Abstract— In this paper, a novel transmitting scheme for multiple-input multiple-output (MIMO) satellite relay-based multi-user multi-beam communications is proposed. It is considered that multiple terrestrial relay nodes employ amplify-and-forward (A-F) relaying and intend to improve the reliability and spectral efficiency of satellite radio links. Zero forcing (ZF) and minimum mean square error (MMSE) signal detection techniques are employed, which have been well-established in terrestrial wireless communication systems. Numerical results are provided to quantify the performance gain of the proposed system configuration in terms of the bit-error-rate (BER) and the channel capacity.

Index Terms—MIMO, multi-beam, multi-hop, multi-user, relay, satellite communications.

I. INTRODUCTION

Satellite-to-terrestrial (S-to-T) relay-based communications have received the attention of the research community over the last years, since the use of relay nodes can potentially extend the radio coverage, improve the link reliability, and enhance the channel capacity [1]. Wireless relays are widely adopted in new wireless standards of 4G and beyond [2], [3]. The most usual types of relay modes are the amplify-and-forward (AF) mode and the decode-and-forward (DF) mode. In the first case, the relay is a conventional repeater, which amplifies the received signal and forwards it to the destination. In the second case, the relay has an active role. Specifically, the relay decodes the received signal, performs baseband signal processing, and then retransmits 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.

To further improve system capacity and link reliability, the multiple-input multiple-output (MIMO) technology is the dominant candidate for both terrestrial [4]-[9] and satellite [10]-[13] systems. However, the application of multiple antennas in satellite communications is not straightforward, due to some special features of satellite systems [13]. Besides, MIMO signal processing techniques have been applied in multi-beam satellite [14]-[16] and dual-satellite scenarios [17]. Multi-user detection can also enhance the spectral efficiency of the forward link (FL) [18].

This paper proposes a novel MIMO transmitting scheme for multi-beam MIMO multi-user satellite communication systems with the combination of multiple terrestrial relays. The satellite radio channel is modeled using the Loo distribution [19], while the widely adopted Rician distribution is used in order to model the terrestrial channel. Moreover, A-F relaying techniques are applied and zero-forcing (ZF) and minimum mean square error (MMSE) detection schemes are utilized [18]-[20].

The rest of the paper is organized as follows. In Section II, the system model of the proposed transmission scenario is presented and the corresponding assumptions, technologies, and detection schemes are described. In Section III, a performance analysis is demonstrated and simulation results are provided. Finally, conclusions are drawn in Section VI.

II. SYSTEM MODEL

The system model employed throughout this paper considers a source node represented by a satellite, multiple terrestrial relay nodes, and multi-user destination nodes, all equipped with multiple antennas (see Figs. 1 and 2). The multi-beam system comprises \( R \) intermediate relay nodes with \( M_t/M_r \) transmit/receive antennas, which amplify and forward the received signals to the destination. In addition, the source and destination nodes employ \( N_t \) and \( N_r \) antennas, respectively. A downlink wireless communication radio channel is considered, where the communication link between the source and the relay nodes represents the satellite link and the connection between relay and destination nodes denotes the terrestrial wireless link.

![Fig. 1. The system model for the multi-user MIMO satellite multiple-relay transmission scheme.](image-url)
The received signal vector $y_1$ at the relays is given by

$$y_1 = H_{sr}x + n_1,$$  

where $H_{sr}$ is the source-relays MIMO channel matrix, $x$ is the data vector, and $n_1$ is the noise vector, which denotes the additive white Gaussian noise (AWGN) at the relays branches. The received signal at the destination is given by

$$y_2 = H_{rd}y_1 + n_2,$$  

where $a$ is the amplification factor with constant values, the matrix $H_{rd}$ is the relays-destination MIMO channel matrix, and $n_2$ is the noise vector, which denotes the AWGN at the destination branches. Using (1), (2) becomes

$$y_2 = H_{rd}aH_{sr}x + H_{rd}an_1 + n_2.$$  

Therefore, the received signal in the destination becomes

$$y_2 = Hx + n,$$  

where $H = H_{rd}aH_{sr}$ and $n = H_{rd}an_1 + n_2$.

