MULTI-SATELLITE DIVERSITY THROUGH THE USE OF OTFS

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Abstract

We consider the use of multiple low-Earth orbit (LEO) satellites to improve the spectral efficiency of beyond-5G (B5G) non-terrestrial networks. In these networks, the use of LEO constellations is foreseen to ensure a global coverage and, typically, multiple satellites are in visibility with the user terminal. In a scenario like this, we consider the adoption of the orthogonal time frequency space (OTFS) modulation. In this modulation format, conceived for doubly-selective terrestrial channels, the information symbols are placed in the Doppler-delay (DD) domain, wherein the time-varying channels are quasi-static and sparse. Through proper pilot schemes and channel estimation algorithms, the Doppler-delay pairs and the channel gains of the different scatterers of a terrestrial channel can be estimated and coherent detection can be then performed. The same channel estimation and detection algorithms also enable the exploitation of diversity, in case of multiple satellites transmitting the same OTFS signal. The different satellites will be, in fact, characterized by different Doppler-delay pairs and channel gains, making the scenario similar to the case of a wireless channels with different scatterers. A cell-free architecture can be thus conceived with a significant improvement with respect to a scenario where each user is served by a single satellite.

1. Introduction

In LEO satellite communications, the throughput of the link significantly depends on the satellite elevation angle, the higher the elevation, the higher the throughput. In addition, a line-of-sight (LoS) link between the satellite and the terrestrial user terminal (UT) is not always granted: due to the fast movement of the satellite, the LoS link can be indeed unexpectedly shadowed/obstructed by physical objects nearby the UT, such as buildings and trees. As it is well-known, these phenomena cause a serious impairment to the link reliability, and proper measures must be taken to circumvent them. Satellite macro diversity [1], i.e., the joint use of several satellites to serve the same UT, is an effective way to reduce the link outage probability for LEO satellite links and to ensure a more uniform throughput: under the assumption that the satellites serving the same UT have independent trajectories and are located in different portions of the sky, the individual UT-satellite links may be reasonably assumed to be subject to shadowing in a mutually independent way, thus implying that the overall outage probability decreases exponentially with the number of employed satellites and that the coverage is more uniform. Needless to say, practical implementation of satellite diversity poses a number of technical challenges, due to the need to combine at the UT two or more paths possibly arriving at different epochs, and with different Doppler frequencies and phases.

In terrestrial networks, the short distance between the UT and the serving access points (APs), makes these technical challenges less complicated. Specifically, for terrestrial beyond-5G wireless networks, researchers are actively investigating the so-called *cell-free massive MIMO* deployment [2,3]: several APs serve simultaneously a smaller number of UTs in the same time-frequency slot. The APs are connected to a central-processing-unit (CPU); uplink decoding happens at the CPU, while tasks such as uplink channel estimation and beamforming computation may happen locally at each AP using locally available information. In other words, in terrestrial networks, this technology combines the physical layer operation of massive MIMO, the joint coherent signal processing at multiple APs of network MIMO, and the network ultra-densification. For these reasons, cell-free massive MIMO systems retain the advantages of massive MIMO, while at the same time being capable of providing macro-diversity gains, similarly to LEO satellite diversity. The time-division-duplex is exploited and uplink/downlink channel reciprocity within each channel coherence time is exploited to avoid downlink channel estimation.

In wireless networks based on satellites, unfortunately, uplink channel estimation cannot be done, and also phase compensation (which is usually done in terrestrial cell-free massive MIMO systems) is unfeasible. The only thing that can be realized is timing compensation for a certain chosen location on the ground. The UTs will thus receive one or more signals with different Doppler shifts, different phases, and, only for certain positions, the same delay. Mimicking a cell-free massive MIMO system for a satellite-based network is thus not possible, and proper approaches are to be followed in order to be able to achieve the gains theoretically granted by the use of diversity. One possible mean to cope with the above challenges is to choose a proper modulation scheme. Indeed, due to the presence of Doppler shifts, orthogonal frequency division multiplexing (OFDM) does not appear the ideal choice, and suitable alternatives are to be considered. The orthogonal time frequency space (OTFS) modulation has been recently proposed [4] as a new modulation scheme specifically designed to work in the presence of linear time varying propagation channels. Several papers have already assessed the merits of OTFS. As an example, [5] has provided a comparison between OFDM and OTFS in the presence of sparse channels; the paper [6] addresses the problem of channel estimation for OTFS systems, whereas papers [7] and [8] address the problem of receiver design for OTFS, a task generally more complicated than it is for the OFDM modulation. Papers [9,10], instead, investigate the promising potentialities of OTFS when joint communication and sensing tasks are to be performed using the same transceiver. Despite the vast interest that OTFS has been attracting in the last few years, its exploitation in non-terrestrial networks has not yet been considered so far.

