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Contents

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1 Introduction

This document is a collected summary of literature surveys performed in the ANTERRA project on the topic of beam-finding and synchronization. The findings are sorted and summarized per Doctoral Candidate (DC).

2 Literature surveys

2.1 DC 1

Regarding beam-finding concepts, actively-Scanned Phased-Array antennas offer a way to efficiently perform the acquisition and tracking of fast-moving NTN platforms, such as LEO satellites. Having an individual transceiver module per array element, the obtained data can be processed to determine the Direction of Arrival (DOA) of incoming signals. With the direction(s) obtained, beamforming can then be performed.

Perhaps the most powerful DOA acquisition algorithms are the so-called subspace methods [1]. These make use of the properties of the spatial covariance matrix of the array. Due to the distances between the elements and the angle of incoming plane waves, there will be a delay of arrival at the kth element. Therefore, baseband signals at each array element then have both a time and phase shift between them. Assuming narrowband signals, the signal time shift between the elements can be ignored. This leaves us with the data vector of the array being a linear combination of the steering vectors of the DOAs for our particular array and incoming signal, with noise added. The spatial covariance matrix, E{x_n x_n^H } where x_n is the data vector, can be unitarily eigendecomposed into orthogonal signal eigensubspace (where our matrix of steering vectors lies) and noise eigensubspaces.

Some methods, such as the classic MUSIC [2] and all their subsequent modifications, check the orthogonality of all possible steering vectors with respect to the noise subspace, creating a sort of “pseudo-spectrum” where the peaks indicate the DOAs. However, more accuracy requires more values to check and entails higher computational load. Other methods, such as ESPRIT [3] and related algorithms, employ rotational invariances and symmetries within the array to obtain DOAs. While less computationally expensive than pseudo-spectrum methods, the array needs to fulfill some conditions. As such, some conformal and sparse array distributions would not be valid.

The main problem of subspace methods lies in the reliability of the spatial covariance matrix (and noise and signal subspace) computation. Several time steps need to be taken into account to properly compute them, taking time, and eigendecomposition is computationally taxing, making it unfeasible to perform. One possible solution is to use subspace “trackers” that update the subspaces each time step by taking the old matrix and a single new array data vector [4][5][6]. However, this only partially solves the problem. Another limitation is that such methods do not work for coherent signals.

New subspace methods, either specifically for LEO or general, tackle these issues. For example, in [7] a method is developed using spatial smoothing to detect the DOA of coherent signals. In [8], a parallel-processed ESPRIT modification for each group of sub-arrays. allows for computational time reduction.

Concerning synchronization, the greatest concern in LEO satellite communications is Doppler shift due to the relative speed between user equipment (UE) and satellite. Furthermore, since a satellite may serve several users in a single beam footprint with potentially different speeds, a “cell-wide” correction is not a complete solution.

Examples of work towards possible solutions include [9], where they use the mathematical properties of Zadoff-Chu (ZC) sequences included in the Primary Synchronisation Sequence (PSS) frames to detect the Doppler shift to compensate as a shift in peaks after a correlation process. In [10], researchers propose an SDR-tested algorithm using distributed MIMO, working in baseband by use of a fixed LO.

Considering the use of common OFDM-based communication but applied to LEO, the researchers in [11] introduce an algorithm to compensate Doppler shift in a single frame of data. The employ the Cyclic Prefix of OFDM frames and distribute a limited number of pilot signals among some of the subcarriers. In [12], a procedure is shown where weights for each OFDMA subcarrier are estimated in a way that optimizes an objective function to perform coarse time synchronization. A fine synchronization is subsequently performed using Recursive Least Squares.

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2.2 DC 2

Synchronization

Satellites orbiting in non-geostationary orbits (NGSO), suffer from signal synchronization problems at the receiver, same as in any wireless communication system. These synchronization problems [1] arise from carrier frequency offset (CFO), carrier phase offset (CPO), sampling rate offset, and additionally due to the fast-orbiting speeds they suffer from Doppler shift [2]. As per the 3rd Generation Partnership Project (3GPP), a LEO satellite operating at an altitude of 600 km experiences a maximum Doppler shift of 480 kHz and a Doppler rate of -5.44 kHz s^(-1) for a Ka-band downlink frequency of 20 GHz [3]. This level of Doppler shift is comparable to the symbol rate or sub-carrier interval in the communication system, resulting in significant degradation of demodulation performance. Additionally, the Doppler shift can vary within a single physical frame due to the high Doppler rate. Hence, it is crucial for LEO satellite communication to have real-time estimation and pre-compensation of the substantial and rapidly changing Doppler shift early in the receiver processing stage. The same problem occurs in MEO satellites, although it is less severe due to the slower orbiting speeds. In this subsection we will focus on state-of-the-art solutions to the Doppler shift synchronization for LEO satellites.

