Spectrally Efficient Transmitter Diversity Scheme for Optical Satellite Feeder Links Employing Multiple Signal Sidebands

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Abstract

Optical links between ground stations and geostationary orbit (GEO) satellites suffer from the atmospherically induced phase piston and intensity fluctuations. This aggravates stable signal detection in the uplink scenario. In this work transmitter diversity is studied as a fading mitigation technique in GEO satellite feeder uplinks. A single sideband scheme is used as a spectrally efficient frequency division technique compatible with intensity modulation and direct detection. A spectral efficiency of 0.56 bit/s/Hz with twofold diversity gaining 2.3 dB at BER = 10^{-3} was obtained by simulation.

1 Introduction

Free-space optical (FSO) communications is an attractive alternative to microwave technology in geostationary communication satellite feeder link applications due to the possibility of transmitting information with high data rate, small antenna size, secure communication, and no spectrum licensing requirements. GEO satellites are envisaged to provide Terabits per second transmission rates by means of optical links [1]. However, optical links through the atmosphere suffer from intensity fluctuations, also called scintillation, and atmospherically induced phase piston variations [2]. It aggravates stable signal detection in the uplink scenario. Morever, beam wandering gives rise to pointing errors at the satellite which causes deep fades, hence loss of signal. To overcome pointing errors, the beam divergence can be made larger so the receiver at the satellite is always illuminated. This comes with the drawback of lower received power which requires high sensitive receivers for signal detection. To increase the received power, a narrow beam can be used, but this increases the misalignment between the beam and the receiver giving rise to deep and long fades.

Transmitter diversity techniques can be employed beneficially in GEO feeder links as they provide atmospheric fading mitigation as required for reliably receiving signals [3]. **Figure 1** shows a realization of the spatial diversity scheme. Since the atmospheric correlation length is on the order of a fraction of a meter for the uplink channel, the separation *d* between the transmitters can be around *d* = 1 m. With this spatial separation on ground, the turbulent paths are de-correlated and the fading effects on the uplink signal are reduced using standard diversity schemes taken from RF technology. The benefits of transmitter diversity schemes have been experimentally shown in [4]. The carriers of the data signals were chosen as to have minimum spectral overlap to avoid interference. This however, results in a spectrally inefficient system. To achieve Terabits per second throughput, a communication system needs to be spectrally more efficient.

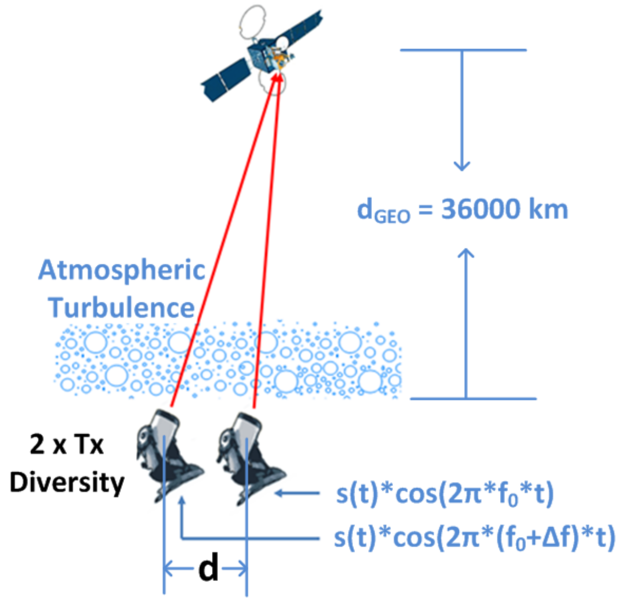

Figure 1 Spatial diversity scheme with two transmitters in a GEO feeder uplink [4]

For the implementation of the transmitter diversity it is essential to prevent the cross-interference between transmitted signals by means of a proper division technique. Wavelength-division is easy to implement and quite robust, but spectrally very inefficient. We propose a solution to this problem by employing a scheme in which the mutual interference between transmitted signals is avoided by using frequency division based on single sideband (SSB) transmission. Intensity modulation at the ground station transmitters and direct detection at the satellite receiver are deployed where the two individual transmitters send SSB signals which propagate through two uncorrelated atmospheric channels and are equally combined in a single receiver.

