Delayed Frame Repetition for Free Space Optical Communication (FSO) Channel

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Abstract

Free space optical communication is gaining interest because of its various advantages like high data rate, high power efficiency, no license regulation etc. However, one has to overcome the challenge of distortion and fading caused by atmospheric turbulences and bad weather conditions. Free space optical communication channel is a time variant channel. Sometimes, the channel has a very good condition and sometimes atmospheric condition gets very bad. Variable data rate is an efficient solution to cope with such situations. The system would run at maximum data rate in good conditions and can be adapted to work at lower data rate in worse situations. This paper discusses about one of the techniques to lower the data rate called Delayed Frame Repetition (DFR) for fading channels. It reduces the user data rate while maintaining the same channel data rate. The basic idea is to retransmit the data after a delay which is greater than fading length of the channel. Similar to spatial diversity systems, different combining techniques like Selective Combining (SC), Maximum-Ratio Combining (MRC) and Equal-Gain Combining (EGC) are studied. Numerous simulations are presented for MRC technique considering thermal limited PIN detector as a receiver, and for channel modelling artificially generated power vectors that are based on real measurements are used. Overall results show that DFR can be very useful for fading channel. MRC being the most efficient combining technique, it is used for evaluating the performance of DFR for different channel conditions with good, medium, bad scintillation indices, and different delays between retransmitted frames.

1 Introduction & Motivation

Free space optical communication offers large advantages compared to conventional RF communications like high data rate, unregulated spectrum, high power efficiency and high security. However, FSO channel is affected by atmospheric turbulence and weather condition. This distorts the signal passing through the atmosphere and causes loss of data. Various sophisticated coding and interleaving techniques can be designed in order to cope with the challenges. However, the channel condition is time variant. Coding and interleaving schemes designed for very challenging channel condition will be redundant, when the channel gets better. For such scenario, adaptive/variable data rate is a very efficient technique. Particularly for satellite downlink channel, various measurement results show that atmospheric turbulence is higher at lower elevation compared to higher elevation [1], [2]. In such scenario, a link can be setup with different data rates for different elevation angles. Moreover, different satellite terminals have different requirements and are made compatible for certain data rates. Therefore, it is very important for ground station to support different data rates and be able to easily switch between them.

Systems can be initially set-up at highest data rate and various techniques can be used to reduce the data rate [2], [3], [4], [5], [6]. The user data rate can be varied while keeping the same channel data rate, or by varying the channel data rate as well. One of the techniques to reduce the user data rate while maintaining the channel data rate, called Delayed Frame Repetition (DFR), is proposed in this paper. Data rate can be reduced by half simply by retransmitting the frame after certain delay that is longer than the fading length of the channel. This technique is mainly useful for fading channel. It helps to mitigate fades in addition to reduce the user data rates.

2 FSO Channel

FSO channel has been studied in various books, papers and is theoretically modelled in various ways with certain accuracy [7], [8]. However, in this paper artificially generated power vectors that are based on real channel measurements during the satellite downlink project (KIODO) [1] are used. The KIODO project was a demonstration of FSO link between Japanese OICETS satellite to DLR's optical ground station (OGS-OP) [9].

One of the important parameters for assessing the channel measurement is scintillation index (SI), which is the measure of the variation/fluctuation of the signal. **Figure 1** shows the intensity SI of the measured signal during different KIODO trials (# 2, 3, 4 and 7). It can be seen that SI of value 0.1, 0.3 and 1 can represent good range of channel conditions.

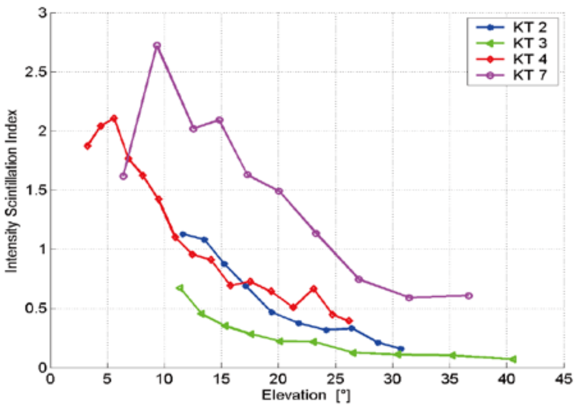

Figure 1. Intensity scintillation index derived from images of the "Profiler" camera vs elevation plot for different Trial #2, 3, 4 & 7 from KIODO Downlink [1].

