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Uninterrupted communication in LEO networks using soft handover with imperfect CSI

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***Abstract*—Satellite mobility plays a crucial role in maintaining seamless communication in space-to-ground links. To ensure uninterrupted connectivity, efficient handover strategies need to be implemented in satellite networks. In this work, we focus on the optimization of a soft-handover technique in the uplink, where one satellite acts as a relay for another one. Specifically, with both amplify-and-forward (AF) and decode-and-forward (DF) relaying techniques, we investigate several modulation and coding schemes under imperfect ground-to-satellite (G2S) channel estimation. We also compare maximal ratio combining (MRC) and selection combining (SC), with coded block error rate (BLER) as the performance parameter. Our results are presented based on realistic (G2S) channel models specified by 3GPP. The simulation results show that AF with SC can be a viable low-complexity solution, provided that a large enough power is allocated to pilots and the inter-satellite link is strong.**

***Index Terms*—Satellite communications, Non-Terrestrial Networks, LEO constellations, soft handover, Inter-Satellite Link**

I. Introduction

The integration of terrestrial and non-terrestrial networks (NTNs) emerges as a pivotal element in realizing the 6G vision of global ubiquitous connectivity. NTNs, especially those utilizing low-earth orbit (LEO) satellites, are gaining prominence due to their potential to complement terrestrial networks where they underperform or cannot reach, such as remote or underserved regions and during disaster relief operations.

LEO satellites, orbiting at altitudes ranging from 500 to 2000 kilometers, are well-poised to contribute to the 6G infrastructure. These NTNs provide substantial benefits over their geostationary counterparts, such as lower latency and potentially higher throughput [1], [2]. However, since a LEO satellite provides a limited coverage on the earth surface, tens of them need to be employed in the same LEO, in order to ensure uninterrupted connectivity with static ground users (GU). Also, LEO satellites have a very short orbital period, thus they remain in visibility for a limited amount of time (a few minutes), so that there is need for frequent handover even for a static GU.

In this paper, we explore the uplink dynamics of a satellite communication system within the context of soft-handover (SH) mechanisms where two satellites cooperate to improve the communication performance. One of such satellites acts as a relay, by forwarding its received signal to the higher-elevation one through the inter-satellite link (ISL). We first optimize the achieved throughput by applying an adaptive modulation-and-coding scheme (MCS), which is driven by the received line-of-sight (LoS) signal-to-noise ratio (SNR). Moreover, we study the impact of imperfect channel state information (CSI) on system performance, assessing how accurately satellites need to estimate channel coefficients. Finally, we compare the efficiency of maximum ratio combining (MRC) and selection combining (SC), examining their ability to optimize signal reception during the handover process. We choose the (coded) block error probability (BLER) as the performance parameter and we consider two relaying protocols: amplify-and-forward (AF) and decode-and-forward (DF), with an emphasis on understanding how the ISL can facilitate smoother transitions.

In our work, realistic models for both ground-to-satellite (G2S) and ISL channels are employed, conforming to the latest 3GPP recommendations.

The outcome of our investigation provides valuable insights into the design principles of future LEO systems, underpinning SH as a viable solution for ensuring continuous and reliable satellite communication.

Previous works dealing with SH and multisatellite reception are [3] and [4]. However, [3] considers a very different scenario with a time-dispersive channel and performs high-level performance assessment, without delving into physical-layer design. Instead, [4] considers the same channel model of this paper, but shows uncoded performance only. Our previous work [5] already deals with the communication system considered in this paper, but does not consider adaptive MCS and assumes perfect CSI. The concept of multisatellite reception has been extended in [6], where multiple satellite relays forward their received signal to the serving satellite. Also in that case, however, the analysis is limited to QPSK modulation. Unlike previous works, we perform BLER-based optimization of the LEO system uplink, by simulating a realistic environment in which the time evolution of satellite elevations is obtained by geometrical considerations, the G2S link is based on the 3GPP standard channel model defined in [7], [8], the ISL channel model is based on [5], [9] and imperfect CSI is taken into account.

The paper contributions are listed below.

- Given a set of MCSs, and for both AF and DF, we give a mapping from LoS SNR to MCS by optimizing the achieved throughput. In doing this, we suppose channel decoders are threshold devices, with thresholds taken from the AR6JA LDPC code family [10].
- For each MCS, we derive the performance degradation due to imperfect CSI, as a function of pilot power.
- For a chosen MCS, we compare MRC and SC with perfect and imperfect CSI.
- We provide theoretical results comparing MRC and SC performance, and assessing the degradation due to imperfect CSI on an ideal ISL.

II. Scenario description

In this section we first describe the geometric model of the considered G2S and ISL communication. We also detail the communication channel model for both G2S and ISL links.

A. Geometric model

The satellite geometric model we consider in this work is the same employed in [5]. A constellation composed of M satellites is deployed on a low earth orbit. Satellites are angularly spaced by $2\pi/M$ radiants along the orbit, as depicted in Figure 1. For simplicity the orbit is assumed circular, with height h_0 with respect to the ground level, and having inclination i_{K} with respect to the equatorial plane.