Most Doppler shift estimators used in LEO satellite communication fall into two categories: data-aided (DA) [4] and geometric information-based methods [5]. In DA methods, the frequency shift is estimated by analyzing known data symbols such as preambles or pilots [4]. These methods assume that the Doppler shift being estimated is significantly smaller than the symbol rate and that timing information has already been recovered. Geometric information-based methods, on the other hand, predict the Doppler-time curve within the satellite's visibility window based on the relative geometry between the satellite and the ground terminal [5]. This type of Doppler estimation relies on prior knowledge of satellite ephemeris information and the receiver's location.

One of the early papers discussing the Doppler shift and Doppler rate characterization in LEO satellites [6], published in 1998, is based on analytic derivations based on the geometric data of the orbit. In those derivations circular orbit and constant angular velocity is assumed, which limits the validity of the estimations. In a more recent paper from 2007, an accurate doppler frequency shift is made for any satellite orbit [7]. The orbits that are considered are elliptical, and non-spherical mass distribution of the Earth is assumed. The Doppler frequency effects in the L-band are considered for various orbits, and these results can be used to design the receiver phase lock loops.

With the advent of 5G NR and the merging with non-terrestrial networks (NTNs) in future 6G standards [2], more and more Doppler synchronization methods are based on the standardized waveforms of 5G NR [8]–[12]. In [8], the integer and fractional part of the Doppler shift within a primer synchronizing signal (PSS) is estimated in two steps. Precise Doppler rate is calculated by extracting the accumulated phase difference of two consecutive PPS, then the signal is passed through a Kalman filter to improve the stability of the frequency offset estimation in low SNR. An improved timing synchronization method for eliminating large doppler shift in LEO satellites system [9] based on the symmetric property of the Zadoff-Chu (ZC) sequence is proposed to achieve good performance with low complexity. Other methods can be found in [10], [12] Another proposed method that is not based on either data-aided or geometric information-based methods, is the so-called Blind Doppler Shift Estimation and Compensation method [11]. This method is able to track the fast-varying Doppler shift and its accuracy meets the demands for Doppler pre-processing in a low SNR environment. The algorithm is based on a time-vary Burg (TV-Burg) spectral analyzer and an alpha-beta filter, designed to provide a Doppler estimate at each sampling point recursively [11].

Beam-finding

In scenarios involving mobility, the orientation of the antenna in relation to the satellite undergoes continuous changes. As a result, it becomes essential to dynamically update the beam angles in order to ensure a consistently high-quality communication link with the satellite. This requirement applies even in the case of geostationary (GEO) satellites. For low Earth orbit (LEO) or medium Earth orbit (MEO) satellites, tracking the satellite becomes necessary, which entails the dynamic adjustment of beam angles. This need arises not only in dynamic scenarios but also in static cases due to the relative movement of the satellite with respect to the user plane of the antenna.

Reference [13] introduces a robust algorithm for beam-tracking in a millimeter wave mobile communications system, aiming to ensure uninterrupted communication between a base station (BS) and a mobile station (MS). Both the BS and MS are equipped with antenna arrays. The algorithm utilizes an extended Kalman filter (EKF) to track the channel at the static BS, while the beamforming weight is updated using a robust minimum mean squared error beamformer. This beamformer is bounded by the array vector error, which is determined based on the error variance estimated by the EKF. The experimental results demonstrate that our proposed method effectively maintains a link with the MS, exhibiting a smaller mismatch error compared to existing beam tracking methods. These outcomes are particularly noteworthy when considering moderate MS mobility and antenna array size. In reference [14], the authors introduce a beamforming strategy that involves a staring approach. This strategy begins with initial access, followed by trajectory estimation of the satellite and prediction of future beam directions, all aimed at minimizing overhead. While LEO satellites offer uninterrupted connectivity, their high-speed motion necessitates frequent handovers, which can result in decreased data rates. Reference [15] examines the signal-to-noise ratio (SNR) performance of LEO satellites utilizing fixed beams, specifically focusing on the influence of the beamforming codebook update period. The authors propose an algorithm that aims to mitigate SNR degradation by incorporating beam angle compensation and dynamic codebook prediction. Additionally, reference [16] introduces an adaptive tracking algorithm that addresses the beam alignment between a LEO satellite and a ship-borne digital phased array. The algorithm consists of two stages: an observation stage utilizing a 2D multiple signal classification algorithm to estimate the beam direction of the LEO satellite, and a tracking stage employing an extended Kalman filter to facilitate beam alignment following the observation stage.

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2.3 DC 3

Accurate synchronization and beam-finding are critical aspects in LEO NTN, which need to be solved to enable future satellite mega-constellations. The following sub sections highlight the challenges in LEO NTNs concerning synchronization and beam-finding. Details and further challenges can be found in the literature [1-5].

