Performance Evaluation of Delayed Frame Repetition Variable Data Rate technique for Free Space Optical LEO Downlink (OLEODL) Channel for different Receiver types

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Abstract

Delayed Frame Repetition (DFR) is a simple and efficient technique for varying the data rate to cope with varying link budget and fading in free space optical LEO downlink (OLEODL) scenario [1]. The system shall run at highest possible data rate in good channel condition and at lower user data rates when the channel gets deteriorated. In OLEODL scenario, the link budget varies according to the elevation [2]. At lower elevations, the signal propagates longer through the atmosphere causing more free-space loss and creating stronger fluctuations by atmospheric turbulence. Therefore, it is efficient to transmit the data at reduced effective rates at lower elevations. Basic idea of DFR is to retransmit frames after certain delay that is larger than the typical fade duration of the channel. In addition to the gain achieved by varying the data rate, this proceeding also provides diversity gain in the scintillation channel. Unlike varying the data rate by varying the pulse length, this technique avoids the need for changing the receiver bandwidth as per the data rate. This paper evaluates the performance of such systems for channel without fading, medium and bad channels using different receivers namely: shot-noise limited (SNL), avalanche photodiode (APD), and thermal limited PIN (Positive-Intrinsic-Negative). For combining the retransmitted frames, Equal Gain Combining (EGC) technique is used. This paper also investigates the variation of the delay length between retransmitted frames. Simulation results show that it is more advantageous to use DFR for channels with higher scintillation index (SI), and use longer delay. With strong scintillation, even a net sensitivity gain in energy-per-bit can be achieved.

1 Introduction & Background

Optical communication offer very large data throughput which is bottleneck for using conventional Radio Frequency (RF) communications. This is true especially for LEO downlink scenario, where the main goal is to transmit the high resolution data captured in the satellite, to the ground as soon as possible. In addition, it also has high power efficiency, high data security, unregulated spectrum etc. However, this technology is dependent on the weather condition. The optical signal passing through the atmosphere is also affected by atmospheric absorption and turbulence causing more free-space loss. Different kinds of sophisticated coding and interleaving can be used to cope with such problems. However, such high-level coding and interleaving techniques adds redundancy even when the channel is in good condition. Therefore, adapting the data rate according to the channel is efficient technique for time-varying OLEODL channel.

Several OLEODL measurement results show that atmospheric turbulences are higher at lower elevations and get better at higher elevations [2]. Therefore, non-adaptive system needs to use either very strong codes or long interleavers, or operate only at higher elevations. In a typical scenario when LEO satellite is in line of sight of the ground station, its's viewing elevation angle is normally lower. A simulation done in [3] shows that a satellite (500 km orbit height) is seen between 5° and 20° for 64% of the total contact time. This implies that in order to maximize the data downlink, system has to operate at lower elevation angles as well. Operating the system at reduced data rate at lower elevations would allow the data transmission without breaking the link, although at reduced throughput. For an example scenario, **Figure 1-1** taken from the paper [3] shows the relative data rate versus elevation. The left axis shows the bit rate normalized to the zenith. It shows the reduction of bit rates for decreasing elevations. The right axis shows the bit rate change with the elevation, assuming 10 Gbps to be the highest data rate at zenith. It can be seen that to guarantee the link between 5° elevation and zenith, the elevation dependent maximum data rate has to be varied by factor 25.