This paper is thus a first attempt to analyse the OTFS modulation for a non-terrestrial network, in conjunction with a diversity technique. Specifically, this paper is concerned with the design and assessment of a multi-satellite diversity scheme using the OTFS modulation. It will be shown that the proposed scheme permits improving the spectral efficiency values and the performance uniformity across users, regardless of their location, thanks to the use of the multi-satellite diversity. Moreover, the use of the OTFS modulation permits achieving robustness against large Doppler effects and channel time-variance that is typically encountered in satellite communication scenarios.

This paper is organized as follows. Section 2 contains the system model and depicts the investigated scenario. Section 3 is devoted to the description of the considered data detection structures, while in Section 4 we report and comment the obtained numerical results, reporting plots of the pragmatic capacity. Finally, concluding remarks are given in Section 5.

2. Investigated Scenario

In the considered scenario, two LEO satellites transmit the same signal to a single-antenna UT on ground (see Fig. 1). The generalization to the case of more satellites is straightforward.
The signals transmitted from the two satellites undergo different propagation delays $\{\tau_p\}_{p=1}^{2}$ and different Doppler shifts $\{\nu_p\}_{p=1}^{2}$ due to the different distances of the satellites from the UT and the different relative speeds. We will assume that the transmission system is designed such that the propagation delays and the Doppler shifts can be considered as constant for the duration of a transmitted frame. The complex envelope of the received signal $r(t)$ at the UT can thus be expressed as:

$$r(t) = \sum_{p=1}^{2} h_p s(t - \tau_p) e^{j2\pi\nu_p t} + w(t) \qquad (1)$$

where $\{h_p\}_{p=1}^{2}$ are the complex channel gains modelling the different path attenuations, $s(t)$ is the complex envelope of the common signal transmitted by the two satellites and $w(t)$ models the complex additive white Gaussian noise (AWGN) whose real and imaginary components have power spectral density N_0. We investigate the use of the OTFS modulation (see [4,5] and references therein) for its effectiveness in the case of linear and time varying channels like the one we have in this scenario.

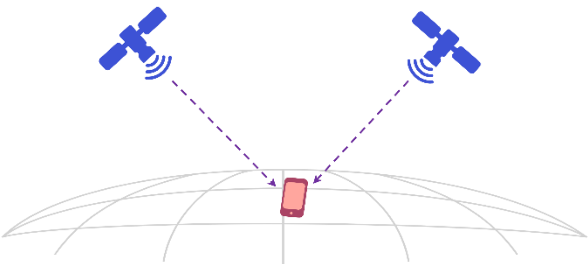

Fig. 1. Investigated scenario.

OTFS modulation is based on the idea to transmit the symbols in the Doppler-delay domain. Data symbols $x[k,l]$, for $k = 0, \dots, N-1$ and $l = 0, \dots, M-1$, belonging to a finite alphabet $\mathbf{C}$ (e.g., some quadrature amplitude modulation (QAM) or phase shift keying (PSK) constellation), are arranged into an $N \times M$ two-dimensional grid in the Doppler-delay domain. These symbols are assumed to be spaced by $1/NT$ in the Doppler domain and $1/M\Delta f$ in the delay domain. The values of T and Δf are usually selected in such a way $\max_p \tau_p < T$ and $\max_p \nu_p < \Delta f$. The symbols are then converted from the Doppler-delay domain to the time-frequency domain through the so-called *inverse* *symplectic finite Fourier transform* (ISFFT). It is nothing else than an inverse discrete Fourier transform with respect to the Doppler and a discrete Fourier transform with respect to the delay and converts the block of symbols $\{x[k,l]\}$ of dimension $N \times M$ into a block of symbols $\{X[n,m]\}$, of the same dimension, defined as

