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Research Article

Availability of a Hybrid FSO/RF Link While Using the Link's Diversity for Packet Scheduling

Liliana Grigoriu

Zentrum für Informations- und Medientechnologie, Universität Siegen, Hölderlinstr. 3, 57076 Siegen, Germany

Correspondence should be addressed to Liliana Grigoriu; liliana.grigoriu@uni-siegen.de

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Hybrid-free space optical and radio frequency wireless links are a way of providing reliable transport of real-time traffic in outdoor wireless environments. We consider a link layer protocol that assigns packets to each physical channel of such a hybrid link, which first attempts to send each packet over one of the links (the main link) and, if unsuccessful, sends the packet over the other link (the backup link). The hybrid link processes high-priority traffic by using the link layer protocol and additional (background) traffic at low priority over the backup link. In this setting, high-priority traffic can be transmitted at a rate as high as the maximum capacity of the main link, assuming that the backup link can compensate for main link capacity deterioration, with no need for reconfigurations aimed at adapting to changes in weather conditions, which is an advantage over other approaches. From the perspective of link availability for high-priority traffic, we compare our approach to using another protocol that does not require reconfigurations, which could be employed if the backup link is expected to have a constant transmission rate during the time interval of interest. For situations where both links can be represented by finite-state Markov models with states corresponding to channel bit error rates, as has been done in previous literature for radio frequency links and for free space optical links affected by strong atmospheric turbulence and Gaussian noise, we give a way to provide probabilistic quality of service guarantees for background traffic assuming that the high-priority traffic is insured to not exceed a given constant rate.

1. Introduction and Related Work

Hybrid wireless free space optical (FSO) and radio frequency (RF) links are a way of providing reliable transport for critical real-time traffic in an outdoor wireless environment, as weather conditions such as fog affect FSO links much more than RF links, while rain affects RF links (with a frequency of at least 300 MHz) much more than it affects FSO links.

Challenges in the usage of FSO links are that the receiver must be in the path of the transmission, which usually has a very small angle and that significant attenuation occurs due to weather conditions such as fog. Approaches to widen the applicability and improve the performance of FSO links have been taken in the following directions: adjusting signal intensity by increasing its power in case there are adverse weather conditions [1, 2], studying and finding ways to increase the transmission angle so that reception is less of a problem, using systems with multiple receivers and multiple transmitters (MIMO) [3, 4], and using hybrid FSO and RF links [1, 5–9] and combinations of two or more of these approaches. Also, multiple recent studies address the performance mixed RF/FSO systems where RF and FSO links are used to bridge separate parts of the transmission path, for example, [10–13].

In this work we focus on hybrid FSO and RF links, specifically on the improvement in their performance when a link layer protocol is used for assigning packets to each link, such that overhead due to reconfiguration of the link is avoided.

In [14] the authors analyze correlations between weather conditions and FSO link attenuation, specifically for fog and snow conditions in different seasons, and at different temperatures and day times, and thus give ways to predict the effect of fog and snow on the optical links, depending on diverse parameters. They propose to use these results to plan ahead for channel fading, by adjusting the link design to include an adequate fade margin, for example, by promising lower overall rates to consumers or planning for signal amplification capabilities. An overview of the factors that can affect an FSO link and methods to determine the attenuation of signal strength caused by them can be found in [15]. These factors can have constant effects such as the free space loss which can be derived exactly from the link range, effects that can last for a significant period of time such as losses due to weather conditions, and effects that can last a very small time such as losses caused by scintillation, a form of atmospheric turbulence. Scintillation can have a fading timescale around several milliseconds according to [14].

In [5], the authors consider the usage of a radio frequency link to complement an FSO link and describe effects of weather conditions on the hybrid link. Millimeter wave radio frequency links have a capacity that is comparable to that of optical links and thus can be used successfully to complement FSO links in the presence of adverse weather conditions [1]. To schedule traffic on hybrid FSO and RF links, routing mechanisms or link layer protocols can be used. Traditionally merging multiple link technologies has been done at the network layer or above, thus using the first approach. For links with nonvarying capacity, such as wired links, or optical links in a stable environment, this approach covers all practical situations. For outdoor wireless links, which have been shown to exhibit both long-term and short-term changes in their capacity over time, this approach has the disadvantage that time-consuming reconfiguration of applications can be triggered by the reconfiguration of the hybrid connection or by rerouting. The rerouting and the link reconfiguration themselves are time-consuming and only effective if they were triggered by a long-term environment change. Izadpanah et al. [5] reported that in order to have a reliable indication that doing reconfiguration is an effective decision, a time window of 5 minutes of monitoring the bit error rate and other parameters of the link is needed, as changes that would be noticed in shorter time periods could be misleading. Their aim was to maintain the capacity of the system at the maximum transmission rate of the main link minus a predefined acceptable margin, thus providing quality of service guarantees for the traffic.

Besides long-term changes caused by the factors like the weather, FSO links exhibit short-term outages, caused, for example, by strong atmospheric turbulence [16], or by birds passing through the link's propagation path. RF links also experience short-term changes in their performance called fading. When short-term changes occur in the performance of one of the links of a hybrid link, the reconfiguration approach is inappropriate, as its time granularity is high. The average values of the measured parameters would not catch the short-term changes, and if a reconfiguration is triggered the change might reverse immediately after the reconfiguration took place. To effectively cover such conditions, in [17] it was proposed to use a link layer protocol to distribute the load among the two underlying links of a hybrid FSO/RF link as an alternative. Such a protocol can decide on a per-packet basis over which link to send the packet, and for this it can use low-level information such as how many times the sending of a packet has already failed, or whether the last packet got through without error. This has the benefit of immediate reactions to short-term changes in the environment such as a small object passing through the ray of an optical link. Also, when only such a protocol is used, the expense of link reconfigurations is avoided.

We consider a system of two wireless links, a FSO link and a RF link, which may be made of more than one link. Among these we designate one to be the main link and the other to be the backup link. We show that a variant of the link layer protocol from [17] ensures that the capacity available for traffic that is first assigned to the main link is at least as high as the maximum capacity of the main link while using forward error correction (FEC) and stop-and-wait automatic repeat request (ARQ) in case the backup link has enough capacity to compensate for main link capacity deterioration, or as good as possible otherwise.

In addition, we analyze the performance of a hybrid link for time intervals when only the considered protocol is used. We first assume that in these time intervals one link (the main link) is a Rayleigh fading channel and that its average bit error rate varies according to a Markov process as was done, for example, in [18], while the backup link has constant capacity. This corresponds to time intervals when one link's signal-to-noise ratio is affected by changes in the environment and the bit error rate of the other link can be approximated to be constant. After that we generalize the model of the backup link to also be a Markov model the states of which correspond to possible average bit error rates.

