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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.

Here we will discuss about following :

- discuss about characteristics and challenges of LEO constellation
- Analysis and comparison of propagation delays ,achievable data rates ,Doppler shift in every physical link of satellite constellation.
- 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).

Key Terms

Terms

- **Pass** - A pass is the period in which a satellite is available for communication with a particular ground position.(few minutes for a LEO satellite, depending on the elevation angle and the relative positions between terminals)
- **Satellite Constellations** - Group of satellites organised in different orbital planes , deployed at same altitude and inclination.
- **Ground terminal** - to denote any communication between device at ground level.
- **Latency** - The total latency is a combination of processing delay, queueing delay, transmission time, and propagation delay, being the latter determined by the physical distance between source and destination.

Advantages of LEO

Advantages

Using LEO constellation with 5G NR provide nearly global coverages and support for :

- enhanced mobile broadband (eMBB)-to offer increased user data rates
- massive Machine-Type Communications (mMTC) - to enable a wide range of Internet of Things (IoT) applications operating over vast geographical areas
- Ultra-Reliable Communications (URC) - provide one-way latency guarantees in the order of 30 ms [2], with typical 2 ms propagation delays between ground and LEO.

Characterstics of LEO

Characterstics

- they are deployed at a altitude of around 600km with typical elevation angle of 30° , has ground coverage of 0.45% of Earth surface.
- 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 indicate 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 . Example Starlink -12000 to 42000 satelites .

Element in space mission

There are three element in every space mission.

- space segment - the satellite constellation
- ground segment - 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
- user segment - rest of communication device on ground level ,including IoT devices (ground terminal)

communication terms

- Free space optical(FSO) and Tradition Radio frequency (RF) , used for communication b/w satellites as well b/w satellite and ground.
- FSO employs ultra -narrow beams to combat the increased attenuation of high carrier frequencies with distances , offering increased transmission ranges, higher data rates, and lower interference levels .But on downside , FSO is highly susceptible to atmospheric effects and pointing errors

continued.....

- RF links present wider beams that enable neighbor discovery procedures, along with the integration into terrestrial RF-based systems , Also, RF links are crucial as fallback solution if FSO communication is infeasible, for example, due to positioning and pointing errors , traffic overload, or bad weather conditions.

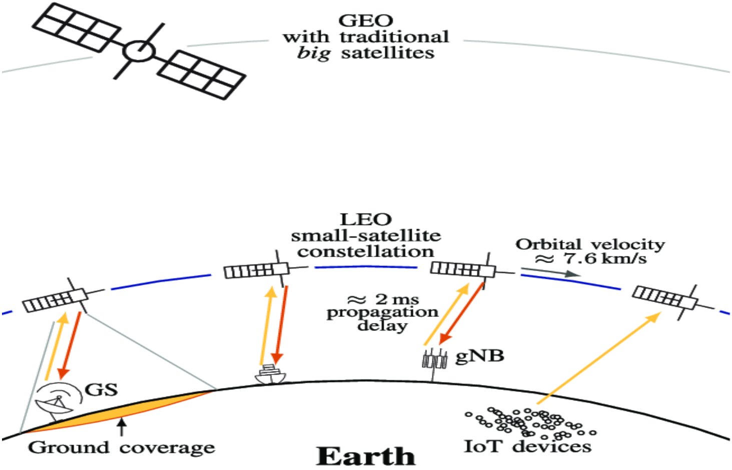
Therefore , a hybrid RF-FSO system has great potential to enhance network flexibility and reliability.

Challenges

there are main two challenges :

- the constellations are dynamic, usually entalling 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.
- Link experience a much larger Doppler Shift than those found in terrestial system .

characterstics of LEO vs GEO constellation



Connectivity

There are three main date traffics in a LEO constellation.

- user data
- control data
- telemetry and telecommand data (TMTC)

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

TMTC are different from network control data and are exchanged between the GSs and the satellites.

TMTC often use seprate antennas and frequency bands .

Physical links

Physical links divided into two :

- inter-satellite links (ISLs)
- ground-to-satellite links (GSLs) , also known as Feeder links .

GSLs

GSLs are mainly dedicated between GS and the satellite.The availability of GSLs and satellite pass is determined by ground coverage and orbital velocity.