$$X[n,m] = \sum_{k=0}^{N-1}\sum_{l=0}^{M-1} x[k,l] e^{j2\pi\left(\frac{nk}{N}-\frac{ml}{M}\right)} \quad (2)$$

for $n = 0, \dots, N-1$ and $m = 0, \dots, M-1$. Then, the continuous time transmitted signal $s(t)$ is generated as

$$s(t) = \sum_{n=0}^{N-1}\sum_{m=0}^{M-1} X[n,m] p_{\mathrm{tx}}(t-nT) e^{j2\pi m\Delta f(t-nT)} \quad (3)$$

i.e., symbol $X[n,m]$ is transmitted at time n and over subcarrier m, and $p_{\mathrm{tx}}(t)$ is a generic transmit shaping pulse. This transform that generates the signal *s(t)* from symbols $\{X[n,m]\}$ is usually called *Heisemberg transform* in the OTFS literature.

By properly selecting the shaping pulse and the values of T and Δf, (3) can represent any of the multicarrier modulation formats available in the literature. As an example, when $\Delta f = 1/T$ and $p_{\mathrm{tx}}(t)$ is a rectangular pulse of duration T, (3) is a classical OFDM modulation with properly precoded information symbols. In this case, the cyclic prefix is not required. In fact, as we will see, despite in the name of OTFS there is still the term "orthogonal", under realistic channel conditions there is no chance to have orthogonality, even when a cyclic prefix is adopted. For this reason, a guard interval of some symbols in the time domain is usually inserted to avoid interblock interference only.

In our scenario, the received signal is given by (1). At the receiver side, without loss of generality, we will use a bank of filters matched to the pulses $\{p_{\mathrm{rx}}(t)e^{j2\pi m\Delta f t}\}_{m=0}^{M-1}$. The signals at the output of this bank of matched filters are sampled at the discrete times $t = nT$, $n = 0, \dots, N-1$, obtaining the samples $\{Y[n,m]\}$. In the OTFS literature, the filtering of the received signal with the bank of matched filters plus sampling is usually called *Wigner transform*. The *symplectic finite Fourier transform* (SFFT) is then used to come back to the samples in the Doppler-delay domain $\{y[k,l]\}$, for $k = 0, \dots, N-1$ and $l = 0, \dots, M-1$:

$$y[k,l] = \frac{1}{NM}\sum_{n=0}^{N-1}\sum_{m=0}^{M-1} Y[n,m] e^{j2\pi\left(-\frac{nk}{N}+\frac{ml}{M}\right)}. \quad (4)$$

The interpretation of the OTFS modulation as a classical OFDM modulation with properly precoded information symbols and post-processing at the receiver has a main advantage. In fact, in this case a classical OFDM transceiver can be reused. Since OFDM is widely used in wireless standards, the transition to OTFS is very easy.

In the following, we will assume that $p_{\mathrm{rx}}(t) = p_{\mathrm{tx}}(t)$, $\Delta f = 1/T$, and that $p_{\mathrm{tx}}(t)$ is a rectangular pulse of duration T. Under these assumptions, the noise samples affecting the useful signal in both samples $\{Y[n,m]\}$ and $\{y[k,l]\}$ are white (the SFFT does not color the noise). These noise samples will be omitted for the sake of notational simplicity. Under the further assumption of absence of interblock interference, received samples $\{y[k,l]\}$ can be expressed as [5,9]:

$$y[k,l] = \sum_{k',l'} x[k',l'] h[k,l,k',l'] \quad (5)$$

where the ISI coefficient of the Doppler-delay pair $[k',l']$ seen by sample $[k,l]$ is given by [5,9]

$$h[k,l,k',l'] = \sum_{p=1}^{2} h_p\, e^{j2\pi\nu_p\tau_p}\Psi_p[k,l,k',l'] \quad (6)$$

where the expression of $\Psi_p[k,l,k',l']$ can be found in [5, 9].