The motion of the satellites is regulated by the Kepler's law which relates the angular speed, ω, with the distance from the Earth center, given by $R_E + h_0$, where R_E is the Earth radius [11]. The angular position of the generic satellite, ℓ, at time t is thus given by $\alpha(t) = \alpha_\ell(0) + \omega t$, where $\alpha_\ell(0)$ is the angular position of satellite ℓ at time $t = 0$, measured with respect to the direction of the ascending node (see Figure 1). The point on the Earth surface located on the straight line connecting the satellite ℓ with the Earth center is denoted as sub-satellite point (SSP). The GU and the SSP, are depicted in Figure 2. The elevation angle of the satellite ℓ at time t, as observed by the GU, is denoted by $\delta_\ell(t)$ and can be found as shown in [11]. The minimum elevation angle that allows a successful communication between the GU and a satellite is $\delta_{\min}$. We also define $d_\ell(t)$ as the distance of satellite ℓ from the GU at time t. In a handover scenario two satellites, say S and T, cooperate to improve the G2S communication performance. One satellite works as relay (R) while the other is the destination (D) of the G2S communication. In the following the subscript ℓ, (indicating the satellite ID) takes the values S or T if we refer to physical satellites, or the values R and D if we refer to logical satellites, i.e. if we refer to the role they have in the communication.

B. G2S and ISL channel models

The G2S channel we consider is the one detailed in [7], [8] and is based on a semi-Markov chain with two states, good (G) and bad (B). When the channel is in state G, obstructions and fading severely degrade the transmitted signal, while when in state B shadowing and fading have a mild impact, and the LoS link between GU and satellite is not obstructed by obstacles.

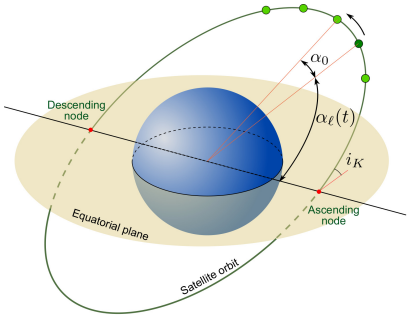

Fig. 1. A LEO constellation composed of M satellites deployed on a circular orbit with inclination i_{K} and height h_0 above the ground. Angles are measured with respect to the direction of the ascending node.

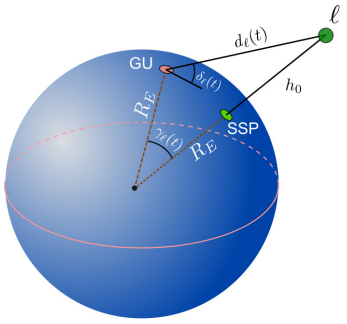

Fig. 2. Geometric model of the ground to satellite communication. The satellite ℓ is orbiting the earth at height h_0 and its elevation angle at time t, as observed by a GU, is denoted by $\delta_\ell(t)$. The G2S link has length $d_\ell(t)$.

The channel is modeled as time varying and its evolution over time results in an alternate sequence of states G and B whose duration are modeled as independent lognormal random variables with different parameters. In each state, the channel coefficient is modeled as a complex random variable with independent magnitude and phase. The magnitude accounts for the effects of Rayleigh fading and lognormal shadowing and is randomly generated according to the Loo distribution. The phase is uniform in $[0, 2\pi]$. Let $h_\ell(t)$ be the channel coefficient of the G2S link, generated at time t and referring to satellite ℓ. Then, the SNR at the satellite receiver is given by

$$\mathrm{SNR}_\ell(t) = \rho_\ell(t)|h_\ell(t)|^2 \tag{1}$$

where $\rho_\ell(t)$ is the LoS SNR, whereas $h_\ell(t)$ takes into account for shadowing and fading. Specifically,

$$\rho_\ell(t) = \left(\frac{c}{4\pi d_\ell(t) f_{\mathrm{G2S}}}\right)^2 \frac{P_{\mathrm{GU}} G_{\mathrm{GU}} G_\ell}{N_0 W_{\mathrm{G2S}}} \tag{2}$$

where P_{GU} is the GU transmit power, G_{GU} and G_ℓ are, respectively, the antenna gains of the GU and of satellite ℓ, c is the speed of light, f_{G2S} is the carrier frequency, N_0 is the noise power spectral density, and W_{G2S} is the signal bandwidth.

The propagation channel on the ISL link follows a much simpler model, compared to the G2S link. The ISL channel is supposed to have a large operating frequency and also a

large bandwidth. In [9] it is shown that, in such conditions, the received signal follows a special AWGN model, accounting for pointing errors due to the misalignment between transmitter and receiver antennas. In [5], we have shown that the effect of pointing errors on the system performance is severe, and that to exploit the advantages of the ISL a suitable minimum precision in the pointing system must be granted. Thus, in this paper, we will suppose a pure AWGN model for the ISL. Specifically, the received SNR on the ISL is given by

$$\rho_{\mathrm{ISL}} = \left(\frac{c}{4\pi d_{\mathrm{ISL}} f_{\mathrm{ISL}}}\right)^2 \frac{P_T G_0^2}{k_B T_0 W_{\mathrm{ISL}}} \tag{3}$$

where P_T is the transmit power on the ISL, G_0 is the antenna gain both at the transmitter and at the receiver, f_{ISL} is the ISL carrier frequency, $d_{\mathrm{ISL}} = 2(R_e + h_0)\sin\frac{\pi}{M}$ is the ISL link length, k_B is the Boltzmann constant, T_0 is the ambient noise temperature, and W_{ISL} is the signal bandwidth.

