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LEO Small-Satellite Constellations for 5G and Beyond-5G Communications

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ABSTRACT The next frontier towards truly ubiquitous connectivity is the use of Low Earth Orbit (LEO) small-satellite constellations to support 5G and Beyond-5G (B5G) networks. Besides enhanced mobile broadband (eMBB) and massive machine-type communications (mMTC), LEO constellations can support ultra-reliable communications (URC) with relaxed latency requirements of a few tens of milliseconds. Small-satellite impairments and the use of low orbits pose major challenges to the design and performance of these networks, but also open new innovation opportunities. This paper provides a comprehensive overview of the physical and logical links, along with the essential architectural and technological components that enable the full integration of LEO constellations into 5G and B5G systems. Furthermore, we characterize and compare each physical link category and explore novel techniques to maximize the achievable data rates.

INDEX TERMS 5G, beyond-5G, low Earth orbit (LEO), radio access network, small-satellite constellations.

I. INTRODUCTION

Constellations of small satellites flying in Low Earth Orbits (LEO) and working all together as a communication network present an attractive solution to support and complement 5G New Radio (NR) and Beyond-5G (B5G) communications [1]–[4]. These constellations are deployed at altitudes between 500 and 2000 km and their integration with 5G NR will provide nearly-global coverage and support for: 1) enhanced mobile broadband (eMBB), to offer increased user data rates; 2) massive Machine-Type Communications (mMTC), to enable a wide range of Internet of Things (IoT) applications operating over vast geographical areas; and 3) Ultra-Reliable Communications (URC), to provide one-way latency guarantees in the order of 30 ms [2], with typical 2 ms propagation delays between ground and LEO.

Unlike Geostationary Orbits (GEO), LEO satellites move rapidly with respect to the Earth’s surface and have a small ground coverage. In particular, the ground coverage of a LEO satellite deployed at 600 km above the Earth’s surface and with a typical elevation angle of 30° is around 0.45% of the Earth’s surface. Moreover, due to the low altitude of deployment, LEO satellites can communicate with diverse types of ground terminals, such as dedicated ground stations (GSs), 5G gNBs, ships and other vehicles, or Internet of Things (IoT) devices. These features and elements, illustrated in Fig. 1 create the need for a relatively dense constellation to ensure that any ground terminal is always covered by, at least, one satellite. Therefore, global commercial deployments usually consist of more than a hundred satellites. For example, Kepler, Telesat, and Starlink constellations will consist of 140, around 300, and between 12000 and 42000 satellites, respectively [5], [6].

Naturally, the need for a high number of satellites introduces a constraint on their individual manufacturing and deployment costs [7]. Therefore, LEO deployments typically incorporate small or even nano satellites, with low manufacturing cost, size, and weight (i.e., under 500 kg) when compared to the traditional big satellites at Medium Earth VOLUME 8, 2020 This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/
Orbit (MEO) and GEO. These characteristics in turn reduce the launching costs. Small satellites have, however, stringent connectivity, processing, and energy constraints [8], exacerbated by long transmission distances and potentially large Doppler shift due to the rapid movement of the LEO space segment.

This paper provides an overview of the unique characteristics and the challenges for LEO small-satellite constellations in the context of 5G and B5G communications. Furthermore, we analyze physical layer and radio access techniques that are not relevant for traditional GEO satellite systems but, on the other hand, are essential to unleash the full potential of dense LEO constellations. Specifically, the contributions of the paper include:

- The description of the characteristics and communication challenges of LEO constellations, and their role in 5G and B5G.
- The analysis and comparison of the achievable data rates, propagation delays and Doppler shift in every physical link in the satellite constellation with parameters taken from the 3GPP technical reports [3].
- A taxonomy for the logical link types in satellite constellations. This includes the different types of data for which each of the link types can be used.
- The identification of the most relevant enabling technologies at the physical layer, the radio access and the radio slicing.
- In the physical layer, the evaluation of the performance gains of adaptive coding and modulation and the use of multiple-input multiple-output (MIMO). In particular, we explore the benefits of distributed MIMO with a set of transmitting small-satellites flying in close formation.
- In the radio access, the analysis of the benefits of resource allocation to mitigate interference with different resource types, namely orthogonal frequencies and codes. This is illustrated in terms of the effective data rates for communication between satellites.