Synchronization

Frequency and timing synchronization in NTNs is critical as satellites are fast-moving objects in relatively far distances covering large cells compared to terrestrial networks. Due to the high satellite speed, high Doppler shifts occur and may result in misaligned transmission and reception frequencies between the user and the satellite node. Moreover, the misalignment will also deviate among users in a cell. Consequently, frequency resynchronization caused by the Doppler shifts, and thus to the relative satellite velocity, is needed to ensure the orthogonality of modern multi-access schemes. Due to the path of the orbit, the propagation delay at low elevation angles is much larger between users at the cell edge compared to users at the center, resulting in synchronization issues due to the different delays. To ensure synchronization, the transmission timings between the users need to be aligned to the satellite node and, depending on the delay, additionally delayed by an offset. Also, the initial access and the channel estimation are complicated since these are established by detecting synchronization signals between the user and the satellite node. In NTN, the channels might vary quickly with time resulting in obsolete estimations due to delays and satellite movement. As a consequence, precise frequency and time synchronization are needed [1,3,5].

Beam-finding

In contrast to terrestrial networks, the cells in LEO NTNs move over time as the satellites move along their orbit with high velocity resulting in frequent cell alternating and increased handovers. Further, future LEO NTNs will operate in millimeter wave (mmW) frequencies to achieve broadband communication with high channel capacities. Typical LEO NTN nodes that operate with mmW frequencies utilize phased array antennas creating fine beams to ensure link budget requirements, thus resulting in a user-aligned communication link. Further, the high speed of LEO satellites along the orbit dominates the relative user mobility and limits the visibility window. Accurate beam alignment and following are key challenges affecting user-tracking, handover, and radio frequency link failure recovery. As a result, efficient beam-finding is required to enable these features without resulting in frequent failures or ping-pongs [1-5].

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2.4 DC 4

Synchronization Methods for Non-Terrestrial Networks

Synchronization plays a crucial role in non-terrestrial networks, particularly in satellite communication systems. Time-Division Multiple Access (TDMA) emerges as a widely employed technique for achieving synchronization. By partitioning the available time into discrete slots and assigning specific slots to individual users, TDMA ensures synchronization between satellites and users. The adoption of TDMA as a synchronization method brings notable benefits, including efficient and coordinated utilization of the wireless medium. This leads to improved energy efficiency, reduced network delays, and minimized collisions, thereby enhancing the overall performance of the wireless communication system. To further enhance energy efficiency and minimize network delays, Wang et al. [1] have proposed a joint TDMA Medium Access Control (MAC) protocol known as SL-MAC, tailored specifically for Low Earth Orbit (LEO) satellite Internet of Things (IoT) systems.

In addition to TDMA, other synchronization methods find application in non-terrestrial networks. Code Division Multiple Access (CDMA) stands out as an efficient communication technique that allows multiple users to share the same frequency band. By employing distinct spreading codes for each user, CDMA enables synchronization through correlation of the received signal with the corresponding code. This correlation enables simultaneous transmission and reception, further enhancing the efficiency of non-terrestrial communication networks.

On the other hand, Orthogonal Frequency Division Multiple Access (OFDMA) presents another synchronization method for non-terrestrial networks. OFDMA divides the available spectrum into multiple orthogonal subcarriers, with each user allocated a specific subset of these subcarriers for communication purposes. The accurate estimation and compensation of frequency and timing offsets enable synchronization within OFDMA systems, leading to efficient and reliable communication.

Furthermore, in the deployment of small satellites, space, weight, and budget limitations necessitate the use of relatively wide-beam antennas [2]. As a result, interference mitigation becomes crucial in the Inter-Satellite Link (ISL) context. In the scenario of intra-plane ISL, where the relative distances between the transmitter and receiver remain fixed, fixed access schemes such as Frequency Division Multiple Access (FDMA) or Code Division Multiple Access (CDMA) offer simple and appealing solutions [3]. However, FDMA requires careful design of the frequency reuse factor to mitigate interference along the satellite's orbit, albeit at the cost of higher bandwidth requirements. On the other hand, challenges associated with CDMA, such as synchronization issues and near-far effects, can be overcome by employing asynchronous CDMA with non-orthogonal codes. These strategies enable efficient and reliable communication in the face of synchronization complexities.

By leveraging various synchronization methods, including TDMA, CDMA, and OFDMA, non-terrestrial networks can effectively manage resource allocation, reduce interference, and optimize overall system performance. These techniques contribute to the seamless operation of satellite communication systems, improving their efficiency, reliability, and capacity to meet the demands of modern non-terrestrial applications.

Beam-Finding Methods

Focus on this section has been given to Digital beamforming, which is a significant area of interest in the field of beamforming techniques, particularly when applied to non-terrestrial networks. It represents a method that leverages digital signal processing and the utilization of multiple antenna elements to optimize the radiation pattern of an antenna array. The primary objective is to shape and steer the transmitted or received beam towards a specific direction or target. This is achieved by making precise modifications to the phase and amplitude of the signals received by each individual antenna element. The use of digital beamforming grants the system the ability to exert dynamic control over the characteristics of the beam.