The satellite channel is modeled using the Loo distribution [19]. Besides, the Rician distribution is utilized, in order to model the wireless communication channel between the multiple terrestrial relays and the terrestrial receiver. The resulting channel for all the users can be expressed by

$$H = H_{sr} \circ B,$$  

where $H$ is the channel matrix from relays to destination, $B$ is the beam gain matrix of size $[\text{number of users} \times \text{number of beams}]$ and $\circ$ is the element wise multiplication [21]. It is considered that one user’s position can be defined based on the angle $\theta$ between the beam center and the receiver location with respect to the satellite and $\theta_{\text{dB}}$ is the corresponding 3-dB angle.

[12]. More specifically, each element of the beam gain matrix can be calculated as follows [22]

$$b(\theta, k) = h_{\max} \left( J_1(u) + 36J_3(u) \right)^2,$$  

where $u = 2.07123 \sin \theta/\sin \theta_{\text{dB}}$ and $J_1$ and $J_3$ are the first kind Bessel functions of order one and three, respectively. In addition, $h_{\max} = \left( \frac{\lambda}{4\pi} \right)^2 \frac{1}{(d_0)^3}$, where $\lambda$ is the carrier wavelength and $d_0 = 3579km$ [21], [23].

A. The satellite radio channel

For the link between the satellite and the terrestrial relays, the Loo distribution [19] is used, which fully describes the corresponding propagation environment in terms of the probability density function (PDF), the average fade duration (AFD), and the level crossing rate (LCR). The channel matrix $H$ of the satellite link using the Loo distribution for the envelope $h_{ij}$ is then given by

$$H_{rd} = \left[ h_{ij} \right] = \left[ \tilde{h}_{ij} \right] + \left[ \overline{h}_{ij} \right] = H_{rd} + \tilde{H}_{rd},$$  

where

$$h_{ij} = \left| h_{ij} \right| \exp(i\phi_{ij}),$$  

$$\tilde{h}_{ij} = \left| \tilde{h}_{ij} \right| \exp(i\tilde{\phi}_{ij})$$  

and $\phi_{ij}$, $\tilde{\phi}_{ij}$ are uniformly distributed over $[0,2\pi]$. The first factor represents the log-normal fading, while the second one describes the Rayleigh fading. Therefore, the Loo distribution as extracted from the (9) is the superposition of the log-normal distribution to model the large scale fading and Rayleigh distribution for the modeling of small-scale fading.

B. The terrestrial wireless radio channel

The terrestrial wireless radio channel is mostly characterized by the surrounding scatterers, which produce multipath components. This environment can be characterized using the Rician distribution as follows [23]

$$H_{sr} = \frac{K}{\sqrt{K + 1}} \overline{H}_{sr} + \frac{1}{\sqrt{K + 1}} \tilde{H}_{sr},$$  

where $K$ is the Rician factor, $\overline{H}$ is a deterministic unit rank matrix, which represent the direct component, and $\tilde{H}$ is the channel matrix of the multipath components. Note that most of research work related with MIMO technology suggests rich scattering environments, i.e., no line-of-sight (LoS) component exists. This ideal propagation environments for the MIMO systems are totally described using the Rayleigh distribution, resulting from the Rician distribution by applying a zero Rician $K$-factor, i.e., $K = 0$. 

Fig. 2. Simple representation of a multi-user MIMO satellite multiple-relay fading channel.
C. Signal Detection schemes

To facilitate the detection of signals from each antenna, the estimated symbols are inverted by a weight matrix \( W \) as follows [24]:

\[
\tilde{x} = \left[ \tilde{x}_1 \tilde{x}_2 \cdots \tilde{x}_N \right]^T = W y_2.
\]  

(10)

Note that there is one detection for each symbol, which depends on the number of the transmit antennas. Hence, a linear combination of the received signals in the destination node is considered. The standard linear detection methods include the well-defined and widely used ZF and MMSE detection techniques. The weight matrix of the ZF technique is given by

\[
W_{ZF} = (H^H H)^{-1} H^H,
\]  