The rest of the paper is organized as follows. Section II presents an overview of LEO small-satellite constellations. Section III details and characterizes the physical and logical links. The integration of constellations in 5G and B5G is discussed in Section IV. Furthermore, enabling technologies in the physical layer, the radio access, and the radio slicing are discussed; the benefits of a subset of technologies are also evaluated. The paper is concluded in Section V.

II. LEO SMALL-SATELLITE CONSTELLATIONS: CHARACTERISTICS AND CHALLENGES

As a starting point, we define some key terms and concepts used throughout the rest of the paper.

A satellite constellation is typically organized in several orbital planes, which are groups of satellites deployed at the same altitude and inclination. A pass is the period in which a satellite is available for communication with a particular ground position, with a typical duration of a few minutes for a LEO satellite, depending on the elevation angle and the relative position between terminals. The minimum elevation angle is typically between 10° and 45° [3], [6].

There are three elements present in every space mission: 1) the space segment, in our case the satellite constellation; 2) the ground segment, with the set of GSs, which are responsible of major control and management tasks of the space segment, plus the ground networks and other mission control centers; and 3) the user segment, which refers to the rest of communication devices at ground level, including IoT devices, smartphones, gateways or cellular base stations. We use the term ground terminal to denote any communication device deployed at the ground level, encompassing the ground and user segments.

There is a close relation between the mass, energy source, and processing and communication capabilities of a satellite. High-throughput eMBB or general-purpose space missions typically involve relatively heavy satellites (above 100 kg). This is the case of well-known commercial missions such as Starlink [6]. Recently, smaller nano- and pico-satellites have increased in popularity due to their low manufacturing and deployment costs, as well as the ability to support a wide range of IoT and broadband applications [9]. Small satellites must have active lifetimes of up to five years to prevent frequent redeployment. Therefore, they usually incorporate photovoltaic panels for energy supply and to charge their batteries, which are used when sunlight is absent. This calls for an adequate balance between energy consumption and performance.

One of the main concerns in satellite communications due to the long transmission distances is latency. The total latency is a combination of processing delay, queuing delay, transmission time, and propagation delay, being the latter determined by the physical distance between source and destination.

Interestingly, wireless communications through LEO satellites over long distances present an advantage in propagation delay with respect to terrestrial communications [10]. This is because electromagnetic waves propagate in space at the speed of light, whereas the propagation speed in optic fiber is around 1.47 times slower. Depending on the packet lengths, data rates, and queuing delays, this advantage may lead to a lower total latency with a LEO satellite constellation than with terrestrial networks over long distances.

In terms of communication technology, both free-space optical (FSO) and traditional radio frequency (RF) are considered for communication between satellites, through inter-satellite links (ISLs), and with the ground terminals, through ground-to-satellite links (GSLs) [3]. FSO links employ ultra-narrow beams to combat the increased attenuation of high carrier frequencies with distance, offering increased transmission ranges, higher data rates, and lower interference levels when compared to RF links [11]. FSO has been demonstrated in ground-to-satellite communication in numerous scientific missions [11] and several planned commercial LEO constellations, such as SpaceX, Telesat, and LeoSat, will deploy laser communication equipment for high-throughput
FSO ISLs [6]. On the downside, FSO is highly susceptible to atmospheric effects and pointing errors. Hence, communication through FSO links requires a combination of precise pointing capabilities with pre-arranged pairing, so that the antennas of the intended receiver and transmitter steer the beams accordingly.

In contrast, RF links present wider beams that enable neighbor discovery procedures, along with the integration into terrestrial RF-based systems. For example, the communication between a ground terminal and a satellite in 5G NR is envisioned to take place either in the S-band around 2 GHz or in the Ka-band, where the downlink operates at 20 GHz and the uplink at 30 GHz [3]. Also, RF links are crucial as fallback solution if FSO communication is infeasible, for example, due to positioning and pointing errors in the space segment, traffic overload, or bad weather conditions. Hence, a hybrid RF-FSO system has great potential to enhance network flexibility and reliability.