We then consider the setting where packets belonging to high-priority traffic are first transmitted over the main link once. If they are not received correctly they are processed at high priority by the backup link which also processes background traffic at low priority. Assuming that the high-priority traffic is policed to not exceed a given rate r, we show how probabilistic quality of service guarantees can be provided for the background traffic.

The new results presented in this work complement and generalize results from [17, 19]. In [17] some properties of the link layer protocol were derived and a lower bound for the availability of the hybrid link for background traffic was obtained by assuming that the main link always has traffic to process and that the backup link processes traffic at a constant rate in the time interval of interest. In [19], the availability of the backup link for low-priority traffic assuming that the main link traffic follows a known Poisson process was approximated, assuming that the backup link has a constant rate, and a way to give probabilistic quality of service guarantees for the low-priority traffic was described. In this work we consider the more general case where the backup link follows a quasistationary channel rather than processing traffic at a constant rate.

In Section 2 we discuss our link model and the proposed resource allocation protocol and derive some preliminary results. In Section 3 we discuss the availability of the hybrid link for high-priority traffic and compare our protocol to another simple protocol we consider, which can be used without link reconfiguration in a special case. In Section 4 we give a way to obtain a stochastic measure for the availability of the backup link for low-priority traffic, assuming that the high-priority traffic does not exceed a constant rate, both in case the backup link processes traffic at a constant rate and

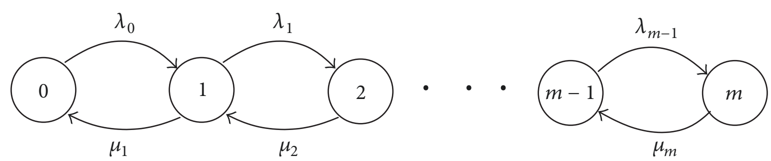

Figure 1: Finite-state Markov model for a wireless link.

in case it follows a quasistationary channel. In Section 5 we show how probabilistic quality of service (QoS) guarantees can be provided using the results from the previous sections and Section 6 contains concluding remarks.

2. Hybrid Wireless Link Model

In order for our presentation to be self-contained, this section presents a setting with parts that are very similar or identical to settings from [17–19].

We consider a wireless network that consists of multiple links, each of which connects two nodes. In order to assess the networks' 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 links' ability to carry the payload traffic. In order to compensate for transmission errors, mechanisms such as FEC and ARQ are used to effectively transmit in their presence. Also, to all packets a *cyclic redundancy check (CRC)* code can be added at the sender. This enables the receiver to determine whether a packet arrived correctly. If the error rate (the ratio between the amount of bits that are not received correctly and the total number of transmitted bits) of a channel changes over time, the amount of redundancy bits can also be changed accordingly, such that error correction can take place with as little as possible overhead.

In the following subsection we discuss models for wireless channels and present the models used in this work, in Section 2.2 we discuss channel configurations, in Section 2.3 we describe our proposed link layer protocol that assigns packets to the two underlying physical channels and discuss further resource allocation aspects, and in Section 2.4 we present some properties of our model of the hybrid link that were derived in [19].

2.1. Models for Wireless Channels. Transmissions of wireless channels can be influenced by multiple factors, such as weather conditions, atmospheric turbulence, and particles interfering with the transmission.

A high bit error rate, when it lasts over a longer period of time, results in a low transmission rate, either because many packets get dropped or because of the high redundancy imposed upon the transmission.

2.1.1. Radio Frequency Channel Model. Many models that describe the channel error statistics for wireless RF channels exist, based on Rayleigh fading [20] or Rician [21] channels.

The Gilbert-Elliott model for RF channels [22, 23] is a Markov model with two states, a "good" state, when the average bit error rate (BER) is low, and a "bad" state, when it is high. Transitions between the two states happen according to a Markov process; that is, when the system is in state "good" there is a probability λ that the system transitions to the state "bad" and when the system is in state "bad" there is a probability μ that the system transitions to state "good" in each moment.

The authors of [24] first study the behavior of a finite-state channel where a binary symmetric channel is associated with each channel state and where Markov transitions between states are assumed. By partitioning the range of the received signal-to-noise ratio (SNR) into a finite number of intervals, finite-state Markov channel models can be constructed for Rayleigh fading channels, for example, by using the methods from [24, 25] or [26]. Thus, a radio channel can be represented by a Markov model with multiple states, which represent situations when the channel exhibits signal-to-noise ratios belonging to one of the chosen intervals. In this work we also use a finite-state Markov model to represent the RF channel. We assume that the bit error rate in a state can be approximated to be the average bit error rate in that state as was done, for example, in [18, 25]. Also, we assume that there are only transitions between two adjacent states, which represent adjacent ranges of the signal-to-noise ratio, as was done in [24–26] (see Figure 1).

2.1.2. FSO Channel Model. The signal intensity and implicitly the bit error rate of free space optical channels can be affected by multiple factors, which result in attenuation of the signal [15, 27], which we enumerate in the Appendix.

In Section 3.1 nothing is assumed about the channel characteristics of the main link or of the backup link, except that the backup link can at all times compensate for main link capacity deterioration. This is a very general case, that allows the FSO link to be either the main link or the backup link and to change its capacity in any way, as long as the mentioned condition is fulfilled. In the rest of this work, we assume that losses resulting from factors other than atmospheric turbulence and noise can be determined and mitigated by design and are not time-varying during a time interval of interest and focus on the effects of strong atmospheric turbulence on the link.

The temporal coherence time of atmospheric turbulence is reported to be of the order of milliseconds [28]. This value is very large compared to the duration of the transmission of a typical data symbol; thus the turbulent atmospheric channel can be described as a "slow fading channel," since it is static over the duration of the transmission of a data symbol [27].

For FSO links that span more than 3 kilometers, as the strength of atmospheric turbulence increases, the number of independent scatterings becomes very large. This does not agree with the Rytov and the log-normal models, which can be successfully used to describe weaker turbulence. For such links the turbulence effect can tend towards saturation and the optical radiation field fluctuation obeys a Rayleigh distribution [16]. This causes the irradiance fluctuation to follow negative exponential statistics as described in (1), which has also been experimentally verified [28]. During the saturation regime, when the scintillation index $\sigma^2_{\mathrm{s.i}} = (E(I^2) - E(I)^2)/E(I)^2$ tends towards 1, in the limit of strong turbulence, other models used to describe strong turbulence (log-normal Rician, I-K distributions, and the K-model) also reduce to the negative exponential model [16, 27]. In this model, the probability density function for the received optical power (irradiance) is given as follows [15]:

$$p(I) = \frac{1}{I_0} \exp\left(-\frac{I}{I_0}\right), \quad (1)$$

for $I \geq 0$, where $I_0 = E(I)$ is the mean irradiance.