III. Soft-handover scheme specification

We now provide details on the considered SH schemes. This includes specifying the structure of the transmitted and received signals, and describing the relaying and signal processing techniques at the satellites.

A. Received signal on the G2S Link

The GU encodes the information bits using a binary channel code with rate R_c. The encoded bits are then mapped to complex symbols, $x[n]$, $n = 1, 2, \ldots, N$ belonging to a unit-energy constellation $\mathcal{S}$. The n-th symbol is transmitted at time $t_n{=}nT_s$ where T_s is the symbol time. The (normalized) signal received by satellite ℓ at time step n, $n = 1, \ldots, N$ is

$$y_\ell[n] \quad = \quad \sqrt{\rho_\ell[n]} h_\ell[n] x[n] + w_\ell[n], \tag{4}$$

where $\rho_\ell[n] \triangleq \rho_\ell(nT_s)$ and $h_\ell[n] \triangleq h_\ell(nT_s)$ are specified in (1) and $w_\ell[n] \sim \mathcal{CN}(0,1)$ represents complex Gaussian noise. In this work, we compare two scenarios. In the first scenario both satellites have perfect knowledge of their respective channels. This knowledge is obtained, for example, through the utilization of pilots. The second scenario involves imperfect CSI, wherein the satellites lack complete and accurate knowledge of their channels. With imperfect CSI, the estimated channel coefficient is given by

$$\widehat{h}_\ell[n] \triangleq h_\ell[n] + w_{\mathrm{CE}}[n] \tag{5}$$

where w_{CE} is a circularly-symmetric complex Gaussian noise sample with zero mean and variance $\sigma^2_{\mathrm{CE}}[n] = \frac{1}{\rho_\ell[n] E_p}$, where E_p is the pilot energy.

B. Relaying Techniques at satellite R

The relaying satellite R may forward its received signal to satellite D using either AF or DF relaying techniques.

In AF the relaying satellites first computes the signal

$$x_{\mathrm{ISL,AF}}[n] = y_{\mathrm{R}}[n]/\sqrt{\widehat{q}[n]}, \quad \forall n \tag{6}$$

where $\widehat{q}[n] = \mathbb{E}[|\widehat{y}_{\mathrm{R}}[n]|^2] = 1 + \rho_{\mathrm{R}}[n]\left(|h_{\mathrm{R}}[n]|^2 + \frac{1}{\sigma^2_{\mathrm{CE}}[n]}\right)$ is a normalization factor. Then it transmits $\sqrt{P_{\mathrm{T}}} x_{\mathrm{ISL,AF}}[n]$ on the ISL link.

In DF the relaying satellite demodulates and decodes the received signal. A block decoding error happens with probability P_B, whose expression is provided in (21). In the case of successful decoding, R re-encodes and modulates the estimated information bits, and transmits to S the signal

$$\sqrt{P_T} x_{\mathrm{ISL,DF}}[n] = \sqrt{P_T} x[n], \quad \forall n \tag{7}$$

If decoding is not successful, R forwards no signal to D.

C. Signal processing at satellite D

The (normalized) signal received by satellite D from R on the ISL link at time step n is given by

$$y_{\mathrm{ISL},\vartheta}[n] = \sqrt{\rho_{\mathrm{ISL}}} x_{\mathrm{ISL},\vartheta}[n] + w_{\mathrm{ISL}}[n], \tag{8}$$

where $\vartheta \in \{\mathrm{AF}, \mathrm{DF}\}$, ρ_{ISL} is defined in (3) and assumed perfectly known, and $w_{\mathrm{ISL}}[n] \sim \mathcal{CN}(0,1)$. Note that when DF relaying is employed and in the case of unsuccessful decoding at R, we assume $P_{\mathrm{R}} = 0$, so that $y_{\mathrm{ISL,DF}}[n] = 0, \forall n$. To improve the overall communication reliability, satellite D applies a receive diversity combining technique on the received G2S and ISL signals. We explore the following options:

- *Maximum Ratio Combining* (MRC): Satellite D combines the signals with estimated optimum gains, obtaining

$$\widetilde{y}_{\mathrm{MRC},\vartheta}[n] = \left(\widetilde{h}_{\mathrm{MRC},\vartheta}[n] + \widetilde{w}_{\mathrm{MRC},\vartheta}[n]\right) x[n] + \widetilde{w}[n], \tag{9}$$