Finally, LEO satellites move rapidly with respect to the ground – at up to 7.6 km/s for an altitude of 500 km – but also with respect to each other in different orbital planes. This leads to two main challenges. First, the constellations are dynamic, usually entailing slight asymmetries that are aimed at minimizing the use of propellant when avoiding physical collisions between satellites at crossing points. Therefore, dynamic rather than fixed mechanisms must be put in place to create and maintain the links. Second, these links experience a much larger Doppler shift than those found in terrestrial systems.

### III. CONNECTIVITY

There are three types of data traffic in a LEO constellation: 1) user data, 2) control data, and 3) telemetry and telecommand (TMTC) data. The latter are inherently different from network control data and are exchanged between the GSs and the satellites. In the downlink, telemetry parameters describing the status, configuration, and health of the payload and subsystems are transmitted. In the uplink, commands are received on board of the satellite to control mission operations and manage expendable resources, for example, propellant. Oftentimes, TMTC uses separate antennas and frequency bands.

#### A. PHYSICAL LINKS AND PERFORMANCE CHARACTERIZATION

The physical links are the broadly classified in GSLs and ISLs. A GSL between a dedicated GS and a satellite, illustrated on the left side of Fig. 1, is also called the feeder link. The availability of a GSL, the satellite pass, is determined by the ground coverage and the orbital velocity (see Fig. 1). Due to the high orbital velocities of LEO satellites, these passes are short and frequent handovers between satellites are necessary to maintain connections with the ground terminals. The optimal pass corresponds to that in which, at some point in time, the satellite crosses over the observer’s zenith point.

On the other hand, ISLs can be further divided into intra-(for satellites in the same orbital plane) and inter-plane ISLs (for satellites in different orbital planes). Furthermore, the ISLs between satellites in orbital planes moving in nearly-opposite directions (one ascending and on descending) are known as cross-seam ISLs. Fig. 2 illustrates the ISLs in a typical Walker star constellation with seven orbital planes.

In this section, we characterize the GSLs and ISLs in terms of propagation delay, Doppler shift, and achievable data rates. Unless otherwise stated, the results presented were obtained by simulation with parameters taken from [3, Section 6]. These are listed in Table 1. Note that the effective isotropic radiated power (EIRP) density is the design parameter for the satellite transmitters, whereas a fixed transmission power is defined for the ground terminals.

The constellation is a Walker star, as illustrated in Fig. 2, with $P$ polar orbital planes deployed at a minimum altitude of 600 km with orbital separation (i.e., altitude...
TABLE 1. Parameter settings.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communication</td>
<td></td>
</tr>
<tr>
<td>Carrier frequency for GSL downlink</td>
<td>$f_c = 20 \text{ GHz}$</td>
</tr>
<tr>
<td>Carrier frequency for GSL uplink and ISL</td>
<td>$f_c = 30 \text{ GHz}$</td>
</tr>
<tr>
<td>Channel bandwidth</td>
<td>$B = 400 \text{ MHz}$</td>
</tr>
<tr>
<td>EIRP density for satellites</td>
<td>$4 \text{ dBW/MHz}$</td>
</tr>
<tr>
<td>Antenna gains for satellites</td>
<td>$38.5 \text{ dBi}$</td>
</tr>
<tr>
<td>Transmission power for ground terminals</td>
<td>$33 \text{ dBm}$</td>
</tr>
<tr>
<td>Transmitter antenna gain for ground terminals</td>
<td>$43.2 \text{ dBi}$</td>
</tr>
<tr>
<td>Receiver antenna gain for ground terminals</td>
<td>$39.7 \text{ dBi}$</td>
</tr>
<tr>
<td>Minimum elevation angle</td>
<td>$30^\circ$</td>
</tr>
<tr>
<td>Atmospheric loss</td>
<td>$0.5 \text{ dB}$</td>
</tr>
<tr>
<td>Scintillation loss</td>
<td>$0.3 \text{ dB}$</td>
</tr>
<tr>
<td>Noise temperature</td>
<td>$354.81 \text{ K}$</td>
</tr>
<tr>
<td>Satellite constellation</td>
<td></td>
</tr>
<tr>
<td>Number of orbital planes</td>
<td>$P \in {7, 12}$</td>
</tr>
<tr>
<td>Number of satellites per orbital plane</td>
<td>$N \in {20, 40}$</td>
</tr>
<tr>
<td>Altitude of orbital plane $p \in {1, 2, \ldots, P}$</td>
<td>$600 + 10(p - 1) \text{ km}$</td>
</tr>
<tr>
<td>Longitude of orbital plane $p$</td>
<td>$(180(p - 1)/P)^\circ$</td>
</tr>
</tbody>
</table>

FIGURE 3. 95th percentile of the propagation delay and Doppler shift at the physical links.