While an acceptable performance metric for analogue channels is given by the average SNR, the usual performance metric used for digital channels is the average BER. This metric, however, does not adequately describe temporary increases in error rates resulting from deep fading caused by strong atmospheric turbulence [29]. To describe deep fading the outage probability P_{out} can be used as a metric [29]. The outage probability is the probability that the BER is greater than a treshold level bit error rate BER*. In [29] a two-state on-off Markov model was used to represent FSO links in clear weather affected by turbulence with outage probability P_{out}. This model can also be used to represent links using spatial diversity [29]. In state *on* packets are received correctly and thus the link functions at its highest capacity, while in state *off*, packets are assumed to be lost.

The outage probability corresponds to the SNR being lower than a treshold level SNR* and to the irradiance being lower than a treshold level I^* [16]. Using characteristics of the FSO link and of the environment, I^* and P_{out} can be derived from BER* as was shown for example in [16] for differential phase-shift keying (DPSK) subcarrier intensity modulated FSO links.

The probability density function from (1) is the same as that of the SNR of Rayleigh fading channels representing RF channels [24–26], which is $p(\gamma) = (1/\gamma)\exp(-\gamma/\gamma_0)$, for $\gamma \geq 0$, where γ is the SNR and γ_0 is the average SNR. We therefore believe that, similar to the partitioning of the ranges of SNR for Rayleigh fading channels, it may be possible to meaningfully partition the range of possible irradiance values into separate ranges and to set up a Markov process corresponding to these ranges. The BER corresponding to diverse values of the irradiance could be determined as was shown in [16] for DPSK subcarrier intensity modulated FSO links. Then, the average BER for the chosen ranges of irradiance values could be derived, thus resulting in a multistate Markov model with states corresponding to average bit error rates. While doing this, it could be assumed, like it was done in [24] for RF channels, that each state of the Markov model corresponds to binary channel with states *on* and *off*, with a given probability that the channel is in state *off*, which corresponds to the average BER in that state.

In this work, we allow for the representation of the FSO link by a stationary channel with an average known BER as a given metric, describing a channel that is not affected by turbulence, by an on-off two-state Markov model, describing a channel that is affected by atmospheric turbulence, which may use spatial diversity [29] and by a more general finite-state Markov model.

2.2. Single Link Markov Model. In this work (except in Subsection 3.1), the main link and the backup link are both modeled by finite-state Markov models with states that correspond to average bit error rates the represented channel can have (see Figure 1). This model is more general than the simple quasistationary channel with two states given by the Gilbert-Elliott model [22, 23] and than a channel which has or can be approximated to have a constant error rate during the time interval of interest.

In [18] Wang et al. derived average capacities C_i for each state i of the Markov model representing such a link, while incorporating the effects of the use of FEC and ARQ. We next go over their calculations.

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. The parameters used for calculating C_i are

(i) l, the number of bits in a packet
(ii) k, the number of payload bits in a packet
(iii) a, the maximum number of correctable bits in a packet
(iv) f_i, the probability of a bit being received incorrectly
(v) and the number C of bits per second the channel can transmit.

The probability q_i that a packet needs retransmission is given as follows:

$$q_i = \sum_{j=a+1}^{n} \binom{l}{j} f_i^j (1 - f_i)^{l-j}. \quad (2)$$

Then we have

$$C_i = C\frac{k}{l}(1 - q_i). \quad (3)$$

Recall that k/l is the ratio of useful bits in a packet. Transitions between states in the mentioned model are labelled with the instantaneous probability that the system switches from one state to another. Also only transitions from a given state i to the states $i-1$ and $i+1$ are allowed. The average transition rate from state i to state $i+1$ is denoted by λ_i and that from state $i+1$ to state i is denoted by μ_{i+1}. The sojourn time in state i before transitioning to state $i+1$ is exponentially distributed with mean $1/\lambda_i$ (and to state $i-1$ with mean $1/\mu_i$).

2.3. Resource Allocation Protocol. We next address a method to exploit the diversity of the physical channel of hybrid

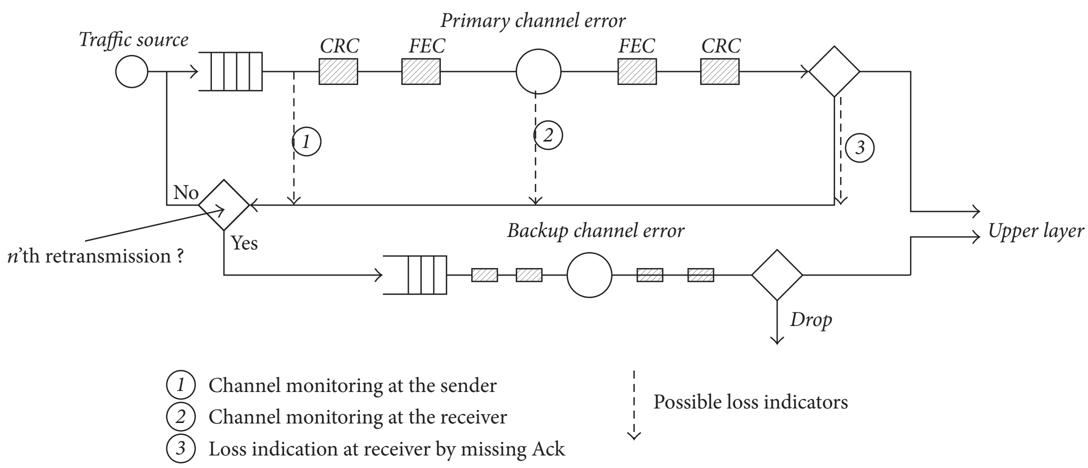

FIGURE 2: Link diversity model [17].

RF/FSO links. Figure 2 illustrates a data transmission scheme that takes advantage of link diversity in form of a primary and a backup channel.

We assume a *simple stop-and-wait* ARQ scheme, used together with FEC, for packet transmission over the links of the hybrid link. A packet belonging to high-priority traffic is first sent over the main link and, if there have been n unsuccessful attempted transmission trials over the main link, the packet is sent over the backup link. Accordingly, n is a parameter of the protocol, which can be adjusted according to what the system functionality needs to ensure. For example, in order to have a higher throughput for the main link traffic one could choose $n = 1$; or in order to maintain a higher availability of the backup link a higher n could be chosen.

