Optimized Power Allocation Strategies in Hybrid Optical Satellite Networks

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1. INTRODUCTION

The **Free Space Optics** (FSO) technology is considered a mature type of wireless communication similar to fiber optics and complementary to RF radio-communication. The incorporation and deployment of **FSO backhaul links** in the 5G framework will be beneficial as they provide: **Inexpensive installation costs**, **limited power consumption**, **low mass**, **enormous spectrum** (THz) and **enhanced secrecy.**

However their availability is seriously degraded in the presence of **foggy or cloudy** weather and mainly due to the so-called **scintillation effects**.

Optical satellite communication systems have been tested and their feasibility has already been demonstrated through various experiments with **GEO, LEO, MEO satellites** among others.

The multiple input multiple output (**MIMO**) antenna systems offer **beam steering** possibilities, **higher data throughput** via **spatial multiplexing** and **advanced diversity** techniques. **MIMO-based relay systems** are commonly employed to improve **coverage** and **reliability** especially when the direct link qualities are poor and the need for **cooperative** or **multi-hop** communication emerges ⇒ Decode-and-Forward, Amplify-and-Forward relaying schemes.

2. PROBLEM & CONTRIBUTION

- A **power allocation** methodology is proposed for a **hybrid fully optical satellite network** comprising of a GEO satellite multi-channel **source**, an optical ground **relay station** and an optical **user equipment**.
- A **dual hop**, **DF** scheme is employed for the downlink optical channels that are affected by **attenuation**, **scintillation** and **spatial correlation.**
- The transmitting nodes have **separate total available powers** and **peak powers** and the power allocation is performed for both source and relay.
- The proposed methodology is based on the **convexity theory** and the **waterfilling algorithm** but also encompasses the **statistical properties** of the channel.
- **Numerical data** are generated to simulate the examined system model for various **channel settings** i.e. scintillation profiles, correlation coefficients and the **methodology's performance** is compared to the Even Power Allocation to show the achieved **spectral efficiency gain**.

3. NETWORK ARCHITECTURE

- Geostationary (**GEO**) satellite source with N_T optical transmit telescopes.
- Optical ground relay station (**OGRS**) with N_T and N_R optical transmit and receive telescopes accordingly.
- Optical ground user station (**OGUS**) with also N_R optical receivers.
- The GEO-OGRS and OGRS-OGUS links form $N_R \times N_T$ **optical MIMO** antenna systems.
- Optical channels are **spatially correlated** and **half-duplex** ⇒ end-to-end transmission in two distinct time slots.

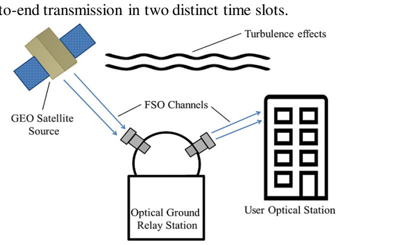


Figure 1. Hybrid optical satellite network architecture. The optical channels are considered correlated and turbulent.

The spatial correlation coefficient between channels n and m of distance d_{nm} is:

$$\rho_{nm}(d_{nm}) = \frac{R_{nm}(d_{nm})}{\sqrt{\sigma^2_{I,n}\sigma^2_{I,m}}} \quad (1)$$

where $-1 \le \rho_{nm} \le 1$ is the spatial correlation coefficient, R_{nm} is the spatial covariance and σ_I^2 is the scintillation index.

The spatial covariance of channels n and m is in turn:

$$R_{nm}(d_{nm}) = \frac{\langle I_n I_m \rangle}{\langle I_n \rangle \langle I_m \rangle} - 1 \quad (2)$$

and the associated scintillation index (SI) of channel n is:

$$\sigma^2_{I,n} = \frac{\langle I_n^2 \rangle}{\langle I_n \rangle^2} - 1 \quad (3)$$

where $\langle I_n \rangle$ is the average value of the received incident irradiance I_n.

Assumptions: On-Off-Keying NRZ (OOK-NRZ) modulation, Direct Detection (DD) decoding scheme, wavelength λ = 1550nm, optical link pointing/tracking errors neglected, CSIT knowledge for source and relay, cloud-free conditions.

