Terrestrial to Satellite Communications Using Multi-antenna Relays Nodes

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Abstract—**Satellite communications and relaying techniques have been receiving the attention of the research community over the last years. This paper proposes a terrestrial to satellite communication system aided by terrestrial relay nodes to facilitate a robust, reliable, and efficient communication link and improve the spectral efficiency. In particular, this paper concentrates on evaluating the spectral efficiency and bit error rate (BER) performance of terrestrial to satellite multiple-input multiple-output (MIMO) amplify and forward (AF) relay links. Zero Forcing (ZF) and Minimum Mean Square Error (MMSE) multi-antenna decoding techniques are employed, which have been well established in terrestrial wireless communications. Numerical results are provided to quantify the performance gain of the proposed communication system.**

Keywords–Amplify and forward (AF) relaying; Loo distribution; minimum mean square error (MMSE; multiple-input multiple output (MIMO) techniques; satellite communications; Zero Forcing (ZF).

I. INTRODUCTION

The satellite communications play a crucial role in wireless and mobile communications [1] [2]. There are many practical cases where the terrestrial communications are not able to provide a link between the communicated parties due to troublesome propagation conditions or extremely high link distance. Satellite communications are able to overcome these constraints and provide a reliable wireless link to the communicated parties. In order to improve system capacity and link reliability, Multiple-Input Multiple-Output (MIMO) technology is the dominant candidate for both terrestrial [3]–[8] and satellite [9]–[11] use. However, multiple antenna systems are not directly applicable to the satellites due to some special features of such communication systems. The key concept of MIMO technology is to take the advantage of multipath components of the propagation channel which produce multiple uncorrelated channels at the destination. So, in order to achieve uncorrelated channels there is a constraint regarding the inter-element distance at both the transmitter and receiver antennas. The propagation channel between the satellite and the earth station is characterized by its high propagation loss and the small number of existing scatterers. Therefore, so as to achieve uncorrelated channels, the desired inter-element distance is increased. Satellites refrain thousands of kilometers from the earth and there is no power supply apart from the solar power and the stored batteries energy and therefore, the multiple Radio-Frequency (RF) chains could reduce the life of a satellite.

Since there is not enough space to place many antenna elements in the satellites, additional techniques were investigated to maximize the capacity and reliability gain. Initially, polarization techniques were proposed in order to maximize the available MIMO channels using co-located antennas. However, the terrestrial to satellite communications may benefit from some new emerging technologies. Wireless relay systems [12] [13] are widely adopted in the new wireless standards of 4G and beyond. The role of a relay varies from scenario to scenario, depending on the needs and the specifications of the communication. The use of relay nodes may assist to the coverage extension, link reliability and/or capacity improvement. The most usual and well-defined types of relay modes are the Amplify and Forward (AF) and the Decode and Forward (DF) modes. In the first case the relay is a conventional repeater which just amplifies the received signal and forwards it to the destination. In the second mode, the relay has an active role being able to decode the received signal, perform baseband signal processing and retransmit the signal to the final destination. Despite the fact that relay systems are able to offer more degrees of freedom, their adoption in satellite communications is not duly considered.

In this paper, we present a novel system model for terrestrial to satellite communications with the combination of terrestrial relay systems and MIMO technology [14]–[17]. The performance evaluation and the benefits of such a system are analytically described. The main purpose of this paper is to determine the advantages of the aforementioned technologies in as more realistic scenarios as possible. For that reason, we modeled the terrestrial to satellite wireless channel using the Loo distribution [18] which describes in the most effective way the space conditions. In addition, we used the widely adopted Rician or Rayleigh distribution in order to model the terrestrial channel and some practical detection schemes to the receiver. The rest of the paper is organized as follows: in Section II, we present the system model, while in Section III, we analyze all the detected schemes applied in the model. The main results of the paper are presented in Section IV, where the advantages of such a system are analytically discussed. Finally, in Section V, we conclude the paper.

II. SYSTEM MODEL

We consider an AF, single user MIMO system with multiple full-duplex relays. A system model is given in Figure 1.