FIGURE 4. Median and 95th percentile of the data rates at the physical links in an interference-free environment.

We consider a connection-oriented network, where the links are pre-established and the satellites and ground terminals have perfect beam steering capabilities. Hence, the gain at each established link is the maximum antenna gain. The inter-plane ISLs are established according to a greedy matching algorithm presented in [12] and thoroughly analyzed in [13]; the interested reader can find more technical details in this latter reference. The results presented in Fig. 3 for the GSL rates were obtained by distributing $10^5$ users over the Earth’s surface within the ground coverage of a satellite following a homogeneous Poisson point process (PPP).

Fig. 3 shows the 95th percentile of the propagation delay and the Doppler shift for each physical link in the constellation. The latter is calculated as $f_D = v_f/c$, where $v$ is the relative speed between the transmitter and the receiver, $f_c$ is the carrier frequency, and $c$ is the speed of light. Note that propagation delays of less than 4 ms are typical in the GSLs. Besides, similar propagation delays were achieved at both the intra- and inter-plane ISLs with a total of 480 satellites. Such short delays are physically unattainable in GEO systems and enable multi-hop transmissions that comply with the requirements established by the 3GPP for the user- and control-plane latency of 50 ms round trip time (RTT) [1].

Time alignment is another challenge introduced by the long transmission distances. For example, the minimum propagation delay in the GSL to a satellite at 710 km (i.e., the maximum altitude with $P = 12$) is 2.3 ms, which occurs at the zenith point. However, as illustrated in Fig. 3, the ground terminals near the edge of coverage of the same satellite will experience propagation delays that are up to 1.7 ms longer. Hence, mechanisms are needed to accommodate or compensate for these temporal shifts.

Fig. 3 also shows that a Doppler shift of nearly 600 kHz is typical in the GSLs, which is comparable and even greater than that in the inter-plane ISLs. This is because cross-seam ISLs were not implemented. This is a common practice, for example, followed in the upcoming Kepler constellation, because of the huge Doppler shift when the satellites move in nearly opposite directions. For instance, if the cross-seam ISLs are implemented with $P = 7$ and $N = 20$, the 95th percentile of the Doppler shift with is 1.46 MHz. As a reference, the system bandwidth for NB-IoT is only 180 kHz. In contrast, the intra-plane ISLs are not affected by Doppler shift because the intra-plane distances are rather stable.

Next, Fig. 4 presents the median and 95th percentile of the achievable instantaneous data rates at the physical links in an interference-free environment. That is, the rates are chosen from an infinite set of possible values to be equal to the capacity of an additive white Gaussian noise (AWGN) channel at specific time instants. Naturally, the distances in the GSLs and in the intra-plane ISLs are less variable than in the inter-plane ISLs. Because of this, the 95th percentile of the rates is similar to the median in the GSLs and intra-plane ISLs but much greater for the inter-plane ISLs.

Besides contributing to the Doppler shift, the movement of the satellites complicates the implementation of inter-plane ISLs by creating frequent and rapid changes in the inter-plane ISLs and greatly reducing the time a specific inter-plane ISL can be maintained, termed inter-plane contact times. Hence, these links require frequent handovers, which involves
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sensing, and routing, possibly exploiting distributed intelli-
related control applications such as distributed processing,
detection, and telemetry.

collection and transmit application data, such as in Earth obser-
example, to distribute instructions for ISL establishment and
control operations initiated by the ground station. For
illustrated in Fig. 5 and described in the following.