4. CHANNEL MODEL

The systemic expressions are the following:

$$\mathbf{Y}_1 = \mathbf{H}_1\mathbf{X}_1 + \mathbf{n}_1 \qquad \mathbf{Y}_2 = \mathbf{H}_2\mathbf{X}_2 + \mathbf{n}_2 \quad (4)$$

where $\mathbf{Y_1}, \mathbf{Y_2}$ are the received signal vectors of OGRS and OGUS respectively, $\mathbf{H_1}, \mathbf{H_2}$ are the GEO-OGRS, OGRS-OGUS optical MIMO channel matrices, $\boldsymbol{X}, \mathbf{X_2}$ are the transmitted signal vectors of GEO, OGRS respectively and $\mathbf{n_1}, \mathbf{n_2}$ are the optical detection noise vectors with constant variance $\boldsymbol{\sigma_n}$.

The optical signal propagation is deteriorated by the atmospheric attenuation and turbulence causing **irradiance losses** and **scintillation**:

$$I = I_{avg} \cdot e^{2X_t} \quad (5)$$

where I_{avg} is the average received irradiance and X_t is a random process that represents the log-amplitude of the field fluctuations.

$$I_{avg} = \frac{2}{\pi} P_t \cdot \eta_t \cdot \eta_r \cdot \eta_{atm} \cdot \frac{1}{W^2(D)} \exp\left(\frac{-2r^2}{W^2(D)} \right) \quad (6)$$

where η_t, η_r are the quantum efficiencies of the transmitter and receiver, η_{atm} is the atmospheric transmittance, D(m) is the optical link distance, r is the radial distance from the beam center and $W(D)$(m) is the beam waist after propagation of distance D.

We consider the special case of **weak turbulence** (SI<1) and satellite links with elevation angle greater than 20 deg. Then I is a log-normally distributed process with I_{avg} of a collimated Gaussian beam and SI given by Rytov:

$$\sigma_I^2 = 2.25 k^{\frac{7}{6}} \sec^{\frac{11}{6}}(\zeta) \int_{A_{OGRS}}^{A_{GEO}} C_n^2(z)(z - A_{OGRS})^{\frac{5}{6}} dz \quad (7)$$

where k (rad/m) is the wavenumber, λ(m) is the communication wavelength, ζ is the zenith angle, C_n^2 is the refractive index structure parameter, z is the altitude from ground and A_{OGRS}, A_{GEO} are the altitudes of OGRS and GEO satellite.

The probability density function (PDF) of I is thus **lognormal**:

$$f_I(I) = \frac{1}{I\sqrt{2\pi}\sigma_I} \exp\left\{ -\frac{\left[\ln\left(I / I_{avg} \right) + \frac{1}{2}\sigma_I^2 \right]^2}{2\sigma_I^2} \right\} \quad (8)$$

The channel capacity of the optical MIMO DF dual hop system in (bps/Hz) is derived from the Shannon theorem as:

$$C_s = \min(C_1, C_2) \quad (9)$$

where the correspondent capacities are expressed as:

$$C_1 = \frac{1}{2}\log_2 \left| \mathbf{I} + \frac{1}{\sigma_n^2} \mathbf{H}_1 \mathbf{Q}_1 \mathbf{H}_1^{\mathbf{H}} \right| \quad C_2 = \frac{1}{2}\log_2 \left| \mathbf{I} + \frac{1}{\sigma_n^2} \mathbf{H}_2 \mathbf{Q}_2 \mathbf{H}_2^{\mathbf{H}} \right| \quad (10)$$

where $\mathbf{I}$ (N_RxN_R) is the identity matrix, $\mathbf{Q_1}$ and $\mathbf{Q_2}$ are the covariance matrices of transmitted symbols $\mathbf{X_1}$ and $\mathbf{X_2}$ accordingly.

From the Singular Value Decomposition (**SVD**) technique we obtain parallel, independent fading channels:

$$C_1 = \frac{1}{2}\sum_{k=1}^{rank(\mathbf{H}_1)} \log_2\left(1 + \frac{P_{1,k} \cdot \gamma_{1,k}^2}{\sigma_n^2} \right) \quad C_2 = \frac{1}{2}\sum_{k=1}^{rank(\mathbf{H}_2)} \log_2\left(1 + \frac{P_{2,k} \cdot \gamma_{2,k}^2}{\sigma_n^2} \right) \quad (11)$$

where $P_{i,k}$(i=1,2) are the transmitted powers regarding the GEO and OGRS transmitters, $\gamma_{i,k}$ (i=1,2) are the eigenvalues of matrices $\mathbf{\Lambda_1}$ and $\mathbf{\Lambda_2}$.

