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Simulative Performance Analysis of ARQ Schemes for Free-Space Optical Inter-HAP Channel Model

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Abstract

Automatic Repeat reQuest (ARQ) data link layer protocols improve the reliability of communication in Free Space Optical (FSO) fading channels using feedback information. The objective of this paper is to analyse the simulative performance of different ARQ mechanisms for a FSO inter-High Altitude Platform (HAP) scenario. A bi-directional symmetrical inter-HAP channel was modelled considering the combined influence of atmospheric turbulence-induced scintillation and miss-pointing induced fading at the receiver. Then selected ARQ schemes were investigated via event-based simulations in terms of transmission efficiency.

1 Introduction

Free Space Optical (FSO) communication systems are a promising approach using collimated laser beams to transmit and receive data at very high data rates overcoming interference and bandwidth exhaustion [1]. Some applications of FSO are suited for a diverse variety of point-to-point communication applications over large distances - such as between satellites, High Altitude Platforms (HAPs), Unmanned Aerial Vehicles (UAVs), aircrafts, ground stations and other areas. HAPs are quasi-stationary airships or aircrafts operating in stratospheric altitudes between 17km to 22 km [2]. These communication platforms have significant advantages compared to “classical” terrestrial and satellite communications, e.g., large coverage area (compared with an individual terrestrial cell) and low cost in launch and maintenance [3]. The performance of an Inter-HAP FSO channel is affected primarily by Index of Refraction Turbulence (IRT) that leads to irradiance fluctuations in the received signal known as scintillation. The overall performance is reduced due to additional effects such as miss-pointing and tracking errors at the receiver resulting in additional fading of the optical signal [4], [5], [6]. A typical optical inter-HAP scenario is shown in **Figure 1**.

Automatic Repeat reQuest (ARQ) schemes provide efficient error control techniques also for FSO communication systems to achieve reliable transmission on the data-link layer [7], [8], and [9]. Any ARQ scheme has to be tailored and designed specific for the FSO Inter-HAP channel or scenario based on its fading statistics and Bit Error Probability (BEP) characteristics.



Figure 1: FSO Inter-HAP communication scenario [4].

In this paper, we refine the channel model presented in [6] for a bi-directional symmetrical Inter-HAP link of 400km considering the joint influence of optical scintillation induced by IRT and beam miss-pointing. This Inter-HAP channel model is then investigated via simulations and Bit Error Probability (BEP) characteristics are generated. Based on these results, the performance of different ARQ mechanisms in terms of transmission efficiency is investigated via event-based simulations. The performance results additionally regard commonly used Reed Solomon code - RS (255,239) - Forward Error Correction (FEC).

The remainder of the paper is organized as follows: The channel description is detailed in Section 2. In Section 3, simulation of selected ARQ mechanisms, simulation parameters definition, and transmission efficiency is described. Numerical results are presented and discussed in Section 4 and section 5 concludes the paper.

2 Channel Description

In this section, we describe the channel model of a bi-directional inter-HAP link.

2.1 Impact of Atmosphere

2.1.1 Optical Turbulence

An optical link is impacted by different effects of the atmosphere. As the beam propagates through the atmosphere, optical turbulence distorts its wavefront, leading to spatial intensity deviations. The altitude profile for the C_n^2 parameter, which scales the atmosphere's index-of-refraction structure function, is generated using the Hufnagel-Valley (H-V) model [1].

In this paper, we consider two values of wind speed to calculate C_n^2 profiles at 10m/s and 30m/s which gives us the best and worst case respectively. The calculations are in compliance with measured data [10]. The two cases of varying strengths of C_n^2 profile along the altitude are shown in **Figure 2**. For our scenario, we are interested in the typical HAP altitude range from 17 to 22km. We can observe the difference in the strengths of C_n^2 profile with respect to the change in wind speeds [1].

