Frequency Reuse in Dual Satellite Settings: an Initial Evaluation of Full Duplex Operation

Daniel Martiñán-Otero
Signal Theory and Communications Department,
University of Vigo,
36310 - Vigo, Spain
Email: dmartinan@gts.uvigo.es

Carlos Mosquera
Signal Theory and Communications Department,
University of Vigo,
36310 - Vigo, Spain
Email: mosquera@gts.uvigo.es

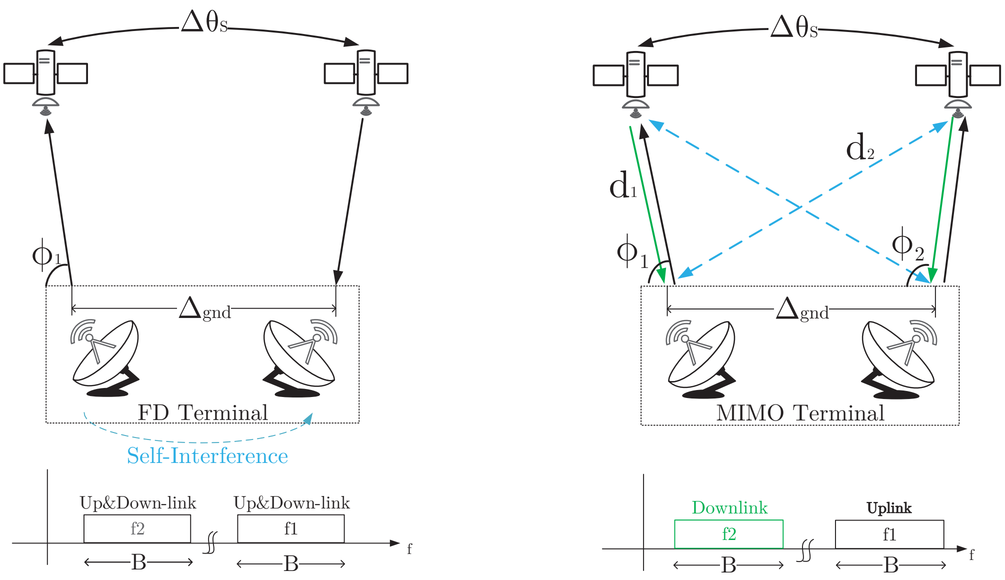
***Abstract*—Reuse of spectral resources is a way of pushing transmission rates beyond current limits. In the case of satellite communications, this is achieved in multibeam coverage and multiple polarization links, for example. In this paper, we make an initial evaluation of the reuse of the same time and frequency resources for both transmission and reception, in what is known as In-Band Full Duplex, and which is being considered as a promising technology for terrestrial wireless systems. The rate limits for the exchange of information between two ground antennas and two satellites are obtained as a function of the capability of suppressing the self-interference which is caused by the Full Duplex operation. Half Duplex single antenna rate is easily overcome in most cases, whereas Full Duplex performance is highly dependent on the self-interference cancellation, and MIMO operation has a high sensitivity on the antennas separation.**

I. Introduction

The improved spectral efficiency of recent satellite communications (SatCom) services has followed the progress of technology and the evolution of standards. Multibeam satellites, for example, make it possible to increase the spatial reuse of the frequency resources [1]. Some techniques routinely applied in terrestrial systems can inspire new developments in the SatCom domain after careful consideration; this is the case, for example, of multiple antennas communication [2]. Although multibeam satellites use many feeds to synthesize the different spot-beams, when we use the term MIMO (Multiple-Input Multiple-Output) we are rather considering more than one antenna for transmission and/or reception to achieve some multiplexing or diversity gain [3]. In the quest for a better exploitation of spectral resources, Full Duplex (FD) communication is being considered as a promising solution for wireless terrestrial systems [4], [5]. The simultaneous use of the same frequencies for both transmit and receive directions at the same time is conventionally ruled out as impractical due to the coupling caused by the large interference that a given transmitter generates to its own receiver. This is why regulation and communication standards preclude the simultaneous allocation of time and spectral resources to both incoming and outcoming signals. Nevertheless, the potential doubling of the spectral efficiency has spurred the research efforts which have given good results for the design of on-frequency relays [6], for which some baseline attenuation can be achieved by physical separation and proper positioning of receive and transmit antennas. A radio transceiver using the same frequency for transmission and reception seems to require a combination of self-interference techniques in both analog and digital domains to achieve cancellation values as high as needed in some terrestrial wireless systems. Satellite links pose additional challenges due to the high imbalance between transmit and receive powers. Even further, in order to prevent the saturation of the radio front-end, the attenuation of the unwelcome strong signal at the analog front-end is key for the feasiblity of the FD concept. Thus we focus on schemes with two antennas [7], for transmission and reception, respectively, separated by a certain distance, although single antenna settings have been recently proposed for terrestrial links built on advanced analog cancellation circuits [4].