3 Delayed Frame Repetition

One of the intelligent ways to reduce the data rate in case of bad channel condition is to retransmit the frame after a delay that is greater than coherence time of the channel. FSO channel is varying with time. The figure below shows short excerpt of the power measurement of example FSO channel. Assuming the threshold to be half of the

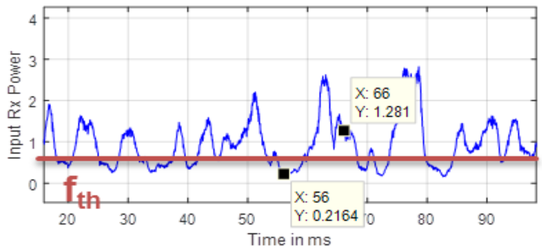

Figure 2. Excerpt of an example power vector showing fading threshold (f_{th}) and fading/non-fading instances.

mean received power, various instances can be seen when signal is below or above the fading threshold (f_{th}). Frames that are transmitted at the instance when signal is below fading threshold are received erroneously, and frames that are transmitted when the signal is above fading threshold are correctly received at the receiver. Therefore, as shown in **Figure 2**, if a frame is transmitted at faded instance (e.g. time at 56 ms) and is retransmitted at another instance (after some delay e.g. at time at 66ms) then there is a high probability that one of the repeated frames will not undergo fading, and all received frames can be combined in different beneficial ways. A simple block diagram showing how the delayed frame retransmission can be realized is shown in **Figure 3.** A frame "F_i" is transmitted and is retransmitted after certain delay. During this delay time, other frames are transmitted. All signals then go through the FSO channel and are combined later at the receiver.

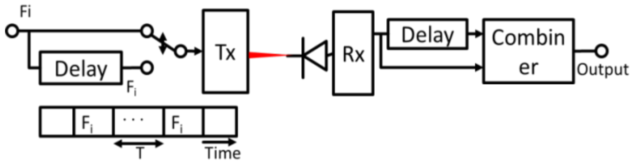

Figure 3. Block diagram showing delayed frame retransmission. F_i frame is transmitted once and retransmitted after a delay of T time.

4 Received signal combining

Repeated frames arriving at the receiver can be combined in different ways as explained in following subsections. Considering the PIN receiver, the received electrical signal after optical/electrical conversion can be expressed as below [10].

$$r_e = RhI_0 + n$$

Where, I_0 is the emitted light intensity, R is electrical/optical conversion factor and h is the channel atmospheric turbulence and attenuation. Moreover, for simplicity, thermal noise limited receiver is considered such that n is Gaussian additive noise of variance ${\sigma_n}^2$ with zero-mean, and is independent of the signal I $(I = hI_0)$. If the signal is retransmitted after certain delay then the combined electrical signal at the receiver can be expressed as below:

$$r_{total} = R\sum_{i=1}^{N}(h_i I_0 + n_i)$$

where N is the total number of repetitions.