In [4], the resource sharing beamforming access (RSBA) scheme, a grant-free access scheme, is investigated. The design incorporates a blind and open-loop beamformer, eliminating the need for channel estimation or beam scanning. The proposed beamforming technique falls under the category of digital beamforming solutions, which avoid the use of fixed beamforming matrices. This technique enables IoT access to a LEO satellite equipped with a digital beamforming phased array. Unlike the hybrid beamforming architecture with a fixed beamforming matrix, the proposed setup offers spatial processing that provides flexibility in steering the LEO reception pattern to any desired location. The key feature of the proposed beamformer is its blind nature, which eliminates the need for acquiring channel state information at the receiver (CSIR) or performing beam scanning in the spatial domain. Therefore, it operates as an open-loop beamforming technique. This eliminates the complexity associated with precoding schemes that require user feedback due to the adoption of frequency division duplexing (FDD) in satellite communications. Additionally, the proposed beamformer does not rely on previous channel estimation, making it suitable for IoT grant-free (GF) access and bypassing the limitations of using time division duplexing (TDD) schemes in satellite systems [5]. Furthermore, the satellite line of sight channel simplifies the problem of identifying the direction of arrival for users, which is more challenging in terrestrial communications due to multipath-induced ambiguity. Finally, the implementation of the proposed smart beamforming, where the output of each active antenna element is directly weighted, reduces the collision probability in massive IoT access.

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2.5 DC 5

Beam finding

Mm-wave antennas can be diverse in its design, but one parameter is always the same for all mm-wave antennas which is high gain. Due to the property of mm-wave, free space propagation losses are high compared to microwave propagation for the same distance. High gain, however, is coupled to the beamwidth which results in smaller beam in exchange for higher gain. In mm-wave, this beam width can be as small as couple degrees or even less than 1 degree. This creates a new problem; the beam is very sensitive for disturbances. Thus, a solution is required to find this beam and ability to track it.

A solution can be found in Photonics, using Lidar sensing information to track the receiver combined with a Recurrent neural network to successful predict beam decisions. This method has proven to be able to predict 88.7% accuracy for optimal beam decisions [1]. Another solution is shown within the Terahertz range which is to use motion sensor to track the receiver. This track allows the systems to estimate the displacement of the center of the antenna half-power bandwidth allowing to drastically decrease the search space during beam alignment procedure. It is shown that this method, will decrease the outage due misalignment by 10% to 30% [2].

Synchronization

Synchronization is an important aspect within communication. For cooperative tasks, both transmitter and receiver must be synchronized. Synchronization between satellites and base stations on earth can be challenging thus many methodologies are investigated. A very typical method is the two-way message exchange, but the accuracy of synchronization and ranging is decreasing when the clock is not ideal. And clock is assumed to be fixed for certain amount of time which is not always true. Thus, a new method is shown using doppler frequency shift phenomena combined with and Extended Kalman Filter for time synchronization and ranging method. Simulation has shown that improved the accuracy of the tie synchronization and has a higher convergence time compared to only using very recent published method of using only Extended Kalman Filter [3]. Although the simulated results are promising, more research is required into synchronization of NTN networks.

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2.6 DC 6

LEO satellite antennas, typically placed on spacecraft in LEO altitudes (~600 Kms), are characterized by coverage requirements (wide) up to 60 degrees half-cone angle. The LEO constellations, which are aimed to have hundreds of satellites, must have antennas designed with an aim to easily reproduce so as to benefit from the production of many identical elements. Hence, the antenna must address the ease of manufacturing, assembly, integration, and testing. Additionally, LEO satellites encounter extreme corrosive effects due to the presence of atomic oxygen, and this effect is the most predominant on the antenna surface. This may be of certain significance to the thermal performance of the antenna [1]. With respect to the diverse requirements of LEO antennas, various research has been carried out in terms of beam scanning techniques, integration, and mass, to realize the optimum design for the LEO missions. LEO systems require their terminals to be able to steer its beam while they move in the sky. The steering/scanning method employed can help classify antennas into mechanical and electrically scanned antennas. Research to introduce new beam scanning techniques has been carried out. For instance, concerning mechanical scanning, full 2-d pointing systems using complex mechanical gimbals, hybrid systems, planar quasi-optical systems, and rotatable surface systems have been employed for beam scanning. On the contrary, in electronic scanning, tunable reflect and transmit arrays, liquid crystalbased antennas, electronic chipsets, and Si multichannel chips are used for beam scanning. [2]-[3]. Besides, beam tracking and beam synchronization techniques adopted for the LEO satellite mission play a significant role to maintain the constant connection between the users and the fast-moving satellites. Unlike GEO satellite communications, the channels of the LEO satellites missions are subject to an additional demeaning factor of Doppler shifts due to its movements at a speed of roughly 9.7 km/s and the signal processing techniques used for tracking and synchronization of beam aids in maintaining the quality of service (QoS) of link and improving the availability. Beam-tracking techniques rely on beamforming vectors such as the channel state information, beamforming angle, and direction of the beam to appropriately track the incoming beam. On the other hand, parameters such as carrier frequency offset, carrier phase offset, sampling phase offset, etc., are used for synchronization. A few state-of-the art beam tracking and beam synchronization techniques are presented hereafter. In [4], a simple tracking technique based on a multibeam antenna using a dual parabolic cylindrical reflector with automatic orientation is presented. Frequency Diverse Array Antenna for Tracking Low Earth Orbit Satellite with direct and continuous scanning is proposed in [5]. A Frequency Diverse Array (FDA) antenna providing range-angle-time dependent beampattern is reported in [6]. On the other hand, in [7], a coarse synchronization-based technique is proposed for receiving inbound satellite signals while managing sensitivity affected by large Doppler shifts. An optical phase synchronization using the power feedback loop technique is demonstrated in [8].

