LEO Satellite Diversity in 6G Non-Terrestrial Networks: OFDM vs. OTFS

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***Abstract*— Non-terrestrial networks will play a crucial role in future wireless 6G systems to ensure ubiquitous connectivity and to complement terrestrial networks. With reference to a low Earth orbit (LEO) constellation, this letter performs a comparison in terms of pragmatic capacity between the orthogonal frequency division multiplexing (OFDM) and the orthogonal time frequency space (OTFS) modulation in a scenario where multi-satellite diversity is employed to ensure a more uniform throughput and to increase the system reliability against unforeseen blockages. The considered scenario is akin to a cell-free system, wherein each user may be jointly served by multiple satellites for better and more stable performance. Numerical results reveal that multi-satellite diversity is effective in increasing the link performance and that OTFS provides a better performance and is thus more robust to the impairments caused by the heavy Doppler shifts.**

***Index Terms*— Orthogonal time frequency space (OTFS), delay-Doppler, satellite communication, diversity, orthogonal frequency division multiplexing (OFDM).**

I. INTRODUCTION

FUTURE 6G wireless networks will natively integrate non-terrestrial devices, including UAVs, high-altitude platforms, and space-borne satellites. Among these, low Earth orbit (LEO) satellite mega-constellations have attracted a huge interest, both in academia and industry. Several private companies are indeed pioneering this new technology, while academic researchers are also attracted by the several technical challenges that these systems pose [1].

Given the large number of satellites forming a mega-constellation, it is naturally expected that macro-diversity schemes will be widely used in order to increase the system reliability. Indeed, 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 [2], 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 shifts and phases.

It should be noted that there is an analogy between a satellite mega-constellation, made of a huge number of rather simple satellites connected to terrestrial gateways, and a terrestrial cell-free massive MIMO deployment, made in turn of several simple access points (APs) connected to central processing units (CPUs) [3], [4]. Of course, in a terrestrial cell-free massive MIMO system the short distance between the UT and the serving APs makes the system realization less complicated. Specifically, time-division-duplex is adopted and uplink/downlink channel reciprocity within each channel coherence time is exploited to avoid downlink channel estimation. In non-terrestrial networks based on satellites, instead, uplink channel estimation is hardly feasible, and also phase compensation (which is usually done in terrestrial cell-free massive MIMO systems) is difficult to achieve. Timing and Doppler shift compensation for a certain chosen location on the ground can be instead quite easily realized. The UTs will thus receive one or more signals with different phases, and, only for certain positions, the same delay/Doppler shift. 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

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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 [5] 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, [6] has provided a comparison between OFDM and OTFS in the presence of sparse channels, while the letter [7] addresses the problem of channel estimation for OTFS systems.

Papers [8], [9], 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 for the last few years, its exploitation in non-terrestrial networks has been so far neglected. This letter and its conference version [10] start investigating the use of the OTFS modulation for a non-terrestrial network, in conjunction with a diversity technique. Specifically, this work deals with the design and assessment of a multi-satellite diversity scheme using the OTFS modulation, also in comparison with the traditional OFDM modulation. Results highlight the benefits provided by satellite diversity, as well as that the use of the OTFS modulation permits achieving increased robustness (w.r.t. OFDM) against the large Doppler effects and the channel time-variance that is typically encountered in satellite communication scenarios. This letter is organized as follows. Section II contains the system model and depicts the investigated scenario. Section III is devoted to the description of the considered detectors and channel estimators, while in Section IV we report and comment the obtained numerical results. Finally, concluding remarks are given in Section V.