4.1 Selective Combining (SC)

In case of selective combining, all the received repeated frames (N) are checked and the one with best SNR will be chosen, whereas others are neglected. This scheme is very simple however; not very efficient as information contained in other unchosen received frames is unexploited. Mathematically it can be expressed as:

$$SNR_{SC} = \max(SNR_1, SNR_2, \dots, SNR_N)$$

If SNR of the system is known then Q factor can be calculated using the relation: $Q = \sqrt{SNR}$ [11]

$$Q_{SC} = \max(Q_1, Q_1, \dots, Q_N)$$

4.2 Maximum Ratio Combining (MRC)

MRC is optimum way of combining where each incoming signal is weighted with the channel coefficients before combining. This technique is very optimum however; it is more complicated as it requires the channel state information. The total SNR in this case is derived as [12]:

$$SNR_{MRC} = \sum_{i=1}^{N} SNR_i$$

$$Q_{MRC} = \sqrt{\sum_{i=1}^{N} {Q_i}^2}$$

4.3 Equal Gain Combining (EGC)

EGC is a technique that lies between SC and MRC. In this case, all signals are combined but with unity weights. Therefore, it does not necessarily require knowledge of channel state information. The total SNR for EGC is derived as:

$$SNR_{EGC} = \left(\sum_{i=1}^{N} \sqrt{SNR_i}\right)^2 / N$$

$$Q_{EGC} = \left(\sum_{i=1}^{N} Q_i\right) \Big/ \sqrt{N}$$

5 Simulation Results and Discussion

Performance of DFR depends on the channel condition (channel with different PSI), delay between retransmitted frames and the repetition factor (RepFact). Such effects are studied with the help of simulations using MRC combining technique. For simulation, 1 Gbps of high data rate is considered and commercially available CWDM PIN receiver is used as a receiver. For modelling the channel, three different artificially generated power vectors that follow lognormal behaviour and have PSI of 0.1, 0.3 and 1 values are used and details of each power vectors are listed in **Table 1.** The power samples w.r.t. time, the probability distribution function (pdf) and auto covariance of the power vector with PSI = 0.1 is graphically presented in **Figure 4.**

For DFR, delay between two repeated frames is an important factor and it depends on correlation of the power vector (channel) itself. To determine the delay, a parameter called $\boldsymbol{\rho}$ $\left(\boldsymbol{\rho} = \frac{\boldsymbol{delay}}{\boldsymbol{HWHM\ ACOV}}\right)$ is introduced which is defined as the ratio of delay of DFR and half-width-half-maximum auto-covariance (HWHM ACoV) of the channel. All simulation parameters are presented in **Table 1**.

Data rate	1 Gbps
Receiver	Commercial CWDM PIN Receiver [Table III #11 in paper [13]]
RepFact	1, 2,3,4
Frame size	2040 bits
Power vector 1	PSI = 0.1, HWHM ACoV = 2.45ms
Power vector 2	PSI = 0.3, HWHM ACoV = 2.45ms
Power vector 3	PSI = 1, HWWM ACoV = 2.25ms
$\boldsymbol{\rho}$	0.5, 1, 2, 10

Table 1. Parameters used for simulations. All power vectors are 100 second long and sampling rate of 10000 samples per second.