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2.7 DC 7

Satellites use MIMO (Multiple-Input Multiple-Output) beam tracking techniques to enhance their communication links with ground stations. MIMO beam tracking allows satellites to dynamically adjust their antenna beams to maintain a strong and stable connection with the receiving antennas on the ground, even as the satellite and ground station are in motion relative to each other. The satellite is equipped with an array of antennas that can transmit and receive signals in multiple directions simultaneously. These antennas are often arranged in a phased array configuration, which allows for electronic steering of the antenna beams. By adjusting the phase and amplitude of the signals across the antenna array, the satellite can form and steer multiple beams simultaneously. When establishing a connection with a ground station, the satellite performs an initial beam acquisition process. This process often involves sending test signals and measuring the quality of the received signals at the ground station. This process is called beam finding. Once the initial beam is acquired, the satellite continuously monitors the channel conditions by estimating the quality of the communication link. As the satellite and ground station move relative to each other or experience changes in the environment (such as atmospheric conditions or interference), the satellite adjusts the antenna beams to maintain an optimal connection. This is achieved by periodically evaluating the channel conditions and updating the beamforming parameters to direct the beams towards the best path. The satellite utilizes feedback from the ground station to adapt its beamforming parameters and improve the communication link. Sophisticated algorithms are employed on the satellite to dynamically adjust the beamforming parameters based on the received feedback. These algorithms take into account various factors such as signal quality, interference levels, Doppler shifts, and other environmental conditions to optimize the beam direction and shape for maximum signal strength and minimal interference.

A frequency reuse based Massive MIMO scheme has been proposed in [1] for LEO satellite communication. A space based user grouping algorithm has been developed for the user management with statistical channel state information sCSI resulting in high data rate in the system. In [2] a satellite handover scheme has been presented for LEO satellite communication. During the handover process, block length has been reduced to achieve a faster response time. Capacity evaluation using this finite block length shows good results in terms of signal-to-interference-plus-noise ratio (SINR). For high speed LEO satCom, beam prediction becomes an difficult owing to the frequent switching. Beam prediction method based on overhead angle has been discussed in [3].

Synchronization

In satellite communication, signal between the satellite and the ground station terminal needs to be synchronized to ensure proper communication between transmitter and receiver. This becomes a challenge given the fast speed of Low Earth Orbit satellites (LEO) satellite. Movement of the satellite causes time delay as well as the doppler shift in the received signal. Doppler shift will results in carrier frequency and phase offset, resulting in degraded performance of the system. For the optimal performance of 5G receiver, this phase shift should be less than 5ppm. For a satellite operating at 30GHz, the observed doppler shift can reach to 750kHz, causing the frequency offset to 25ppm, way higher than the recommended value [4]. Hence, dedicated efforts are performed to reduce the frequency offset and ensure the synchronization of this system for optimal communication performance.

In [5] doppler shift estimation algorithm has been proposed for a LEO satellite system. First integral and fractional part of the doppler has been evaluated within a prime synchronization signal and next precision rate has been found between two consecutive synchronization signal. Another time synchronization method has been proposed in [6] using symmetric and conjugate Zadoff-Chu (ZC) sequences. This method achieves as good SNR system performance with low complexity. An adaptive algorithm that can estimate the frequency offset variance has been presented in [7]. This method can provide acquisition for signals with very low SNR by receiving one training signal only. For an orthogonal frequency division multiplex (OFDM) systems, repeated short pseudo-noise sequences based preamble system has been discussed in [8]. This system provides easier detection of the signal as compared to conventional complex detection system.

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2.8 DC 8

Mobile satellite communications are a key enabler of non-terrestrial networks to deliver services globally, from rural villages to oceans where conventional terrestrial networks become inaccessible [1]. In addition, LEO orbit has attracted the most interest from the community, given its major advantages over other orbits, such as its reduced delay [2]. An architectural trend for future missions is to have Distributed Satellite Systems (DSS), where two or more satellites are involved, matching the paradigm of the space industry where smaller and cheaper satellites are being developed [3] [4]. Furthermore, its potential increases when it is intended to behave as a single system with several distributed transceivers, known as Distributed Beamforming (DBF) [5].