In this paper we elaborate some initial considerations on the potential reuse of the same spectrum for communication between ground and space in both directions. Current regulation allocates different bands for uplink and downlink for most cases, although Time-Division Duplexing (TDD) is used, for example, by Iridium for its mobile service in L band, with both transmission directions alternatively used in time. The application of cognitive radio to satellite communications makes also a case for the need of FD operation. On the one hand, simultaneous sensing and transmission can achieve a more effective reuse of spectral resources. On the other hand, the same frequency band allocated on a primary basis for an uplink can be reused for the downlink of a cognitive user [8]. In this paper Full Duplex will always refer to In-Band Full Duplex, that is, the ability to transmit and receive simultaneously on the same frequency band. However, some mechanisms which have been proposed to increase the spectrum reuse and are commonly credited as Full Duplex [9], do use in fact different frequencies for the transmission and reception from the same site; they can deal with the simultaneous transmission on the same frequency band from two different sites which communicate through the satellite. Self-interference cancellation is needed upon reception of the combined signal at each site, in a sort of analog network coding scheme [10]. Commercial systems such as PCMA (Paired Carrier Multiple Access) and Carrier-in-Carrier fall within this category.

As study setup we will consider a fixed system, with two on-ground antennas separated by a short distance as a simple passive attenuation mechanism of self-interference (SI), as depicted in Figure 1a. In that figure one terrestrial antenna transmits by using the whole available bandwidth, interfering the receive antenna which is also using the same spectrum. Alternatively, the same antennas can be operated



(a) Full Duplex.

(b) MIMO.

Fig. 1: Dual satellite setting.

on a MIMO configuration, as depicted in Figure 1b, by using different pieces of spectrum for transmission and reception. Both antennas are expected to be located within the same premises (micro-scale site diversity [11]).

The need for an active SI cancellation (analog, digital or both) in Figure 1a will depend on how attenuated the interfering signal gets to the receive antenna. Analog cancellation will be needed if the dynamic range of the input amplifier and digital conversion stage are not sufficient to accomodate the additional interfering power. Both antennas will have their corresponding radio heads, including the analog cancellation subsystem (if needed) at the receive antenna; in this configuration, analog cancellation would take place by converting the digital baseband version of the transmit signal to RF on the receive side, and applying the corresponding delay and scaling [12]. Both antennas will be connected to a common baseband transceiver for digital processing of transmit and receive signals. Two different satellites will separately channelize the uplink and downlink signals. Thus, we do not rely on the on-board cancellation of self-interference, assuming that the in-band interference picked-up by the receive satellite can be neglected or, at least, can be compared to other sources of interference. Although satellites can be essentially considered as relays, and technology is well-developed to combat interference in terrestrial on-frequency relays [6], things are much more complicated on-board; among other issues, processing is very limited and antennas cannot be physically decoupled, since they point to Earth. The satellites are expected to channelize the in-band signals to another location on Earth, not shown in Figure 1, as the frequency allocation of this additional link is not a matter of this study.

In the next section we compute the deterministic channel capacity for both FD and MIMO cases as an initial approach, before including a simple statistical description of the ground to space channel to compare the respective outage capacities. We will also show a few numerical results to get some insight on the expected performance of FD in the ground to space link.