II. System Model

We consider a scenario where P LEO satellites transmit the same signal to a single-antenna UT on ground (see Fig. 1).[1] The signals transmitted from the P satellites undergo different propagation delays $\{\tau_p\}_{p=1}^P$ and different Doppler shifts $\{\nu_p\}_{p=1}^P$ 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

$$r(t) = \sum_{p=1}^{P} h_p s_p(t-\tau_p) e^{\jmath 2\pi\nu_p t} + w(t)\,, \tag{1}$$

where $\{h_p\}_{p=1}^P$ are the complex channel gains modeling the different path attenuations, $s_p(t)$ is the complex envelope of the signal transmitted by the p-th satellite and $w(t)$ models the complex additive white Gaussian noise (AWGN) whose real and imaginary components have power spectral density N_0. We have $s_p(t) = e^{j(2\pi\widetilde{\nu}_p + \widetilde{\theta}_p)} s(t-\widetilde{\tau}_p)$, with $\widetilde{\nu}_p$, $\widetilde{\theta}_p$ and $\widetilde{\tau}_p$

[1]Parameter P can be considered as the number of satellites in visibility with the UT, which can be much smaller than the number of satellites making up the constellation.

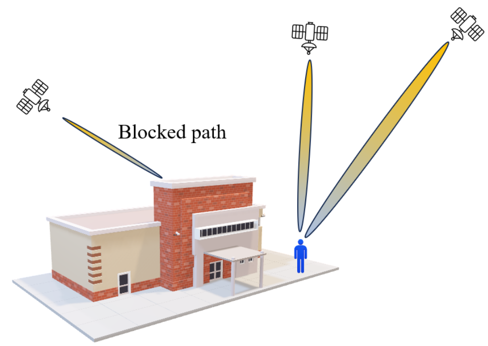

Fig. 1. A representation of the considered scenario. A user is simultaneously connected to several satellites in order to realize macro-diversity and achieve robustness again unexpected blockages.

the frequency offset, phase and delay compensation factors for the p-th satellite, and $s(t)$ is the ordinary information-bearing waveform transmitted by all the P satellites serving the considered UT.

For the OTFS modulation, the data-symbols $\{x[k,l]\}$ (drawn from a finite alphabet $\mathcal{C}$) for $k = 0, 1, \ldots, N-1$ and $l = 0, 1, \ldots M-1$ are arranged into an $N \times M$ 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 $\max_p\{\nu_p\} < \Delta f$. Symbols are then converted to the time-frequency domain through the so-called *inverse symplectic finite Fourier transform* (ISFFT), i.e.,

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

for $n = 0, \ldots, N-1$ and $m = 0, \ldots, M-1$. Based on the above notation, the continuous-time transmitted signal $s(t)$ is expressed as

$$s(t) = \sum_{n=0}^{N-1}\sum_{m=0}^{M-1} X[n,m] p_{\text{tx}}(t-nT) e^{\jmath 2\pi m\Delta f(t-nT)}\,, \tag{3}$$

i.e., symbol $X[n,m]$ is transmitted at time n and over subcarrier m, and $p_{\text{tx}}(t)$ is a generic transmit shaping pulse.

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 $p_{\text{tx}}(t)$ is a rectangular pulse of duration T, (3) is a classical OFDM modulation with properly precoded information symbols. To improve the spectral efficiency, instead of adopting a cyclic prefix, a guard interval of some symbols is inserted in the time domain to avoid interblock interference only. This is denoted in the literature as reduced-CP [11].

In our scenario, the received signal is given by (1). At the receiver side, without loss of generality, we will assume to use a bank of filters matched to the pulses $\{p_{\text{rx}}(t)e^{\jmath 2\pi m\Delta f t}\}_{m=0}^{M-1}$, where $p_{\text{rx}}(t)$ is a proper receive impulse response. The signals at the output of this bank of matched filters are sampled at the discrete times $t = nT$, $n = 0, \ldots, N-1$, obtaining the samples $\{Y[n,m]\}$.

The *symplectic finite Fourier transform* (SFFT) is then used to get back to the Doppler-delay domain $\{y[k,l]\}$, for

$k = 0, \ldots, N-1$ and $l = 0, \ldots, M-1$:

$$y[k,l] = \frac{1}{NM} \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} Y[n,m] e^{\jmath 2\pi\left(-\frac{nk}{N}+\frac{ml}{M}\right)} . \qquad (4)$$

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, and since OFDM is widely used in wireless standards, this makes the transition to OTFS very easy.