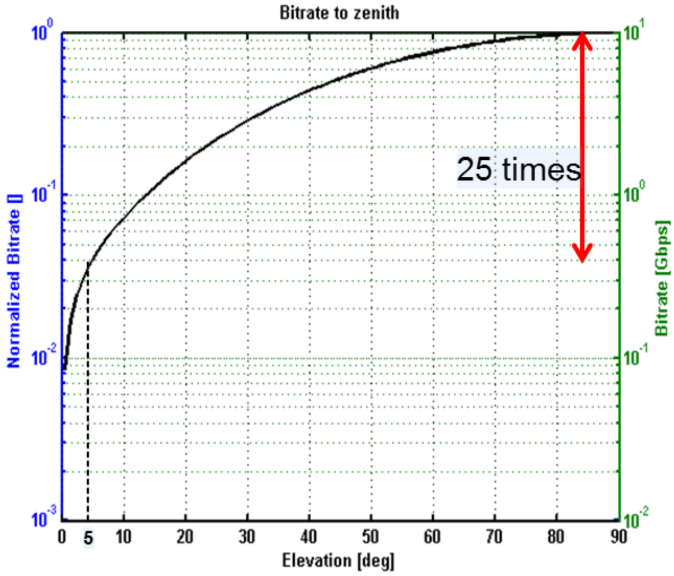

Figure 1-1: Transmittable data-rate based on mean received power (no scintillation considered) as a function of elevation for reference scenario. (Copied from [3])

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Various techniques to vary the data rate according to the channel condition, are discussed in literature [4–7]. In FSO, direct detection modulation formats like On-Off-keying (OOK) are popular for their simplicity. For OOK, data rate (both user and channel data rate) can be varied by changing width of the pulse. This is a simple method but it requires changing the filter at the receiver to match the pulse width, which is not feasible for varying the data rate according to elevation, during one pass. Another option which avoids this issue is to use return to zero (RZ) OOK and change the duty cycle, keeping the pulse width constant.[8]. Similar gains can be achieved by lowering the user throughput but maintaining the channel data rate, for example by varying the code rate [9]. It can also be done by repeating the frame after certain delay. The technique is called as Delayed Frame Repetition (DFR) and is explained briefly in Section 2.

2 Delayed Frame Repetition (DFR)

The basic idea of DFR is to retransmit the frame after certain delay that is greater than the fading length. Gain is achieved by combining two or more instances of the same frame that was transmitted through different channel conditions (uncorrelated); however, the throughput is reduced.
Similar to diversity schemes, frames can be combined in different ways, namely Selective Combining (SC), Equal-Gain Combining (EGC) and Maximum Ratio Combining (MRC). SC is simplest option where one of the instances of the frame that has higher SNR is selected. EGC and MRC combine all the repeated frames. The former combines them equally and the later weighs each instance with the channel coefficients, therefore, requiring the channel information. The paper presents results for equal gain combining scheme for simplicity.

3 Simulation Environment

3.1 Receiver

For simulation, on-off keying (OOK) direct detection modulation with hard decision is considered. In OOK receivers, the receiver telescope collects the optical signal, filters undesired background light, focusses onto the photodetector surface and converts it to an electrical current. This decision unit then detects a pulse (for bit '1') or no pulse (for bit '0') depending on if the received photocurrent is greater or less than the threshold I_{th}, which is derived in [10]. In addition to the modulated signal, shot noise and thermal noise widen its level distribution which may lead to the false detection of the pulse or missed detection, causing errors. For evaluation, average bit error rates and corresponding required photons per data bits are calculated and presented in the paper.
Three different types of receivers are considered, namely ideal shot noise limited (SNL), Avalanche photodiode (APD) and thermal limited PIN. Following parameters are used in the simulation for different receiver types.

SNL	APD	PIN
$i_t = 0$	$i_t = 5.9E-12$	$i_t = 5.9E-12$
M = 1	$M=20$	$M=1$
$F_a = 1$	$F_a = 8$	$F_a = 1$
$\sigma_t = 0$	$\sigma_t = i_t\sqrt{B}$	$\sigma_t = i_t\sqrt{B}$
${\sigma_s}^2 = 2eRBP_P$	${\sigma_s}^2 = 2eM^2F_aRBP_P$	${\sigma_s}^2 = 2eRBP_P$
$\sigma_0 = 0$	$\sigma_0 = \sigma_t$	$\sigma_0 = \sigma_t$
$\sigma_1 = \sigma_s$	$\sigma_1 = \sqrt{{\sigma_s}^2 + {\sigma_t}^2}$	$\sigma_1 = \sqrt{{\sigma_s}^2 + {\sigma_t}^2}$

Where, σ_t and σ_s are standard deviation of the thermal noise and shot noise distributions respectively. B is the bandwidth, R is the responsivity of the detector, e is charge of an electron, M is the APD gain and P_P is the peak power. i_t is thermal noise current density in $A/\sqrt{Hz}$. σ_0 and $\sigma_1$are standard deviations of noise distribution for zeros and ones respectively [10].