A logical link is a path from the source transmitter to the
end receiver. Hence, data travels over many different physical
links, which may not be known by the two end-points. In our
case, there are two different kinds of end-points, a satellite
[S] and a ground terminal [G], which enables the definition
of four logical links, which may utilize one or several of the
physical links, GSL and ISL. These four logical links are illustrated in Fig. 5 and described in the following.

Ground to Ground [G2G]: Classical use of the network, where information is relayed between two distant points on the ground. Is also used for handover, routing and coordination of relays.

Ground to Satellite [G2S]: Mainly used for maintenance and control operations initiated by the ground station. For example, to distribute instructions for ISL establishment and routing, but also for caching and telecontrol.

Satellite to Ground [S2G]: Relevant when the satellites collect and transmit application data, such as in Earth observation, but also needed for handover and link establishment with GSs, radio resource management (RRM), fault detection, and telemetry.

Satellite to Satellite [S2S]: Mainly relevant for satellite-related control applications such as distributed processing, sensing, and routing, possibly exploiting distributed intelligence. Also used for topology management, including neighbor discovery, link establishment, and other autonomous operations in the space segment.

The use of the different physical and logical links is tightly related to the final application. In LEO constellations we identify not only applications that are inherited from terrestrial networks, but also those that are native to space communications.

One exemplary application is the use of the constellation as a multi-hop relay network to increase the coverage of IoT deployments in rural or remote areas, where the cellular and other relaying networks are out of range [1]. In such applications, the IoT devices wake up periodically to send status updates. These updates are forwarded within the con-
stellation until reaching the nearest satellite to the destination with an established link to a ground terminal. This end-to-end application relies on the [G2G] logical link.

Another example are LEO constellations for Earth and/or space observation, both of which are native applications to satellite networks. In these, the satellites are equipped with cameras and sensors that can operate in the visible, near-
infrared, thermal or microwave spectral domain. Naturally, the [S2G] is needed to retrieve the information in ground. Besides, the [S2S] link can be exploited for cooperation among satellites, for example, to point the cameras to a particular position when a first spacecraft detects an unusual event.

IV. INTEGRATION OF LEO INTO 5G AND BEYOND

In this section we provide an overview of the status of the standardization process and the most relevant radio access technologies to support 5G services in LEO constellations.

A. 3GPP: ONGOING WORK

Truly ubiquitous coverage is one of the major 5G drivers, and will only be possible through a close integration of satellite networks into 5G and B5G networks. For that, the 3GPP is working in the integration of Non-Terrestrial Networks (NTN) in future releases of 5G NR [2], [3]. This encompasses LEO, MEO, and GEO satellites, but also air-borne vehicles such as High Altitude Platforms (HAPs) operating typically at altitudes between 8 and 50 km. The goal is to ensure an end-to-end standard in the Release 17 timeframe – the second phase of 5G – originally scheduled for 2021. Specifically, a dedicated study for NTN IoT was agreed in December 2019, paving the way to introduce both narrowband IoT (NB-IoT) and evolved MTC (eMTC) support with satellites.

Two 5G satellite implementations are envisioned: transparent or regenerative payload [3]. In the first one, the satellites merely serve as relays toward the ground and, in the second one, satellites are a fully or partially functional gNBs that can perform, for example, encoding/decoding and routing. Hence, the regenerative payload implementation enables the use of the 5G logical interface between gNBs, the so-called Xn, to connect distant gNBs through the constellation. Moreover, the 3GPP considers two options of multi-connectivity in NTN, having the user equipment (UE) connected to one satellite and one terrestrial network, or to two satellites [3]. Another interesting application of LEO constellations is to backhaul fixed or moving terrestrial gNBs in areas with no additional terrestrial infrastructure.
There are two options to connect the 5G UEs to the constellation. The first option is through a gateway (i.e., a relay node), which uses the constellation for backhaul. The big advantage of this approach is that legacy UEs are fully supported and no additional RF chain is required. The second option is having the UEs to communicate directly with the satellite or the HAP. With this second option, the coverage of the constellation is maximized, but the limited transmission range of the UEs becomes the main challenge. Nevertheless, this may not be a hindrance in the case of low-power wide-area technologies such as NB-IoT in selected scenarios: the maximum NB-IoT coupling loss of 164 dB is, in principle, sufficient to directly communicate at 2 GHz (i.e., S-band) with LEO satellites at heights up to 700 km. Specifically, with these parameters, the maximum FSPL for an elevation angle of 30° is 163.31 dB.