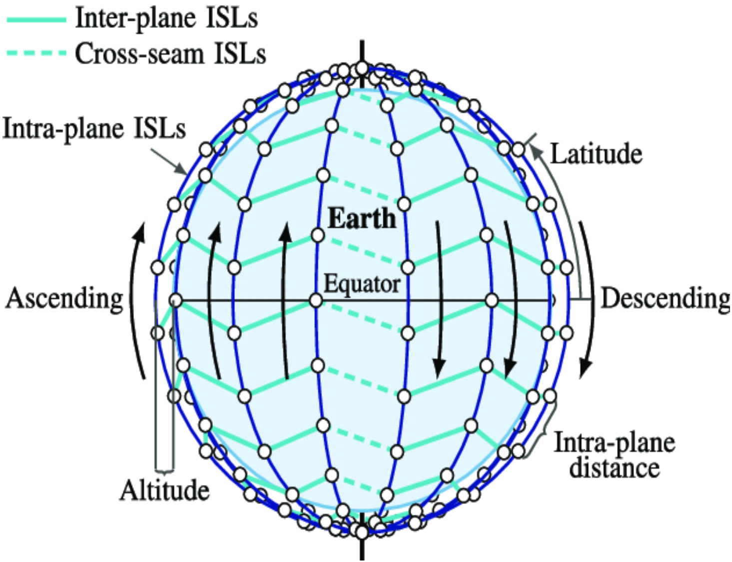
ISLs

ISLs are further devide :

- intra ISLs - for satellites in same plane
- inter ISLs - for satellites in different orbital planes

ISLs between the satellite in orbital planes moving in opposite direction are known as cross-stream ISLs .

Walker star LEO constellation



GSls and ISLs in term of propogation dalay , Doppler effect and achievable data rates

Communication

Parameter	Setting
Carrier frequency for GSL downlink	$f_c = 20GHz$
Carrier frequency for GSL uplink and ISL	$f_c = 30GHz$
Channel bandwith	B = 400 MHz
EIRP density for satellites	4 dBW/MHz
Antenna gain for satellites	38.5 dBi
Transmission power for ground terminals	33 dBm
Transmitter antenna gain for ground terminals	43.2 dBi
Receiver antenna gain for ground terminals	39.7 dBi
Minimum elevation angle	30 °
Atmospheric Loss	0.5 dB
Scintillation loss	0.3 dB
Noise Temperature	354.81 K

Satellite Constellation

Number of orbital planes	P $\in \{7, 12\}$
Number of satellite per orbital plane	N $\in \{20, 40\}$
Altitude of orbital plane p $\in \{1, 2, 3...., P\}$	600 + 10(p-1) km
Longitude of orbital plane p	$(180(p\text{-}1)/P)^\circ$

Table: Parameter Setting

Altitude of orbital plane $p \in \{1, 2, \ldots, P\}$	$600 + 10(p-1)$ km
Longitude of orbital plane p	$(180(p-1)/P)^\circ$

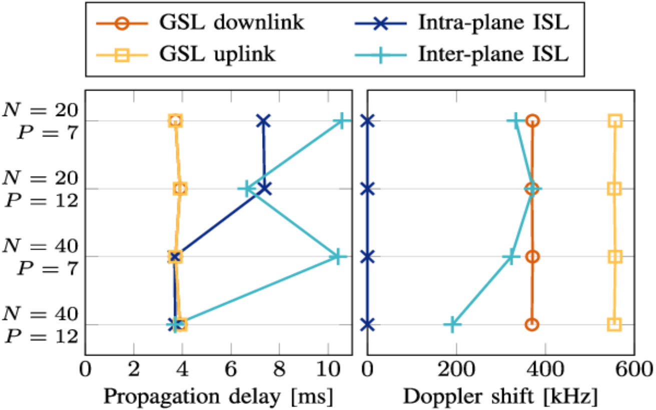
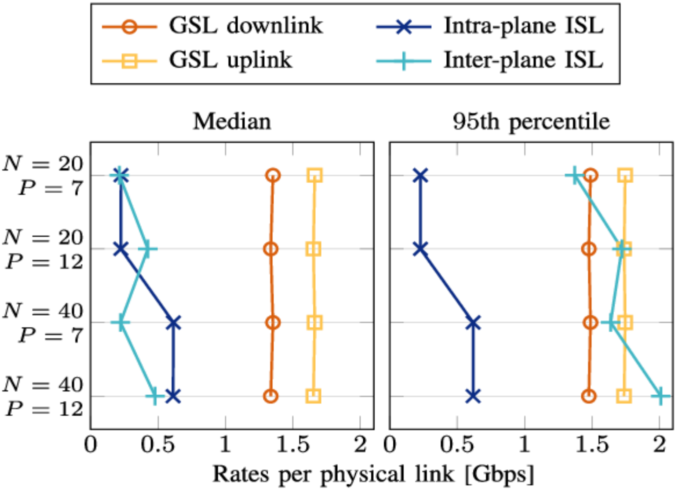


FIGURE 3. **95th percentile of the propagation delay and Doppler shift at the physical links.**

1. The results presented in figure 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).
2. we assume the condition so that the gain at each established link is the maximum antenna gain.
3. Doppler shift in each physical link is calculated by $f = \frac{vf_c}{c}$ where v is the relative speed between transmitter and receiver and f_c is the carrier frequency. propagation delay of less than 4 ms are observed in GSLs and ISLs which are unattendable in GEO constellation.