3.2 Equal Gain Combining for DFR

The calculation for simulations for EGC scheme is explained below. For example, if the repetition factor (RF) is considered to be n, signals and noise at different time instances (1,2 …n) are added as shown in equations 3-1-3-8. For simplicity, background noise and dark currents are neglected. The received current is then calculated as shown in equation 3-9 and finally output bit stream is generated by using hard decision as shown in equation 3-10 and 3-11.

$$ {\sigma_{sc}}^2 = \sum_{i=1}^{n} ({\sigma_{si}}^2) \quad \text{3-1} $$

$$ {\sigma_{tc}}^2 = \sum_{i=1}^{n} ({\sigma_{ti}}^2) \quad \text{3-2} $$

$$ {\sigma_{1c}}^2 = {\sigma_{sc}}^2 + {\sigma_{tc}}^2 \quad \text{3-3} $$

$$ {\sigma_{0c}}^2 = {\sigma_{tc}}^2 \quad \text{3-4} $$

$$ P_{Rx\,c} = \sum_{i=1}^{n} P_{Rx\,\mathrm{i}} \quad \text{3-5} $$

$$ I_{pc} = R.P_{Rx\,c} \quad \text{3-6} $$

$$ I_{0c} = 0 + I_{tc}(t) \quad \text{3-7} $$

$$ I_{1c} = MI_{pc} + I_{sc}(t) + I_{tc}(t) \quad \text{3-8} $$

$$ I_{Rx\,c} = \begin{cases} I_{1c} \; for\ all\ ones \\ I_{0c} \; for\ all\ zeros \end{cases} \quad \text{3-9} $$

$$ I_{th} = \frac{\sigma_{0c} < I_{1c} > + \sigma_{1c} < I_{0c} >}{\sigma_{0c} + \sigma_{1c}} \quad \text{3-10} $$

$$ b_{out} = \begin{cases} 0 \; for\ all\ I_{Rx\,c} \le I_{th} \\ 1 \; for\ all\ I_{Rx\,c} > I_{th} \end{cases} \quad \text{3-11} $$

Where,
${\sigma_{si}}^2$ is shot noise variance at instance i.

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${\sigma_{ti}}^2$ is thermal noise variance at instance *i.*
${\sigma_{sc}}^2$ & ${\sigma_{tc}}^2$ are combined shot & thermal noise variance.
σ_{0c} & σ_{1c} are combined noise std. dev. for bits 0 and 1:
$P_{Rx\,i}$ is received power at instance *i.*
I_{pc} is combined received current at photodetector:
$I_{sc}(t)$ & $I_{tc}(t)$ are combined shot and thermal noise currents. They are independent random processes with approximately Gaussian statistics with variance ${\sigma_{sc}}^2$ & ${\sigma_{tc}}^2$ respectively.
I_{1c} & I_{0c} are combined current distribution of bit 1 and 0.
$I_{Rx\,c}$ is combined received current. I_{th} is threshold photodetector current and b_{out} is output bit stream

3.3 OLEODL Channel

FSO channel has been described in literature and theoretically modelled in different ways [11], [12]. In this paper, artificially generated power vectors (using PVGeT tool [13]) that are based on the real measurements during the satellite downlink project (KIODO) [12] are used. The quality of channel can be represented by a parameter called Power Scintillation Index (PSI) which is the measure of fluctuation of the received signal. For the simulation; ideal channel without fading, good channel with PSI=0.1 and bad channel with PSI=1, are used. The **Figure 3-1** and **Figure 3-2** show the PDF (top) and correlation behaviour (bottom) of the channel with PSI 1 and 0.1 respectively.