The identification of the three 5G services is done in NR with the standardized 5G Quality of Service (QoS) Identifiers (5QIs). These consist of a set of pre-set values for the most frequently used services, such as the latency budget, the maximum error rate or the priority levels. Moreover, dynamic 5QIs can be defined for services that do not fit the pre-defined list. With the 5QI the network is able to properly treat the packets according to the type of service. To account for the fundamental limitations and/or performance differences between terrestrial and satellite networks, it has been proposed to include new Radio Access Technology (RAT) identifiers to indicate in each packet that a UE is using an NTN. This is necessary to, e.g., avoid a timer expiration if the 5QI is not compatible with the RAT type [14].

### B. PHYSICAL LAYER

The waveform defines the physical shape of the signal that carries the modulated information through a channel. In NR, the defined waveform is based on Orthogonal Frequency Division Multiplexing (OFDM) [15], [16], which is very sensitive to Doppler shifts. As observed in Section III-A, equalization complexity regardless of the magnitude of the Doppler shift. However, in case of severe Doppler shifts, factor graph based equalization for FBMC transmissions outperforms the OFDM system in terms of complexity and performance [18]. Nevertheless, maintaining OFDM is convenient to provide compatibility with terrestrial UEs.

Modulation schemes for satellite communications usually involve low modulation orders for robustness and low peak-to-average power ratio (PAPR) to enable the use of nonlinear power amplifiers. The preferred choice in recent commercial LEO missions is amplitude and phase-shift keying (APSK) with modulation orders up to 16 [6]. Hence, the most suitable modulation schemes supported by 5G NR are quadrature phase-shift keying (QPSK) and quadrature amplitude modulation (QAM) with modulation order 16.

Terrestrial gNBs adapt the modulation and coding scheme to the current channel conditions, for which the UEs must transmit information about the channel quality to the gNB [16]. In satellite systems, the channel conditions are mainly determined by the path loss, which can be easily predicted from the constellation geometry. In addition, rain fade, antenna pointing errors, noise, and interference create frequent, yet minor, changes.

Nevertheless, the high orbital velocities of LEO satellites creates significant, yet predictable, changes in the path loss at the GSL. For the transmission of short packets in the GSL, the priority is to minimize link outages and packet errors to avoid long RTTs for feedback. In these cases, fixed robust modulation and coding schemes are preferred.

On the other hand, adaptive coding and modulation is interesting for long packet transmissions in the GSL, where the predictability of the path loss can be exploited. As an example, Fig. 6 shows the evolution of the achievable rate with time for a LEO satellite in a polar orbit at an altitude of 600 km for two different ground terminals deployed along the Equator. The first is the optimal pass, where the shift in longitude between the ground terminal and satellite is \( \beta = 0 \) and, the second one, is a typical pass where \( \beta = 4^\circ \). Naturally, communication is not possible when the elevation angle is below the minimum, thus, the achievable rate becomes zero for that case. The simulation parameters, except the transmission power, are those listed in Table 1.

As it can be seen, the peak of the achievable rate occurs at around 2 minutes after the satellite establishes the GSL with the ground terminal at \( \beta = 0^\circ \). This is because the duration of the optimal pass is 4.1 minutes in this example. At this peak, the achievable rate can be up to 31% and 14% higher than the minimum for \( P_{\text{TX}} = 30 \) dBm and \( P_{\text{TX}} = 50 \) dBm.
respectively for the ideal pass. In comparison, the pass of the
simultaneously transmitting towards a GS.

to a GS from multiple
amented by cooperatively transmitting to a GS from multiple
as 
[19]. In the space segment, this separation can be imple-
icted by cooperatively transmitting to a GS from multiple
satellites, flying in close formation.

Pure LoS connections and the large transmission distances
etween satellites and ground terminals introduce some
unique challenges that need to be overcome. In particular,
exploiting the full MIMO gain requires a large array aperture,
its peak achievable rate is around 1 bps/Hz lower for both
considered power levels, which is significant.