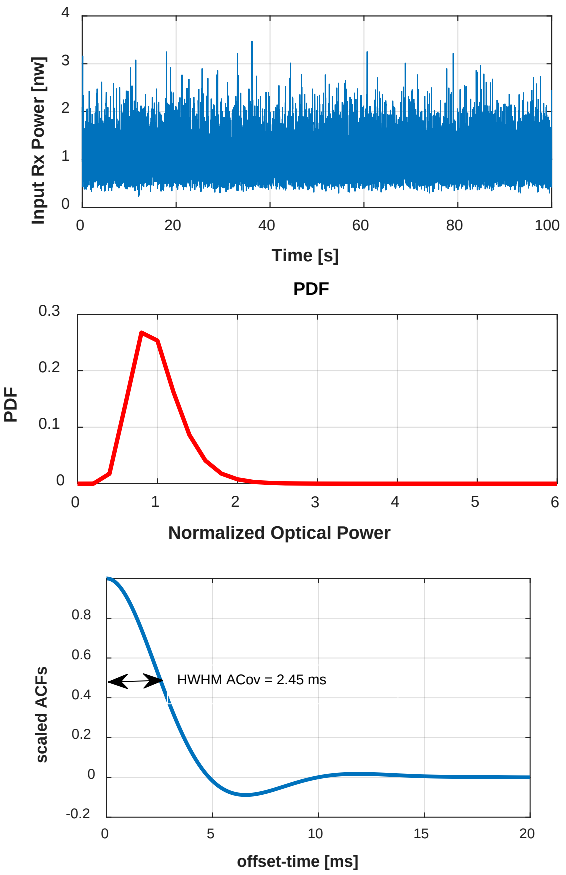

Figure 4. Generated Power Vector 1 with Power Scintillation Index of 0.1. Top figure shows normalized power samples w.r.t time, middle figure shows the pdf (lognormal) of the power and the last figure shows the auto covariance.

Firstly, the performance of the receiver (PIN receiver) is simulated using the receiver model as presented in paper by Giggenbach et al. [13]. The paper presents a model that can calculate the BER for the selected receiver model if the power required for achieving BER=2.3E-3 (Q = 2) and slope is known [13].

$$Q(\overline{P}_{Rx}) = 2\left(\frac{\overline{P}_{Rx}}{\overline{P}_{Q=2}}\right)^n$$

$$n = \frac{\ln 3}{\ln s}, \qquad s = \frac{\overline{P}_{Q=6}}{\overline{P}_{Q=2}}$$

Where $\overline{P}_{Rx}$ is mean received power, $\overline{P}_{Q=2}$ power required for achieving $Q = 2$ and $\overline{P}_{Q=6}$ is power required for achieving $Q = 6$ and s is the span-parameter.
Knowing Q, BER can be calculated as:

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right)$$

And assuming one frame contains m bits, frame error rate (FER) can be calculated as:

$$FER = 1 - (1 - BER)^m$$

Since no error correction is used, one erroneous bit in the frame causes complete loss of the frame.
In this paper, we focus more on MRC as according to literatures [12], MRC outperforms SC and EGC.

5.1 Maximum Ratio Combining (MRC)

The performance of delayed frame repetition using maximum ratio combining is analyzed in detail for different channel conditions and different delay values as mentioned in **Table 1**. Performance in terms of FER vs Photons per data bit and also FER vs mean received channel power, are graphically presented in figures below for PSI = 0.1 and 1 respectively. The gain/loss in terms of photon per data bit for more PSI and delay are presented in **Table 2**. It is quite clear from figures for FER vs mean received channel power that reducing the data rate for challenging channel condition, always brings some gain. However, by repeating frames a number of times, reduces the throughput (user data rate). Therefore, for fair comparison received photons per data bit are calculated. Although, reducing data rate already improves the system, the technique that reduces the data rate and yet requires less photons per data bit is more desirable.
The analysis shows that DFR is more advantageous for challenging channel with higher scintillation index. **Figure 5** and **6** show the DFR performance for the channel with PSI of 0.1 with ρ = 0.5 and ρ = 2 respectively. In this case, higher number of repetitions requires more photons per data bit even for longer delay. However, for channel with PSI of 1 (see **Figure 7** and **Figure 8**), the DFR has some gain in terms of photons per data bit.
It can also be observed that the performance for DFR system with the delay double of the correlation time of the channel (i.e. ρ =2), performs better than for the delay that is half of the correlation time (i.e. ρ =0.5**)**. This shows that increasing the delay and repetition factors improves the performance for channels with higher PSI.
Moreover, **Table 2** shows that the system does not improve by increasing the delay further longer as the gain already decreases for ρ =10 in comparison to ρ =2. It can also be observed that repetition factor 3 over 2 has much higher gain than compared to repetition factor 4 over 3. Repetition factor 1 represents no repetition i.e. frames are sent only once.