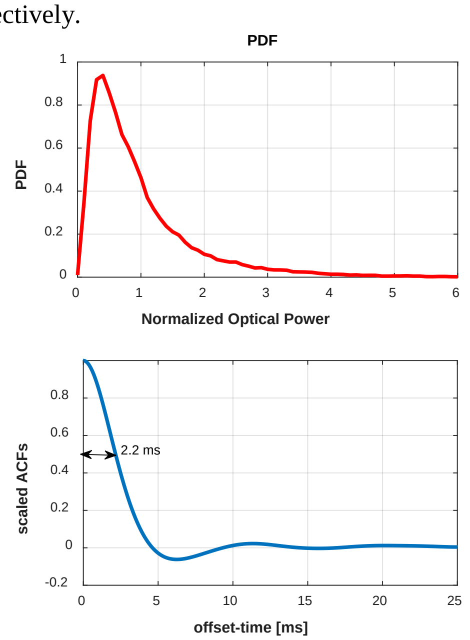

Figure 3-1: Generated power vector with PSI = 1; top: PDF(lognormal), bottom: plot of auto covariance showing half width at half maximum (HWHM) covariance =2.2 ms.

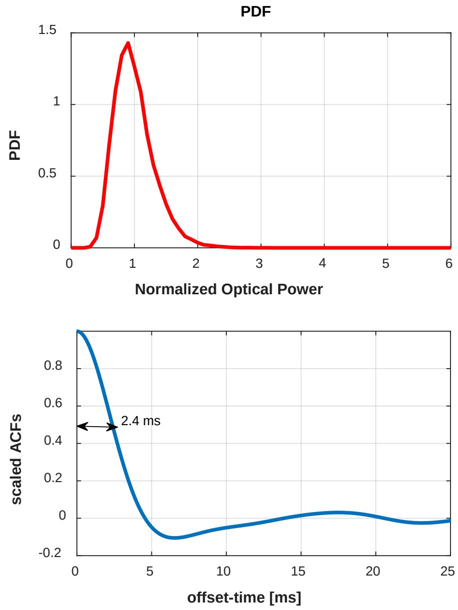

Figure 3-2: Generated power vector with PSI = 0.1; left: PDF(lognormal), right: plot of auto covariance showing HWHM covariance = 2.4 ms.

4 Simulation Results

Bit-wise simulations for DFR are done for ideal, good and bad channels using different receiver types as explained in section 3. Repetition factors (RF) of 1, 2, 3 and 4 are considered, where RF 1 means no DFR is performed and RF n means that same frame is transmitted n times with some delay. Effects of different delays between retransmitted frames are also studied. For this, parameter named as Delay Factor (DF) is used which is the ratio of the delay and HWHM covariance of the channel. The performance is measured in terms of number of average photons per bit (ppb) required to achieve certain BER. ppb can be calculated as: $ppb = \frac{P_{Rx}}{hc/\lambda}\frac{1}{DR}$, where P_{Rx} is average power, h is planck's constant, c is the speed of light, λ is the wavelength and DR is the effective data rate which is the ratio of maximum possible data rate and RF. Summary of the parameters and their values used in the simulations are listed in **Table 1**:

Maximum possible data rate	1 Gbps
DF	0, 0.5,1, 3, 5
Channel (PSI)	Ideal: noFading Good:PSI =0.1 Bad: PSI = 1
RF	1(no DFR), 2, 3, 4
Rx types	SNL, APD, PIN

Table 1: Parameters and their values used in the simulation

4.1 No Fading channel

For ideal channel without fading, the performance of implementing DFR is presented in **Figure 4-1** for delay of 1.1ms. Since the channel is completely correlated, the effect of delays does not play any role. Therefore, the result for only one delay is presented in the paper. For ideal

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channel without fading, repeating the frames requires more photons per bit except for ideal SNL. The ideal SNL performs the best requiring few photons per user bit (ppb) to achieve BER of 2E-3 and PIN performs the worst requiring several thousands of ppb. The chosen APD required around 200-400 ppb to achieve the same BER. The BER of 2E-3 is chosen arbitrarily as a base BER to compare different systems, assuming that some basic coding techniques that can provide error free transmission for BER less than 2E-3, will be used. It can be exactly evaluated by doing simulations including FEC in DFR which is foreseen in future. In **Figure 4-1** , the curve for no Fading and RF =1 overlaps since there is no fading.

