nt_{tr} time after they arrived at the main link. Therefore if the system started processing at a time 0, the first possible rerouting of a high-priority packet happens at time nt_{tr}, and until any time t only the high-priority packets that arrived until time $t-nt_{tr}$ could have been sent to the backup link. Thus for $t < nt_{tr}$ we have $P_{Bi}(t,0)=1$, and $P_{Bi}(t,q)=0$ for $q>0$. Then

$$F_B(t,ql) = \int_0^{t-nt_{tr}} P(t_1(t-nt_{tr})=\tau) \sum_{k=0}^{q} F_A(\tau,\lceil k/p_1\rceil l)P_{B2}(t-nt_{tr}-\tau,q-k)\, d\tau. \tag{10}$$

To calculate such an integral's value, a discretization of the infinite set of real numbers has to be done. This is also necessary for calculating and representing the functions T_i. Thus, the integral can be calculated as a sum of function values for small intervals $[\tau_j,\tau_{j+1})$, such that $T_1(t-nt_{tr},\tau_j)$ is known for all interval ends. For example, we can choose $\tau_i=\epsilon i$ for some small number ϵ. Since $T_1(\tau_i)=0$ when $i<0$, only values $T_i(\tau_i)$ for $i\geq 0$ may need to be determined. Let τ_p be the smallest interval end which fulfills $t-nt_{tr}\leq\tau_p$. Then, using $P(t_1(t-nt_{tr})\in(\tau_{j-1},\tau_j]) = T_1(t-nt_{tr},\tau_j)-T_1(t-nt_{tr},\tau_{j-1})$, we obtain the probability that at most l packets are rerouted to the backup link until a time $t=t'+nt_{tr}$:

$$F_B(t,ql) = \sum_{j=0}^{p-1}[P(t_1(t')\in(\tau_{j-1},\tau_j]) \sum_{k=0}^{q} F_A(\tau_j,\lceil k/p_1\rceil l)P_{B2}(t'-\tau_j,q-k)\ ]. \tag{11}$$

Furthermore, the following formula can be used to calculate $P_{Bi}(t,q)$:

$$P_{Bi}(t,q) = \sum_{j=\lfloor\frac{q-0.5}{p_i}\rfloor}^{\lfloor\frac{q+0.5}{p_i}\rfloor} P_A(t,j) = \sum_{j=\lfloor\frac{q-0.5}{p_i}\rfloor}^{\lfloor\frac{q+0.5}{p_i}\rfloor} \frac{e^{-\lambda t}(\lambda t)^j}{j!}. \tag{12}$$

3.4. **Availability for Low-Priority Traffic.** The cumulative probability distribution of the service curve of the backup link for low-priority traffic results:

$$F_{SB}(t,x) = P(tC_B-B(t)\leq x) = P(B(t)\geq tC_B-x) = 1-F_B(t,tC_B-x) \tag{13}$$

The method can be generalized to accommodate m states of the primary link. For example, for the case when there are three states we have

$$F_B(t+nt_{tr},ql)=\int_0^t P(t_1(t)=\tau_1)\int_0^{t-\tau_1}P(t_2(t)=\tau_2)\sum_{k_1+k_2+k_3\le q}P_{B1}(\tau_1,k_1)$$
$$P_{B2}(\tau_2,k_2)P_{B3}(t-\tau_1-\tau_2,k_3)d\tau_2 d\tau_1. \qquad (14)$$

From this F_{SB} can be calculated as shown above. The generalization to m states is obvious, but it may become computationally harder to obtain the results as m grows. A general formula for the case with m states is as follows:

$$F_B(t+nt_{tr},ql)=\int_0^t P(t_1(t)=\tau_1)\int_0^{t-\tau_1}P(t_2(t)=\tau_2)\dots\int_0^{t-\tau_1-\tau_2-\dots-\tau_{m-2}}$$
$$P(t_{m-1}(t)=\tau_{m-1})\sum_{k_1+k_2+\dots+k_m\le q}P_{B1}(\tau_1,k_1)P_{B2}(\tau_2,k_2)\dots P_{Bm-1}(\tau_{m-1},k_{m-1})$$
$$P_{Bm}(t-\tau_1-\tau_2-\dots-\tau_{m-1},k_m)d\tau_{m-1}\dots d\tau_2 d\tau_1. \qquad (15)$$