The detailed implementation of this scheme depends on what mechanisms are available to detect packet loss, which then trigger retransmission. Figure 2 shows three possibile loss indicators, which are (i) channel monitoring at the sender, (ii) channel monitoring and notification inside the network, and (iii) loss indication at the CRC 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.

The use of the backup link in this model is described as follows. Any high-priority packet that arrives at the backup link after being sent incorrectly over the main link has priority over additional low-priority traffic, which, upon arrival at the hybrid link, is sent directly to the backup link. This second type of traffic is thus processed at a lower priority by the backup link.

Since both links are represented by finite-state Markov models, any one of them can be the main link or the backup link. The exact assignment can be chosen according to the information given in the practical situation, for example, assigning the link that is expected to have a better performance in the time interval of interest to be the main link.

2.4. Probability That a Packet Reaches the Backup Link. In [17], the probability with which a (high-priority) packet reaches the backup link given the system parameters and the state i in which the main link was when the packet was first transmitted was calculated. As in [25], it was assumed that during one packet transmission time the link changes at most once its state. We denote with τ the transmission time of one packet, including loss notification, expressed in seconds. We have $\tau = l/C$, where l is the number of bits in a packet as defined above. Let $\mathrm{BP}(i,k)$ be the probability that the packet reaches the backup link if its k-st transmission starts in link state i. We next summarize the procedure to calculate $\mathrm{BP}(i,k)$ from [17]. We have

$$\begin{aligned}\mathrm{BP}(i,k) = q_i \big[& (1-\mu_i\tau-\lambda_i\tau)\,\mathrm{BP}(i,k+1) \\ & + \lambda_i\tau\mathrm{BP}(i+1,k+1) + \mu_i\tau\mathrm{BP}(i-1,k+1)\big].\end{aligned} \tag{4}$$

Here, we assume that $\lambda_m = 0$ and $\mu_0 = 0$ and that $\mathrm{BP}(m+1,k) = 0 = \mathrm{BP}(-1,k)$ for any k, such that transitions to the inexisting states -1 and $m+1$ are ignored. Also $\mathrm{BP}(i,n+1) = 1$, since after n unsuccessful transmissions the packet is sent to the backup link.

The first term in the square parentheses is the probability that the system stays in state i during the k'th retransmission of the packet and that the packet reaches the backup link afterwards, the second term is for the situation in which the main link changes to state $i+1$, whereas the last term is for the case in which the main link changes to state $i-1$. The sum of these terms is multiplied by q_i, the probability that the k'th retransmission fails. The above equation can be easily developed into a recursive procedure to calculate $p_i = \mathrm{BP}(i,1)$.

The delay with which a packet reaches the backup link after it reaches the main link is constant and equal to n times τ.

3. Availability for High-Priority Traffic

In this section we focus on the availability of the hybrid link for high-priority traffic. We consider the resource allocation protocol from the previous section: high-priority traffic is sent over the main link for a maximum of n attempts, and after that it is processed at high-priority by the backup link, while background traffic is processed by the backup link at low priority. We also assume that a stop-and-wait ARQ scheme is used together with FEC. Since in this section we only talk about high-priority traffic, we may at times refer to it as just *traffic*.

3.1. General Property. We next point out a general property of our protocol with $n = 1$, which is independent of models chosen for the two links that compose the hybrid link. If a packet is not transmitted successfully at the first attempt over the main link, it is sent to the backup link for processing while the main link continues by processing the next packet. Thus, assuming that the backup link can compensate for deterioration in the capacity of the main link, the traffic is processed at the maximum capacity of the main link. The assumption that the backup link can carry all high-priority traffic sent to it can be true since by design one can choose to have enough availability of the backup link to match that of the main link as has been done in [5] and because weather conditions that would affect the capacities of both links such that their cumulative capacity drops below that of the maximum main link capacity are likely not encountered. For example, in [5], it was observed that this did not happen over a period of multiple months. Furthermore, heavy rain, which affects RF links the most, does not affect FSO links very much, while thick fog, which affects FSO links the most, is not as damaging to RF links.

3.2. Average Availability in Each Link State. We next use the Markov model from the previous section to represent the main link. We denote the average capacity offered by the hybrid link to high-priority traffic when the link layer protocol is used with parameter n and when the link is in state i with $C_{h,n,i}$. Note that, for each value of the parameter n of the protocol, there is a different set of values p_i, as they were calculated in the previous section. In each state i we have the average capacity available for high-priority traffic

$$C_{h,n,i} = C_i + C\frac{k}{l}p_i = C\frac{k}{l}\left(1 - q_i\right) + C\frac{k}{l}p_i. \tag{5}$$

The first term represents the average maximum rate of high-priority traffic transmitted over the main link when it is in state i (as shown in Section 2.2), while the second term represents the high-priority packets that can be rerouted to the backup link in this situation, that is, the additional capacity that results from the fact that packets that are not transmitted correctly over the main link are processed by the backup link. Here, as before, p_i is the probability that a packet reaches the backup link if it started being processed in state i, l is the number of bits in a packet, k is the number of useful bits in a packet, and q_i is the probability that a packet needs retransmission after being sent over the main link when it is in state i. If the protocol parameter is $n = 1$ we have a special case of the situation discussed in the previous subsection. Then, all packets that are not transmitted correctly over the main link at the first attempt are sent to the backup link and we have $p_i = q_i$ for all $i \in \{1, \ldots, m\}$. In this case the total capacity offered to high-priority traffic is equal to the maximum capacity of the main link if the backup link can compensate for main link fading

$$C_{h,1,i} = C\frac{k}{l}, \tag{6}$$

for all $i \in \{1, \ldots, m\}$.

3.3. Additional Availability due to Backup Link Usage. Next, we discuss the total capacity of the hybrid link for high-priority traffic in the general case when $n > 1$ in Section 3.3.1. In Section 3.3.2, we discuss the additional capacity offered to high-priority traffic over a time period of length t compared to the case where only the main link is used, described as the cumulative probability distribution of the amount of additional traffic that can be processed in such a time period. The stochastic measure for the availability of the hybrid link for high-priority traffic which we derive in Section 3.3.1 can be used to provide probabilistic quality of service guarantees, as we will show in Section 5.

3.3.1. Total Availability for High-Priority Traffic If $n \neq 1$. We next approximate the cumulative probability distribution of the total amount of traffic that can be served in a time period by the hybrid link using our protocol in the general case where the protocol parameter n can take other values than 1. To this end, we calculate the cumulative probability distribution of the (stochastic) service curve of the hybrid link when it uses our protocol.