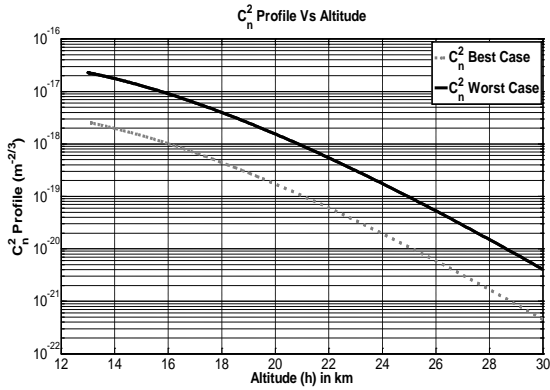


Figure 2: Best and worst case C_n^2 profiles over altitude.

The curves shown in **Figure 3** illustrate the C_n^2 profile along the Inter-HAP link path over the curved earth surface. We can see that the turbulence strength is strongest in the middle as this is the lower part of the link.

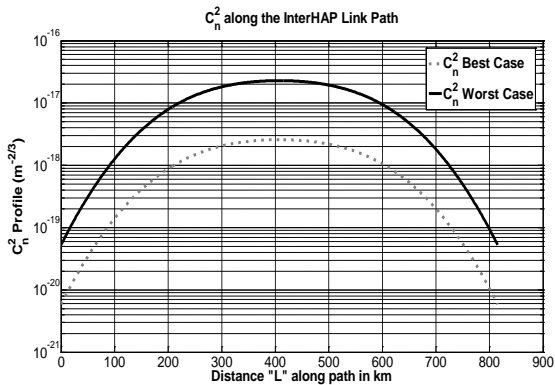


Figure 3: Inter-HAP C_n^2 path profile along link distance.

2.2 Impact of Pointing Error

Pointing errors have a significant impact on the FSO Inter-HAP link performance influencing the Bit Error Probability (BEP) [11]. So, the divergence angle plays an important role for the average BEP performance [12]. Small divergence angles result in large pointing losses, while increasing divergence angles reduce the loss due to pointing error but increase intensity losses. We consider a residual pointing error $\sigma_{rms} = 20\mu\text{rad}$ and a Full Width Half Maximum (FWHM) divergence angle of $85\mu\text{rad}$ based on [13] where a trade-off between divergence angle and pointing losses are found.

2.3 Inter-HAP Scenario

For this paper, we dimension our inter-HAP bi-directional channel to a link distance of 400km where both HAPs are placed at an altitude of 22km resulting in a graze height (G_h) of 18.87km. G_h is the minimum height of the optical link above the surface of the earth. Based on this dimensioning we define two scenarios named as Best and Worst case using the two C_n^2 -profiles described in section 2.1.1 respectively. The intensity Scintillation Index (S.I) is defined as the normalized variance of irradiance fluctuations. The defined scenarios are shown in **Table 1**.

C_n^2 Case	L (km)	H_{hap} (km)	G_h (km)	S.I
Best	400	22	18.87	0.008
Worst				0.65

Table 1: Bi-directional inter-HAP link scenario

2.4 Link Budget Calculation

To calculate a Link budget for an Inter-HAP scenario, different parameters have to be taken into consideration. **Table 2** shows the link budget calculation for the Inter-HAP scenario defined in section 2.3.

Parameters	Symbol (Unit)	Value
Mean Transmit Power	P_{Tx} (Watt)	0.055
Inter-HAP Link Distance	L (km)	400
Channel rate (including 8b/10b line code)	R (Gbps)	1.25
Wavelength	λ (nm)	1550
FWHM Beam Divergence at transmitter	θ_{Tx} (μrad)	85
Receiver Aperture Diameter	D_{rx} (cm)	15

Atmospheric Loss	$a_{\text{atmos}}(\text{dB})$	0.670
Receiver sensitivity for BER=1E-06	$S_{\text{Rx}}(\text{nW})$	128.26
FEC Coding Gain for BER =1E-6 for RS (239,255)	$\text{FEC}_{\text{gain}}(\text{dB})$	4
Link Margin	$L_m(\text{dB})$	0.01

Table 2: Static link budget for bi-directional Inter-HAP scenario (no dynamic scintillation loss regarded).