3.5. The No-Queuing Assumption is Conservative. Assuming that at the beginning of the considered time interval there is no queue at the entrance of the main link, F_{SB} in Equation (12) approximantes conservatively the traffic rerouted through the backup link. The inaccuracy results from the fact that our calculation method assumes that an attempt to send the packets over the primary link happens immediately upon the arrival of the packet. This implies that, if rerouted, the packet would reach the backup link earlier than if the packet were to encounter a queue at the entrance of the main link. Therefore, the probability that a certain amount of traffic x reaches the backup link until time t according to our model, $P(B(t)\ge x)$, is higher than or equal to the actual probability $P(rB(t)\ge x)$ that this happens in reality, that is the cumulative distribution function of the traffic amount that is rerouted to the backup link while taking possible queuing into consideration, F_{rB}, fulfills

$$F_{rB}(t,x)=1-P(rB(t)\ge(\lfloor x/l\rfloor+1)l)\le 1-P(B(t)\ge(\lfloor x/l\rfloor+1)l)=F_B(t,x). \qquad (16)$$

Then, if F_{rSB} is the cumulative probability distribution of the service curve provided for background traffic when taking queuing into consideration, we can conclude that $F_{rSB}(t,x)\ge F_{SB}(t,x)$ for any t and x.

To be noted is that our approximation $F_B(t,x)$ of the cumulative probability distribution of amount of traffic sent to the backup link is accurate for each time moment t for which there is no queue at the entrance of the main link.

3.6. Avoiding Over-conservative Estimation. Given that in our model packets arrive according to a Poisson distribution, it may be that until a time moment t more packets are considered in our model than can be processed by the main link until that time. To avoid an over-conservative approximation we can use a lower bound F_{SBmin} for the availability of the backup link for low-priority traffic. This bound can be calculated for the case when the main link is backlogged, i.e. when there always is traffic for it to process, by using the method derived in [8] for the calculation of the cumulative probability distribution of a wireless link's service curve. This method could be adapted by replacing the average capacities of the link in each state with the average rate at which traffic is rerouted to the backup link in that state from our model [2]. Doing this leads to an upper bound for the CDF of the amount of traffic that is rerouted to the backup link, from which a lower bound for the availability of the backup link results.

Then, for each t and x, $1 - min(F_{SBmin}(t, (\lceil x/l \rceil - 1)l), F_{SB}(t, (\lceil x/l \rceil - 1)l)))$ provides a conservative approximation of the probability that the backup link can service an amount x of low-priority traffic until time t, which in a very small amount of situations may be better than $1 - F_{SB}(t, (\lceil x/l \rceil - 1)l))$.

3.7. QoS Guarantees. The cumulative probability distribution of the service curve of the backup link for background traffic can be used to provide probabilistic QoS guarantees. For example, if we know that a certain amount x of low-priority traffic needs to be processed until time t, the probability that this is done successfully is

$$P(S_B(t) \geq x) = 1 - P(S_B(t) \leq (\lceil x/l \rceil - 1)l) = 1 - F_{SB}(t, \lceil x/l \rceil - 1)l). \quad (17)$$

Furthermore, if we know that the low-priority traffic arrives in chuncks of size x which need to be processed within a time amount t, and if it can be assumed that by the arrival of these chuncks no queue of traffic exists at either link, the same probability that this is done sucessfully for each traffic chunck applies.

A lower bound for the availability of the backup link which does not depend on the traffic at the entrance of the main link can be obtained by assuming that the main link is always backlogged. A more accurate approximation for the availability of the backup link can be obtained as described above.

4. Conclusion

In this paper we gave a method to conservatively approximate the stochastic service curve for low-priority traffic processed by a hybrid FSO and RF link which also processes high-priority Poisson traffic, when a link diversity protocol is used for packet scheduling. This approximation improves over an approximation which would consider the situation when there is always queuing at the main link.

After describing the model of the hybrid link, we gave a way to calculate the cumulative probability distribution of the high-priority traffic which is rerouted to the backup link. We then used this result to determine the cumulative probability distribution of the service curve of the backup link for low-priority traffic, and showed how quality of service guarantees can be obtained for this traffic. We also showed how over-conservative estimation resulting from the fact that the incoming high-priority traffic can be more than the main link can process in the considered time interval.

An interesting related question is how to approximate the cumulative probability distribution of the stochastic service curve for low-priority traffic when there is voice high-priority traffic, which can be represented by a Markov modulated Poisson process [19]. A generalization of the results to the case when the backup link also follows a quasistationary channel can also be developed.

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