II. Channel Capacity

Two antennas in communication with two satellites to exchange a common source of information can be considered as a 2x2 MIMO system (Figure 1b), and as such we want to discuss first their expected performance to put into perspective the potential merits of an FD system. As initial approach, we consider a deterministic line-of-sight 2x2 MIMO setting, with a direct signal path between each antenna pair. The angular separation $\Delta\theta_S$ between the satellites is not too large, so the antenna gains differences can be neglected. The communication model is given by

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{w} \tag{1}$$

where $\mathbf{x} \in \mathcal{C}^2$, $\mathbf{y} \in \mathcal{C}^2$ and $\mathbf{w} \sim \mathcal{CN}(0, N_0\mathbf{I})$ denote the transmitted signal, received signal and white Gaussian noise of variance N_0 respectively at each symbol time. The channel matrix is $\mathbf{H} \in \mathcal{C}^{2\times 2}$.

The capacity of the MIMO communication for an uninformed transmitter is given by [13]

$$C_{\text{mimo}} = B \cdot \log_2 \det\left(\mathbf{I} + \frac{P}{2LN_0B} \cdot \mathbf{H}\mathbf{H}^H\right) \tag{2}$$

with P the total transmit power (including the antenna gains), which is divided equally between the two transmit antennas, L the common attenuation term, and the two-sided noise power spectral density $N_0 = kT$, with k the Boltzmann constant ($k = 1.38 \cdot 10^{-23} W/K$) and T the noise temperature. Separation between uplink and downlink uses Frequency Division

Duplexing, with an overall bandwidth $2B$ half divided between both links.

For the case at hand, assuming the same attenuation for all four links as a result of the free-space propagation losses[1], the channel matrix is composed of phase terms of the form

$$[\mathbf{H}]_{ij} = \exp\left(-j\frac{2\pi d_{ij}}{\lambda_c}\right) \quad (3)$$

with $\lambda_c = c/f_c$, f_c the carrier frequency and d_{ij} the distance from jth transmitter, $j = 1, 2$ to ith receiver, $i = 1, 2$. Note that the carrier frequency in $\mathbf{H}$ is different for both uplink and downlink. From geometrical considerations in Figure 1b, we have for the downlink [3]

$$\mathbf{H} = [\ \exp(-j2\pi d_1/\lambda_c)\mathbf{h}_1 \quad \exp(-j2\pi d_2/\lambda_c)\mathbf{h}_2\ ] \quad (4)$$

with d_1, d_2 the distance from each satellite to one of the terrestrial antennas, and $\mathbf{h}_k = [\ 1 \quad \exp(-j2\pi\Delta_{\text{gnd}}\cos(\phi_k)/\lambda_c)\ ]^t$, k =1,2. With this, the channel capacity in (2) is now written as

$$C_{\text{mimo}} = B{\cdot}\log_2\left(1 + \frac{P}{2LN_0B}\lambda_1^2\right) + B{\cdot}\log_2\left(1 + \frac{P}{2LN_0B}\lambda_2^2\right), \quad (5)$$

and

$$\lambda_1^2 = 2(1 + |\cos\theta|), \quad (6)$$
$$\lambda_2^2 = 2(1 - |\cos\theta|) \quad (7)$$

where

$$|\cos\theta| = \frac{1}{2}\left|1 + \exp(-j2\pi\Delta_{\text{gnd}}(\cos\phi_1 - \cos\phi_2)/\lambda_c)\right|. \quad (8)$$

If we define $\rho \doteq P/LN_0B$ in (2) and (5), then we have that the link capacity is a periodic function of $\cos\phi_1 - \cos\phi_2$, taking values between $2B \cdot \log_2(1+\rho)$ and $B \cdot \log_2(1+2\rho)$, as depicted in Figure 2, which shows the capacity variation as a function of the separation between antennas. Due to the high frequency (18 GHz), transmission capacity is very sensitive to the antennas separation.

On the other side, in an attempt to increase the spectral efficiency of the system, the reuse of the same frequency band for both up and downlinks can be considered, at least to compare its potential performance to that of the MIMO system. As sketched in Figure 1a, the limiting factor is the interference caused by the transmit signal on the receive front-end. This self-interference can render the system useless unless is dealt with, and minimized to the point that the frequency reuse gain compensates for the residual interference. Such interference is absent in the MIMO configuration, even with co-located antennas, thanks to the use of fixed analog filters which avoid the leakage of the strong radiated signal back into the receiver. Strictly speaking, the transmit satellite could also interfere the receive one, although we will assume that the radiating antenna pattern and orbital separation are such that this interference can be neglected.