  where $\widetilde{h}_{\mathrm{MRC},\vartheta}[n]$ is the equivalent channel at time step n, and $\widetilde{w}[n]$ and $\widetilde{w}_{\mathrm{MRC},\vartheta}[n]$ are complex normal noise samples with zero mean and variances $\widetilde{h}_{\mathrm{MRC},\vartheta}[n]$ and $\sigma^2_{\mathrm{MRC},\vartheta}$, respectively. To obtain (9) let us define $\mathrm{SNR}_{\mathrm{D}}[n] = \rho_{\mathrm{D}}[n]|\widehat{h}_{\mathrm{D}}[n]|^2$, $\mathrm{SNR}^{\mathrm{AF}}_{\mathrm{ISL}}[n] = \widetilde{\rho}_{\mathrm{R}}[n]|\widehat{h}_{\mathrm{R}}[n]|^2$, and $\mathrm{SNR}^{\mathrm{DF}}_{\mathrm{ISL}}[n] = \rho_{\mathrm{ISL}}$ where $\widetilde{\rho}_R[n] = \frac{\rho_{\mathrm{ISL}}\rho_{\mathrm{R}}[n]}{\rho_{\mathrm{ISL}} + \widehat{q}[n]}$ is the LoS SNR on the cascaded relay channel.
  In the case of AF, we have

$$\widetilde{h}_{\mathrm{MRC,AF}}[n] = \mathrm{SNR}_{\mathrm{D}}[n] + \mathrm{SNR}^{\mathrm{AF}}_{\mathrm{ISL}}[n] \tag{10}$$

$$\sigma^2_{\mathrm{MRC,AF}} = \frac{1}{E_p}\left(\mathrm{SNR}_{\mathrm{D}}[n] + \frac{\widetilde{\rho}_R[n]}{\rho_R[n]}\mathrm{SNR}^{\mathrm{AF}}_{\mathrm{ISL}}[n]\right) \tag{11}$$

$$\begin{aligned}\widetilde{y}_{\mathrm{MRC,AF}}[n] =& \sqrt{\rho_{\mathrm{D}}[n]}\widehat{h}^*_{\mathrm{D}}[n] y_{\mathrm{D}}[n] \\ &+ \sqrt{\frac{\widehat{q}[n]\widetilde{\rho}_R[n]}{\rho_{\mathrm{ISL}} + \widehat{q}[n]}}\widehat{h}^*_{\mathrm{R}}[n] y_{\mathrm{ISL,AF}}[n]\end{aligned} \tag{12}$$

  Instead, for DF,

$$\widetilde{h}_{\mathrm{MRC,DF}}[n] = \mathrm{SNR}_{\mathrm{D}}[n] + \mathrm{SNR}^{\mathrm{DF}}_{\mathrm{ISL}}[n] \tag{13}$$

$$\sigma^2_{\mathrm{MRC,DF}} = \mathrm{SNR}_{\mathrm{D}}[n]/E_p \tag{14}$$

$$\widetilde{y}_{\mathrm{MRC,DF}}[n] = \sqrt{\rho_{\mathrm{D}}[n]}\widehat{h}^*_{\mathrm{D}}[n] y_{\mathrm{D}}[n] + \sqrt{\rho_{\mathrm{ISL}}} y_{\mathrm{ISL,DF}}[n]. \tag{15}$$

- *Selection Combining* (SC): Satellite D will select the signal with the estimated maximum received power, obtaining

$$\begin{aligned}\widetilde{y}_{\mathrm{SC},\vartheta}[n] =& I_{\{\mathrm{SNR}^{\vartheta}_{\mathrm{ISL}}<\mathrm{SNR}_{\mathrm{D}}\}} y_{\mathrm{D}}[n] + \\ & I_{\{\mathrm{SNR}^{\vartheta}_{\mathrm{ISL}}>\mathrm{SNR}_{\mathrm{D}}\}} y_{\mathrm{ISL},\vartheta}[n]\end{aligned} \tag{16}$$

where I_E is 1 if event E is true, 0 if event E is false.

Notice that AF requires the knowledge of the channel $h_{\mathrm{R}}[n]$ at satellite D, while DF does not.

IV. BLER ANALYSIS

We consider the BLER after combining at satellite D as the performance parameter of the considered SH scheme. To compute it, we assume that the channel decoder works as a threshold device, i.e., it succeeds in decoding if and only if the input mutual information (MI) per bit exceeds a given code-dependent threshold C_T. This is a good approximation of the real decoder behavior when the block length is large enough.

Consider the AWGN channel $\mathcal{Y} = \sqrt{\rho}\mathcal{H}\mathcal{X} + \mathcal{W}$, where $\mathcal{W} \sim \mathcal{CN}(0,1)$, $\mathcal{H}$ is unknown and distributed according to pdf $f_{\mathcal{H}}$ and $\mathcal{X}$ is a modulation symbol belonging to constellation $\mathcal{S}$. The receiver knows a noisy version of $\mathcal{H}$, denoted $\widehat{\mathcal{H}} = \mathcal{H} + \mathcal{W}_{\mathrm{CE}}$, $\mathcal{W}_{\mathrm{CE}} \sim \mathcal{CN}(0, \sigma^2_{\mathrm{CE}})$ being the channel estimation error. The distribution of $\mathcal{W}_{\mathrm{CE}}$ conditional on $\widehat{\mathcal{H}} = \widehat{h}$ is given by

$$f_{\mathcal{W}_{\mathrm{CE}}|\widehat{\mathcal{H}}}(w|\widehat{h}) = \frac{f_{\mathcal{H}}(\widehat{h}-w)\mathrm{e}^{-|w|^2/\sigma^2_{\mathrm{CE}}}}{\int f_{\mathcal{H}}(\widehat{h}-w')\mathrm{e}^{-|w'|^2/\sigma^2_{\mathrm{CE}}}\,\mathrm{d}w'} \tag{17}$$