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

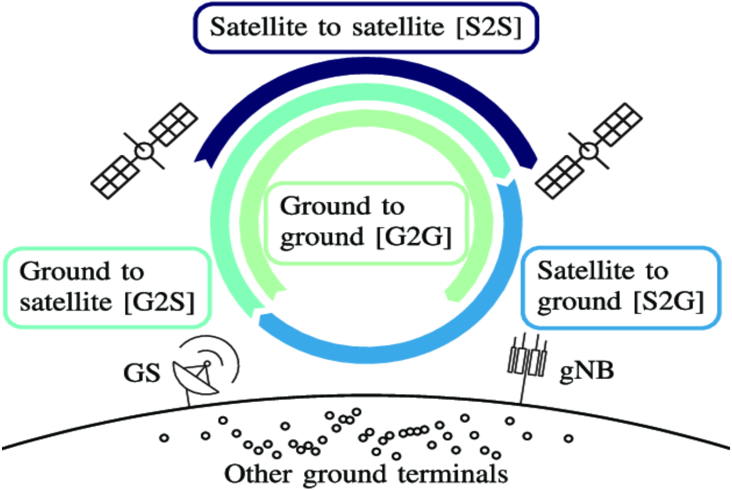
- the rates are chosen from an infinite set of possible values to be equal to the capacity of an additive white Gaussian noise (AWGN) channel at specific time instants.
- the 95th percentile of the rates is similar to the median in the GSLs and intra-plane ISLs but much greater for the inter-plane ISLs.
- 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 neighbor discovery and selection (matching), as well as signaling for connection setup. Despite all these challenges implementing the inter-plane ISLs comes with massive benefits.

Logical link

Logical link is the path from source transmitter and end reciever . Data travels over many different physical links which may not be known by two end points . In our case , there are two end point Satellite[S] and Ground[G] which give rise to four logical link.

- Ground to Ground [G2G] - Classical use of network,also used for handover ,rooting and coordination of delays
- Ground to Satellite[G2S] - used for maintenance and control operation initiated by ground station
- 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]-used for satellite related control application , and also used for some autonomous operation in space segment.

Four Logical links



Applications

- One application is to use as multi hop relay network to increase the coverage of IoT deployment in rural or remote area where cellular and relay network are out of range.
- This end-to-end application is possible through G2G logical link.
- 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

Integration of LEO into 5G and beyond 5G

A:3GPP Ongoing Work

- 3GPP is working in the integration of Non-Terrestrial Networks (NTN) in future releases of 5G NR
- Dedicated study also going on to introduce narrowband IoT and evolved MTC supprt with satellites.

5G Satellite Implementation

- Transparent - satellite merely serve as relay toward the ground
- Regenerative payload - satellites are a fully or partially functional gNBs,also enables the use of the 5G logical interface between gNBs, the so-called Xn, to connect distant gNBs through the constellation.
- 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

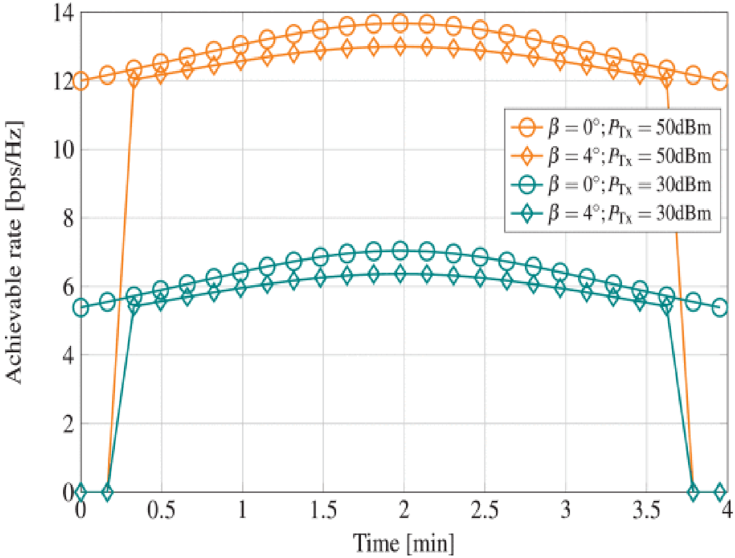
Connection of 5G UEs to constellation

- 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.

B:Physical Layer

- The waveform defines the physical shape of the signal that carries the modulated information through the channel.
- In NR, the defined waveform is based on Orthogonal Frequency Division Multiplexing (OFDM),which is very sensitive to Doppler shift.Several alternatives like UFMC , GFDM , FBMC are used ,which allow higher robustness against Doppler shift.
- NR supports Quadrature Amplitude Modulation (QAM) schemes. Within QAM, Binary Phase-Shift Keying (BPSK) and Quadrature Phase-Shift Keying (QPSK), are often used in satellite communications, although Amplitude and Phase Shift Keying (APSK) is the preferred technique in LEO commercial missions . The main benefit of APSK in space is its low peak-to-average power ratio (PAPR), which makes it suitable when using power amplifiers with nonlinear characteristic.