The system comprises R intermediate relay nodes which lie between source and destination nodes that have N_t and N_r antennas respectively. Each relay node has M_r transmit/receive antennas (assuming that $M_r = M_t$). The source node transmits

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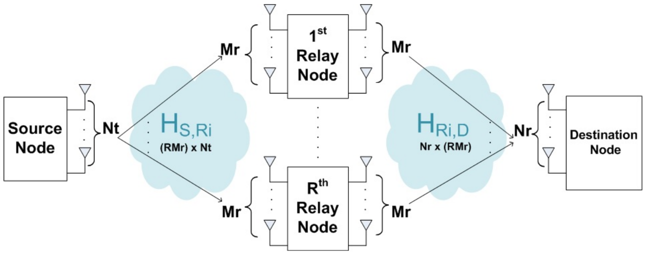

Figure 1. System Model

to the relay nodes and the relay nodes amplify and forward their received signals to the destination. In the described model, we focus in the uplink communication where the connection between source and relay nodes illustrate the terrestrial link, while the communication link between relay nodes and destination represents the satellite link. The destination node is represented by a satellite. The $(M_r R) \times 1$ received signal at the relays is given by

$$\mathbf{y}_{R_i} = \mathbf{H}_{S,R_i}\mathbf{x} + \mathbf{n}_{R_i}. \tag{1}$$

The matrix $\mathbf{H}_{S,R_i}$ is the $(M_r R) \times N_t$ source-relays channel matrix which is presented analytically in Section IV-A. The quantity $\mathbf{n}_{R_i}$ is a vector of zero mean additive white Gaussian noise with the same dimensions as the corresponding received signal. $\mathbf{x}$ is the $N_t \times 1$ input data vector.

The $N_r \times 1$ received signal at the destination from the relays is given by

$$\mathbf{y}_D = \mathrm{a}\mathbf{H}_{R_i,D}\mathbf{y}_{R_i} + \mathbf{n}_D, \tag{2}$$

where a is the amplification factor with constant values, the matrix $\mathbf{H}_{R_i,D}$ is the $N_r \times (M_r R)$ channel matrix which is analytically described in Section IV-B, $\mathbf{y}_{S,R_i}$ is the received signal at the relays and $\mathbf{n}_D$ is a vector of zero mean additive white Gaussian noise with the same dimensions as the corresponding received signal.

Using (1) in (2):

$$\begin{aligned}\mathbf{y}_D &= \mathrm{a}\mathbf{H}_{R_i,D}\mathbf{y}_{R_i} + \mathbf{n}_D \\ &= \mathrm{a}\mathbf{H}_{R_i,D}\left(\mathbf{H}_{S,R_i}\mathbf{x} + \mathbf{n}_{R_i}\right) + \mathbf{n}_D \\ &= \mathrm{a}\mathbf{H}_{R_i,D}\mathbf{H}_{S,R_i}\mathbf{x} + \mathbf{H}_{R_i,D}\mathrm{a}\mathbf{n}_{R_i} + \mathbf{n}_D.\end{aligned} \tag{3}$$

So, the received signal at the destination will be:

$$\mathbf{y}_D = \mathbf{H}\mathbf{x} + \mathbf{n} \tag{4}$$

where $\mathbf{H} = \mathrm{a}\mathbf{H}_{R_i,D}\mathbf{H}_{S,R_i}$ and $\mathbf{n} = \mathrm{a}\mathbf{H}_{R_i,D}\mathrm{a}\mathbf{n}_{R_i} + \mathbf{n}_D$.

The overall end-to-end received signal-to-noise-ratio (SNR) at each destination receiver antenna element γ is given by [19]–[22]

$$\gamma = \frac{\gamma_1\gamma_2}{\gamma_1 + \gamma_2 + 1} \tag{5}$$

,
where $\gamma_j = |\mathbf{H}_j|^2 \big/ N_0$, $j = 1, 2$ represents the per-hop received SNR.