In the following we will suppose that $f_{\mathcal{H}}(\widehat{h}-w)$ can be approximated as uniform for values of w for which the numerator of (17) is non-negligible. Equivalently, we assume that $\mathcal{W}_{\mathrm{CE}}$ is approximately independent of $\widehat{\mathcal{H}}$, a realistic hypothesis for a moderate value of σ^2_{CE}. Let $p\left(s|y,\rho,\widehat{h}\right)$ be the a-posteriori probability of the event $\{\mathcal{X}=s\}$ given the received sample and the estimated channel coefficient. With the above approximation, we can write

$$p\left(s|y,\rho,\widehat{h}\right) = K\exp\left\{-\frac{|y-\sqrt{\rho}\widehat{h}s|^2}{\rho|s|^2\sigma^2_{\mathrm{CE}}+1}\right\} \tag{18}$$

where K is a normalization constant.

Suppose $\mathcal{S}$ has size 2^m, i.e., each constellation symbol corresponds to m bits. At the transmitter, the binary encoded information is mapped onto $\mathcal{S}$ according to a given mapping. Let $\mathcal{S}_i(0)$ be the subset of symbols whose i-th bit in this mapping is equal to 0. Thus, the conditional Bit-Interleaved Coded Modulation (BICM) MI is computed as

$$C(y,\rho,\widehat{h}) = 1 - \frac{1}{m}\sum_{i=1}^{m} h_b\left(p_i\left(0|y,\rho,\widehat{h}\right)\right) \tag{19}$$

where $h_b(p) = -p\log_2 p - (1-p)\log_2(1-p)$ is the binary entropy function and

$$p_i\left(0|y,\rho,\widehat{h}\right) = \sum_{s\in\mathcal{S}_i(b)} p\left(s|y,\rho,\widehat{h}\right) \tag{20}$$

Using a channel code of length N_c symbols to transmit on the considered channel, we model the block error probability of the corresponding channel decoder as

$$P_B(e|\mathbf{y},\boldsymbol{\rho},\widehat{\mathbf{h}}) = I_{\left\{\overline{C}(\mathbf{y},\boldsymbol{\rho},\widehat{\mathbf{h}})\le C_T\right\}} \tag{21}$$

where $\mathbf{y},\widehat{\mathbf{h}},\boldsymbol{\rho}$ denote the length-N_c vectors of the received samples $y[n]$, estimated channel coefficients $\widehat{h}[n]$, and SNR values $\rho[n]$, respectively and

$$\overline{C}(\mathbf{y},\boldsymbol{\rho},\widehat{\mathbf{h}}) = \frac{1}{N_c}\sum_{n=1}^{N_c} C(y[n],\rho[n],\widehat{h}[n]) \tag{22}$$

is the average BICM MI per bit on the code block. With reference to (9) and (16) for MRC and SC respectively, the performance in terms of BLER of the SH scheme will be given by

$$P_{B,\mathrm{SH},\eta,\vartheta}(e) = \mathbb{E}_{\widetilde{\mathbf{y}}_{\eta,\vartheta},\widetilde{\mathbf{h}}_{\eta,\vartheta}} P_B(e|\widetilde{\mathbf{y}}_{\eta,\vartheta},\mathbf{1},\widetilde{\mathbf{h}}_{\eta,\vartheta}) \tag{23}$$

where $\eta \in \{\mathrm{MRC},\mathrm{SC}\}$, $\vartheta \in \{\mathrm{AF},\mathrm{DF}\}$, $\mathbb{E}_z$ is the average with respect to random variable z and $\mathbf{1}$ is an all-1 vector. As a comparison, the BLER performance for hard handover (HH), where the GU switches instantly from satellite S to the satellite T, is

$$P_{B,\mathrm{HH}}(e) = \mathbb{E}_{\widehat{\mathbf{y}}_{\mathrm{D}},\widehat{\mathbf{h}}_{\mathrm{D}},\boldsymbol{\rho}_{\mathrm{D}}} P_B(e|\widehat{\mathbf{y}}_{\mathrm{D}},\boldsymbol{\rho}_{\mathrm{D}},\widehat{\mathbf{h}}_{\mathrm{D}}). \tag{24}$$

A. Performance theoretical analysis

In this subsection, we report some analytical results regarding the BLER of the different system variants introduced in the previous sections. First of all, the following proposition, whose proof is omitted for lack of space, reveals that, even in the presence of imperfect CSI, no matter what the channel realization is, MRC has a better average performance than SC, provided that pilots are transmitted with a suitable power.

Proposition 1: Under the approximation of low channel-estimation noise for which (18) holds, if the pilot power satisfies $E_p \ge \max_{s\in\mathcal{S}}|s|^2$, we have

$$P_{B,\mathrm{SH},\mathrm{MRC},\vartheta}(e) < P_{B,\mathrm{SH},\mathrm{SC},\vartheta}(e) \tag{25}$$

for $\vartheta \in \{\mathrm{AF},\mathrm{DF}\}$.