Evolution of achievable rate for GSL downlink



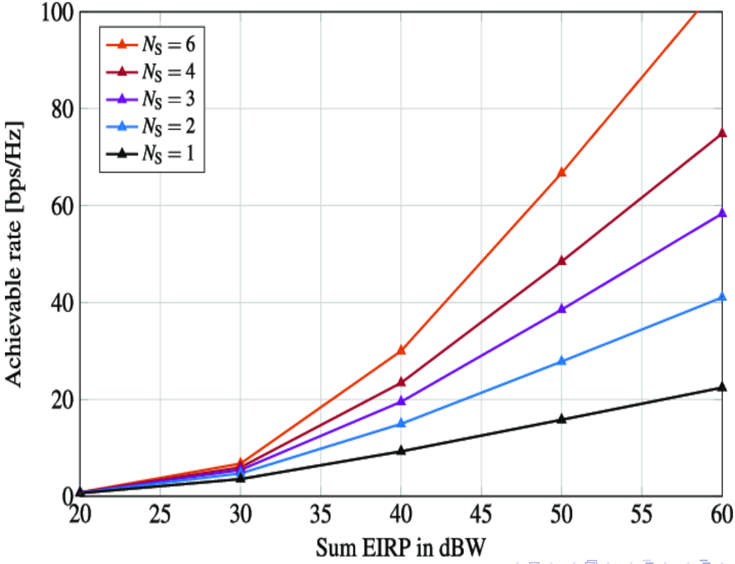
Evolution of achievable rate for GSL downlink

1. 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 $\beta = 4^\circ$
2. 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.
3. In comparison, the pass of the ground terminal at $\beta = 4^\circ$ is around 0.8 minutes shorter and its peak achievable rate is around 1 bps/Hz lower for both considered power levels, which is significant.

MIMO

- enable the high data rate communications, also increased spectral eficiency in eMBB traffic through LEO constellations
- In particular, exploiting the full MIMO gain requires a large array aperture, i.e., large distances between transmit and/or receive antennas.
- In the space segment, this separation can be implemented by cooperatively transmitting to a GS from multiple satellites, lying in close formation.

Achievable rate for NS satellites in close formation and simultaneously transmitting towards a GS.



Data used

1. The achievable rate of Ns satellites transmitting cooperatively to a single GS as a function of the sum EIRP of all NS satellites is shown.
2. Each of these satellites is equipped with $N_t = 12/N_S$ antennas ,GS is equipped with a uniform linear array (ULA) consisting of 100 antennas having a gain of $GR_x = 20$ dBi each , and and GS antennas are spaced $\lambda_c/2 = 7.5$mm apart.
3. The ULAs axis is aligned with the ground trace of the satellites. The downlink transmission takes place in the Ka-Band at a carrier frequency of $f_c = 20$ GHz
4. Observation - achievable rate increases with the number of transmitting satellites
5. In addition, this joint transmission allows to form very narrow beams which leads to better spatial separation and, thus, higher spectral efficiency when serving different GSs located geographically close to each other on the same time-frequency resources

Radio Access

- principal RA protocols : grant-based and grant free
- Grant-based RA is the go-to solution in 5G, which is a two-step random access procedure can redude the excessive delay and time alignment in satellite communications.
- grant-free RA
  - transmission of short and infrequent data packets.
  - non-orthogonal medium access (NOMA) techniques that incorporate successive interference cancellation (SIC) is used.
  - in case of intra-plane ISLs , we can use some fixed access schemes like FDMA and CDMA.
  - while in case inter-plane ISLs , the predictability of the constellation geometry can still be exploited by a centralized entity to allocate orthogonal resources for inter-plane communication.

Radio slicing

1. Network slicing is a key 5G feature to support heterogeneous services and to provide performance guarantees by avoiding performance degradation due to other services.
2. 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 eficiency. Instead, non-orthogonal slicing may bring benefits in terms of resource utilization at the expense of a reduced predictability in the QoS.
3. 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

Conclusion

- In this paper, we described the main opportunities and connectivity challenges in LEO small-satellite constellations.
- we characterized the physical links in LEO constellations in terms of propagation delay, Doppler shift, and achievable data rates
- Furthermore, we provided an overview and taxonomy for the logical links, in connection with the used physical links and relevant use cases.
- we discussed about several PHY/MAC and radio slicing enabling technologies and outlined their role in supporting 5G connectivity through LEO satellites.