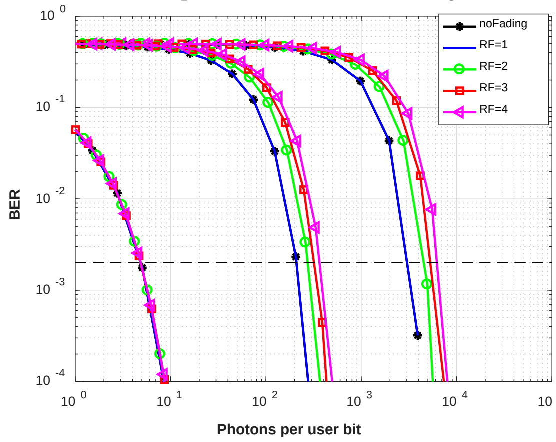

Figure 4-1: BER vs ppb for DFR with delay = 1.1ms and RF 1,2,3&4 for no fading channel. Curves on the left: SNL, mid: APD, right: PIN. The dashed horizontal line shows the line for arbitrary BER of 2E-3.

4.2 Fading channel with PSI 1

The performance of DFR for SNL, PIN and APD is presented for different delay factors (DF = 0.5, 1, 3) in **Figures 4-2**, **4-3** and **4-4** respectively for bad channel condition with PSI = 1. In each plots, it can be seen that the performance of APD receiver lies in between PIN and SNL. Considering that the system will have forward error correction that can correct all errors up to BER of 2E-3, we measure the gain at this point. The gain/loss here is calculated as $10\log_{10}(ppb(RF=1)/ppb(RF=n))$. Implementation of DFR in this channel provides even a net sensitivity gain. For APD receivers when DF =1 we gain up to 0.6dB in terms of required photons per bit. The gain increases up to 2dB when DF = 3 i.e. delay = 6.6 ms which is minimum ACF point (at negative overshoot). Increasing the DF further to 5, does not bring further gain to the system (see **Table 2**). Using very short delay DF = 0.5 the performance in terms of photons per bit gets a bit worse (<1.5dB). If the delay is zero, meaning the frames are repeated one after another, it requires 2.6dB more photons per bit for RF=4 than for RF=1. Details of the performance for different channel conditions, Rx types, RFs and DFs are listed in **Table 2** and graphically presented in **Figures 4-8**, **4-9** and **4-10**. It has also be found that the gain of using DFR is highest for SNL receiver types.

In addition to delay and Rx types, the effects of repetition factors (RF) were also evaluated. According to **Table 2** and **Figure 4-9**, for DF =3 in case of APD, RF=2 has 1.6 dB gain over RF=1 and RF = 4 has 2 dB gain. However, increasing the RF to larger numbers would not further improve the performance, as more redundancies are added than the gain itself.

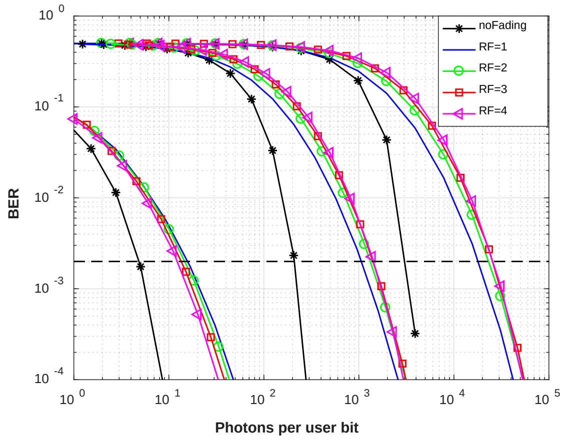

Figure 4-2: BER vs ppb for DFR with DF = 0.5 and RF 1,2,3&4 for channel with PSI =1. Curves on the left: SNL, mid: APD, right: PIN. The dashed horizontal line shows the line for arbitrary BER of 2E-3.

