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Free Space Optical Communication System against Channel Fading

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Abstract

A statistical channel model for multiple-input multiple-output (MIMO) free-space optical (FSO) communication systems is developed. It is impaired by atmospheric and misalignment fading. A slow-fading channel model is considered and the outage probability is derived as a performance measure. The diversity gain defined as the Signal-to-Noise Ratio (SNR) exponent at high SNR is analyzed. Interestingly in the presence of misalignment fading the diversity gain depends only on the misalignment variance and is independent of the number of transmitters M and receivers N. Increasing the number of transmitters and receivers only results in a lower probability of outage for a given SNR, however, the rate of change is unaffected. Contrary to this case, the diversity gain of MIMO FSO systems in the presence of atmospheric fading and no misalignment is shown to be proportional to the number of transmitters and receivers, in particular the product M N.

Keywords: *Signal to Noise Ratio (SNR), MIMO, Free-Space Optical (FSO).*

1. Introduction

The use of multiple antennas at the transmitter and receiver in wireless systems, popularly known as MIMO (multiple-input multiple-output) technology, has rapidly gained in popularity over the past decade due to its powerful performance-enhancing capabilities. Communication in wireless channels is impaired predominantly by multi-path fading. Multi-path is the arrival of the transmitted signal at an intended receiver through differing angles and/or differing time delays and/or differing frequency (i.e., Doppler) shifts due to the scattering of electromagnetic waves in the environment. Consequently, the received signal power fluctuates in space (due to angle spread) and/or frequency (due to delay spread) and/or time (due to Doppler spread) through the random superposition of the impinging multi-path components. This random fluctuation in signal level, known as fading, can severely affect the quality and reliability of wireless communication. Additionally, the constraints posed by limited power and scarce frequency bandwidth make the task of designing high data rate, high reliability wireless communication systems extremely challenging.

MIMO technology constitutes a breakthrough in wireless communication system design. The technology offers a number of benefits that help meet the challenges posed by both the impairments in the wireless channel as well as resource constraints. In addition to the time and frequency dimensions that are exploited in conventional single-antenna (single-input single-output) wireless systems, the leverages of MIMO are realized by exploiting the spatial dimension (provided by the multiple antennas at the transmitter and the receiver).

The advantages of multiple-input multiple-output (MIMO) systems have been widely acknowledged, to the extent that certain transmit diversity methods (i.e., Alamouti signaling) have been incorporated into wireless standards. Although transmit diversity is clearly advantageous on a cellular base station, it may not be practical for other scenarios. Specifically, due to size, cost, or hardware limitations, a wireless agent may not be able to support multiple transmit antennas. Examples include most handsets (size) or the nodes in a wireless sensor network (size, power).

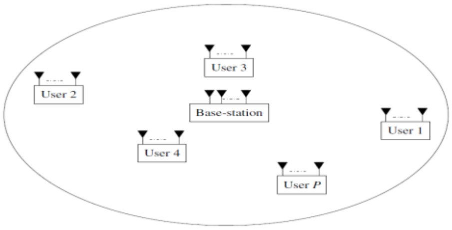


Fig.1. MIMO cellular system

2. MIMO Technology

MIMO technology that help achieve such significant performance gains are array gain, spatial diversity gain, spatial multiplexing gain and interference reduction. These gains are described in brief below

2.1 Array gain

Array gain is the increase in receive SNR that results from a coherent combining effect of the wireless signals at a receiver. The coherent combining may be realized through spatial processing at the receive antenna array and/or spatial pre-processing at the transmit antenna array. Array gain improves resistance to noise, thereby improving the coverage and the range of a wireless network.