Deterministic service curves are defined as functions that give a lower bound on the amount of traffic that can be serviced by a link over a time interval of length t [30]. A service curve gives for each time t the maximum amount of traffic $S(t)$ the link can process until that time. Here, $S(t) = \int_0^t C(\tau)d\tau$, where $C(\tau)$ is the processing rate or the capacity of the link at time τ. Their stochastic counterparts, with the same definition but for channels the capacity of which at each time τ is not known precisely, are called stochastic service curves in [18], and their cumulative probability distributions $F_S(t, x)$ can be used to provide probabilistic QoS-guarantees for real-time traffic.

In [18], a method is given to calculate the cumulative probability distribution of the stochastic service curve $S(t)$ of a wireless link the capacity of which varies after a Markov modulated process, $F_S(t, x) = P(S(t) \le x)$.

We can model the capacity offered by the hybrid link to high-priority traffic due to the use of the backup link and of our protocol by assigning to each state i of the Markov model representing the main link the capacity $C_{h,n,i}$ from (5), which is the average capacity offered by the hybrid link to high-priority traffic in state i. The resulting Markov model thus represents the availability of the hybrid link for high-priority traffic. Then, by applying the method presented in [18] we can obtain the cumulative probability distribution of the maximum amount of high-priority traffic that can be processed until time t, $F_H(t, x) = P(H(t) \le x)$, where $H(t)$ is the maximum amount of high-priority traffic that can pass though the hybrid link until time t. Here, again, we assume that the backup link can transmit the high-priority packets that come to it in a timely manner, which, as we argued before, seems to be a reasonable assumption, as it was observed that weather conditions tend to not reduce the capacity of both links such that the sum of their capacities is less than the maximum capacity of the main link [5].

3.3.2. Additional Availability for High-Priority Traffic. The high-priority traffic that is processed in addition to what the main link can process by itself is the amount of high-priority traffic that is resent to the backup link. We denote with $B_{\max}(t)$ the amount of high-priority traffic sent to the backup link until time t assuming that until time t the main link is backlogged: that is, that there always is traffic for it to process. Denote with $F_{h,\text{additional}}(t,x) = P(B_{\max}(t) \leq x)$, the probability that until time t at most x high-priority traffic is sent to the backup link. We can model the additional capacity offered by the hybrid link due to the use of the backup link and of our protocol by assigning to each state i of the Markov model representing the main link a capacity

$$C_i' = C\frac{k}{l}p_i. \tag{7}$$

The capacity C_i' assigned to each state i in the resulting Markov model thus represents the average maximum possible amount of high-priority traffic that can be sent to the backup link by our protocol when the main link is in state i. Then, by applying the method from [18], the cumulative probability distribution of the maximum amount of additional high-priority traffic that can be processed until time t, $F_{h,\text{additional}}(t,x) = P(B_{\max}(t) \leq x)$, can be determined.

3.4. Comparison to Other Protocol. As noted before, it may be that for a time interval of interest the backup link can be approximated to have constant capacity. For example, this can happen if the FSO link is the backup link and it can be approximated to have a constant capacity for a period of time, for example, because there is no strong atmospheric turbulence and the weather conditions that influence its performance are expected not to change in that time.

When knowing that for a time interval the backup link will have a constant transmission rate, it may be suggested that the high-priority traffic should be sent over the backup link (link B) up to that constant rate and, in case additional traffic comes, it should be sent over the link with the variable error rate (link A). We consider the case when the protocol's parameter is $n = 1$. This results in the following algorithm for the situation when the backup link has a constant transmission rate r_B and the main link's error rate varies after a Markov process:

(1) Send high-priority traffic over link B if it comes at a rate that is less than or equal to r_B.

(2) If the traffic arrives at a higher rate than r_B send packets at rate r_B over link B and all remaining packets over link A.

The advantage of this approach compared to the one presented before is that if there is enough high-priority traffic, the full constant capacity of link B is used, while additional capacity is available over link A in case the traffic arrives at a higher rate than the capacity of link B. The unpredictability of the rate at which link A transmits packets can be considered as a disadvantage compared to the use of the protocol from the previous sections: if the traffic arrives too bursty, a high amount of packets may be sent to link A while it has a low capacity, causing it thus to process traffic at a low rate, while link B may become idle, causing the system to have an availability for high-priority traffic that is significantly worse than that from the setting discussed previously. To somewhat mitigate this effect, traffic could be policed to not arrive at a rate higher than the sum of the maximum rates of the two links. Even when doing so, if the traffic arrives in bursts of the maximum rate allowed, in case both links have the same maximum capacity, half of it is sent to link A, which can process it for a very long time if the weather causes it to have a very low capacity, significantly exceeding the time required by link B to process all the traffic. We note that our protocol would have simply sent all or almost all traffic to the backup link if the main link happened to have a very low transmission rate.

Of course, if the backup link happens to have a very low transmission rate for a long period of time, our protocol could also suffer from the effect that packets sent to the backup link may take a long time to process, even when we set $n = 1$. However, in such a situation the backup link would certainly have to transport much less packets than half the traffic, as in that case usually the main link has a high transmission rate as weather conditions tend to not cause both links to have very low capacities at the same time, which is suggested, for example, by the study from [5].

4. Availability for Low-Priority Traffic When the High-Priority Traffic Does Not Exceed a Constant Rate

In this section we derive a stochastic lower bound for the availability of the backup link for low-priority traffic, assuming that only the link layer protocol with $n = 1$ is used and that the high-priority-traffic, which arrives at the main link, does not exceed a maximum rate r. This can be ensured by using a leaky bucket to police the high-priority traffic.

Constant rates are easy to include in contracts, and, as we have seen in Section 3, if the protocol from [17] is used with $n = 1$, a rate as high as the maximum capacity of the main link can be offered for the high-priority traffic, assuming that the backup link has enough capacity to compensate for main capacity deterioration.

In Section 4.1 some system properties are derived and it is assumed that the backup link has a constant capacity C_B during the time interval of interest, while in Section 4.2 we consider the more general situation where the backup link can be represented by a quasistationary channel.

4.1. System Properties. We first calculate the cumulative probability distribution of the maximum possible amount of high-priority traffic that is sent to the backup link until each time t and then determine a stochastic measure of the availability of the backup link for low-priority traffic from this information. The first step generalizes the results from Section 3.3.2 where the maximum rate that the high-priority traffic can be ensured to have was considered, which is equal to Ck/l for $n = 1$. In the following we assume without loss of generality that r is at most this maximum rate $r_{\max} = Ck/l$. High-priority traffic arriving at a higher rate would be processed by the main link at rate $r_{\max}$, which is why no generality is lost by this assumption, as from the point of view of how traffic is processed, this case is identical to a situation where the high-priority traffic arrives at a rate which is at most $r_{\max}$.