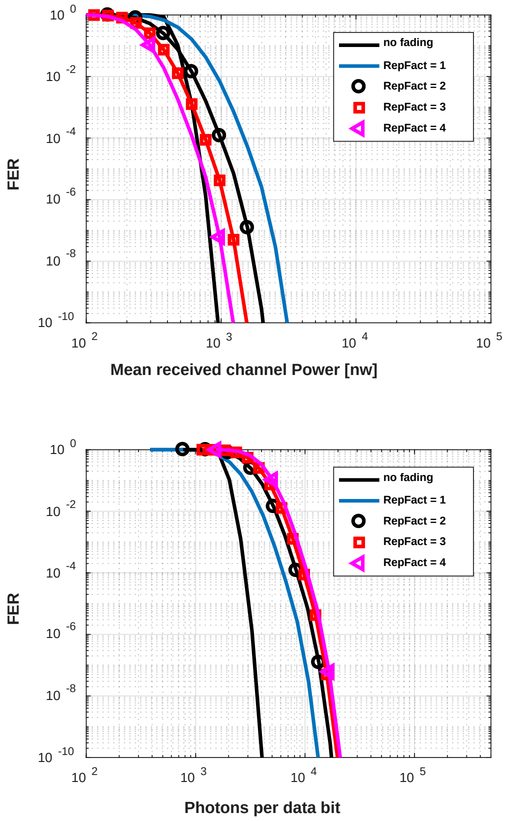

Figure 5. Performance in terms of mean received channel power (top) and photons per data bit (bottom), of DFR with MRC for the channel with PSI = 0.1, and ρ = 0.5.

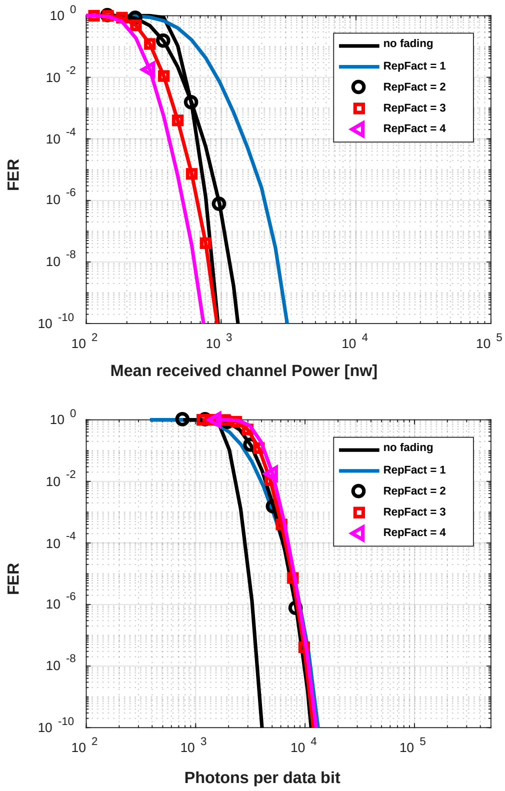

Figure 6. Performance in terms of mean received channel power (top) and photons per data bit (bottom), of DFR with MRC for the channel with PSI = 0.1, and $\rho = 2$.

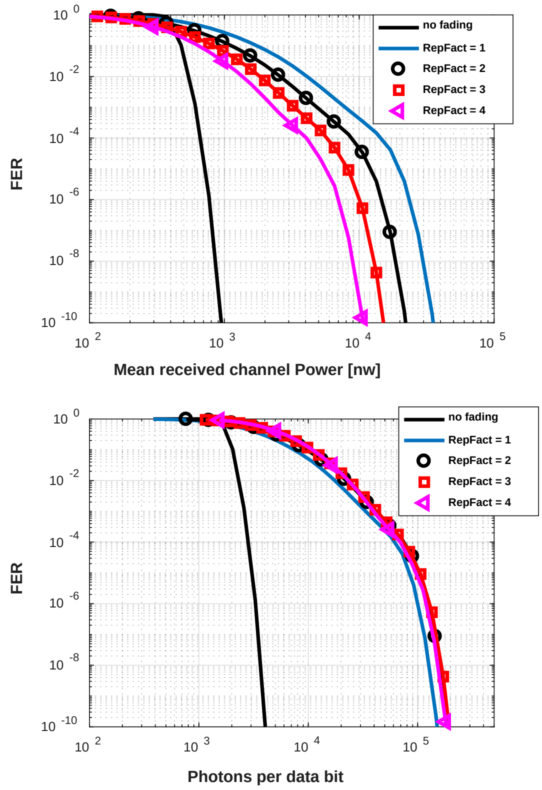

Figure 7. Performance in terms of mean received channel power (top) and photons per data bit (bottom), of DFR with MRC for the channel with PSI = 1, and $\rho = 0.5$