III. SIGNAL DETECTION SCHEMES

In the following, we are going to use linear detection schemes. To detect the signals from each antenna element, the estimated symbols derive by applying a weight matrix $\mathbf{W}$ to the channel matrix in order to invert its effect [23] :

$$\tilde{\mathbf{x}} = \left[\tilde{x}_1\ \tilde{x}_2\ \ldots\ \tilde{x}_{N_t}\right]^T = \mathbf{W}\mathbf{y}_D. \tag{6}$$

The standard linear detection methods include the well-defined techniques of the Zero-Forcing (ZF) and the Minimum Mean Square Error (MMSE) techniques. The weight matrix of the zero-forcing technique for $N_r \geq N_t$ is given by:

$$\mathbf{W}_{ZF} = \left(\mathbf{H}^H\mathbf{H}\right)^{-1}\mathbf{H}^H, \tag{7}$$

where $(\cdot)^H$ is the Hermitian transpose operation. So, the estimated result will be:

$$\begin{aligned}\tilde{\mathbf{x}}_{ZF} &= \mathbf{W}_{ZF}\mathbf{y}_D \\ &= \left(\mathbf{H}^H\mathbf{H}\right)^{-1}\mathbf{H}^H\left(\mathbf{H}\mathbf{x} + \mathbf{n}\right) \\ &= \mathbf{x} + \left(\mathbf{H}^H\mathbf{H}\right)^{-1}\mathbf{H}^H\mathbf{n}.\end{aligned} \tag{8}$$

In order to maximize the post-detection Signal to Interference plus Noise Ratio (SINR), the MMSE weight matrix for $N_r \geq N_t$ is given as:

$$\mathbf{W}_{MMSE} = \left(\mathbf{H}^H\mathbf{H} + \sigma^2\mathbf{I}\right)^{-1}\mathbf{H}^H. \tag{9}$$

As we can see the MMSE receiver uses the statistical information of noise σ^2 . Using the MMSE weight matrix in (6), we have the following relationship:

$$\begin{aligned}\tilde{\mathbf{x}}_{MMSE} &= \mathbf{W}_{MMSE}\mathbf{y}_D \\ &= \left(\mathbf{H}^H\mathbf{H} + \sigma^2\mathbf{I}\right)^{-1}\mathbf{H}^H\left(\mathbf{H}\mathbf{x} + \mathbf{n}\right) \\ &= \mathbf{x} + \left(\mathbf{H}^H\mathbf{H} + \sigma^2\mathbf{I}\right)^{-1}\mathbf{H}^H\mathbf{n}.\end{aligned} \tag{10}$$

In order to improve the performance of linear detection techniques, the ordered Successive Interference Cancellation (SIC) was initially proposed in [24] [25]. In this technique, the receiver estimates the first symbol, using a linear detector (i.e., ZF, MMSE). More specifically, the best transmitted signal is determined using the minimum norm, as long as its weight vector resulting from the transformed channel matrix depending on the reception technique. So, for the SIC-ZF technique the effect based on (8) will be:

$$\tilde{\mathbf{x}}_{SIC-ZF} = \mathbf{W}_{ZF}\tilde{\mathbf{y}}_i, \tag{11}$$

where $\tilde{\mathbf{y}}_i = \mathbf{y}_D - h_i\tilde{\mathbf{x}}_{ZF}$ for the i^{th} stream estimation.

Likewise for the SIC-MMSE technique will be:

$$\tilde{\mathbf{x}}_{SIC-MMSE} = \mathbf{W}_{MMSE}\tilde{\mathbf{y}}_i, \tag{12}$$

where $\tilde{\mathbf{y}}_i = \mathbf{y}_D - h_i\tilde{\mathbf{x}}_{MMSE}$ for the i^{th} stream estimation.

IV. PERFORMANCE EVALUATION

This Section is based on the system model which is described in Section II. More specifically, we focus in the next two scenarios. In the first scenario, as illustrated in Figure 2, we use a single relay MIMO system with two transmit, receive and relay antennas.

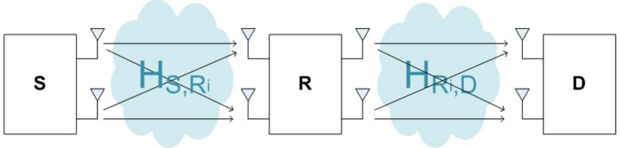

Figure 2. First Scenario

The second scenario, presented in Figure 3, demonstrates the case with two synchronized relay nodes equipped with a single antenna each one, in contrast to the first one that there is only one relay with two antenna elements.