The capacity of the backup link channel which is assigned to low-priority traffic can be time-varying, either because of time-varying bit error rate as explained earlier, or because of contention with the high-priority traffic. In the case we first consider, we assume that the backup link provides a total capacity of a given constant rate, thus the capacity assigned to background traffic depends only on the traffic that is reassigned from the main link to the backup link.

We denote with $\mathrm{SB}(t)$ the service curve of the backup link for low-priority traffic, that is, the amount of background traffic that can be serviced by the backup link over a time interval of duration t (or until time t). We describe $\mathrm{SB}(t)$ by its cumulative probability distribution, F_{SB}, which we calculate. The service curve SB depends on (a) the arrival of the traffic to the primary link, (b) the error distribution of the primary link, and (c) the recovery mechanism that reroutes the traffic from the primary link to the backup link.

The following Lemma is useful for ensuring that the time between the arrival of high-priority packets at the backup link is not greater than the time between their arrivals at the main link.

Lemma 1 (no queuing at the main link if $n = 1$). *If the high-priority traffic that arrives at the main link does not exceed the maximum rate $r_{\max} = C(k/l)$ at which the primary link can process traffic, and when each packet that cannot be recovered after transmission over the main link is sent to the backup link, no queuing occurs at the main link. As before, k is the number of useful bits in a packet, while l is the packet size.*

Proof. The processing time of a high-priority packet at the main link is fixed and equal to l/C, the number of bits in a packet divided by the capacity of the link. This is because after a packet is transmitted the first time no further main link resources are used for it, since in case of a failed transmission the packet is sent to the backup link. As a consequence, if the rate r at which the high-priority traffic arrives at the main link is always policed to not be greater than $r_{\max}$, no new high-priority packet can arrive while another high-priority packet is being processed by the main link. Thus, no queue forms at the main link. □

In the following we assume that the traffic follows a fluid model, as was also done in [31, 32]. Let $A(t)$ be the amount of traffic that arrived at the main link until time t. Since there is no queuing the same amount of traffic started being processed until that time. Let $B(t)$ be the traffic that is rerouted from the primary link to the backup link in a time interval of duration t. We calculate the cumulative probability distribution of $B(t)$, $F_B(t,x) = P(B(t) \leq x)$ assuming that the arrival rate of the high-priority traffic is r. Let $M(t)$ represent the Markov process which determines the state of the main link, that is, $M(t) = i$, if at time t the main link is in state i. Let $F_i(t)$ be the cumulative probability distribution of the amount of high-priority traffic that arrives at the backup link until time t if at time t the main link is in state i. $F_i(t,x)$ is then the (conditional) probability that if the main link is in state i at time t, the high-priority traffic which is sent to the backup link until time t has a total amount that is at most x: $F_i(t,x) = P(B(t) \leq x \mid M(t) = i)$.

The cumulative probability distribution of the amount of the high-priority traffic that is sent to the backup link until time t is given by

$$F_B(t,x) = \sum_{i=0}^{m} \pi_i F_i(t,x), \qquad (8)$$

where π_i is the probability that the main link is in state i. The equality results directly from the definition of $F_i(t,x)$. We next calculate $F_i(t,x)$.

The probabilities π_i are invariant at any time and exist when the system is stationary. They can be calculated by solving the system $Q\pi = \pi$, where $\pi = (\pi_1, \pi_2, \ldots, \pi_m)^{\perp}$ and Q is a matrix given as follows: $Q_{ii} = 1 - (\lambda_i + \mu_i)$, $Q_{i,i+1} = \mu_i$, $Q_{i+1,i} = \lambda_i$, and $Q_{ij} = 0$ if $j \notin \{i-1, i, i+1\}$ [18].

Analogous to the method used in [18], we set up a system of partial differential equations from which we can calculate $F_i(t,x)$. First, we set up a set of difference equations assuming that the main link changes states only once during the time interval $(t, t+\Delta t]$ and does that very close to the end of the time interval. The system can be in state i at time $t + \Delta t$ if it was in state $i-1$ at time t and changed states towards state i in the time interval $(t, t+\Delta t]$, if it was in state i at time t and did not change states, or if it was in state $i+1$ at time t and changed states to state i.

According to Lemma 1 no high-priority traffic is queued at the entrance of the main link if $n = 1$, and thus the average amount of traffic that is sent from the main link to the backup link in a time interval $(t, t+\Delta t]$ if the main link is in state $i-1$ in that time interval is $p_{i-1}[A(t+\Delta t) - A(t)] = p_{i-1} r \Delta t$.

Therefore, the probability that at most x high-priority traffic is sent to the backup link until time $t + \Delta t$, assuming that the main link was in state $i-1$ at time t and in state i at time $t + \Delta t$, is

$$\begin{aligned} P(B(t+\Delta t) \leq x \mid (M(t+\Delta t) = i) \wedge (M(t) = i-1)) \\ = \lambda_{i-1} \Delta t F_{i-1}(t, x - p_{i-1} r \Delta t). \end{aligned} \qquad (9)$$

This is because we assumed that the main link changes states very shortly before time $t + \Delta t$.

Similar arguments can be made about the cases where the system is in state i at time $t + \Delta t$ and did not change states in the time interval $(t, t+\Delta t]$: $P(B(t+\Delta t) \leq x \mid (M(t+\Delta t) = i) \wedge (M(t) = i)) = (1 - (\mu_i + \lambda_i)\Delta t) F_i(t, x - p_i r \Delta t)$ and where it was in state $i+1$ at time t and in state i at time $t + \Delta t$:

$P(B(t+\Delta t) \leq x \mid (M(t+\Delta t) = i) \wedge (M(t) = i+1)) = \mu_{i+1}\Delta t F_{i+1}(t, x - p_{i+1} r \Delta t)$. We obtain for $i \in \{2, \ldots, m-1\}$

$$\begin{aligned} F_i(t+\Delta t, x) &= \lambda_{i-1}\Delta t F_{i-1}(t, x - p_{i-1} r\Delta t) \\ &\quad + (1 - (\mu_i + \lambda_i)\Delta t) F_i(t, x - p_i r \Delta t) \\ &\quad + \mu_{i+1}\Delta t F_{i+1}(t, x - p_{i+1} r \Delta t). \end{aligned} \quad (10)$$

For the cases $i = 0$ and $i = m$, the equation is true if we consider $\mu_0 = 0$ and $\lambda_m = 0$, which corresponds to the fact that there is no transition from state 1 to state 0 or from state m to a state $m+1$.