(11)

where \( (\cdot)^H \) is the Hermitian transpose operation. Thus, we obtain:

\[
\tilde{x}_{ZF} = W_{ZF} y_2 = (H^H H)^{-1} H^H (H x + n) = (H^H H)^{-1} H^H H x + (H^H H)^{-1} H^H n
\]

\[
= x + (H^H H)^{-1} H^H n.
\]  

(12)

To maximize the post-detection signal to interference plus noise ratio (SINR), the MMSE weight matrix is given by

\[
W_{MMSE} = \left( H^H H + \sigma^2 I \right)^{-1} H^H.
\]  

(13)

The MMSE receiver uses the statistical information of noise \( \sigma^2 \). Thus, we obtain:

\[
\tilde{x}_{MMSE} = W_{MMSE} y_2
\]

\[
= \left( H^H H + \sigma^2 I \right)^{-1} H^H (H x + n)
\]

\[
= \left( H^H H + \sigma^2 I \right)^{-1} H^H H x + \left( H^H H + \sigma^2 I \right)^{-1} H^H n
\]

\[
= x + \left( H^H H + \sigma^2 I \right)^{-1} H^H n.
\]  

(14)

D. Channel Capacity

The ergodic capacity (in bits/sec/Hz) of a MIMO dual-hop AF system can be written as follows [25]

\[
C(\rho) = \mathbb{E}\{ \log_2 \det( I_{(N_t)} + \frac{SNR}{2} H H^H) \},
\]  

(15)

where

\[
R_a = I_{(N_t)} + a H_{RD} H_{RD}^H
\]  

(16)

and \( a \) is the constant value of amplification factor. In the proposed system model, we consider an MPSK (AF), multi-relay MIMO system with full-duplex relays. However, in a more realistic scenario, the capacity of a MIMO channel using linear detector (LD) can be written as:

\[
C_{LD} = \sum_{i=1}^{t} \log_2(1 + SINR_i),
\]  

(17)

where the \( SINR_i \) for each receiver is different. The SINR for the MMSE receiver in MIMO wireless communications for the \( k \)th spatial stream can be expressed as [26]-[29]

\[
SINR_k^{MMSE} = \frac{1}{\left( I_{N_t} + SNR H H^T (R_a)^{-1} H \right)_k}.
\]  

(18)

\[
SINR_k^{ZF} = \frac{SNR}{\left( H^T (R_a)^{-1} H \right)_k}.
\]  

(19)

III. PERFORMANCE EVALUATION

This section demonstrates the performance of the proposed communication scenario in terms of the bit error rate (BER) and the available channel capacity. Fig. 3 presents the simulation scenario, where \( N_t = N_r = 2, R = U = \) Number of beams = 7, and \( M_r = 1 \). The random user and relay positions are calculated using the method described in Fig. 4.
In Fig. 5, the end-to-end BER performance is presented for QPSK modulation, which is crucial for all the wireless systems and especially the satellite communications. To simulate the MMSE detection scheme, (4), (11) and (12) were used, while for the ZF detection scheme (4), (13) and (14) were adopted. One observes that the best signal detection is achieved with the MMSE detection scheme. The difference between the two signal detection techniques is approximately 1 dB. Note that the adoption of beams would derive to a gain approximately 1-1.5 dB [30].

Fig. 6 demonstrates the system channel capacity in the case of the MMSE detection scheme using (17) and (18) and in the case of the ZF detection scheme using (17) and (19). One observes that the MMSE detection scheme is better than the ZF and the difference is about 15 dB. Finally, there is a gain in the capacity results due to the existence of beams [25].

IV. CONCLUSION

In this paper, the benefits of a multi-beam MIMO satellite multi-user system aided by multiple relay nodes have been investigated. Simulations have been performed, in order to evaluate the system performance in different scenarios. The results have shown the gain in the BER performance as well as the gain in the achievable channel capacity by applying different detection schemes. These results have also underlined that using the MMSE detection scheme can offer better performance than using ZF detection scheme.

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