These different applications require a correct and perfect synchronization between all the elements that make up the system, both between inter-satellite links and in links with the terrestrial segment, where factors such as time, frequency and phase are involved.

For instance, for DSS communications, Multiple Input Multiple Output (MIMO) techniques can be applied if all terminals involved are synchronized at the symbol level [6], thus implying clock accuracies with nanosecond precision to guarantee, at least, a bandwidth of a few hundred MHz [7]. Indeed, synchronization is a limiting factor for some applications to be feasible [8].

Achieving this time, frequency and phase synchronization is complicated when the reference signal is different at each of the nodes of the distributed system, and is further complicated if the distance between these nodes is greater than the wavelength of the signal and if this distance varies over time due to relative movement [9].

To achieve this synchronization, algorithms based on one of the three parameters mentioned above are used. After all, the aim of the synchronization algorithm is to converge all the initial reference signals into a single one with the best possible accuracy. A critical aspect is time synchronization together with phase synchronization [5].

An example of time synchronization is the one shown in the article [10]. The transmitted signal is considered frequency shifted in order to take into account the Doppler effect on LEO satellites. The received signal is considered to be temporally shifted with the satellite's internal clock. To estimate this transmission delay, an FFT is performed in the frequency domain and the received cells are multiplied by the conjugate of the transmitted cells. This gives an estimate of the transmission channel in the frequency domain. By performing an IFFT, we obtain it in the time domain. In this way, a response equivalent to a simple delay is obtained, where a Dirac delta is involved. Finally, the delay is estimated from the amplitude of each element of the estimated time response, thus locating the maximum value. Although the operation is somewhat complex because it involves IFFTs, the time estimation shows quite optimal values.

On the other hand, a phase synchronization algorithm is shown in the article [11]. It investigates a multi-loop phase synchronization system with a special loop filter to compensate for the linear phase increase caused by a uniform motion between two remote nodes, such as the moving satellites in this case.

Finally, in the article [6], an example of a carrier synchronization algorithm is shown. For this purpose, a baseband scheme for frequency and phase synchronization is developed, which uses a phase tracking algorithm based on Kalman filtering or PLL [12].

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2.9 DC 9

Synchronization

Non-terrestrial networks (NTNs) are characterized by stringent carrier frequency, phase, and sample time synchronization requirements [1]. In addition to effects common with terrestrial networks, signals in NTNs, especially those incorporating low-earth orbit (LEO) satellites, suffer from the so-called Doppler shift due to the relative motion between satellites and user equipment (UE) [2].

In reference [3], a frequency synchronization scheme is presented for a bistatic Synthetic Aperture Radar (SAR) that utilizes the direct return signal for compensation of a time-varying Doppler shift. Reference [4] on the other hand highlights that terrestrial network timing synchronization methods can be adopted for NTN communications. Zhao et al. [5], improve localization and synchronization accuracy by considering both time-of-arrival measurements and the sequential Doppler shift. Finally, the authors in [6] introduce a phase synchronization scheme that counteracts the self-interference of full-duplex systems by transmitting two carrier signals around a central frequency.

Beam-finding

For sufficient link budget, NTNs incorporate highly directional beams. Therefore, capable tracking and beam-finding techniques are vital for seamless handovers and to maintain uninterrupted links in networks that feature high relative velocities between their nodes [7]. Zhao et al. [8] combine mechanical feedback and a perturbation-based tracking algorithm. Additionally, traditional beam-finding methods can suffer high computational costs and make unrealistic assumptions about signal and noise models. In reference [9], a neural network-based approach is presented that outperforms traditional DoA algorithms for conditions like those of the training environments. Finally, in reference [10], the beam-finding process is split into an observation phase and a tracking phase. During the observation phase, the MUSIC algorithm is used to estimate the satellite beam direction. In the tracking phase, extended Kalman Filter adaptive tracking improves the estimation accuracy of the DoA.

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2.10 DC 10

In Non-terrestrial Network, satellites and airborne are moving very fast and feature larger cells compared to terrestrial networks. In fact, it causes synchronization problems because there is a large differential propagation delay between users inside the same cell [1]. Further, satellites and airborne velocity introduces a high Doppler frequency offset and normalized carrier frequency offset (CFO), where produces a lack of uplink synchronization and significant difference in timing advance (TA) between user equipment's located at the same cell. Currently, the User equipment uses global navigation satellite system (GNSS) to resolve the UL synchronization issues, but it is not always feasible for low power user equipment such as IoT devices. To solve this problem, it is proposed to compensate the TA and Doppler with respect to a reference point in the cell, while considering the GNSS capabilities [2].