The input-output equation (5) highlights that we have a linear system with two-dimensional ISI. The magnitude of $\Psi_p[k,l,k',l']$ depends on $[k,l,k',l']$ through the differences $k-k'$ and $l-l'$. Defining the Dirichlet kernel function

$$D_n(x) = \frac{1-e^{j2\pi x}}{1-e^{j2\pi x/n}}$$

we can express [5,9]

$$|\Psi_p[k,l,k',l']| \simeq \frac{1}{NM}|D_N(k'-k+\nu_p NT)| \cdot |D_M(l'-l+\tau_p M\Delta f)|.$$

A plot of $|D_N(x)||D_M(x)|$ is shown in Fig. 2. We are now able to understand the effect of the channel on the transmitted symbols. Let us first assume that only one satellite is present. In this case, every symbol is shifted by the same quantity proportional to the Doppler-delay pair (ν_1, τ_1) associated to that satellite. When ν_1 and τ_1 are multiple of the grid spacings in the Doppler-delay domain ($1/NT$ in the Doppler domain and $1/M\Delta f$ in the delay domain), there is a simple shift. Otherwise, there is also a leakage of energy in the adjacent positions, as illustrated by Fig. 3.

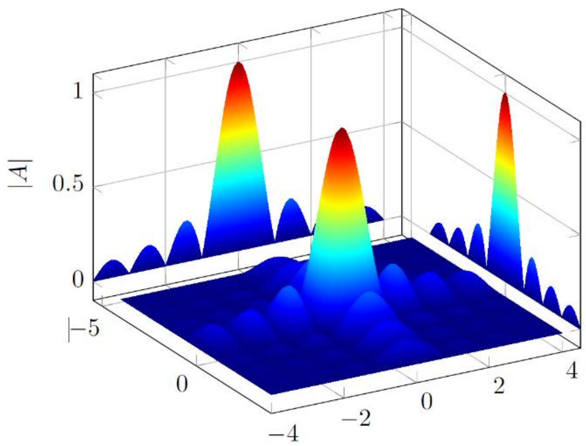

Fig. 2. Plot of $|D_N(x)||D_M(x)|$.

When 2 satellites are present, we have 2 different shifts. It is thus clear that we can have orthogonality only in the case of one satellite and when ν_1 and τ_1 are multiple of the grid spacings. In this case, a symbol-by-symbol detector can be employed. In a more realistic case orthogonality is hardly obtained and more sophisticated detectors, also taking interference into account, have to be employed.

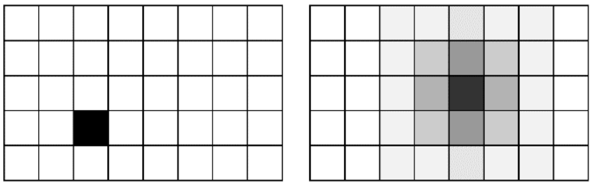

Fig. 3. Effect of the channel with a single satellite on the generic transmitted symbol. The original position of the symbol is shown on the left. The position of the same symbol after the channel is shown on the right. The shift has to be understood as a circular shift.

The input-output equation (5) can be organized in matrix form. Writing the $N \times M$ matrices of transmitted symbols and received samples as NM-dimensional column vectors (stacking the columns of the corresponding matrices on top of each other), we obtain the block-wise input-output relation in the form

$$\boldsymbol{y} = \boldsymbol{\Psi}\boldsymbol{x} + \boldsymbol{w}$$

where

$$\boldsymbol{\Psi} = \sum_{p=1}^{2} h_p \, e^{j2\pi\nu_p\tau_p} \boldsymbol{\Psi}_p$$

and matrices $\{\boldsymbol{\Psi}_p\}$ are $NM \times NM$ matrices obtained from $\Psi_p[k,l,k',l']$, while $\boldsymbol{w}$ denotes the AWGN with zero mean and covariance matrix $2N_0\mathbf{I}_{NM}$ ($\mathbf{I}_{NM}$ is the $NM \times NM$ identity matrix).