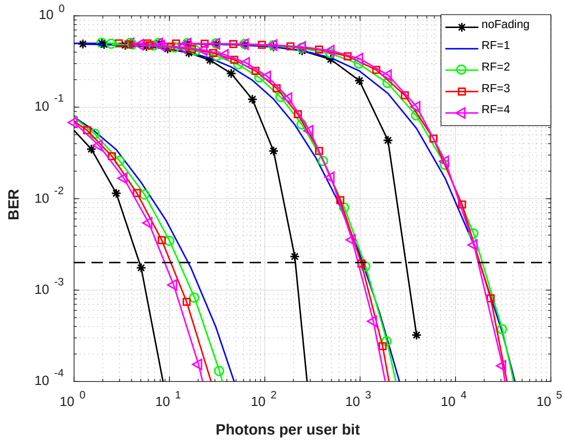

Figure 4-3: BER vs ppb for DFR with DF = 1 and RF 1,2,3&4 for channel with PSI = 1. Curves on the left: SNL, mid: APD, right: PIN. The dashed horizontal line shows the line for arbitrary BER of 2E-3.

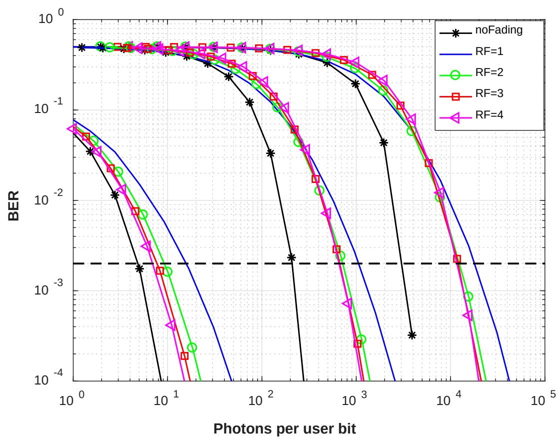

Figure 4-4: BER vs ppb for DFR with DF = 3 and RF 1,2,3&4 for channel with PSI = 1. Curves on the left: SNL, mid: APD, right: PIN. The dashed horizontal line shows the line for arbitrary BER of 2E-3

4.3 Fading Channel with PSI 0.1

For simulating good channel condition, the channel vector with PSI 0.1 was generated and used. DFR does not seem to bring diversity gain in case of good channel condition; however, it reduces the data rate when needed at lower elevation angles.

Since the channel condition is very good, increasing the repetition factors increases (slightly) the number of ppb needed to achieve the same BER except for SNL receivers. For APD when DF=3, the losses are <0.6dB for RF=2 and ~1.5dB for RF=4.

According to **Figures 4-5**, **4-6** and **4-7**, the loss due to fading compared to non-fading channel is <1.5dB (for APD) which could be compensated by additional FEC. This is foreseen to be investigated.

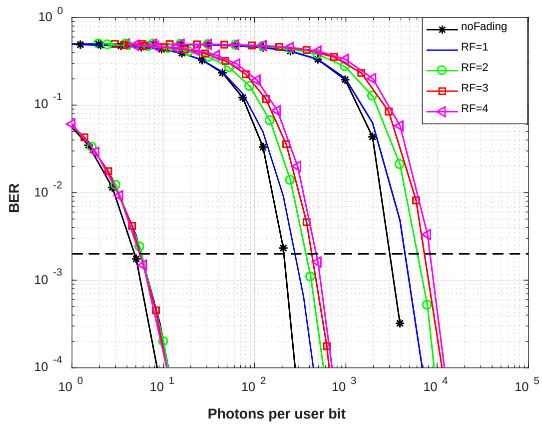

Figure 4-5: BER vs ppb for DFR with DF = 0.5 and RF 1,2,3&4 for channel with PSI = 0.1. Curves on the left: SNL, mid: APD, right: PIN. The dashed horizontal line shows the line for arbitrary BER of 2E-3