There are different approaches to reduce the self-interference [14] which shall not be discussed here. We would rather focus on some fundamental performance limits for a given cancellation amount, enhanced by the additional reduction achieved by the isolation between transmitter and receiver, thanks to the high directivity of the antennas and the propagation losses.

[1]We consider that the different propagation time between the signals is properly addressed at the receive side [2].

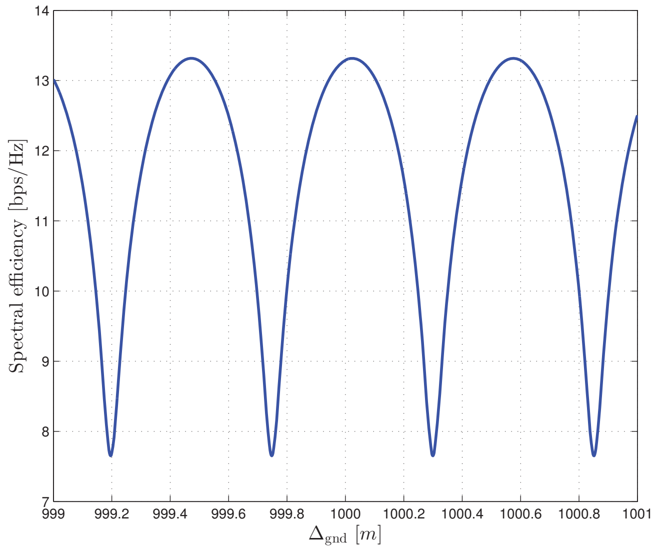


Fig. 2: Spectral efficiency of a 2x2 MIMO ideal link as a function of the distance between the terrestrial antennas. The reference signal to noise ratio is $\rho = 20$ dB. Frequency $f_c = 18$ GHz.

We compute next the capacity of the downlink, since it is the one suffering most from the SI. We need to keep in mind that the overall bandwidth $2B$ is available for this case (twice that for MIMO if the links dimensioning is symmetric). Statistical characterization of self-interference is an active area of research in terrestrial wireless systems [15]. We will assume a Gaussian distribution for the residual SI; the spherical diffraction model in ITU-R SM.2028-1-Annex 2 will be used to account for the median path losses L_{g} between the transmit and the receive antenna, separated by Δ_{gnd} meters. With this, the downlink channel making use of the $2B$ bandwidth has a capacity given by

$$C_{\text{fd}} = 2B \cdot \log_2(1 + \rho') \quad (9)$$

with

$$\rho' \doteq \frac{P_{\text{s}}G_{\text{s}}G_{\text{g}}/L}{2N_0B + \alpha_{\text{si}}P_{\text{g}}/L_{\text{g}}} \quad (10)$$

where P_s denotes the satellite transmit power, and G_s, G_g the satellite and terrestrial antenna gains, respectively. As a conservative approach, we have assumed that the antenna gains in the direction of the SI contamination are 0 dB, which makes notation also simpler. In fact, recommendations ITU-R S.580-6 and ITU-R S.465-6 specify the mask that the radiation diagrams must comply with, and which would lead to negative gains (in dB) in most latitudes. The SI is also attenuated by the propagation losses L_{g}.

The parameter $0 < \alpha_{\text{si}} < 1$ in (10) represents the active cancellation degree of the FD system [7], which can take place in the radio frequency analog domain, in the digital baseband

TABLE I: Simulation parameters

Space to Earth propagation losses	$L = 209$ dB
Reference frequency	f_c =18 GHz
Terrestrial antenna gain	$G_g = 40$ dB
Satellite G/T	$(G/T)_s = 4$ dB
Terrestrial G/T	$(G/T)_g = 15$ dB
Bandwidth	$B = 10$ MHz
Separation between terrestrial antennas	$\Delta_{\text{gnd}} = 1$ Km
Terrestrial location	University of Vigo Campus
Satellites orbital separation	$\Delta\theta_S = 2^0$

or in both. Note that an ideal SI free scenario (α_{si}=0) in (10) would yield the following maximum FD capacity:

$$\max(C_{\text{fd}}) = 2B \cdot \log_2(1 + \rho/2) . \tag{11}$$

The bidirectional capacity is the sum of both uplink and downlink capacities. Since uplink and downlink frequencies are different, the corresponding dependence with antennas separation, as illustrated in Figure 2, will differ. For simplicity, we will consider that the range of values that the MIMO sum capacity can take is