In this work, we first perform the experiments to find the optimum carrier separation between the two on-off keying

(OOK) signals with data rate R_b = 32 Gbit/s. This maximum data rate is limited by the bandwidth of the Photoreceiver. The goal is to find the spectral efficiencies for the unfiltered and filtered signals. The optical filters from a standard multiplexer device with an ITU-T 100GHz grid are used to perform filtering of the double sideband signals. Here, the idea is to find how much the frequency separation of the two carriers can be reduced by filtering the unwanted sideband as compared to the case of unfiltered signals. After that, MATLAB-based simulations are performed to verify the experimental results. After establishing the simulation platform, steeper and narrower realistic optical filters are used in the simulation to increase the spectral efficiency of the transmission system. Using these filters, the unwanted sidebands of the individual signals are considerably suppressed. These sidebands are then used in the simulations for data transmission and to show transmitter diversity as an effective fading mitigation technique in the presence of index-of-refraction turbulence (IRT) and phase variations of atmosphere in the GEO satellite feeder uplink.

1.1 Atmospheric Channel to GEO Satellite

The knowledge of the atmospheric channel is crucial for evaluating the performance of the transmitter diversity scheme with SSB transmission. The atmospheric fading due to IRT and phase variations in the form of phase piston is described in the following subsections.

1.1.1 Intensity Fading

To include the turbulence induced fading in the simulations, a measured GEO uplink fading signal from [3] is used. An example of the temporal fluctuations of this optical signal is shown in **Figure 2**. It has a power scintillation index *PSI* of 0.33 which is for weak scintillation and follows log normal distribution [5].

1.1.2 Phase Piston

Due to atmospheric turbulence, the phase of the optical field is distorted which results in the distorted wavefront at the receiver instead of a plane wavefront. Thus the optical field experiences phase fluctuations which have a significant effect on the interference between the two transmitted SSB signals. This effect of constructive and destructive interference due to phase fluctuations increases as the difference between the carrier frequencies of the two signals becomes smaller. These phase distortions are characterized as phase pistons [2]. The temporal evolution of phase pistons is shown in **Figure 3.** The phase fluctuations are much slower than intensity fluctuations but the effect is quite significant as the data rate increases. For example, during fade duration of few milliseconds, millions of bits can be lost for data rates on the order of Gbit/s. Also, the out-of-phase signals due to phase fluctuations can cause destructive interference, meaning total loss of signal.

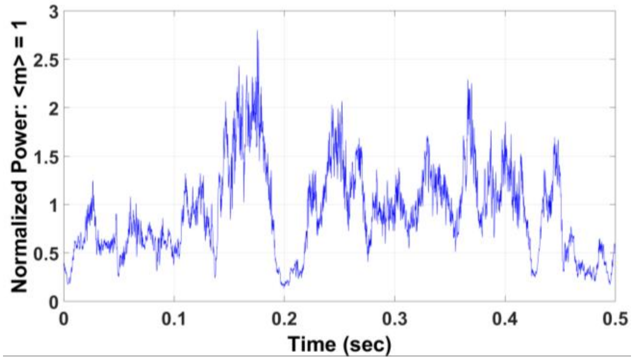

Figure 2 Measured received power at GEO satellite with 8 kHz sampling frequency

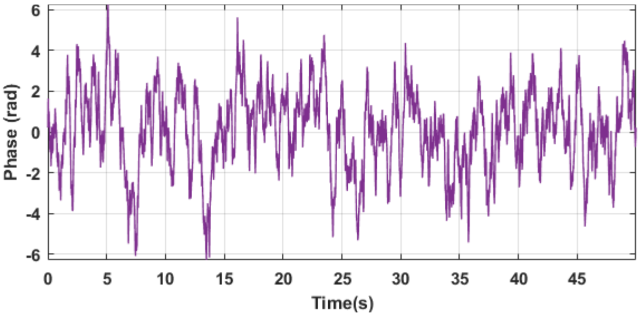

Figure 3 Temporal evolution of phase piston

2 EXPERIMENTAL SETUP

The block diagram of the laboratory experiment is shown in **Figure 4** where two freely tunable continuous wave (CW) laser sources are modulated by the same R_b = 32 Gbit/s PRBS7 sequence of data, generated by a bit pattern generator (BPG) using a Mach-Zender modulator (MZM). The carrier frequencies are detuned from the neighboring optical filters' centers to suppress the unwanted sidebands as much as possible so that the carrier channel spacing can be minimized.

The 3 dB and 20 dB optical bandwidths BW_o of the optical filters are 60 GHz and 120 GHz, respectively. The filtered signals are then split by a 90/10 splitter to view the optical spectrum; the remaining power is fed to the preamplifier which provides sufficient power to the PIN photodiode having electrical bandwidth BW_e = 24 GHz. Online digital signal processing is performed to estimate the bit error rate (BER) by, first, down-sampling the received data using a square timing recovery algorithm [6] and then doing bit-by-bit comparison with the transmitted PRBS7 bit pattern. The same measured filters are used in simulations to produce upper and lower sidebands from the two individual signals. **Figure 5** verifies the experimentally obtained spectral efficiencies (SE) with simulations for the filtered and unfiltered signals.