Dividing these equations by Δt and taking the limit when $\Delta t \rightarrow 0$, we obtain the system of differential equations corresponding to constant rate arrivals. It is given for each $i \in \{1, \ldots, m-1\}$ by

$$\begin{aligned} &\frac{\partial F_i(t,x)}{\partial t} - p_i r \frac{\partial F_i(t,x)}{\partial x} \\ &\quad = \lambda_{i-1} F_{i-1}(t,x) - (\mu_i + \lambda_i) F_i(t,x) \\ &\quad\quad + \mu_{i+1} F_{i+1}(t,x). \end{aligned} \quad (11)$$

The cases $i = 0$ and $i = m$ are treated as before (assigning $\lambda_m = 0$ and $\mu_0 = 0$). The initial conditions are given for each $i = 0, 1, \ldots, m$, as $F_i(0, x) = 0$ if $x \leq 0$ and $F_i(t, x) = 1$ if $x > 0$.

This system of first-order hyperbolic partial differential equations can be solved numerically resulting in the functions F_i. Thus we can obtain $F_B(t,x) = \sum_{i=0}^{m} \pi_i F_i(t,x)$.

In order to describe the remaining capacity of the backup link for background traffic when it gives priority to the high-priority traffic coming from the main link, we compute the cumulative probability distribution of the service curve provided for the background traffic, $F_{\mathrm{SB}}(t,x)$. We have

$$\begin{aligned} F_{\mathrm{SB}}(t,x) &= P(tC_B - B(t) \leq x) = P(B(t) \geq tC_B - x) \\ &= 1 - F_B(t, tC_B - x). \end{aligned} \quad (12)$$

Recall that C_B is the capacity of the backup link, which in this subsection we assume to be constant.

Theorem 2 (traffic upper bounded by rate r). *If the incoming high-priority traffic is upper bounded by a predefined rate r, then the cumulative distribution of the amount of high-priority traffic that arrives at the backup link is upper bounded by F_B.*

Proof. Suppose that the arrivals of the high-priority traffic are upper bounded by rate r. Recall that we only consider the situation where $r \leq r_{\max}$, as noted at the beginning of this subsection. According to Lemma 1 no high-priority packet waits at the main link before being processed, as no high-priority traffic queue forms at the main link. The average high-priority traffic rate that goes to the backup link in state i is $p_i r$ if the incoming traffic has rate r and is at most $p_i r$ if the incoming traffic is upper bounded by the rate r. Therefore, the average rate of the high-priority traffic that goes to the backup link when the high-priority traffic rate is upper bounded by r is less than or equal to the average rate of the high-priority traffic that goes to the backup link when the incoming high-priority traffic has constant rate r. □

As stated before, this case has practical applicability because traffic can be controlled to arrive with a maximum constant rate and because a maximum rate is easy to specify in contracts.

4.2. Generalization of the Backup Link Model. Next, we give a way to calculate the availability of the backup link for low-priority traffic even when it cannot be assumed that the backup link has a constant transmission rate. To this end, we assume that the backup link either follows an on-off Markov process, or a Gilbert-Elliot model, or a multistate Markov model. The probabilistic model is assumed to be unrelated to that of the main link for the period for which the availability analysis occurs. We consider the most general of the mentioned models, the multistate Markov model. As noted in Section 2, a multistate Markov model can adequately represent a Rayleigh fading channel which is often used to describe RF links and is more general than a two-state on-off Markov model, which can be used to describe FSO links affected by strong atmospheric turbulence and Gaussian noise. The cumulative probability distribution $F_{\mathrm{TB}}(t,x)$ of the stochastic service curve $\mathrm{TB}(t) = \int_0^t C_B(\tau)d\tau$ for the *total* amount of traffic that can be processed by the backup link until time t can be determined as shown in [18] for wireless links represented by Markov models with multiple states.

Also, the cumulative probability distribution $F_B(t,x)$ of the amount of high-priority traffic that can be present to the backup link until time t can be determined as shown in Section 4.1. We aim to calculate $F_{\mathrm{SB}}(t,x)$, the availability of the backup link for low-priority traffic as given by the cumulative probability distribution of the maximum amount of low-priority traffic that can be processed by the backup link until time t.

We have

$$\begin{aligned} F_{\mathrm{SB}}(t,z) &= P(\mathrm{TB}(t) - B(t) \leq z) \\ &= \int_{y=0}^{\infty} P(B(t) = y)\, P(\mathrm{TB}(t) \leq y + z). \end{aligned} \quad (13)$$

Thus,

$$F_{\mathrm{SB}}(t,z) = \int_{y=0}^{\infty} P(B(t) = y)\, F_{\mathrm{TB}}(t, y+z). \quad (14)$$

The maximum possible high-priority traffic amount resent to the backup link until time t is $tC_{\max}$, including the bits added by the forward error correction protocol to the payload traffic. The maximum amount of useful bits that can be resent to the backup link until time t is $tC_{\max} * (k/l)$ or $tr_{\max}$. Recall that in our previous calculations we referred to the amount of useful (payload) bits that are transferred. Also, since the traffic arrives in packets, at any time, the amount of payload high-priority traffic that is received by the backup link must be a multiple of k. Thus, for each positive integer j and according to the definition of F_B, we can use in our calculations that

$$P(B(t) = jk) = F_B(t, jk) - F_B(t, j(k-1)) \quad (15)$$

and that for any number x that is not a multiple of k that $P(B(t) = x) = 0$.

From the above considerations, noting that the maximum total amount of packets that can be resent to the backup link until time t if the high-priority traffic is policed to have a maximum rate (of useful bits) $r_{\max}$ is $r_{\max}/k = C_{\max}/l$, we obtain from (14)

$$F_{SB}(t,z) = \sum_{j=0}^{\lceil tr_{\max}/k \rceil} \left[F_B(t, jk) - F_B(t,(j-1)k)\right] \cdot F_{TB}(t, jk + z). \quad (16)$$

Here, j represents all possible numbers of low-priority traffic packets that can be processed by the backup link until time t. Given F_B and F_{TB}, the sum from (16) can be easily calculated.

Even if F_B does not result from high-priority traffic that is policed to have a (maximum) constant rate, such as the F_B resulting from the main link processing Poisson traffic considered in [19], (16) can be used to calculate the availability for low-priority traffic for the backup link in the general case where it follows a quasistationary channel.

5. Probabilistic Quality of Service Guarantees

As was also shown in [19] with regard to background traffic, we can derive probabilistic quality of service guarantees using cumulative probability distribution of the service curve of a link for some type of traffic of interest. The link can be the backup link and the traffic the low-priority traffic from Section 4, or link can be the hybrid link using the protocol with $n > 1$ and traffic can be the high-priority traffic as described in Section 3.

We next show the general way how this is done.