3. Detection Algorithms

In the following, we will discuss possible detectors under the assumption of perfect channel state information, i.e., perfect knowledge of the channel matrix $\boldsymbol{\Psi}$ at the receiver. The estimation of $\boldsymbol{\Psi}$, which is outside the scope of this paper, can be performed as described in [5]. A first soft-output detector that can be conceived is a linear minimum mean square error (LMMSE) detector. It is based on the following consideration. If we assume that $\boldsymbol{x}$ is a Gaussian vector, the optimal estimator of $\boldsymbol{x}$ according to the MMSE criterion results to be linear and has thus expression

$$\hat{\boldsymbol{x}} = \boldsymbol{\Psi}^{\mathrm{H}} \left[\boldsymbol{\Psi}\boldsymbol{\Psi}^{\mathrm{H}} + \frac{2N_0}{X^2} \mathbf{I}_{NM} \right]^{-1} \qquad (7)$$

where $X^2 = E\{x^2[k,l]\}$ is the mean square value of the constellation symbols. The LMMSE detector has a very good performance but an impractical complexity. In fact, its implementation requires the inversion of an $NM \times NM$ matrix, thus with a complexity proportional to $(NM)^3$. In a time-variant scenario, when the matrix $\boldsymbol{\Psi}$ changes at every block, for large values of the product NM this complexity cannot be afforded. A simplified LMMSE detector has been proposed in [8] which is, however, based on the simplified assumption that ν_p and τ_p are multiple of the grid spacings in the Doppler-delay domain. In a practical scenario, when this assumption is not fulfilled, a significant performance degradation is observed [9].

Other soft-output detection algorithms derived using the framework based on factor graphs (FG) and the sum-product algorithm (SPA) have been proposed in [7,9]. In particular, that in [9] exhibits an excellent trade-off between performance and complexity and will be considered in the following. The reader can refer to [9] for the details. This message passing (MP) algorithm is based on the equivalent sufficient statistics

$$\boldsymbol{z} = \boldsymbol{\Psi}^{\mathrm{H}}\boldsymbol{y} = \boldsymbol{G}\boldsymbol{x} + \boldsymbol{\Psi}^{\mathrm{H}}\boldsymbol{w}$$

having defined $\boldsymbol{G} = \boldsymbol{\Psi}^{\mathrm{H}}\boldsymbol{\Psi}$. For this reason, it will be denoted to as $\mathrm{MP_G}$.

As mentioned, we will assume perfect knowledge of the channel matrix $\boldsymbol{\Psi}$ at the receiver. Indeed, matrix $\boldsymbol{\Psi}$ can be estimated by using, for example, the pilot-based scheme proposed in [5]. This investigation will be the subject of a further study.

4. Simulation Results

In our simulation setup, we assume a carrier frequency $f_c = 5$ GHz, a system bandwidth $B = 2$ MHz, $M = 128$ and $N = 50$, thus the subcarrier spacing is $\Delta f = 15.652$ kHz and the symbol time is 66.6 μs. For the satellite scenario, we assume two different cases: *comparable channel gains* and *unbalanced channel gains* for the two paths and in the following we explain the difference.

Table I. Satellites orbital parameters for the simulated scenarios.

First scenario		
Orbital parameters	Satellite 1	Satellite 2
Semi-major axis [m]	7616400	7576300
Eccentricity	0.0011	0.0013
Inclination [°]	87.9888	87.8240
Right Ascension of Ascending Node [°]	114.1692	307.5095
Argument of Periapsis [°]	42.6046	42.7865
True Anomaly [°]	295.8847	42.1175
Period [s]	6615.1	6563
Second scenario		
Orbital parameters	Satellite 1	Satellite 2
Semi-major axis [m]	7594800	7592600
Eccentricity	0.0015	0.0015
Inclination [°]	87.9854	87.9857
Right Ascension of Ascending Node [°]	114.9085	115.0746
Argument of Periapsis [°]	75.4521	65.3493
True Anomaly [°]	343.6983	64.7552
Period [s]	6586.9	6584.1

The orbital parameters of the two simulated scenarios are reported in Table I. These orbits are derived from the OneWeb constellation [11] two-line element set (TLE), by choosing two proper couples of satellites once an arbitrary position of the UT is defined. In both cases the two orbits are almost the same except for the direction of travel: in the first case the two satellites travel the respective orbits in opposite directions, whereas in the second case the two satellites travel the respective orbits in the same direction, but with a slight delay with respect to the user position on the ground. Then, we selected a particular time instant in each scenario, in which both satellites were in visibility with given delay, Doppler effects and gain with respect to the UT. As a consequence of the two different directions of travel, we observed that in the first case the channel strengths of the two paths were similar, i.e., comparable channel gains, and in the second one they were considerably different, i.e., unbalanced channel gains. In the following figures, we assume QPSK modulation for the information symbols.