In the following, we will assume $p_{\text{rx}}(t) = p_{\text{tx}}(t)$, $\Delta f = 1/T$, and that $p_{\text{tx}}(t)$ 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 [6], [8]

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

where the intersymbol interference (ISI) coefficient of the Doppler-delay pair $[k',l']$ seen by sample $[k,l]$ is given by [6], [8]

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

where the expression of $\Psi_p[k,l,k',l']$ can be found in [6] and [8].

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 Dirichelet kernel function

$$D_n(x) = \frac{1-e^{\jmath 2\pi x}}{1-e^{\jmath 2\pi x/n}} ,$$

we can express

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

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 [6]

$$\boldsymbol{y} = \boldsymbol{\Psi} \boldsymbol{x} + \boldsymbol{w} , \qquad (7)$$

where

$$\boldsymbol{\Psi} = \sum_{p=1}^{P} h_p e^{\jmath 2\pi \nu_p \tau_p} \boldsymbol{\Psi}_p \qquad (8)$$

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).

III. Detection Algorithms and Channel Estimation

The employed soft-output detection algorithms was derived using the framework based on factor graphs (FG) and the sum-product algorithm (SPA), as proposed in [8] and [12]. In particular, the detector in [8] exhibits an excellent trade-off between performance and complexity and will be considered in the following. The reader can refer to [8] for the details. This message passing (MP) algorithm is based on the equivalent sufficient statistics

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

having defined $\boldsymbol{G} \triangleq \boldsymbol{\Psi}^H \boldsymbol{\Psi}$. For this reason, it will be denoted to as $\text{MP}_{\boldsymbol{G}}$.

The matrix $\boldsymbol{\Psi}$ can be estimated by using, for example, the pilot-based scheme proposed in [6], not detailed here due to lack of space. This scheme allows to estimate the triplets (h_p, ν_p, τ_p) for each satellite and is based on a specifically tailored pilot structure. Let us consider, in fact, a block in the Doppler-delay domain composed by all zero symbols but one non-zero with enough energy to be well distinguishable and positioned anywhere within the block. At the receiver, most of the energy will concentrate at P positions on the two-dimensional block corresponding to the pairs (ν_p, τ_p) (one per satellite), with some diffusion to the surrounding positions according to the Dirichlet kernel functions. Intuitively, the estimation of the pairs (τ_p, ν_p) is performed by searching the peaks of the magnitude of the received samples grid (as suggested in [7]). This intuitive estimation procedure is, however, only able to provide the integer parts of the Doppler and delay shifts, associated to the Doppler-delay grid point collecting the maximum energy. The fractional parts are linked to the dissipation of the energy around the peak points and must be treated separately [6].

In general a block of dimension $N \times M$ of transmitted symbols contains both information bearing symbols and pilot symbols. The arrangement of pilot symbols consists of a rectangular region placed in the block containing two types of symbols:

- *Zero Pilots*: Placed between information symbols and non-zero pilots to guarantee no significant interference between them.
- *Peak Pilot*: A pilot symbol with high energy, collecting the energy of the whole pilot field, is placed at the grid center. Its shifts in the Doppler-delay grid are used to provide the initial coarse estimation of the P Doppler-delay pairs (ν_p, τ_p), which results to be fast and simple.

Given this pilot arrangement, the number of pilot symbols has to be optimized to match the optimal performance-overhead tradeoff, while keeping constant the total block energy. An interesting alternative to the pilot scheme considered in this work is represented by superimposed pilots [13], not considered here for a lack of space.

In the simulation results we will consider, for comparison, the performance of a similar scenario making use of the OFDM modulation. In this case, a symbol-by-symbol linear minimum mean square error detector, the channel estimation

TABLE I
SATELLITE ORBITAL PARAMETERS

	Scenario A		Scenario B	
	Satellite 1	Satellite 2	Satellite 1	Satellite 2
Name	Oneweb-0039	Oneweb-0043	Oneweb-0047	Oneweb-0008
Altitude [m]	1227000	1227000	1235000	1201000
Semi-major axis [m]	7583500	7585100	7612000	7573300
Eccentricity	0.000723	0.0011	0.000725	0.00097418
Inclination [°]	87.9854	87.9857	87.9888	87.8240
Right Asc. of Asc. Node [°]	114.9085	115.0746	114.1692	307.9045
Argument of Periapsis [°]	152.1282	109.7577	76.3343	57.4874
True Anomaly [°]	267.0222	127.1442	262.1551	132.0545
Period [s]	6572.3	6547.4	6609.4	6559.0

scheme based on compressed sensing and proposed in [6], and the corresponding pilot scheme, will be used.