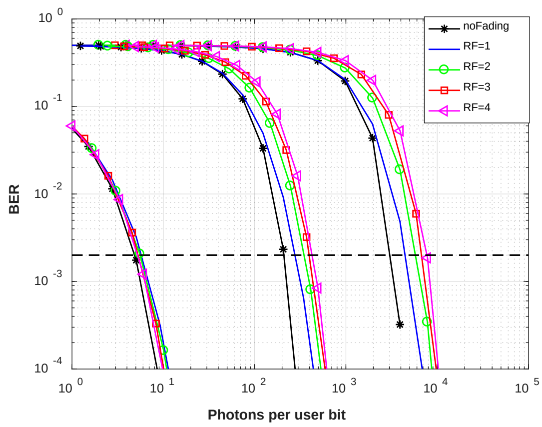

Figure 4-6: BER vs ppb for DFR with DF = 1 and RF 1,2,3&4 for channel with PSI = 0.1. Curves on the left: SNL, mid: APD, right: PIN. The dashed horizontal line shows the line for arbitrary BER of 2E-3

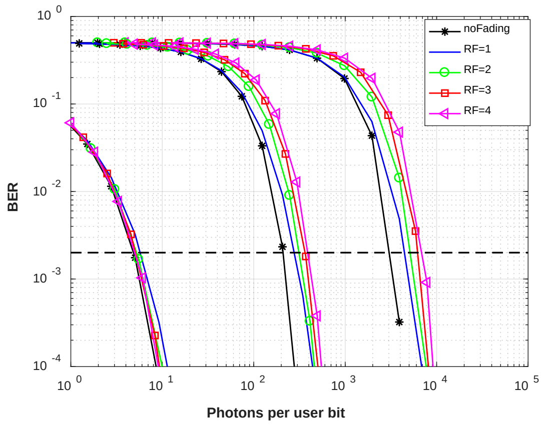

Figure 4-7: BER vs ppb for DFR with DF = 3 and RF 1,2,3&4 for channel with PSI = 0.1. Curves on the left: SNL, mid: APD, right: PIN. The dashed horizontal line shows the line for arbitrary BER of 2E-3

The table below summarizes the gain of DFR for using different receiver types and using different delay factors for different channel conditions and are represented graphically in **Figures 4-8, 4-9 and 4-10** for SNL, APD and PIN receivers respectively.

Rx type	DF	RF=2	RF=3	RF=4
		PSI = 1		
SNL	0	0	0	0
	0.5	0.3	0.6	1
	1	0.9	1.8	2.4
	3	2.32	3	3.5
	5	2.1	2.9	3.48
APD	0	-1.32	-2.15	-2.68
	0.5	-0.9	-1.2	-1.3
	1	0.2	0.3	0.6
	3	1.67	1.99	2.05
	5	1.44	1.86	1.99
PIN	0	-1.47	-2.3	-2.9
	0.5	-1.1	-1.5	-1.5
	1	0	-0.2	0.2
	3	1.6	1.7	1.8
	5	1.32	1.62	1.77
		PSI = 0.1		
SNL	0	0	0	0
	0.5	0	0.02	0.02
	1	0.07	0.3	0.4
	3	0.39	0.51	0.62
	5	0.28	0.49	0.64
APD	0	-1.28	-2.04	-2.68
	0.5	-1.22	-1.84	-2.32
	1	-1.2	-1.5	-1.8
	3	-0.59	-1.23	-1.51
	5	-0.6	-1.26	-1.51
PIN	0	-1.44	-2.32	-3
	0.5	-1.37	-2.08	-2.7
	1	-1.1	-1.7	-2.3
	3	-0.6	-1.4	-1.8
	5	-0.67	-1.47	-1.9

Table 2: Gain in terms of photons per bit at arbitrary BER = 2E-3 for different receiver types, channel conditions and delay factors. Gain $(dB) = 10\log_{10}(ppb(RF=1)/ppb(RF=n))$