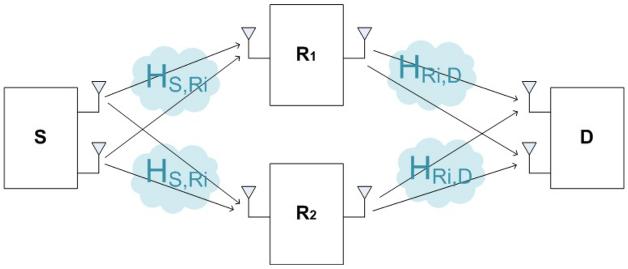

Figure 3. Second Scenario

We will demonstrate the performance of the proposed MIMO architecture in terms of bit error rate (BER) and systems capacity. In order to retrieve more realistic results, a lot of attention was paid on the appropriate wireless propagation channel model selection due to the particular properties of satellite communications.

A. Terrestrial Wireless Channel

The adopted scenarios, previously described, consist of terrestrial and satellite transceivers which consequently lead to two different propagation channel environments. The terrestrial wireless channel is mostly characterized by the existing scatterers which produce multiple signal components. This environment within a simulation study could be emulated using the Rician distribution as [26]:

$$\mathbf{H}_{S,R_i} = \sqrt{\frac{K}{K+1}}\bar{\mathbf{H}}_{S,R_i} + \sqrt{\frac{1}{K+1}}\tilde{\mathbf{H}}_{S,R_i}, \tag{13}$$

where K is the Rician factor, $\bar{\mathbf{H}}$ is a deterministic unit rank matrix which represent the direct component and $\tilde{\mathbf{H}}$ is the channel matrix of the multipath components. Most of work done so far in MIMO performance evaluation is based on the assumption that the involved parties communicate in a rich scattering environment. This means that there is no Line-of-sight (LOS) component and so the gain of MIMO is maximized due to the uncorrelated channel in the input of the multiple antenna elements. This ideal environment for the MIMO performance is totally described using the Rayleigh distribution, resulting from the Rician distribution by applying a zero K factor due to the no existence of a LOS component.

B. Satellite Wireless Channel

For the link between the land mobile and the satellite we have to use a statistical model being able to take into account all the propagation channels characteristics. A well-defined model developed for that case is the Loo distribution [18]. The channel matrix $\mathbf{H}$ of the satellite link using the Loo distribution for the envelope h_{ij} is then given by [18]

$$\mathbf{H}_{R_i,D} = [h_{ij}] = [\bar{h}_{ij}] + [\tilde{h}_{ij}] = \bar{\mathbf{H}}_{R_i,D} + \tilde{\mathbf{H}}_{R_i,D}, \tag{14}$$

where

$$\begin{aligned} h_{ij} &= |h_{ij}| \exp\left(j\varphi_{i,j}\right) \\ &= \left|\bar{h}_{ij}\right| \exp\left(j\bar{\varphi}_{i,j}\right) + \left|\tilde{h}_{ij}\right| \exp\left(j\tilde{\varphi}_{i,j}\right), \end{aligned} \tag{15}$$

and $\bar{\phi}_{ij}$, $\tilde{\phi}_{ij}$ are uniformly distributed over $[0, 2\pi]$.

The first factor represents the Lognormal fading while the second one describes the Rayleigh fading. Therefore, the Loo distribution as extracted from the previous equation is the superposition of the lognormal distribution to model the large-scale fading and Rayleigh distribution for the modeling of small-scale fading. So, the Loo probability density function is given by

$$\begin{aligned} p\left(|h_{ij}|\right) = &\frac{|h_{ij}|}{b_0\sqrt{2\pi\sigma^2}} \times \\ &\int_0^\infty \frac{1}{\bar{h}_{ij}} \exp\left[-\frac{\left(\ln\bar{h}_{ij} - \mu\right)^2}{2\sigma^2} - \frac{|h_{ij}|^2 + \bar{h}_{ij}^2}{2b_0}\right] \\ &I_0\left(\frac{|h_{ij}|\,\bar{h}_{ij}}{b_0}\right) d\bar{h}_{ij} \end{aligned} \tag{16}$$

where b_0 is the average scattered power resulting from the multipath components while σ and μ are the standard deviation and mean respectively and finally $I_0\left(\cdot\right)$ is the zero order modified Bessel function of the first kind.