IV. Simulation Results

In the simulated scenario, for both OFDM and OTFS based systems, a carrier frequency of 5 GHz was assumed, with system bandwidth of 0.5 MHz, $M = 32$ and $N = 50$, so that the subcarrier spacing was $\Delta f = 15.625$ kHz and the symbol time was 64 μs.[2] Two different satellite link scenarios were used, both taken from the Oneweb constellation [14]. For the sake of simplicity, we considered $P = 2$ satellites in each scenario, but the analysis can be easily generalized to a higher number of satellites. The orbital parameters are reported in Table I and are derived from the two-line element set (TLE); we chose two scenarios where the two satellites travel in the same direction or in opposite directions on two very similar orbits. The UT on ground has instead a fixed position. In the following, we assume a QPSK modulation for the information symbols, and we accounted for a 10% pilot symbols for both OTFS and OFDM systems (in this latter case, it corresponds to the presence of both pilot symbols and cyclic prefix).

We report the performance in terms of pragmatic capacity η, measured in bit/s/Hz versus the signal-to-noise ratio (SNR) of the first path, that was computed by fixing the noise power spectral density and normalizing the signal power with respect to the shortest slant range attenuation, and then letting the signal power vary according to the SNR and the satellites position. 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 [8]. We assume that the two satellites perfectly compensate for delay and Doppler shifts at one point on the Earth, that we call *ideal UT position*. At this location, the signal contributions from the two satellites arrive simultaneously. Then, we denote an *offset* distance of 800 m of the UT from the ideal position, which entails residual uncompensated delay and Doppler shifts. In Fig. 2, we show the performance of OTFS and OFDM for both $P = 1$ and 2 in the case of a given static position of the satellites in scenario A. We can see that OTFS shows a significant performance

[2]Notice that these parameters values were chosen in order to keep the simulation time affordable.

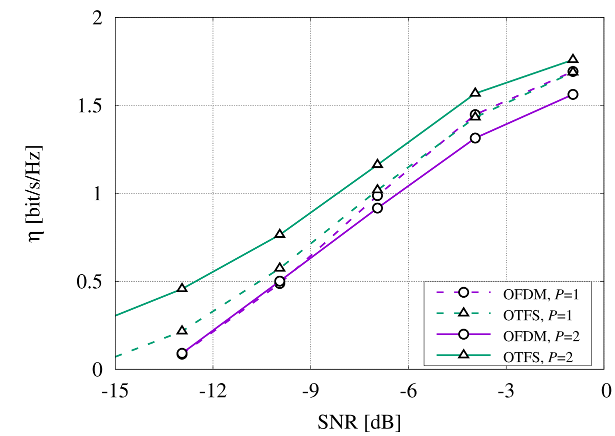

Fig. 2. Pragmatic capacity comparison in case of first satellite elevation 71° and slant range 1313 km, second satellite elevation 39° and slant range 2359 km, in propagation scenario A.

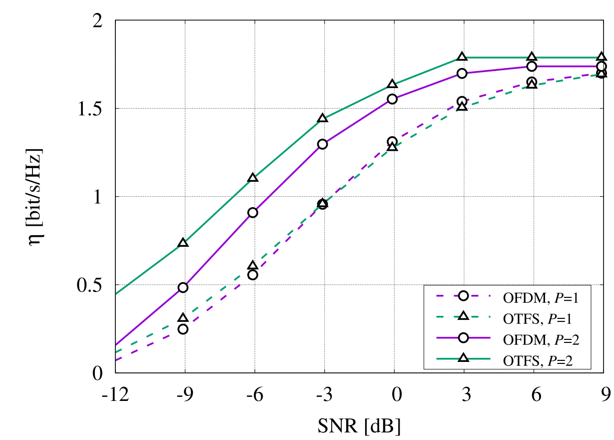

Fig. 3. Mean pragmatic capacity of the whole satellite passage in propagation scenario A.