MIMO is yet another key enabler for high data rate
communications. Although MIMO has tremendous potential
for increased spectral efficiency in eMBB traffic through
EO constellations, MIMO techniques have, so far, been
mostly restricted to terrestrial communication systems.
Pure LoS connections and the large transmission distances
between satellites and ground terminals introduce some
unique challenges that need to be overcome. In particular,
exploiting the full MIMO gain requires a large array aperture,
axial satellite with a large antenna array. In addition, this
satellites provides a considerable gain over equipping a sin-
gle satellite with a large antenna array. In addition, this
joint transmission allows to form very narrow beams which
leads to better spatial separation and, thus, higher spec-
tral efficiency when serving different GSs located geo-
graphically close to each other on the same time-frequency
resources [20].

C. RADIO ACCESS

Radio access in the GSL is, essentially, random access (RA)
due to the large amount of nodes and the fact that both the
number of ground terminals and the traffic patterns are not
known in advance. There are two principal types of RA proto-
cols: grant-based and grant-free. Grant-based RA is the go-to
solution in 5G and the newly proposed new two-step random
access procedure can mitigate the excessive delay and time
alignment issues of the legacy four-step procedure in satellite
communications [3]. Nevertheless, due to the large individual
coverage of the satellites, the capacity of the grant-based RA
of 5G can be easily surpassed if the ground terminals are
allowed to perform direct access to the satellites.

On the other hand, grant-free RA is preferred for the
transmission of short and infrequent data packets that
characterizes massive IoT. Nevertheless, the long distance
between end points prevents the use of traditional chan-
nel sensing protocols [21]. Instead, non-orthogonal medium
access (NOMA) techniques that incorporate successive
interference cancellation (SIC) may be better suited [22].

Due to space, weight and budget limitations, small-satellite
may incorporate relatively wide-beam antennas [8]. Therefore,
inference mitigation in the ISL may be required. In the
 intra-plane ISL, the transmitter and the receiver do not
change because the relative distances are preserved. There-
fore, fixed access schemes like Frequency Division Multiple
Access (FDMA) or Code Division Multiple Access (CDMA)
are simple and attractive solutions [9]. With FDMA, the
frequency reuse factor to mitigate interference along the orbit
must be properly designed, which comes at the cost of
higher bandwidth requirements. On the other side, the chal-
lenges of CDMA, for example, synchronization or near-far
effects, can be overcome by using asynchronous CDMA with
non-orthogonal codes.

On the other hand, in the inter-plane ISL, the satellite
pairs may change frequently over time and the distances
are not preserved. This is specially true because commercial
LEO constellations usually present slight asymmetries in the
orbital planes to minimize the risk of (physical) collisions
between satellites [23]. Nevertheless, the predictability of the
constellation geometry can still be exploited by a centralized
tegrity (e.g., a GS or a satellite with sufficient storage space
and processing power) to allocate orthogonal resources for
inter-plane communication. By doing so, an efficient resource
utilization can be achieved while mitigating the potential
interference among inter-plane, but also between inter-plane
and intra-plane ISL.

FIGURE 7. Achievable rate for \( N_s \) satellites in close formation and
simultaneously transmitting towards a GS.
global choice at each iteration. The parameters settings are listed in Table 1. A worst-case scenario for interference is considered (i.e., with omnidirectional antennas). The data rates are calculated to ensure zero outage probability and the interference is treated as AWGN. The cross-seam ISLs are not implemented due to the large Doppler shift.

Two types of multiple access methods are considered: 1) orthogonal FDMA (OFDMA), where the bandwidth $B$ is divided into a given number of sub-carriers of the same bandwidth $B_{sc}$, and 2) CDMA, where $K \in \{2^k : k \in \mathbb{Z}\}$ orthogonal Walsh codes, whose spreading factor is equal to $K$, are used. The data rates with both OFDMA and CDMA were calculated to ensure a zero-outage probability with the maximum feasible value of the interference for all the established ISLs. Note that, for OFDMA, the EIRP decreases as the number of orthogonal subcarriers increases due to the constant EIRP density.