In Figure 4, the different terrestrial channel distributions are compared in terms of bit error rate. Both of them use the same parameters, $N_t = N_r = 2$ and $R = 1$ with $M_r = 2$ in the ZF signal detection. As expected similar to the terrestrial links [27] the Rician is worse than Rayleigh in this detection scheme.

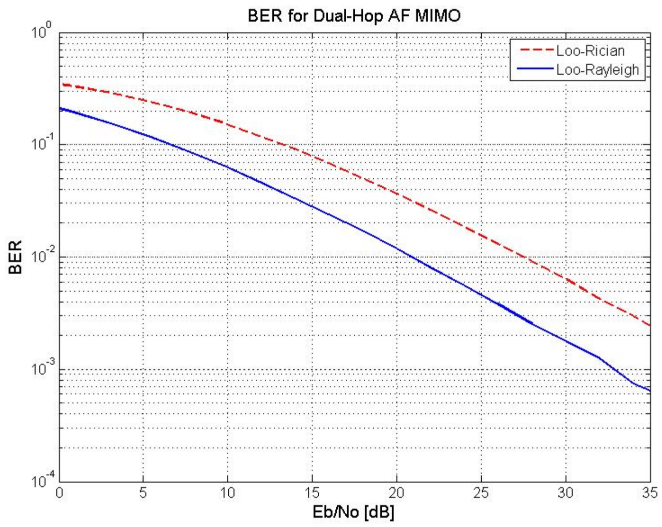

Figure 4. Comparison of terrestrial channel with Rician and Rayleigh distribution ($\gamma_2 = 2\gamma_1$)

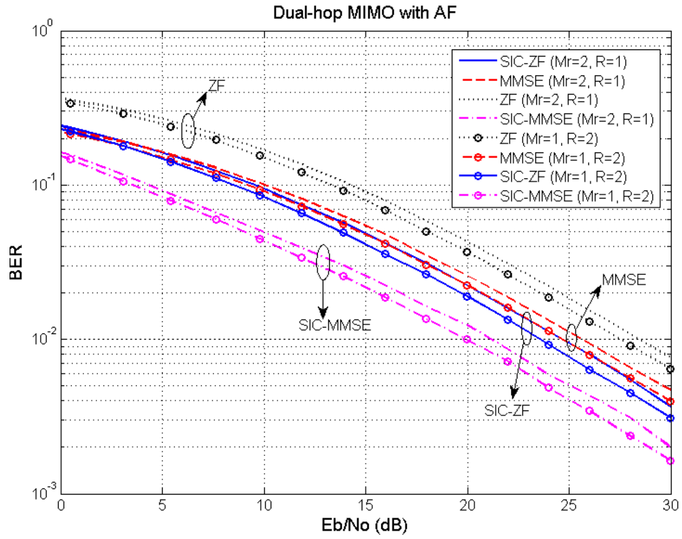

Figure 5. End-to-end BER performance($\gamma_2 = 2\gamma_1$)

C. BER Results

The main scope within this work is to define the performance of land to satellite communication using relay nodes. As previously analyzed, in order to model the terrestrial link between the transmitter and the relay station, Rician distribution is applied with different K factors in order to achieve a realistic simulation environment. The only difference between the two scenarios described in Section II is the number of antenna elements in the relay stations. In our first scenario as illustrated in Figure 2, transmitter, receiver and one relay station are equipped with two antennas each one and Rician factor $K = 10dB$, while in the second scenario depicted in Figure 3, two relays are used with one antenna each one and Rician factor 8dB and 10dB, respectively. In any case, the signal reaches the destination through the relay/relays station/stations. In Figure 5, we present the end-to-end BER performance for quadrature phase-shift keying (QPSK) modulation which is crucial for all the wireless systems and especially the satellite communications which are sensitive to data loss due to the limited resources.

As expected the best signal detection is achieved with the SIC-MMSE while the worst with the ZF for both scenarios. In addition, when the case with more single-antenna relays outperforms the case where a single relay is adopted with more antenna elements. Whereas, one would expect the same bit error rate results for both scenarios, there is a difference around 1-1.5 dB, due to different Rician factor in the channel distribution when more than one relay are used.