Let $S(t)$ be the service curve of the link of interest for the traffic of interest and F_S the cumulative probability distribution of $S(t)$. Here, we assume that the traffic of interest is considered without the overload caused by FEC, and thus the amount of useful bits in a packet is k. By the definition of F_S we have $F_S(t, x) = P(S(t) \le x)$. This can be used directly to obtain $P(S(t) \ge x) = 1 - F_S(t, x - 1)$, as we know that x is a number of bits and can thus not be fractional.

When considering that each packet contains k useful bits and taking into account the fact that the traffic arrives in packets, we obtain that the probability that an amount x of background traffic is processed in a time interval of duration t is

$$\begin{aligned} P(S(t) \ge x) &= 1 - P\left(S(t) \le \left(\left\lceil \frac{x}{k} \right\rceil - 1\right)k\right) \\ &= 1 - F_S\left(t, \left\lceil \frac{x}{k} \right\rceil - 1\right)k. \end{aligned} \quad (17)$$

In addition, if in the situation from Section 3 it is known that the high-priority traffic arrives in chunks of size x which need to be processed within a time amount t, and if it can be assumed that immediately before these chunks arrive no queue of high-priority traffic exists at either link, the same probability that this is done successfully for each traffic chunk applies, as was also noted in [19] for the situation considered there. We recall that in Section 3 we assumed that the backup link can compensate for main link fading, which was necessary for obtaining F_S.

For the situation from Section 4, in order for (13) to hold, it is assumed that no high-priority traffic is queued at the backup link at time 0. Thus, even though according to Lemma 1 no queuing of high-priority traffic occurs at the entrance of the main link when using our protocol with $n = 1$, this does not imply that (17) holds for any time interval, but only for time intervals at the beginning of which there is no queue of high-priority traffic at the entrance of the backup link. In other words, we can choose as time 0 any moment at which there is no queue of high-priority traffic at the entrance of the backup link, and then the probability that the backup link can process at least x low-priority traffic until time t is given as follows, using the notation F_{SB} from Section 4 in (16):

$$\begin{aligned} P(S_B(t) \ge x) &= 1 - P\left(S_B(t) \le \left(\left\lceil \frac{x}{k} \right\rceil - 1\right)k\right) \\ &= 1 - F_{SB}\left(t, \left\lceil \frac{x}{k} \right\rceil - 1\right)k. \end{aligned} \quad (18)$$

Here, S_B denotes the service curve of the backup link for low-priority traffic. While obtaining these results, we first used the approximation of a fluid model for the traffic in order to obtain cumulative probability distributions of stochastic service curves and, then, in this section, we used the results obtained thus and took advantage of knowing that the amount of traffic processed must be an integer number of bits that come in an integer number of packets.

6. Conclusion

In this work we analyzed the availability of hybrid FSO and RF link, when the link layer protocol proposed in [17] is used for assigning packets to each link.

In a situation where two types of traffic are processed, we showed that a variant of this protocol can ensure a transmission rate for the high-priority traffic that is as high as the maximum possible transmission rate of the main link while using FEC and stop-and-wait ARQ, assuming that the backup link can compensate for deterioration in the capacity of the main link. We also compared this protocol to another simple protocol that could seem appealing in case the backup link is known to have a constant transmission rate over a time interval of interest and showed that the initially considered protocol is more stable in the sense that it is better suited to handle adverse conditions, while the other protocol allows for a significantly higher capacity for the high-priority traffic in time intervals with good and very good conditions.

In addition, assuming that the high-priority traffic is ensured to not exceed a given constant rate, we gave a way to provide probabilistic quality of service guarantees for low-priority traffic for the same protocol variant. We considered the situations where the main link can be represented by a multistate quasistationary channel and where the backup link can be assumed to have a constant transmission rate and the more general case where the backup link also can be represented by a quasistationary channel.

Appendix

We next enumerate factors that can affect FSO links:

(1) *Absorption* occurs when the propagating photons of the FSO link interact with molecules in the atmosphere. Absorption is wavelength-dependent, and there are wavelengths that can be chosen for the FSO link such that the molecules in the atmosphere do not cause absorption [27], if desired. The resulting atmospheric absorption losses can otherwise be determined from the transmission range, the zenith angle, and the optical depth.

(2) *Scattering* results from interaction of the FSO transmission with particles that are in the atmosphere. It also induces noise in a FSO link by scattering the sky radiance into the receiver [27]. The scattering process depends on the radius r of the particles encountered during the propagation process and on their relation to the wavelength λ of the beam (we have Rayleigh scattering for $r < \lambda$ and Mie scattering for $r \approx \lambda$, and for $r > \lambda$ the scattering process is explained by diffraction theory [15]). The attenuation resulting from scattering can be determined if parameters pertaining to the particles that are encountered by the link are known [27].

(3) *Free space loss* results from the distance between the sender and the receiver and can be derived directly from that distance.

(4) *Beam divergence* causes the beam to spread out due to diffraction, such that the receiver aperture is only able to collect a fraction of the beam. The attenuation caused by this loss can be determined for a diffuse source from the irradiance of the source, the transmitter and receiver aperture areas, the length of the path, and the area of the optical source and for nondiffuse sources from the transmitter and receiver aperture areas, the length of the path, and the wavelength of the optical link [27].

(5) *Weather conditions* cause loss that can result from

  (a) fog, which causes an attenuation that can be derived from the parameters of the fog or from the visibility range,
  (b) snow, which causes an attenuation that can be derived based on the snowflake size and snowfall rate or from the visibility range,
  (c) rain, which causes an attenuation that can be derived from the rain rate given in mm/hr.

(6) *Pointing loss* results from random platform jitter at the receiver and can be derived from the beam jitter angle and the transmitter beam divergence [15].

(7) *Atmospheric turbulence* is caused by so-called eddies, cells of air of different temperature than the surrounding air, which may occur in the path of the beam and result in the following phenomena:

  (a) Beam wander: eddies that are larger than the transmitter beam size cause the beam to be deflected and to miss the receiver [15]. This effect is negligible in case of downlink signals from satellites.
  (b) Beam scintillation: eddies with sizes of the order of the beam size will lead to irradiance fluctuations resulting from focusing and defocusing the beam. Scintillations cause deep random signal fades [15].
  (c) Beam spreading: if the beam size is larger than the eddy, then a small portion of the beam will be diffracted and scattered. This leads to reduction in the received power density and will also distort the received wavefront. This effect is negligible if certain measures are taken [15].

(8) *Noise* at the receiver is composed of *background noise* due to radiations from the sky and from the sun, and *thermal noise* is caused by thermal fluctuations of electrons in the receiver circuit [16].

Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

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