In the following, we report the performance in terms of pragmatic capacity, measured in bit/s/Hz versus the signal-to-noise ratio (SNR) of the first path. The pragmatic capacity is defined as the mutual information of the virtual channel having at its input the constellation symbols and at its output the detector soft outputs. It is representative of the achievable rate under the assumption of separate detection and decoding, i.e., without "turbo" reprocessing of the decoder output [9]. We assume that the two satellites perfectly compensate for delay at one point on the Earth, that we call *reference point.* At this location, the signal contributions from the two satellites arrive simultaneously.

In the following, we denote as *offset* the distance of the UT from the reference point. In Fig. 4 we show the performance of the OTFS in the case of comparable channel gains when the UT is on the reference point, i.e., with offset of 0 km, and compare the performance with the case where the UT is served only by one satellite. We can see that, especially with the MP_G detector, a significant performance improvement can be obtained serving the UT with two satellites, i.e., $P = 2$, with respect to the use of only one satellite. These results confirm that the multi-satellite diversity offers a considerable performance improvement using the OTFS modulation with the MP_G detector. This gain will be further observed when the paths between the UT and the satellites can be obstructed, as shown in the following. Conversely, in the case of the LMMSE detector (7), this gain is lower, and we observe a performance improvement only for low values of SNR. In Fig. 5, we assume to serve the user with two satellites and compare the performance for two values of offset. We can see that the proposed deployment is robust to the offset variations because the two paths are, in both cases of offset values, two different points on the $M \times N$ grid used in the OTFS modulation; thus, as expected, no performance variation is observed. Note that this holds in the hypothesis of $\tau_{max} < T$ as discussed in Section 2. In Fig. 6, we include the effect of shadowing, i.e., the paths between the satellites and the UT can be obstructed with 5% probability. We can observe that the use of multi-satellite diversity allows to obtain a more robust and reliable link with respect to the case in which only one satellite is employed to communicate with the UT, especially when we use the MP_G detector. Finally, in Figs. 7 and 8, we report the performance of the MP_G detector in the scenario with unbalanced channel gains with and without shadowing. We again see that the multi-satellite diversity strongly improves the system performance, especially in the case in which the communication system exploits the second (weaker) satellite. Indeed, from Fig. 8, going from the communication via the weaker satellite to the multi-satellite diversity, the pragmatic capacity at an SNR value of 5 dB goes from 1.2 to 1.76, i.e., we obtain a 46% performance improvement.

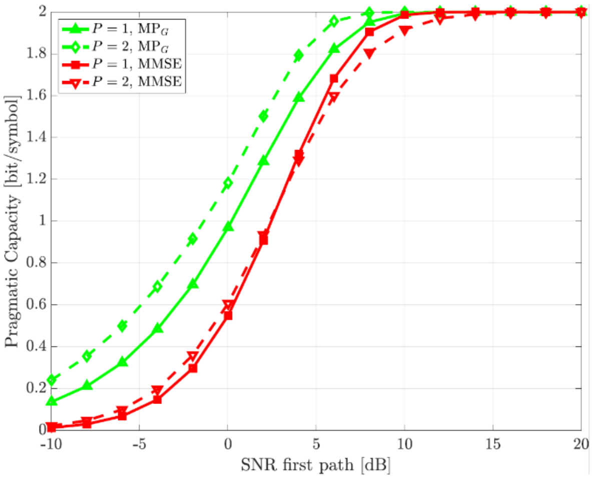

Fig. 4. Comparable channel gains, offset=0 km.

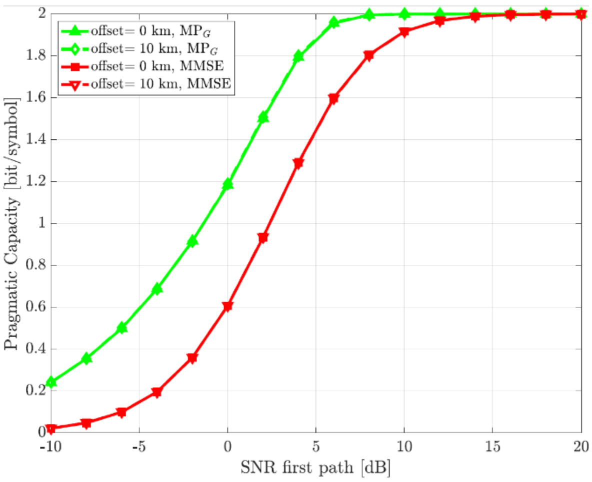

Fig. 5. Comparable channel gains, comparison with different offsets, $P = 2$.