2.1.1 Spatial diversity gain

As mentioned earlier, the signal level at a receiver in a wireless system fluctuates or fades. Spatial diversity gain mitigates fading and is realized by providing the receiver with multiple (ideally independent) copies of the transmitted signal in space, frequency or time. With an increasing number of independent copies (the number of copies is often referred to as the diversity order), the probability that at least one of the copies is not experiencing a deep fade increases, thereby improving the quality and reliability of reception. A MIMO channel with M_T transmit antennas and M_R receive antennas potentially offers M_T M_R independently fading links, and hence a spatial diversity order of $M_T M_R$

2.1.2 Spatial multiplexing gain

MIMO systems offer a linear increase in data rate through spatial multiplexing, i.e., transmitting multiple, independent data streams within the bandwidth of operation. Under suitable channel conditions, such as rich scattering in the environment, the receiver can separate the data streams. Furthermore, each data stream experiences at least the same channel quality that would be experienced by a single-input single-output system, effectively enhancing the capacity by a multiplicative factor equal to the number of streams. In general, the number of data streams that can be reliably supported by a MIMO channel equals the minimum of the number of transmit antennas and the number of receive antennas, i.e., min [M_T M_R]. The spatial multiplexing gain increases the capacity of a wireless network.

2.1.3 Interference reduction and avoidance

Interference in wireless networks results from multiple users sharing time and frequency resources. Interference may be mitigated in MIMO systems by exploiting the spatial dimension to increase the separation between users. For instance, in the presence of interference, array gain increases the tolerance to noise as well as the interference power, hence improving the signal-to-noise-plus-interference ratio (SINR). Additionally, the spatial dimension may be leveraged for the purposes of interference avoidance, i.e., directing signal energy towards the intended user and minimizing interference to other users. Interference reduction and avoidance improve the coverage and range of a wireless network. In general, it may not be possible to exploit simultaneously all the benefits described above due to conflicting demands on the spatial degrees of freedom. However, using some combination of the benefits across a wireless network will result in improved capacity, coverage and reliability.

2.2MIMO in Cellular Networks

In a cellular wireless communication network, multiple users may communicate at the same time and (or) frequency. The more aggressive the reuse of time and frequency resources, the higher the network capacity will be, provided that transmitted signals can be detected reliably. Multiple users may be separated in time (time-division) or frequency (frequency-division) or code (code-division). The spatial dimension in MIMO channels provides an extra dimension to separate users, allowing more aggressive reuse of time and frequency resources, thereby increasing the network capacity.

Figure 1 is the schematic of a cell in a MIMO cellular network. A base-station equipped with L antennas communicates with P users, each equipped with M antennas. The channel from the base-station to the users (the downlink) is a broadcast channel (BC) while the channel from the users to the base-station (the uplink) is a multiple-access channel (MAC). The set of rate-tuples (R_1,R_2,……..R_P) that can be reliably supported on the downlink or uplink constitutes the capacity rate region for that link. Recently, an important duality has been discovered between the rate regions for the downlink and uplink channels. In order to understand the possible gains from MIMO technology in a multi-user environment, consider the uplink of a cellular MIMO system where all the users simultaneously transmit independent data streams from each of their transmit antennas, i.e., each user signals with spatial multiplexing. To the base-station, the users combined, appear as a multi-antenna transmitter with PM antennas. Thus the effective uplink channel has a dimension of L×PM. This effective channel will have a considerably different structure from the $\mathbf{H}_w$ MIMO single user channel due to path-loss and shadowing differences between users.

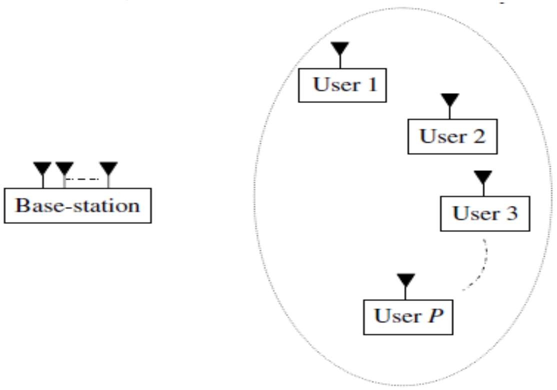


Fig.2 Distributed MIMO: multiple users cooperate to form a virtual antenna array that realizes the gains of MIMO in a distributed fashion.

However, with rich scattering and L ≥ PM, we can expect that the spatial signatures of the users are well separated to allow reliable detection. Using a multi-user ZF receiver will allow perfect separation of all the data streams at the base-station, yielding a multi-user multiplexing gain of PM. The use of more complex receivers for multi-user detection and the associated performance trade-offs. A similar thought experiment can be applied for the downlink, where the base-station exploits the spatial dimension to beam information intended for a particular user towards that user and steers nulls in the directions of the other users, thus completely eliminating interference.