2.5 Channel Simulation

Based on our inter-HAP channel scenario and link budget calculations we generated a time series of received power. An inter-HAP channel, under the influence of IRT, can be modelled as a scintillation channel with fades and surges. In case of weak turbulence, generally the influence of turbulence is modelled as a random process with log normal distribution. The **Figure 4** shows the PDF of generated optical receiver power with joint effect of turbulence plus pointing error based on the method described in [14].

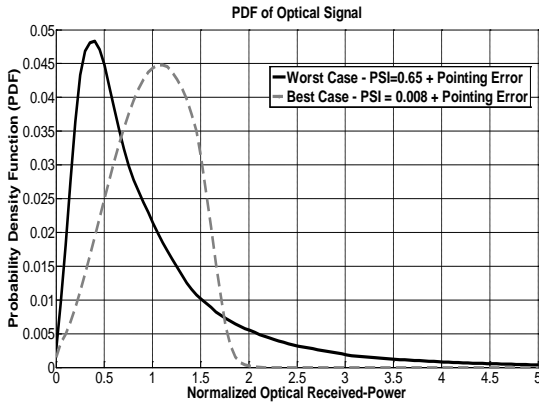


Figure 4: PDF of optical received power.

2.6 Bit Error Probability (BEP)

An optical channel shall be characterized by its fading behavior [1]. The sources of these fades can be due to index of refraction turbulence effects in the atmosphere and pointing error at the receiver which is known as turbulence induced fading and pointing error induced fading respectively [15]. This means the combined effect of scintillation effect and pointing error result in fades and surges in the received signal, which occur at rather large time scales compared to the hap-to-hap propagation delay of $1.33 \mu\text{s}$. Surge is defined as the event when the instantaneous received power is over the mean received power and Fade is defined as the event when the instantaneous received power is below the mean received power.

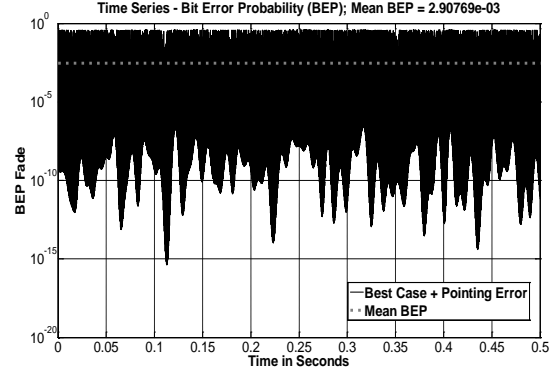


Figure 5: Bit Error Probability over time – best case.

In our channel presented in section 2 we consider joint effects of both atmospheric turbulence-induced fading and pointing error-induced fading. These fading events result in unevenly distributed and varying BEP over time. In case of our channel, the bit errors are unevenly distributed over the transmitted data due to fading effects and the quantity of BEP varies based on the current state of the channel. These timely varying behaviors of BEP for our bi-directional inter HAP link is shown for the selected best and worst case channel conditions in **Figure 5** and **Figure 6** respectively. A horizontal straight line in these diagrams indicates the mean value of the simulated BEP.

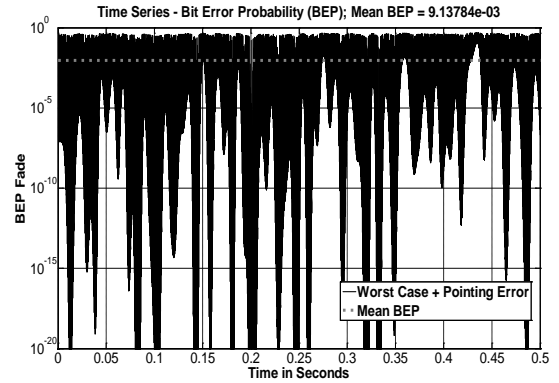


Figure 6: Bit Error Probability over time – worst case.