The UE tries to find accessible base stations and read information about access settings. These are offered in the SS block that the base stations send, which also comprises the PSS and SSS (primary and secondary synchronization signals) [3]. The random access (RA) technique is utilized to: establish synchronization to new cells; resynchronize to the present service cell; and request UL scheduling if a dedicated scheduling-request resource has not yet been established. The RA procedure is used by a non-terrestrial network (NTN) terminal that is still in the IDLE mode to establish uplink synchronization in the CONNECTED mode, connect to a new cell during initial access, or request resources for uplink transmission [3].

The task of adjusting the TA and Doppler offset with regard to an RP (reference point) in a cell falls on the ground base station. The BS pre-compensates the offsets in the DL and post-compensates the offsets on the received UL signal. The UE calculates the total of the local oscillator offset and residual Doppler during the DL synchronization procedure. To calculate the offsets, the UE has to know its own position, the position and velocity of the satellites, and the coordinates of the RP. In addition to the use of GNSS to address this issue, [4] proposes a different approach that involves employing a positioning solution based on time difference of arrival (TDOA) data [2].

In [4] proposes a time-frequency synchronization scheme for OFDM-based wireless communication over large Doppler frequency offsets. First, coarse symbol timing and frequency synchronization are achieved based on a specially designed preamble. Second, it uses a correlation operation between PSS symbols to achieve precise symbol timing synchronization. Finally, the remaining frequency offset is estimated and tracked by the first-order filter's frequency-locked loop. [5] proposes an improved time synchronization method for LEO satellite communications. It takes advantage of the symmetric properties of ZC sequences and the conjugation of ZC sequences to achieve good performance with low complexity.

The cross-correlation algorithms [6] and the autocorrelation algorithms can be used to synchronize time in an OFDM system. A few studies have synchronization for integrated 5G LEO SatCom systems as their main emphasis. [7] employs a parallel detector where each detector employs the PSS cross-correlation with a predetermined frequency offset. When the frequency offset is quite big, this approach performs well, but its implementation is highly difficult. [8] employ modified prolate spheroidal sequences (DPSS) to reduce the significant frequency offset, but this method is difficult and necessitates knowledge of the maximum Doppler shift.

On satellite's Ka-band intersatellite link (ISL) payload employs a narrow beam phased array antenna [9] to transmit and receive signals. A TDMA ranging system was created employing dual one-way pseudo-code measurement. The dual one-way pseudo-code measurement is decoupled in the Ka-band ISL system's two-way time synchronization approach in order to determine the relative clock difference and separation between two satellites.

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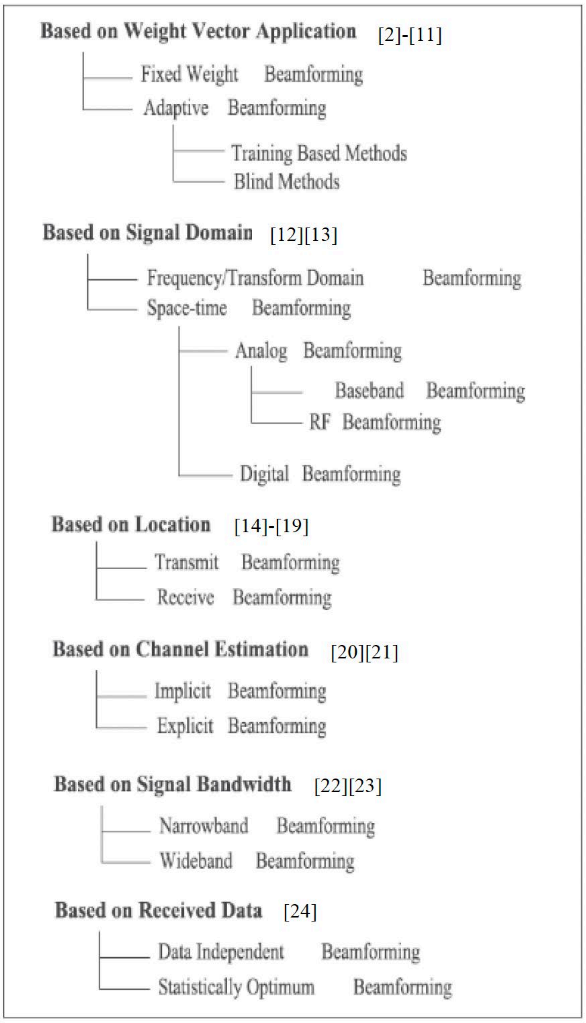
2.11 DC 11

Non-terrestrial networks employing mm-wave frequencies would most likely require beamforming methods in order to achieve sufficient coverage and to compensate for excessive path and penetration losses [1]. Figure 1 shows some typical beamforming approaches that are often used in practice.



Along with beamforming challenges, non-terrestrial networks would also face synchronization issues, especially at low elevation angles where there may be a very large differential propagation delay between users at the cell edge and those at the cell center [25]. Several techniques on synchronization in non-terrestrial networks, especially for LEO satellites, have been listed in literature. In [26], a synchronization technique based on Zadoff-Chu sequence has been proposed to counter the adverse effects of large doppler frequency shifts. In [27], a Maximum Likelihood estimation approach has been suggested. Certain other techniques involving Deep Neural Networks (DNNs) are also being considered for synchronization [28][29].