3. Modules Explanation

3.1 Channel Model

This section explains the MIMO FSO system and channel fading. The model considers MIMO FSO system with M transmitters (lasers) and N receivers (apertures). In all cases, intensity modulated PAM signaling with direct detection is considered.

The received N × 1 vector $y = [y_1, \dots, y_N]^T$ is given by

$$y = H^T x + z$$

where H is an M x N channel matrix where the entry $H_{mn} \geq 0$ represents the channel gain from transmitter m to receiver n with m=1, . . .,M and n = 1, . . .,N and $(\cdot)^T$ is the transpose operator. The vector $x = [x_1, \dots, x_M]^T$ is the transmitted set of symbols and $z = [z_1, \dots, z_N]^T$ is a noise vector of independent components modeled as signal independent white and Gaussian distributed.

The signal-to-noise ratio is defined as SNR = P/σ and the channel gain

$$H = \sum_{n=1}^{N} \sum_{m=1}^{N} H_{mn}$$

accounts for the combined effects of atmosphere and misalignment fading where

$$H_{mn} = H_{mn}^{a} H_{mn}^{p}$$

where H_{mn}^{a} and H_{mn}^{p} are independent random variables representing the atmospheric and time varying misalignment (pointing) fading respectively between transmitter m and receiver n.

In the weak turbulence regime the channel gain due to atmospheric turbulence is well modeled by

$$H_{mn}^{a} = e^{X_{mn}}$$

where X_{mn} is a Gaussian random variable. Assume that all X_{mn} are modeled as *independent and identically distributed (i.i.d)* random variables.

For a radial displacement of R_{mn} in the receiver plane between the center of transmitter beam m and the center of aperture n, the loss due to misalignment is

$$H_{mn}^{p} \approx A_0 e^{-2R_{mn}^2 / w^2}$$

where A_0 is the equivalent receiver area and w is the equivalent beam waist at receiver.

3.2 Diversity Gain of MIMO FSO Channels

These section three different misalignment scenarios will be analyzed depending on the random displacements X' and Y'

Symmetric Misalignment in X' and Y' Directions

The displacements X' and Y' have i.i.d Gaussian distributions with zero mean and variance σ_s^2. Defining $\gamma = w/(2\sigma_s)$ the pdf of $T = 2R^2/w^2$ is given by

$$f_T(t) = \gamma^2 e^{-\gamma^2 t}$$

and hence

$$f_V(\mathrm{v}) = \int_0^\infty f_{V|T}(v|t)\, f_T(\mathrm{t})\, \mathrm{dt}$$

$$= \int_0^\infty \frac{1}{\sqrt{2\pi\sigma_G}} e^{-\frac{(\mathrm{v}-(\mu_G-\mathrm{t}))^2}{2\sigma_G^2}} \cdot \gamma^2 e^{-\gamma^2 t}\, dt$$

where

$B_1 = \frac{\gamma^2}{2} e^{\gamma^4} \sigma_G^2 \Big/ 2 - \gamma^2 \mu_G$, and $B_2 = \gamma^2 \sigma_G^2 - \mu_G$.

Substituting $s = v + B2$ the outage probability can be simplified to

$$P_{out}(R) = \frac{1}{2}\left[e^{\gamma^2\left(\eta + \gamma^2\sigma_G^2/2 - \mu_G\right)} erfc\left(\frac{\eta + B_2}{\sqrt{2}\sigma_G}\right) + erfc\left(\frac{\gamma^2\sigma_G}{\sqrt{2}} - \frac{\eta + B_2}{\sqrt{2}\sigma_G}\right)\right]$$

Substituting the results in the asymptotic probability of outage P_{out}^{Asy} given as

$$P_{out}^{Asy}(R_0) = e^{\gamma^2\left(\eta + \gamma^2\sigma_G^2/2 - \mu_G\right)}$$