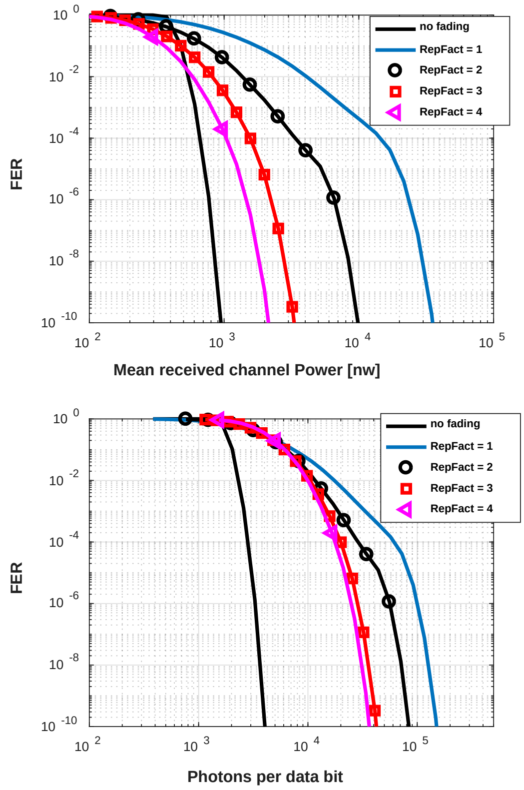

Figure 8. Performance in terms of mean received channel power (top) and photons per data bit (bottom), of DFR with MRC for the channel with PSI = 1, $\rho = 2$.

PSI = 0.1				
	RepFact 1	**RepFact 2**	**RepFact 3**	**RepFact 4**
ρ = 0.5	0dB	-1.2dB	-1.7dB	-1.9dB
ρ = 1	0dB	-0.5dB	-0.5dB	-0.5dB
ρ = 2	0dB	0.3dB	0dB	0dB
ρ = 10	0dB	0.1dB	0.1dB	0.3dB
PSI = 0.3				
ρ =0.5	0dB	-1.2dB	-1.6dB	-1.6dB
ρ = 1	0dB	-0.2dB	0dB	0dB
ρ = 2	0dB	1dB	1.6dB	1.6dB
ρ = 10	0dB	0.7dB	1.4dB	1.8dB
PSI = 1				
ρ = 0.5	0dB	-0.9dB	-1dB	-0.7dB
ρ = 1	0dB	0dB	1dB	1.5dB
ρ = 2	0dB	2.5dB	5.5dB	6dB
ρ = 10	0dB	3.5dB	4.6dB	5.6dB

Table 2. Gain in dB using DFR (different number of repetitions) in terms of Photons per bit to achieve FER of 1E-6 compared to the system without DFR for channel with different PSI values.

6 Conclusion and Outlook

Delayed frame repetition is shown to be a very useful and simple option to vary the data rate and also helps in mitigation of fades. For DFR, the delay that is two times the HWHM ACoV of the channel (i.e. $\rho = 2$) is enough to bring gain in terms of photons per data bit. It has also been observed that the DFR is more advantageous for channels with higher scintillation indices.

In this paper, simulations are done for thermal limited (PIN) receiver model. In future, Avalanche photo diode (APD) and shot-noise limited (SNL) receiver shall be studied and more gains are expected than for the thermal limited PIN receiver. In addition, detail investigation of simple DFR scheme with Forward Error Correction (FEC) that would bring additional gain, shall also be performed.

7 References

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