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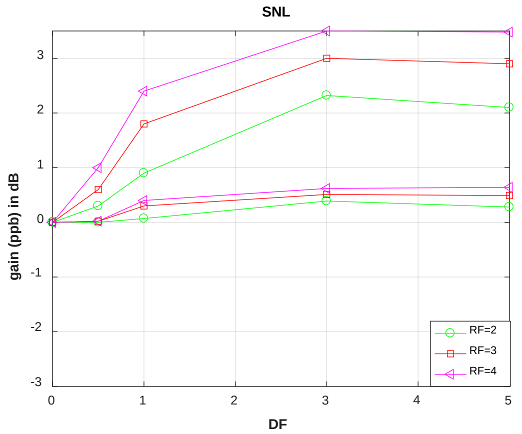

Figure 4-8: Gain or loss in terms of energy per bit in dB for using different RFs compared to RF1 for different DFs for SNL receivers. Upper curves are for PSI = 1 and lower curves are for PSI = 0.1

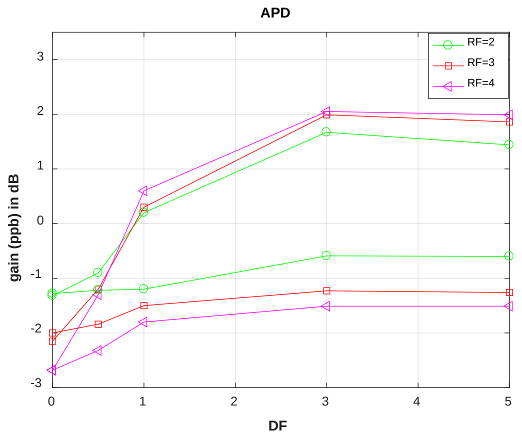

Figure 4-9: Gain or loss in terms of energy per bit in dB for using different RFs compared to RF1 for different DFs for selected APD. Upper curves are for PSI = 1 and lower curves are for PSI = 0.1

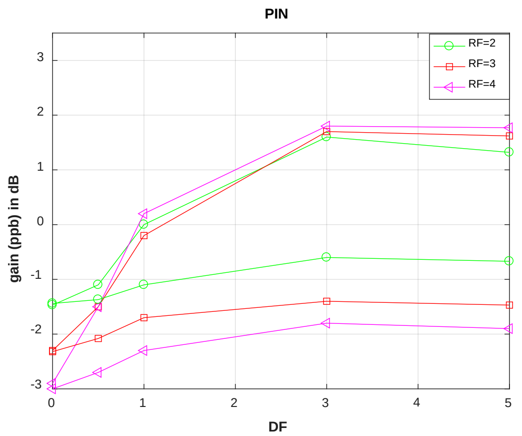

Figure 4-10: Gain or loss in terms of energy per bit in dB for using different RFs compared to RF1 for different DFs for PIN receivers. Upper curves are for PSI = 1 and lower curves are for PSI = 0.1

5 Conclusion and Outlook

For OLEODL channel, varying the data rate according to the elevation is effective solution to cope against variable link budget and fading. The simulation results show that lowering the data rate by delayed frame retransmission is simple and effective technique especially for bad channel with higher scintillation index (example PSI =1). For good channel conditions, using simple DFR without FEC to vary the data rate, requires additional photons per bit to achieve certain BER. Nevertheless, DFR allows varying the data rate according to the elevation without requiring any changes in the receiver hardware, unlike the option of varying the pulse width. In addition, the performance would be improved by including the FEC that is foreseen to be investigated.

For fading channel, DFR performs the best when delay is chosen that is equal to minimum of ACF of the channel. However, for delay sensitive scenarios, it can still be used with shorter delays if additional photons per bit can be provided. Increasing the repetition factors, improves the performance depending on how much data rate reduction is required for the channel.

In this paper, separate simulations were done for channels with certain scintillation index in order to evaluate the performance for different channel states. However, in future, complete OLEODL system operating at suitable data rates at different elevation angles shall be considered.

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