3 Simulation of ARQ Schemes

Automatic Repeat reQuest (ARQ) forms the basis of Data-Link Layer protocols that provide a reliable data transfer [16]. In the performance simulations of ARQ schemes on inter-HAP bi-directional channel we also used (partly) Forward Error Correction (FEC) as an additional error reduction technique. Here, we considered a commonly used Reed Solomon code - RS (255,239) capable of correcting up to 8 symbol errors per frame.

3.1 Event-Based Simulation

To allow detailed investigations, we implemented several sliding-window based ARQ mechanisms from scratch using the event-based OMNET++ simulation library environment and determined the resulting transmission efficiency after ARQ. The ARQ performance is evaluated

with and without an RS (255,239) FEC with the simulation parameters shown in **Table 3**: We selected a frame length n_f of 239 bytes (w/o FEC) resp. 255 bytes (with FEC). For the transfer of ARQ sequence numbers and further control information we assumed an overhead of $n_o = 10$ bytes that is the total number of bits in the header and the number of CRC check bits. The relation of the round-trip time between the two platforms and the transmission time (considering the net data rate of 1 Gbps, i.e. before the 8b/10b line coding) of a frame defined the required sizes of the transmitter window.

Parameter	Without FEC	With FEC	Symbol	Unit
Total Frame Length	1912	2040	n_f	bits
Overhead	80	208	n_o	bits
Window Size	1397	1309	W_s	frames
Net Data Rate	1	1	R_n	Gbps
Link Distance	400	400	L	km
Propagation Delay	1.33	1.33	t_p	ms
Transmission Time	1.912	2.04	t_s	μ s

Table 3: ARQ simulation parameters.

3.2 Transmission Efficiency

For the following considerations we define the Transmission Efficiency (TE) as the fraction of the channel bit rate (before the 8b10b coding) usable for payload transport. To analyse the performance of ARQ schemes, we perform a quantitative comparison of the transmission efficiency. In our inter-HAP bi-directional channel model, the forward channel is used to transmit data and the backward channel is used to transmit only the acknowledgements (ACKs). We also consider a symmetrical error channel, i.e. both forward and backward channel have the same instantaneous BEP. We analyse the performance of two basic two window-based ARQ protocols, Go-back-N (GBN-ARQ) and Selective Repeat (SR-ARQ). An approximate analytical description of these ARQ schemes for a bi-directional inter-HAP link was already presented in [6]. According to [16], the transmission efficiency of these two window-based protocols can be approximated as follows:

$$\text{GBN-ARQ: TE} = (1-P_f) (1-n_o/n_f) / (1 + (W_s-1) P_f) \quad (1)$$

$$\text{SR-ARQ: TE} = (1-P_f) (1-n_o/n_f) \quad (2)$$

Here, P_f denotes the Frame Error Probability (FEP), n_f the number of bits in the information frame, n_o the number of overhead bits in a frame and W_s is the window size (measured in frames).

4 Results and Discussion

In this section, we present the performance in terms of transmission efficiency for the GBN-ARQ and SR-ARQ mechanisms. The simulations are first performed for various constant BEP values. Additionally, the best and worst case inter-HAP scenarios presented in **Table 1** are simulated. The OMNET++ simulation environment uses FEP vectors calculated from time varying BEP fade values shown in **Figure 5** and **Figure 6** – both for the cases with and without FEC. The resulting ARQ performance for these fading channels is indicated in **Figure 7** and **Figure 8** at those BEP values that correspond to the mean BEP of the fading channel. Note: The simulation results also indicate 95% confidence intervals for the individual measurement points that however are barely visible in the diagrams.