improvement with respect to OFDM and when serving the UT with two satellites, i.e., $P = 2$, whereas OFDM performs almost the same for $P = 1$, and actually is further penalized when $P = 2$, due to the destructive interference of the two paths, that, in a few occurrences, can overcome the benefits of diversity. 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. In Figs. 3 and 4, we assume to serve the user during complete satellite passages, i.e., over a time span where both satellites are visible from the UT, and compare the performance for the two scenarios described in Table I by taking into account the shadowing statistics of a suburban non-line-of-sight (NLOS) scenario in S band, as per [15]. Again, an offset distance of 800 m was considered with respect to the perfectly Doppler-delay-compensated ideal position. We 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 OTFS system.

Finally, in Fig. 5, we report the cumulative distribution function (CDF) of the pragmatic capacity during the complete

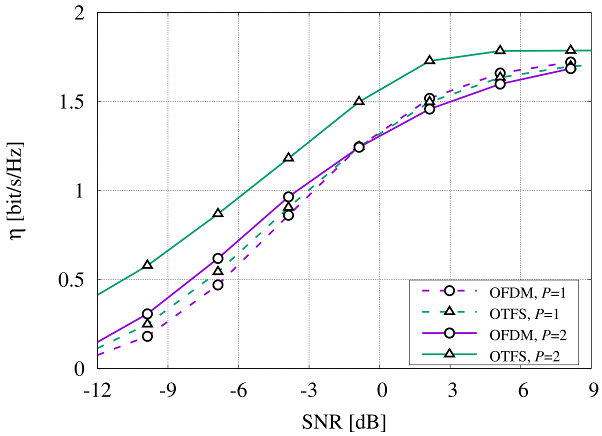

Fig. 4. Mean pragmatic capacity of the whole satellite passage in propagation scenario B.

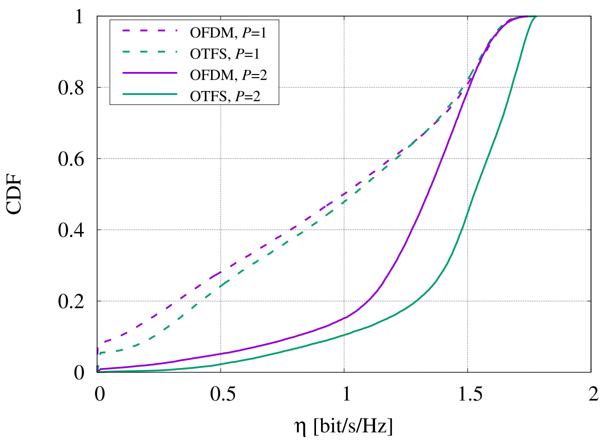

Fig. 5. CDF of the pragmatic capacity in propagation scenario A for SNR$= -3$ dB.

satellite passages for both the OTFS and OFDM modulations, assuming an SNR of -3 dB for scenario A. The figure shows that, as expected in the presence of shadowing, for $P = 1$ there is a non-zero outage probability, whereas for $P = 2$ the connectivity can always be ensured. 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 satellite. Indeed, from Fig. 5, going from the communication via the single satellite to the multi-satellite diversity, the median of the UT serving pragmatic capacity is 1.5 b/s/Hz instead of 1 b/s/Hz, i.e. there is a 50% of improvement. Then, these results suggest that further increasing the number of satellites will not likely improve the performance likewise, since the second satellite already reduces the outage probability of an order of magnitude, whereas the CDFs show a flat region where very small gains are possible, and a steep slope in a region – i.e., for $\eta > 1.2 \div 1.3$ – where performance saturation begins.

V. Conclusion

We investigated the use of the OTFS modulation, in comparison with OFDM, for 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. The comparison with the existing new radio (NR) air interface, i.e., based on the OFDM modulation, showed that OTFS provides a better solution to enable cell-free satellite architectures.

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