$$\begin{aligned} C_{\text{mimo}} &\geq B \cdot \log_2(1 + 2\rho_{\text{dl}}) + B \cdot \log_2(1 + 2\rho_{\text{ul}}) \quad (12)\\ C_{\text{mimo}} &\leq 2B \cdot \log_2(1 + \rho_{\text{dl}}) + 2B \cdot \log_2(1 + \rho_{\text{ul}}) \quad (13) \end{aligned}$$

with

$$\begin{aligned} \rho_{\text{dl}} &\doteq \text{EIRP}_s \cdot (G/T)_g / kLB, \quad (14)\\ \rho_{\text{ul}} &\doteq \text{EIRP}_g \cdot (G/T)_s / kLB, \quad (15) \end{aligned}$$

although a narrower margin will apply in general, given the misalignement between the locations of maxima and minima in Figure 2 for both uplink and downlink. We have used the common transmit and receive metrics EIRP (Equivalent Isotropically Radiated Power) and G/T (antenna gain over receive noise temperature). Both links are coupled in the FD case, since the uplink power leaks back to the receive antenna. The corresponding sum rate can be written as

$$C_{\text{fd}} = 2B \cdot \log_2(1 + \rho'_{\text{ul}}) + 2B \cdot \log_2(1 + \rho'_{\text{dl}}) \tag{16}$$

with

$$\begin{aligned} \rho'_{\text{dl}} &\doteq \text{EIRP}_s \cdot (G/T)_g / \\ &\quad \left(2kBL + \alpha_{\text{si}} \cdot \text{EIRP}_g \cdot (G/T)_g \cdot L/G_g^2 \cdot L_{\text{g}}\right), \quad (17)\\ \rho'_{\text{ul}} &\doteq \text{EIRP}_g \cdot (G/T)_s / 2kBL. \end{aligned}$$

If we assume balanced links, with $\rho \doteq \rho_{\text{dl}} = \rho_{\text{ul}}$, then the respective FD and MIMO aggregated spectral efficiencies can be simplified as follows:

$$\begin{aligned} &\log_2(1 + 2 \cdot \rho) \leq \frac{C_{\text{mimo}}}{2B} \leq 2\log_2(1 + \rho), \\ &\frac{C_{\text{fd}}}{2B} = \log_2(1 + \rho/2) + \quad (18)\\ &\log_2\left(1 + \rho/\left(2 + \alpha_{\text{si}} \frac{(G/T)_g \cdot L}{(G/T)_s \cdot G_g^2 \cdot L_{\text{g}}} \rho\right)\right). \end{aligned}$$

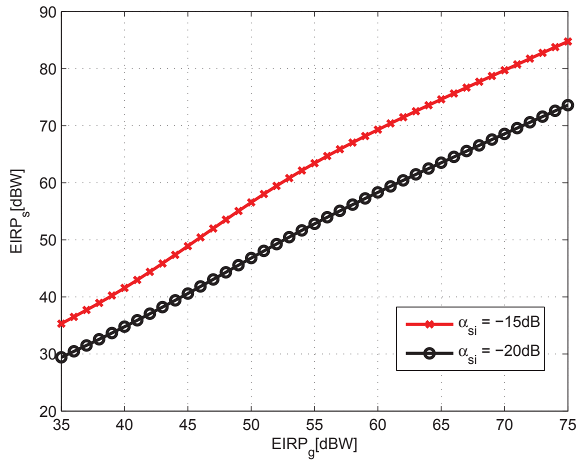


Fig. 3: Rate gain region of FD with respect to HD.

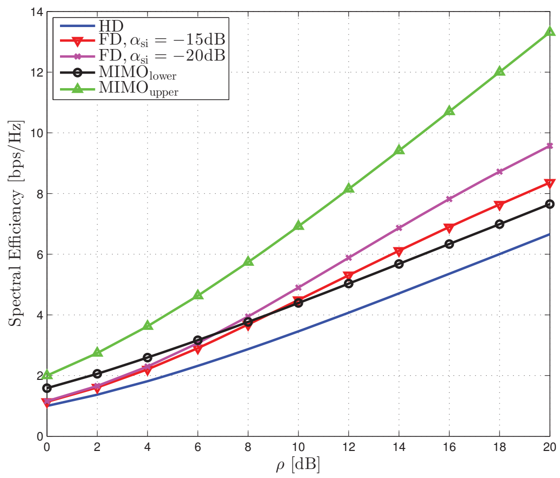


Fig. 4: Aggregated spectral efficiency of an FD link compared with the upper and lower bounds of the MIMO capacity, according to expressions in (18) and Table I. Half Duplex capacity is also shown for reference. $\text{MIMO}_{\text{upper}}$ and $\text{MIMO}_{\text{lower}}$ stand for the upper and lower limits in (18), respectively.