Unidirectional Misalignment

In this scenario $X' \sim (0, \sigma_S^2)$ and $Y' = 0$. The probability density functions of $T = 2X'^2/w^2$ is given by

$$f_T(t) = \frac{\gamma}{\sqrt{\pi t}} e^{-\gamma^2 t}$$

The outage probability is

$$P_{out}(R) = \int_{-\infty}^{\eta} f_V(v)\, dv,$$

$$= \int_{-\infty}^{\eta}\int_{0}^{\infty} f_{V|T}(v|t)\, f_T(t)\, dt\, dv$$

No Misalignment

For comparison, the scenario when $X' = 0$ and $Y' = 0$, i.e., no misalignment, is also considered. The channel gain is given by a modified version of the above statistical channel model's equation

$$H_0 = A_0 \sum_{n=1}^{N}\sum_{m=1}^{N} e^{X_{mn}} \_^{U_{mn}}$$

$U_{mn} = \frac{2}{w^2} \| P_m - P_n \|^2$ and Go is Gaussian with mean

$$\mu_0 = \mathbb{E}\{G_0\} = \log \frac{MN}{\sqrt{1 + \frac{1}{MN}\left(e^{\sigma^2 X} - 1\right)}}$$

and variance

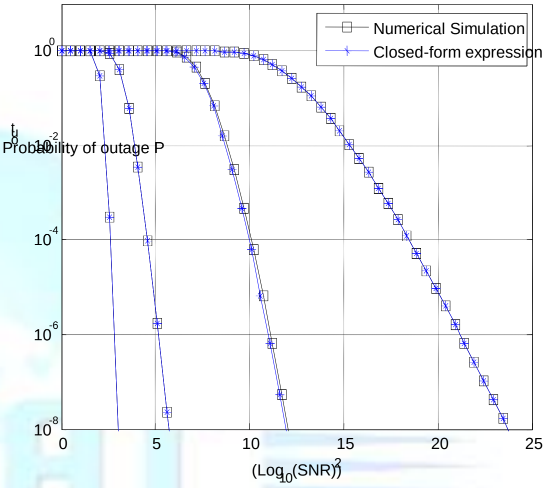
$$\sigma^{2G_0} = \log\left(1 + \frac{1}{MN}\left(e^{\sigma^2 X} - 1\right)\right)$$

The outage probability is given as

$$P_{out}(R_0) = 1 - \frac{1}{2} erfc\left(\frac{\eta - \mu G_0}{\sqrt{2}\sigma G_0}\right)$$

3.3 **Simulation Results**

In this section, we consider a Gaussian-beam of wavelength $\lambda = 1550$ nm, beam waist $w_o = 2$ cm, and radius of curvature $F_o = -10$ m at the transmitter. The beam propagates a distance $L = 1$ km through a turbulent medium characterized by $C^2{}_n$. Each receiver has a circular aperture of radius $a = 5$ cm. The spacing between transmitters (as well as between receivers) is set to $d = 20$ cm which is a typical value for a commercial system and results in independent X_{mn} as shown. Typical misalignment variance of $\sigma^2{}_s = 0.1$ m2 is considered and rate $R_0 = 1$ bits/channel-use is considered



4. Conclusions

A novel generalized statistical model for MIMO FSO channels impaired by atmospheric and misalignment fading is developed. The derived model is utilized to study the outage probability of FSO channels and the diversity gain at high signal-to-noise ratio. Closed-form expressions for the outage probability are derived taking into account different misalignment fading scenarios.

It is shown that, in the presence of atmospheric and misalignment fading, the diversity gain depends only on the misalignment parameters and is independent of both the number of transceivers and atmospheric fading parameters. Contrarily, when atmospheric fading is the only channel impairment, i.e., no misalignment fading, the diversity gain depends on the number of transceivers. Thus a larger diversity gain can be achieved by increasing the number of transmitters and receivers. In all cases increasing the number of transmitters and receivers decreases the outage probability for a given SNR. However, in order to have independent channels gains it is required to sufficiently increase the spacing between receivers which is often practically difficult.

An alternative approach is to utilize a large single-aperture with the equivalent area of the N apertures. This approach provides simple system structure and reduces the fading variance via aperture averaging. Note that, in this case the fading is correlated across the aperture and hence its variance is larger than that of a system with multiple apertures and independent fading at each aperture.

Consequently, multiple-aperture receiver systems achieve improved performance at the cost of additional detector elements.

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