As Fig. 8 shows, the number of orthogonal resources to achieve the peak rates is relatively small: 3 with OFDMA and 4 with CDMA (since $K = 3$ is not a feasible value). Besides, note that both OFDMA and CDMA lead to closely similar rates for all feasible values of $K$. The reason for this is that, for OFDMA, the decrease in noise power with narrow sub-carrier bandwidths is compensated by a decrease in EIRP. On the other hand, the rates with $P = 12$ are usually more than $2 \times$ greater than with $P = 7$. This non-linear increase of the data rates with $N$ was also observed in Fig. 4.

The results presented in Fig. 3, 4, and 8 were obtained considering that the inter-plane ISL are established with the single objective of maximizing the sum of rates in the LEO constellation. However, there are situations in which multiple satellites can benefit from establishing an inter-plane connection with a specific satellite at the same time. In these cases, the inter-plane ISL can be seen as a mesh network. Unlike terrestrial mobile ad-hoc networks, the position of the satellite neighbors can be predicted if the orbital information is available at each node. Protocols from mesh networks for connecting directly, dynamically and non-hierarchically to as many other satellites as possible can be adapted to the specific conditions of the LEO constellation. For instance, the use of relatively wide beams enables the use of distributed approaches, such as the deferred acceptance algorithm [24], where the inter-plane ISL may be established opportunistically based on the individual preferences of the satellites.

**D. RADIO SLICING**

A general-purpose satellite constellation must support the heterogeneity of eMBB, URC, and mMTC services. Besides, the user, control and TMTC traffic have widely different characteristics and requirements. Network slicing [25] is a key 5G feature to support heterogeneous services and to provide performance guarantees by avoiding performance degradation due to other services. In the Radio Access Network (RAN), the conventional approach to radio slicing is to allocate orthogonal radio resources at the expense of a lower network efficiency. Instead, non-orthogonal slicing may bring benefits in terms of resource utilization at the expense of a reduced predictability in the QoS. In particular, non-orthogonal slicing in the RAN, in the form of NOMA for heterogeneous services, may lead to better performance trade-offs than orthogonal slicing in terrestrial communications [26]. However, extensions to these communication theoretical models are needed to characterize the potential gains of non-orthogonal slicing in LEO small-satellite constellations.

The time and frequency multiplexing of services and data traffic with widely different characteristics and requirements introduces similar challenges as in terrestrial networks. For instance, it requires priority-aware mechanisms in the data link and medium access layers to guarantee the efficient delivery of critical packets. However, the space multiplexing has some advantages in LEO constellations, thanks to the line-of-sight conditions, the link diversity, and the availability of multiple antennas with narrow beams.

Until now, LEO, MEO and GEO have been addressed separately in 3GPP. Nevertheless, hybrid architectures combining different orbits may play a major role in future networks [27] and contribute to the network slicing. Hybrid solutions are reminiscent of the evolution towards heterogeneous cellular networks and the mix of cell sizes, but with the added advantage that the diversity in orbits and satellite capabilities can complement each other favorably. For instance, the short transmission times between ground terminals and LEO satellites can be combined with: 1) the wide coverage and the great communication and computation capabilities of GEO satellites and 2) with the available navigation satellites at MEO (e.g., GPS, Glonass, and Galileo constellations). Hence, hybrid architectures provide great flexibility and an increased capacity to accommodate a heterogeneity of application requirements.

**V. CONCLUSION**

In this paper, we described the main opportunities and connectivity challenges in LEO small-satellite constellations. Besides, we characterized the physical links in LEO constellations in terms of propagation delay, Doppler shift, and achievable data rates. Our results showcase that LEO constellations have the potential to fulfill the 5G promise of true ubiquity and to support the generic use cases of eMBB and mMTC, as well as URC with latency requirements of a
few tens of milliseconds. Nevertheless, these physical links present different characteristics and, hence, must be properly designed to unleash the full potential of the constellation. Furthermore, we provided an overview and taxonomy for the logical links, in connection with the used physical links and relevant use cases. Finally, we discussed about several PHY/MAC and radio slicing enabling technologies and outlined their role in supporting 5G connectivity through LEO satellites. Our results illustrate the potential benefits of adaptive coding and modulation schemes in the GSL and of proper resource allocation for multiple access in the ISL.

REFERENCES

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