III. Numerical Evaluation

First we obtain the operating regime for which FD offers a higher capacity than conventional Half Duplex (HD) for the same bandwidth and transmit powers, as it is customary in terrestrial settings [12]. We consider the deterministic case (no fading) and the parameters in Table I to obtain the rate gain region, that is, the range of transmit powers for which the sum rate of up- and down-links is higher for FD. Figure 3 shows the corresponding boundaries for different SI suppression levels. For those EIRP_s values above the curves, the aggregated capacity of both uplink and downlink is higher in the FD case. Note that we are not considering any additional imperfections on the RF frontends, such as incoming signal power dependent noise [12], which might modify the results. Under the considered assumptions, a higher SI suppression capability enlarges the range of received powers for which FD outperforms HD. We need to keep in mind that the terrestrial propagation losses are $L_{\rm g} = 132.5$ dB for all the simulations in this section, which limits the requirements on the active cancellation scheme.

Next we compare the overall spectral efficiency of FD and a coordinated MIMO link. Propagation losses are assumed to be the same for all involved frequencies, although some minor differences do exist in practice. Since the total transmit power is equal in both cases, we have that each satellite in the MIMO setting transmits half of the power; in this regard, the total power spectral density will be double in the MIMO case since the power is allocated in half the bandwidth. Results are shown in Figure 4 for a symmetric link, with the same signal to noise ratio ρ (in absence of SI) in both directions. As expected, the maximum efficiency is achieved by the MIMO communication if the antennas separation is such that both columns of the channel matrix $\mathbf{H}$ are orthogonal. From Figure 4 we can also expect an FD performance which improves with the antennas separation (or equivalently, with higher SI cancellation), whereas the MIMO transmission rate will highly depend on the relative phases, as anticipated in Figure 2. Note that we are also assuming that maximum and minimum MIMO capacity can be achieved for the same configuration in both uplink and downlinks, which is not the case in practice due to the different frequencies.

We have also explored the statistical variation of the MIMO and FD capacity due to the rain attenuation, a major important impairment in satellite communications in Ku-band and above. We follow the methodology in [16] and [17] to obtain the rain statistics and the differential rain attenuation between two ground sites. We assume that the statistics of rain attenuation do not depend on the specific satellite, since the intersatellite distance will be much shorter than the satellite-to-Earth distance. The channel matrix $\mathbf{H}$ in (1) must be right(left)-multiplied by the diagonal matrix

$$\mathbf{D} = \begin{pmatrix} a_1 & 0 \\ 0 & a_2 \end{pmatrix} \tag{19}$$

to account for the rain losses a_1 and a_2 suffered by the first and the second ground stations, respectively, on the up(down)-link. We will not include the rain losses undergone by the interference on the terrestrial path. Their marginal effect, when noticeable, will benefit FD against MIMO due to the reduction of the SI power, so the exposed approach is conservative. For practical purposes the ϵ-outage capacity C^{ϵ} is commonly accepted, as the capacity which exceeds the instantaneous capacity with a probability $1-\epsilon$,

$$\Pr\left[C < C^{\epsilon}\right] = \epsilon. \tag{20}$$

In Figures 5 and 6 we depict the 1% and 0.1% outage capacities of the downlink for comparison, without enforcing power control, and again for moderate active cancellation values. Since a_1 and a_2 in (19) can be different, MIMO capacity is no longer given by (5). The more involved required expressions can be found in [18]. The spectral efficiency is now obtained as C/B for all cases, even though the bandwidth for the FD case is $2B$. Monte Carlo method was used (1e7 realizations) to generate the rain attenuation series given the difficulty of providing analytical closed expressions for the associated channel capacities. Simulation parameters are taken from Table I; as operating point, we have chosen $\rho_{\rm ul} = 10$ dB (without rain), which requires $\text{EIRP}_g = 56$ dBW, and EIRP_s ranging between 35 dBW and 55 dBW. In the FD case, the receiver suffers an amount of interference (before cancellation) equal to -116.5 dBW. Again, the behavior is such that the proper dimensioning of the system can place the FD performance in between the maximum and minimum capacity of the MIMO link, although rain can have a higher impact on FD due to its operation as a single antenna system. In any case, the additional attenuation on the SI path due to the rain has not been considered; its effect will be beneficial for the FD performance due to the additional cancellation.