4.1 GBN-ARQ Performance Results

The TE-performance of GBN-ARQ over channel BEP fade for different cases is shown in **Figure 7**. In the case without FEC, the TE shows a poor performance for BEP values above $1E-07$. Using FEC, we observe a strong improvement: Maximum TE is achieved up to a mean BEP of $3E-04$. Note: The differences between the analytical approximations and the simulation results at high BEP values result from the fact that the equation above does not consider losses of already retransmitted frames.

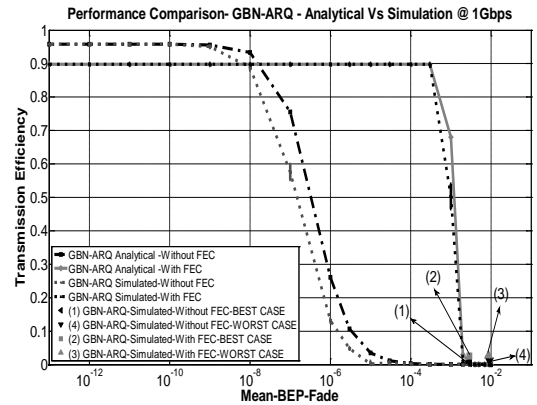


Figure 7: GBN-ARQ performance analysis.

Considering the simulation results of GBN ARQ for the fading channel scenarios and data of section 2.3, we however have to observe that at these BEP ranges GBN cannot recover at both the best and worst case channel – also in the case of using FEC. Here, due to the high BEP and the retransmissions of the large sender window required in the case of GBN the TE drops to a few percent, as visible in **Figure 7**. The ARQ sender is completely occupied with retransmitting and even the usual GBN advantage of cumulative ACKs vanishes.

4.2 SR-ARQ Performance Results

Figure 8 depicts the transmission efficiency of SR-ARQ for different mean channel BEP fade values.

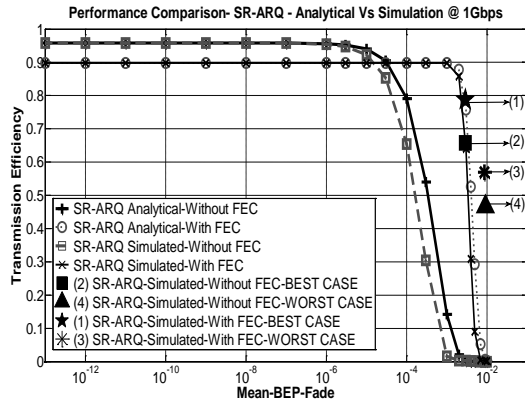


Figure 8: SR-ARQ performance analysis.

We see that the combination of FEC and ARQ provides better results especially in case of higher BEP. Also, we see the cost of FEC at lower mean BEP values with reduced TE and its benefits in the range of higher mean BEP values. This is also observed for the best and worst case scenarios of the fading channel involving a time varying BEP. Note: The differences between the analytical approximations and the simulation results at high BEP values result from the fact that the equation above does not consider losses of ACKs in the backward channel. We also can observe the interesting fact that for the best and worst case channel scenarios (involving turbulence induced fading and pointing error) TE values of around 80% around 57% can be obtained respectively. Especially for the cases without FEC and the worst case channel, these values are considerably higher than those that can be obtained with constant BEP values equal to the mean BEP of the fading channel: Time periods of high BEP loss are over-compensated at other time periods – a starting point for further protocol optimization.

5 Conclusion and Outlook

In this work, we investigated two basic window-based ARQ protocols in OMNET++ simulations and evaluated their resulting performance in terms of transmission efficiency. We also refined the channel model of an inter-HAP scenario from [6] and evaluated the ARQ performances for the best and worst case scenarios. Both turbulence induced scintillation and pointing error induced fading were taken into account. The results confirm the good performance of the SR-ARQ scheme and give way for possible improvements towards a smarter ARQ - e.g. adapting the FEC- strength to the highly varying BEP performance of the channel and / or giving more redundancy to the ARQ acknowledges in the backward channel.

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