5. METHODOLOGY

The power allocation optimization problem is formulated as follows:

$$\text{PA1}: \quad \left\{ P_{1,k}^*, P_{2,k}^* \right\} = \arg\max_{P_{i,k}} \min(C_1, C_2) \quad (12)$$

$$\text{s.t.} \quad 0 \le P_{1,k} \le P_{peak,1}, 0 \le P_{2,k} \le P_{peak,2}$$

$$\sum_{k=1}^{N_T} P_{1,k} \le P_{total,1}, \sum_{k=1}^{N_T} P_{2,k} \le P_{total,2} \quad (13)$$

where $P_{1,k}^*$, $P_{2,k}^*$ are the optimum transmission powers of channel k for GEO and OGRS accordingly, $P_{peak,i}$ (i=1,2) is the peak transmitting power constraint and $P_{total,i}$ (i=1,2) is the total transmitting power constraint.

Introducing the slack variable θ as the minimum of C_1, C_2 we obtain:

$$\text{PA2}: \quad \left\{ P_{1,k}^*, P_{2,k}^* \right\} = \arg\max_{P_{i,k}} \theta \quad (14)$$

$$\text{s.t.} \quad \theta \le C_1, \theta \le C_2 \text{ and } (13)$$

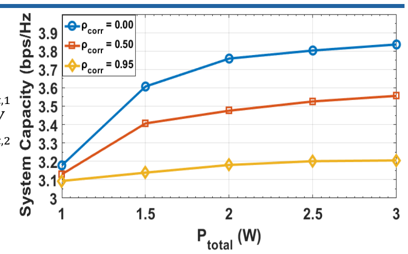
The problem is convex so the Lagrangian is formed, then the Karush-Kuhn-Tucker conditions are necessary and sufficient, yielding:

$$P_1^* = \min\left\{ P_{peak,1}, \max\left\{ \frac{1}{v_1} - \frac{\sigma_n^2}{\gamma_1^2}, 0 \right\} \right\} P_2^* = \min\left\{ P_{peak,2}, \max\left\{ \frac{1}{v_2} - \frac{\sigma_n^2}{\gamma_2^2}, 0 \right\} \right\} \quad (15)$$

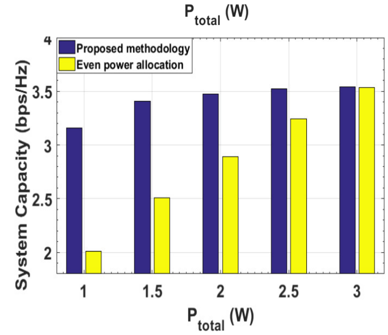
The dual multipliers v_1, v_2 are computed numerically from the total power equations.

6. SIMULATION RESULTS

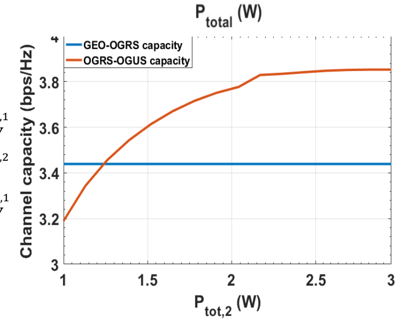
$P_{peak,1} = 1W$
$P_{peak,2} = 1W$



$P_{peak,1} = 1W$
$P_{peak,2} = 1W$



$P_{peak,1} = 1W$
$P_{peak,2} = 1W$
$P_{total,1} = 3W$



CONCLUSIONS

Hybrid optical satellite links are investigated in a MIMO DF dual hop network formation. A power allocation methodology is then proposed for the optimization of the system's capacity under separate peak and total power constraints. The power allocation problem is structured as a convex problem and then solved using the convexity theory and SVD method. Numerical simulations are executed to examine the impact of correlation on system capacity, to evaluate the proposed algorithm's performance through comparison with the EPA algorithm and to give insight to the special case of poor source-relay conditions regarding the system's power efficiency.