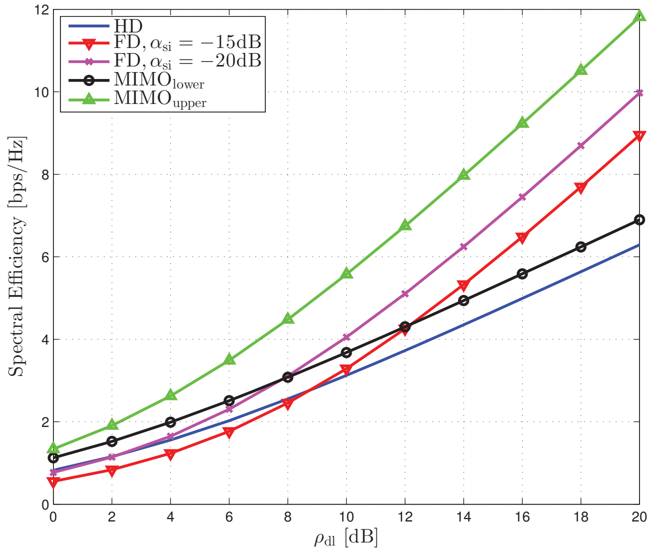


Fig. 5: 1% outage capacity of the downlink for FD, MIMO and HD.

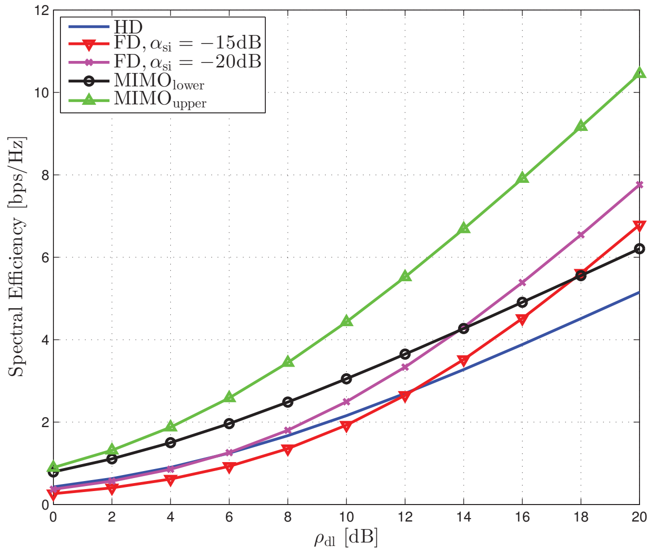


Fig. 6: 0.1% outage capacity of the downlink for FD, MIMO and HD.

IV. Conclusion

This paper has made some preliminary considerations on the reuse of the same frequency for both directions of the communication between space and ground. A dual satellite configuration has been chosen to avoid complex requirements on the satellite communications payload in terms of self-interference cancellation. Two fixed terrestrial antennas acting as transmitter and receiver respectively form the other end of the communication; the In-Band Full Duplex operation gives rise to an undesired coupling which is partly attenuated by passive means (physical separation and antennas radiation pattern). The performance of FD lies in between the maximum and minimum capacity of the 2x2 MIMO system. In both cases performance is highly dependent on a proper calibration effort, in particular self-interference cancellation for FD communication and the synchronization and precise location of the antennas in the MIMO setting. And although simulations were done for GEO satellites and Ku-band frequencies, lower orbit satellites operating with lower transmit powers and lower frequencies are definitely another scenario to address. Finally, polarization is an additional degree of freedom which has not been exploited, and from which FD operation can benefit for the decoupling of transmit and receive signals.