5. Conclusions

We investigated the use of the OTFS modulation in a scenario with multiple LEO satellites to improve the spectral efficiency of non-terrestrial networks. This modulation format, proposed for doubly-selective terrestrial channels, can allow to exploit diversity in case of multiple satellites transmitting the same OTFS signal. The different satellites are, in fact, characterized by different Doppler-delay pairs and channel gains, making the scenario similar to the case of a wireless channels with different scatterers, thus allowing a significant performance improvement with respect to a scenario where each user is served by a single satellite, provided that a proper detector is employed at the receiver.

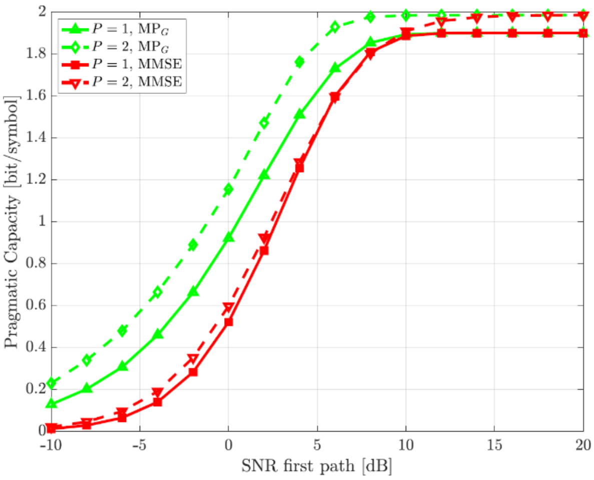

Fig. 6. Comparable channel gains, offset=0 km, 5% shadowing probability.

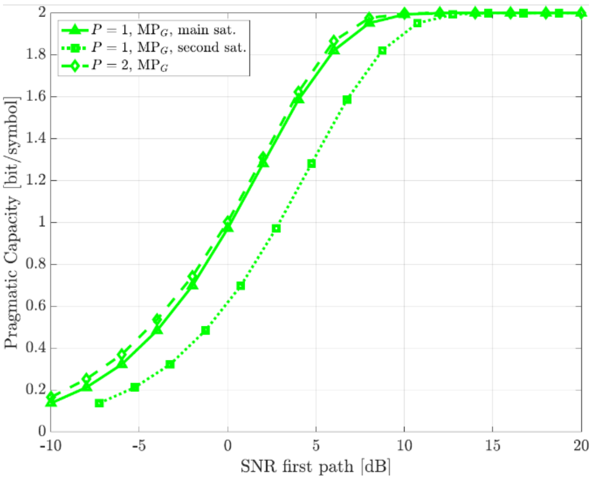

Fig. 7. Unbalanced channel gains, offset=0 km.

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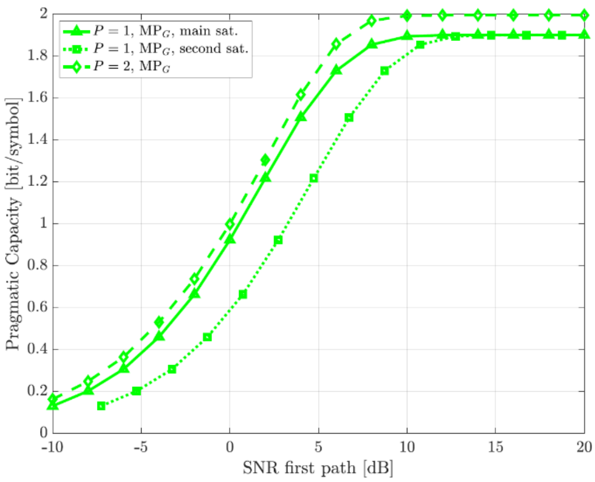

Fig. 8. Unbalanced channel gains, offset=0 km, 5% shadowing probability.

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