Although MRC performs better than SC, it entails a larger computational complexity. In some conditions where one of the two branches is significantly stronger than the other (e.g., when one of the two satellites is momentarily in Non-Line-of-Sight with respect to the GU), SC could be the best trade-off between performance and complexity.

We finally consider the performance of AF for $\rho_{\mathrm{ISL}} \to \infty$. Let $\overline{\mathrm{SNR}}_{\eta,\mathrm{AF}}[n] = \lim_{\rho_{\mathrm{ISL}}\to\infty}\lim_{E_p\to\infty}\mathrm{SNR}_{\eta,\mathrm{AF}}[n]$, for $\eta \in \{\mathrm{MRC},\mathrm{SC}\}$, be the SNR with perfect CSI and ideal ISL. With a simple application of Jensen's inequality, we can bound the asymptotic penalty due to imperfect CSI on the SNR of AF as follows:

$$\frac{\min_{s\in\mathcal{S}}|s|^2}{1+1/E_p} \le \frac{\lim_{\rho_{\mathrm{ISL}}\to\infty}\mathrm{SNR}_{\eta,\mathrm{AF}}[n]}{\overline{\mathrm{SNR}}_{\eta,\mathrm{AF}}[n]} \le \frac{1}{1+1/E_p} \tag{26}$$

for $\eta \in \{\mathrm{MRC},\mathrm{SC}\}$. Notice that both bounds are tight when $\min_{s\in\mathcal{S}}|s|^2 = 1$, like in PSK constellations.

V. Simulation results

In Table I, we report the main parameters of the simulation.

We consider a single satellite pass, in the time window where satellites T and S have an elevation larger than $\delta_{\min}$. The elevation time series for both satellites is quantized on the set of values $\{30°, 45°, 60°, 70°\}$, for which there exist tables of channel parameters in [8, Annex 2, Sect. 2.2]. Given the parameters, the channel coefficients for the two G2S links are then generated independently. The visibility interval of both satellites lasts for about 2 minutes, during which we suppose that 500 code blocks are transmitted.

In the simulations, we consider as the independent variable a reference SNR, which is the LoS SNR when the satellite is at the minimum distance (i.e., the maximum elevation) from the GU. In other words, the reference SNR for satellite $\ell = \{\mathrm{S}, \mathrm{T}\}$ is given by

$$\rho_{\mathrm{ref}} = \frac{P_{\mathrm{GU}} G_{\mathrm{GU}} G_{\ell} L_{\mathrm{ref}}}{N_0 W_{\mathrm{G2S}}} \tag{27}$$

where

$$L_{\mathrm{ref}} = \left(\frac{c}{4\pi h_0 f_{\mathrm{G2S}}} \right)^2 \tag{28}$$

so that the actual LoS SNR is $\rho_{\ell}[n] = \rho_{\mathrm{ref}} L_{\ell}[n] / L_{\mathrm{ref}}$. With the parameters reported in Table I, a reference SNR of 20 dB corresponds to a transmitted power P_{GU} of about 50 mW.

TABLE I
Simulation parameters.

Parameter	Notation	Value
Geometrical model		
Orbit height	h_0	550 km
Orbit inclination	i_{K}	45°
Constellation size	M	63
GU coordinates	$(\lambda_{\mathrm{GU}}, \phi_{\mathrm{GU}})$	(45° N, 7° E)
Minimum elevation	$\delta_{\min}$	25°
Ground-to-satellite (G2S) link		
Carrier frequency	f_{G2S}	2.2 GHz
Transmitted power	P_{GU}	See text
GU antenna gain	G_{GU}	0 dBi
Satellite antenna gain	$G_{\mathrm{S}}, G_{\mathrm{T}}$	50 dBi
Signal bandwidth	W_{G2S}	5 MHz
Environment	-	Suburban
Channel model parameters	-	From [8]
Noise level	N_0	-174 dBm/Hz
Inter-satellite link (ISL)		
Carrier frequency	f_{ISL}	193 THz
Transmitted power	P_T	$\{10, 20, 30\}$ dBW
Ambient noise temperature	T_0	7000 K
Signal bandwidth	W_{ISL}	2% f_{ISL}
TX/RX antenna gain	G_0	90 dBi

A. MCS optimization

In order to optimize the MCS, we have considered the constellation formats and the channel coding rates shown in Table II. The first column represents the number of coded bits per symbol $m = \log_2 S$. For 16-APSK and 32-APSK, optimal ratios between the different symbol radii have been chosen according to [12]. The fourth column shows the MCS efficiency mR_c, expressed in information bits per channel use (pcu). Notice that, for $R_c \geq 1/2$, the coding rate satisfies $R_c = \frac{m-1}{m}$. For the channel codes, in this paper we consider the AR6JA LDPC codes proposed in [10]. These are LDPC codes with very good thresholds on the binary-input AWGN channel, which are shown both in terms of SNR and in terms of MI in the last two columns of Table II. All thresholds have been rederived using density evolution. It is worth noting that the AR6JA code with rates $R_c \leq 1/2$ are taken from [10, Sect. IV] while the others are taken from [10, Sect. III].