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References

[1] J. Arnau, B. Devillers, C. Mosquera, and A. Pérez-Neira, "Performance study of multiuser interference mitigation schemes for hybrid broadband multibeam satellite architectures," *EURASIP J. Wirel. Commun. Netw.*, vol. 2012, no. 1, p. 132, Apr. 2012.

[2] P. Arapoglou, K. Liolis, M. Bertinelli, A. Panagopoulos, P. Cottis, and R. De Gaudenzi, "MIMO over Satellite: A Review," *Communications Surveys Tutorials, IEEE*, vol. 13, no. 1, pp. 27–51, First Quarter 2011.

[3] D. Tse and P. Viswanath, *Fundamentals of wireless communication*. New York, NY, USA: Cambridge University Press, 2005.

[4] D. Bharadia, E. McMilin, and S. Katti, "Full duplex radios," *Proceedings of the ACM SIGCOMM '13*, p. 375, 2013. [Online]. Available: http://dl.acm.org/citation.cfm?doid=2486001.2486033

[5] A. Khandani, "Two-way (true full-duplex) wireless," in *Information Theory (CWIT), 2013 13th Canadian Workshop on*, June 2013, pp. 33–38.

[6] R. Lopez-Valcarce, E. Antonio-Rodriguez, C. Mosquera, and F. Perez-Gonzalez, "An adaptive feedback canceller for full-duplex relays based on spectrum shaping," *Selected Areas in Communications, IEEE Journal on*, vol. 30, no. 8, pp. 1566–1577, September 2012.

[7] M. Duarte, C. Dick, and A. Sabharwal, "Experiment-driven characterization of full-duplex wireless systems," *Wireless Communications, IEEE Transactions on*, vol. 11, no. 12, pp. 4296–4307, December 2012.

[8] S. Maleki, S. Chatzinotas, B. Evans, K. Liolis, J. Grotz, A. Vanelli-Coralli, and N. Chuberre, "Cognitive spectrum utilization in Ka band multibeam satellite communications," *Communications Magazine, IEEE*, vol. 53, no. 3, pp. 24–29, March 2015.

[9] M. Dankberg, M. Miller, and M. Mulligan, "Self-interference cancellation for relayed communication networks," Jan. 4 2000, US Patent 6,011,952. [Online]. Available: http://www.google.es/patents/US6011952

[10] B. Nazer and M. Gastpar, "Reliable physical layer network coding," *Proceedings of the IEEE*, vol. 99, no. 3, pp. 438–460, March 2011.

[11] K. Liolis, A. Panagopoulos, and P.-D. Arapoglou, "An analytical unifying approach for outage capacity achieved in SIMO and MISO broadband satellite channel configurations," in *Antennas and Propagation, 2009. EuCAP 2009. 3rd European Conference on*, March 2009, pp. 2911–2915.

[12] E. Ahmed, A. Eltawil, and A. Sabharwal, "Rate gain region and design tradeoffs for full-duplex wireless communications," *Wireless Communications, IEEE Transactions on*, vol. 12, no. 7, pp. 3556–3565, July 2013.

[13] E. G. Larsson and P. Stoica, *Space-Time Block Coding for Wireless Communications*. Cambridge University Press, 2003.

[14] A. Sabharwal, P. Schniter, D. Guo, D. W. Bliss, S. Rangarajan, and R. Wichman, "In-band full-duplex wireless: Challenges and opportunities," *CoRR*, vol. abs/1311.0456, 2013. [Online]. Available: http://arxiv.org/abs/1311.0456

[15] B. Jiao, M. Wen, M. Ma, and H. Poor, "Spatial modulated full duplex," *Wireless Communications Letters, IEEE*, vol. 3, no. 6, pp. 641–644, Dec 2014.

[16] ITU-R, *Differential rain attenuation*, ITU-R P.1815 Std., Rev. 1, Oct 2009.

[17] ——, *Propagation data and prediction methods required for the design of Earth-space telecommunication systems*, ITU-R P.618 Std., Rev. 11, Sept 2013.

[18] A. Knopp, R. Schwarz, D. Ogermann, C. Hofmann, and B. Lankl, "Satellite System Design Examples for Maximum MIMO Spectral Efficiency in LOS Channels," in *Global Telecommunications Conference, 2008. IEEE GLOBECOM 2008. IEEE*, Nov 2008, pp. 1–6.