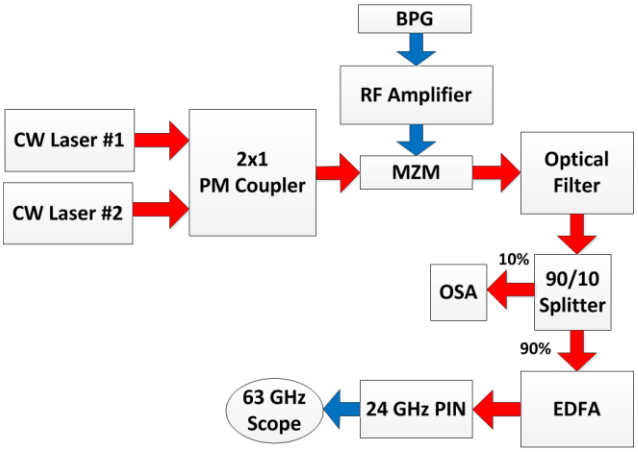

Figure 4 Experimental setup to produce sideband signals using multiplexer optical filters

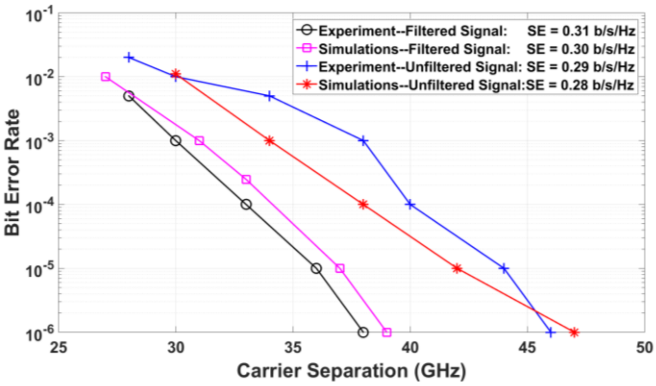

Figure 5 Comparison of theoretical and simulated spectral efficiencies using optical filters from the multiplexer

Spectral efficiencies at BER = 10^{-6} are shown to match closely for both experiments and simulations. Due to broad and less steep filters, this improvement is not significant as compared to the maximum spectral efficiency of 0.25 bit/s/Hz for the unfiltered signals when there is no spectral overlap between the two signals. This is the basis to perform simulations with steeper and narrower filters to increase spectral efficiency of the system.

3 Simulation Setup

MATLAB is used as a simulation platform where data rate R_b, optical carrier frequencies f_0 and f_1, optical filter bandwidths BW_o and electrical filter bandwidth BW_e are scaled down to Gbit/s and GHz range to reduce simulation processing time. **Figure 6** describes the simulation setup for a 32 Gbit/s system where realistic steep and narrowband optical filters are used. The 3 dB and 20 dB bandwidths of the optical filters are 30 GHz and 38 GHz respectively. They are detuned from the carrier frequencies f_0 and f_1 to produce lower and upper sidebands with the resulting spectra as shown in **Figure 7**. SE of 0.56 bit/s/Hz is achieved with a carrier separation of 57 GHz. The individual sidebands then undergo atmospheric turbulence which is modelled by the measured GEO uplink fading from [3], and simulated phase piston from [2] to include effect of atmospheric phase variations on the transmitted signal. The fading used in the simulation has a *PSI* of 0.33 which is for weak scintillation and follows a log-normal distribution [5]. The two atmospheric paths are made uncorrelated by introducing a non-zero time delay between the two fading and phase piston vectors. It ensures that the probability of both signal levels going below receiver sensitivity is lower as compared to transmitting one signal only. The mean received power for both transmitted signals is preserved before propagation into the atmosphere. This is done to ensure that both signals with the same optical to signal noise ratio (OSNR) are faced by the uncorrelated atmospheric turbulences. The effect of uncorrelated phase piston on both signals is crucial when they are equally combined at one receiver. Since the spectral overlap between the two transmitted sidebands is not significant, the effect of statistically independent phase variations is not detrimental.