TABLE II
Considered MCS combinations and AR6JA thresholds.

m	Constellation	R_c	mR_c	Thr. SNR [dB]	Thr. MI [bit]
2	QPSK	1/3	0.667	-0.4017	0.3391
2	QPSK	1/2	1	0.2780	0.5070
3	8-PSK	2/3	2	1.1826	0.6763
4	16-APSK	3/4	3	1.7023	0.7556
5	32-APSK	4/5	4	2.1125	0.8049

For each combination of techniques described in the previous section, we derive the optimal MCS as a function of the reference SNR, according to the value of the throughput obtained by each MCS, defined as

$$G(m, R_c) = mR_c \left(1 - P_{B,SH,\theta}(e)\right) \tag{29}$$

Figure 4 shows the throughput for the different MCSs in three different cases: SH with AF (blue lines), SH with DF (red lines), HH (black lines). The ISL is assumed to be noiseless, i.e., $\rho_{\mathrm{ISL}} = \infty$ and the serving satellite is applying MRC as the combining strategy. The pilot power is set to $E_p = 1$. By mapping a given reference SNR into the MCS that achieves the largest throughput, it is possible to achieve the envelope of the curves in the Figure3. Regarding the comparison between the handover options, AF is always the best one, with a gain over DF of about 0.5 to 1.5 dB, depending on the throughput value. DF gains significantly over HH (at most 1 dB) only for the larger rates.

In the same scenario and for the same three handover options of Figure 4, Figure 5 shows the BLER of the different MCSs. This plot highlights the gain of DF over HH in a perfect CSI scenario, typically of about 2 dB. Another possible mapping of reference SNR to MCS consists in choosing the largest-rate MCS that achieves a given BLER target, e.g., 10^{-4}, if this is achieved by some MCS, or else the lowest rate. Whether it is preferable to achieve the largest throughput or to grant a maximum BLER depends also on the upper layers (for example, use of an efficient link-layer coding scheme on top of the physical layer).

B. Impact of imperfect CSI

Figure 6 shows the impact of imperfect CSI on $P_{B,\mathrm{SH,MRC,AF}}(e)$. In particular, for each MCS, we plot the increase in SNR necessary to achieve $P_{B,\mathrm{SH,MRC,AF}}(e) = 20\%$, with respect to perfect CSI, as a function of the pilot power E_p. For example, with 16-APSK and coding rate $3/4$, to achieve $G(4, 3/4) = 2.4$ bits pcu, the reference SNR must be increased by 1 dB for $E_p = 2$. Noiseless ISL is considered. Except for the lowest coding rate, the SNR gap decreases for a given

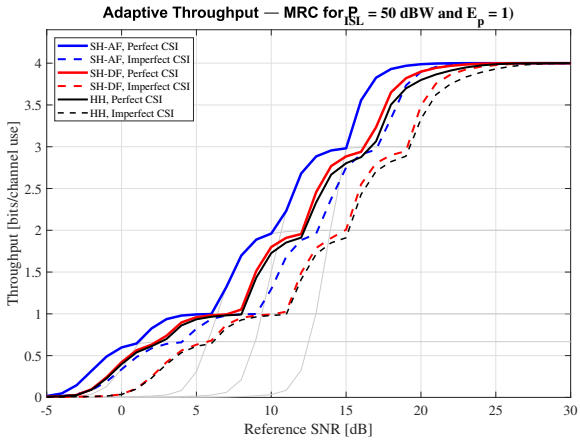

Fig. 3. Adaptive System Throughput of (29) for the different combined MCSs as a function of the reference SNR for three different handover options with MRC strategy .

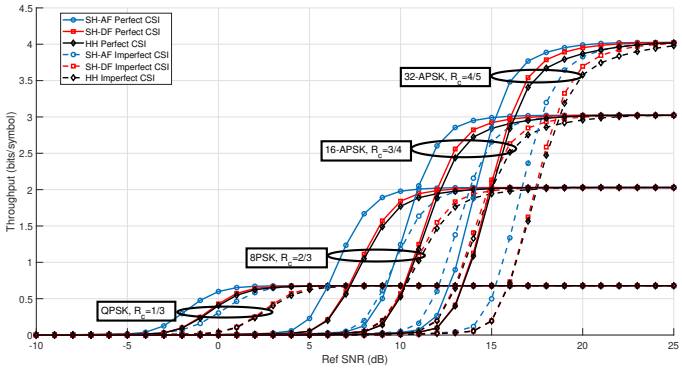

Fig. 4. Throughput of (29) for the each MCSs separetly as a function of the reference SNR for three different handover options with MRC strategy.

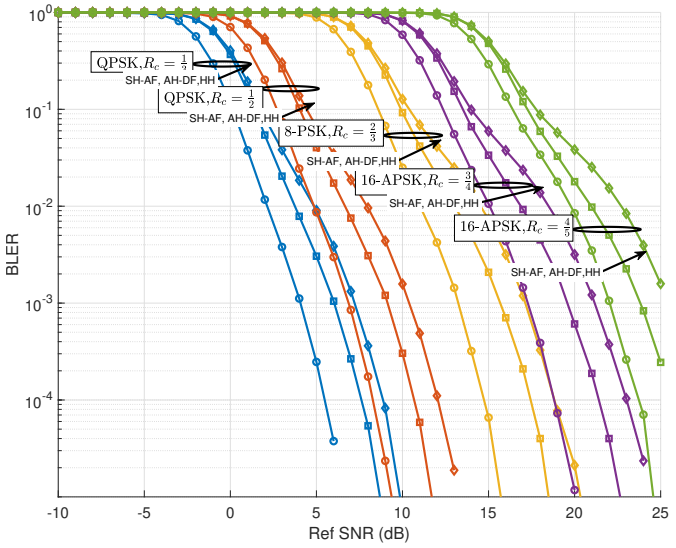

Fig. 5. Achieved BLER for each MCSs as a function of the reference SNR for three different handover options with MRC combining strategy.