D. Capacity Results

The ergodic capacity (bits/sec/Hz) of the AF MIMO dual-hop system described above can be written [28]:

$$C\left(\gamma\right) = E\{\log_2 \det(\mathbf{I}_{N_t} + \gamma\mathbf{H}\mathbf{H}^H\mathbf{R}_n^{-1})\}, \qquad (17)$$

where $\mathbf{R}_n$ matrix is also given by :

$$\mathbf{R}_n = \mathbf{I}_{Nr} + \mathrm{a}\mathbf{H}_{R_i,D}\mathbf{H}^H_{R_i,D}, \qquad (18)$$

where a is the constant value of amplification factor. In our system model, we consider an M-ary Phase Shift Keying (M-PSK) , AF, multirelay MIMO system with full-duplex relays. Whereas, in a more realistic scenario, the capacity of a channel in a MIMO system using Linear Detector (LD) can be written as:

$$C_{LD} = \sum_{i=1}^{k} \log_2\left(1 + SINR_k\right), \qquad (19)$$

where $SINR_k$ for each receiver is different. The SINR for the MMSE receiver in MIMO wireless communications on the $k-th$ spatial stream can be expressed as [29]–[34]:

$$SINR_k^{MMSE} = \frac{1}{\left[\left(\mathbf{I}_{Nt} + SNR\mathbf{H}^H(\mathbf{R}_n)^{-1}\mathbf{H}\right)^{-1}\right]_{kk}} - 1, \qquad (20)$$

where $\mathbf{I}$ is a $N_t \times N_t$ identity matrix and $\mathbf{H}^H$ is the Hermitian transpose of $\mathbf{H}$. The SINR for the ZF receiver, denoted by $SINR_k^{ZF}$, which conditional on $\mathbf{H}$, can be expressed as [32] [35]:

$$SINR_k^{ZF} = \frac{SNR}{\left[\left(\mathbf{H}^H(\mathbf{R}_n)^{-1}\mathbf{H}\right)^{-1}\right]_{kk}}. \qquad (21)$$

So, Figure 6, illustrates the system capacity the case of MMSE and ZF receiver for the two different scenarios, as well as the ideal MIMO capacity.

Similarly to Figure 5, we observe that the best signal detection scheme is the MMSE scheme, while ZF is the one with the poorest performance. Moreover, the achievable

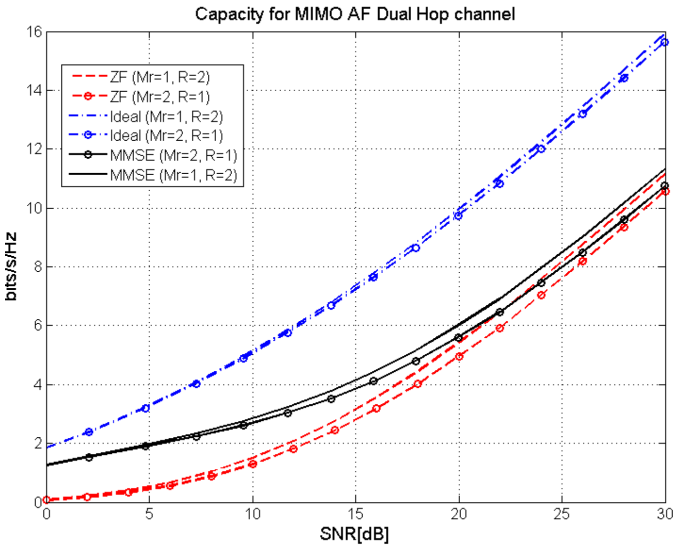

Figure 6. System capacity $(\gamma_2 = 2\gamma_1)$

capacity in all detection schemes of the second scenario is slightly better than in the cases of first scenario.

V. CONCLUSION

In this paper, we have investigated the benefits of MIMO terrestrial to satellite communication using relay nodes. Multiple simulations have been performed in order to evaluate the system in different scenarios by adopting and applying well-known techniques already applied in terrestrial communications. The results show the gain in the bit error rate performance as well as the gain in the achievable capacity by applying different detection schemes in different environment conditions. So, such a communication seems quite promising for the future wireless networks in order to establish a reliable communication even in difficult terrains and/or high distances.

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