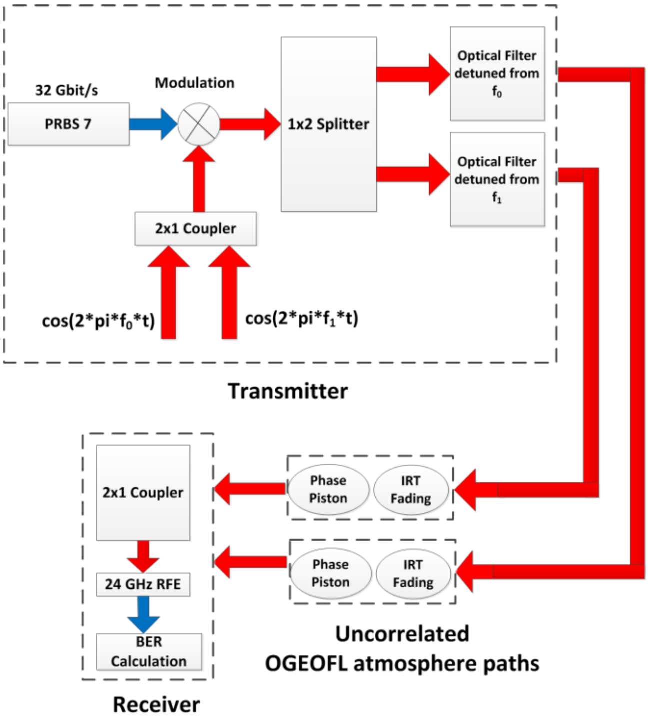

Figure 6 Simulation setup for increasing spectral efficiency with signal propagation through IRT fading and phase piston

The transmitted signal is divided into blocks of bits with each block containing 4000 data bits. Now each data block with a defined mean received power undergoes power variation during each fading transition in the atmosphere. The effect of uncorrelated phase pistons in each atmospheric path is also included in the phases of both data signals. The BER is measured after direct detection of the incoming signal. The electrical filter at the

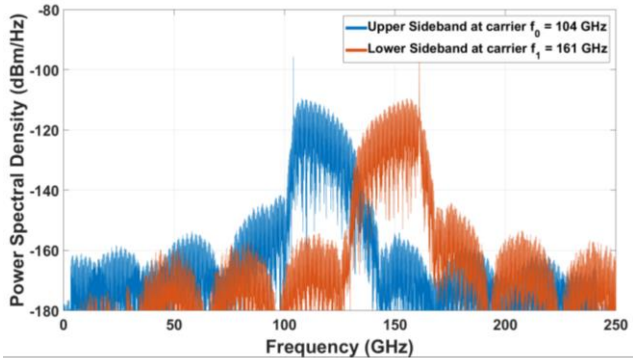

Figure 7 Sideband generation using realistic filters with BW_o = 30 GHz and BW_o = 38GHz as 3dB and 20dB bandwidths respectively

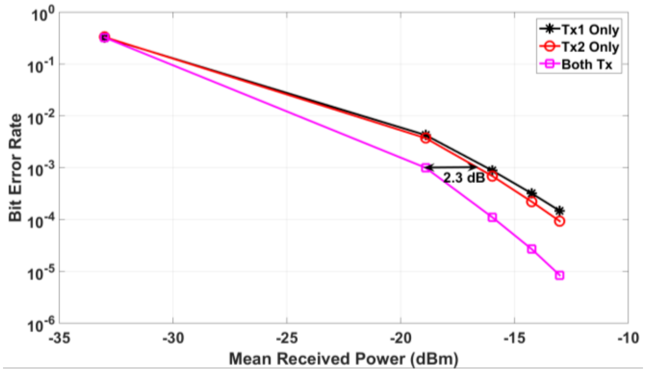

Figure 8 Diversity gain in the presence of measured IRT fading from [3] and simulated phase piston effects on the two data signals.

receiver is a 3rd order Bessel filter with its bandwidth BW_e being 0.85 times the data rate. **Figure 8** shows the receiver sensitivity curves in the presence of turbulence and with one and two transmitters, respectively.
A diversity gain of 2.3 dB at BER = 10^{-3} is observed when two transmitters are used for data transmission through GEO feeder link.

4 CONCLUSION

Simulations verify the experiment results which are obtained with less steep optical filters from a standard multiplexer device. Further, steeper and narrower filters with 3 dB and 20 dB bandwidths BW_o of 30 GHz and 38 GHz respectively are simulated and it is shown to provide increased spectral efficiency of 0.56 bit/s/Hz for a 32 Gbit/s OOK signal. Transmitter diversity combined with a single sideband scheme for increased spectral efficiency is shown to be an effective technique for data transmission, and to mitigate atmospheric fading effects on data signals. The spectral efficiency can be further increased by using steeper and narrower filters, and by reducing the carrier separation between the two transmitters.

5 Literature

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