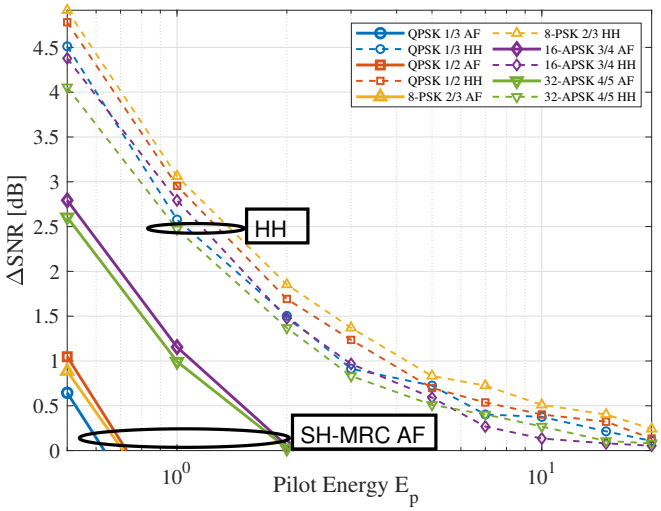

Fig. 6. SNR gap to achieve 80% of the maximum throughput for different MCSs, as a function of the pilot power E_p. comparing SH-AF (MRC) vs HH.

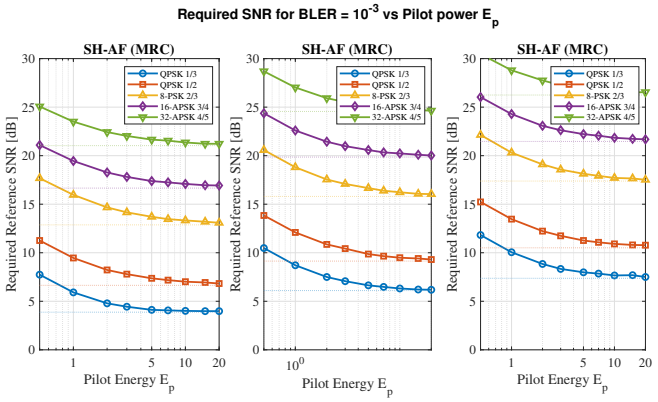

Fig. 7. Required Reference SNR on the G2S to achieve a $BLER = 10^{-3}$ as a function of the pilot power E_p in the imperfect CSI scenario of $\sigma_\ell^2 = \frac{1}{E_p \rho_\ell}$.

E_p with increasing rate. For all MCSs, however, $E_p = 3$ is enough to reduce the SNR gap within 1 dB.

C. Comparison between MRC and SC

Figure 8 shows the BLER comparison between two possible combining techniques at the serving satellite MRC and SC, with different MCS under same conditions. Both perfect and imperfect CSI (with $E_p = 1$) are considered. The results shows that MRC technique clearly outperform SC with all MCS with gap that varies from 3db using QPSK to 6dB with 16-APSK and 32-APSK.For both combining techniques SC and for MRC, the Reference SNR gap due to imperfect CSI is about 3 dB, as expected from the theoretical results shown in Section IV-A. SC shows an SNR gap of less than 1 dB with respect to MRC under imperfect CSI.

VI. Conclusions

In this paper, we have studied a SH mechanism for LEO constellations. Dynamic elevation time series and realistic

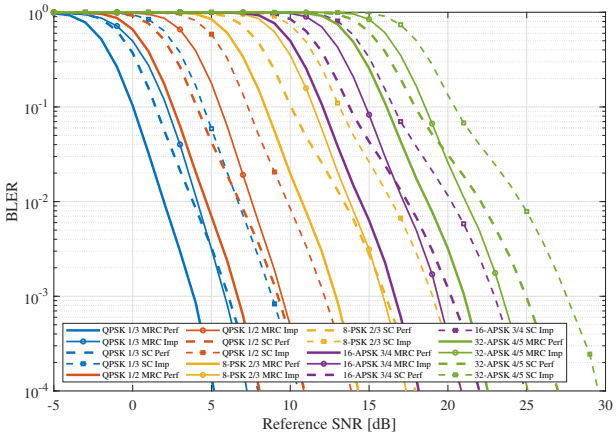

Fig. 8. Comparison between MRC and SC for AF and HH, with and without perfect CSI.

models for the G2S links have been adopted. Extensive simulations have been performed, with several MCS options, to test the impact of imperfect CSI. A comparison of MRC and SC with both perfect and imperfect CSI has been carried out. AF with SC can be the preferable solution, when a large enough power is allocated to pilots and the ISL is strong.

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