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Beam Finding

Beam finding is a very critical part of the current MIMO communication systems. Whether in cellular communications, satellite communications, radar applications, acoustic channels, or medical applications, utilizing a beamforming method helps increase the system's performance. In the context of beamforming, if there is a finite number of predefined selections for beamforming vectors or precoding matrices, the most suitable selection must be made at any given time, depending on the current state of the wireless channel. After an initial access period, the beamforming vector/precoding matrix may need updates as the channel conditions change, especially when at least one of the terminals is mobile. The updates in the beamforming process with respect to the channel state are called beam tracking.

In [1], a graph-based scheduling and feed space beamforming framework for downlink systems are proposed to minimize inter-beam interference in LEO high-throughput satellite (HTS) systems. They construct a graph and cluster users to find the maximum clique. Then, a minimum mean square error (MMSE) beamforming matrix is used for each cluster to better separate users and minimize interference. [2] reviews the MIMO beamforming algorithms for B5G/6G LEO satellite systems and proposes a new beamforming strategy that decouples the problem of finding different users' beamforming vectors with a closed-form solution to maximize each users' signal-to-leakage-and-noise ratio (SLNR). Each LEO satellite from a constellation should be able to cover all terminals within its field of view to obtain global service efficiently. A stepping beam constellation can serve predefined areas instead of covering the whole area where there are unpopulated regions. In [3], a new algorithm for validating new service areas in LEO stepping beam constellations is proposed. LEO satellite communication is examined for its potential for positioning, navigation, and timing in [4], where the potential of beam-based multiplexing techniques is discussed.

Beam pointing accuracy is critical for LEO constellations to provide high data rates. However, frequent repetition of beamforming and channel estimation algorithms increases the overhead, causing a loss in spectral efficiency. Authors in [5] propose a staring beamforming strategy by starting with initial access, estimating the satellite trajectory, and predicting the future directions of the beam to reduce the overhead. Even though LEO satellites can provide seamless connectivity, high-speed motion requires frequent handovers, which can cause decreases in the data rate. A handover-aware downlink beamforming strategy is presented in [6] to overcome the difficulties of handover. In [7], the SNR performance of LEO satellites with fixed beams is investigated with respect to the impact of the beamforming codebook update period. An algorithm is proposed to limit SNR degradation with beam angle compensation and dynamic codebook prediction. An adaptive tracking algorithm is proposed to handle the beam alignment between a LEO satellite and a ship-borne digital phased array [8]. There is an observation stage where a 2D multiple signal classification algorithm is used to estimate the beam direction of the LEO satellite and a tracking stage where an extended Kalman filter is designed for beam alignment after the observation stage.

Synchronization

Synchronization is a critical part of digital communication systems. Different synchronization errors can be observed depending on the nonidealities of the hardware or the imperfections in the baseband processing algorithms. Synchronization offsets can be of different types, such as carrier frequency offset (CFO) and, carrier phase offset (CPO), sampling phase offset (SPO). The issues related to synchronization in LEO satellite communications are similar to the previous digital system. However, there is a particular case for the LEO satellites: the Doppler frequency shift due to very rapid movements on their orbits around the world. Even if the ground station is stationary, severe Doppler shifts can be observed in LEO communication links which need to be considered for accurate synchronization and reliable high-rate communication in the later stages.

[9] considers a timing synchronization method with the Zadoff-Chu sequence to eliminate large Doppler shifts in LEO satellite systems. The focus is on timing synchronization in [10], where the authors propose a method that is not affected by frequency offsets, where they rely on the same frame structure of NR and the conjugate symmetry of the primary synchronization signal, and also a delay-superposition method to improve the performance. The use of application-specific integrated circuits (ASIC) in LEO satellites is examined in [11], where the authors proposed a computing resource multiplexed carrier synchronization joint coherent demodulation scheme to meet the low SNR threshold, short synchronization time, and log logic resource consumption requirements of ASIC. The features of frequency synchronization algorithms in the DVB-S2X standard are investigated in [12], where the Doppler shifts are calculated in the Ka-band, and system performance is studied. Time and frequency synchronization for the downlink of 5G NR systems in LEO satellite channels is examined in [13]. The maximum log-likelihood criterion for timing offsets is used with a priori information that the maximum Doppler shift of the LEO satellite-ground link is within a specific range with discrete prolate spheroidal sequences (DPSS). A CDMA system is considered for the uplink of LEO satellite systems for timing synchronization that utilizes non-coherent pseudo-code ranging [14].

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An undesirable phenomenon that can take place during a communication link whenever there is relative movement between transmitter and receiver is the Doppler effect. In future 6G systems, where satellites in Low Earth Orbit (LEO) are expected to play a major role, frequency shifts due to the Doppler effect might be considerably pronounced because of the relatively high speed of the satellites and the elevated associated frequency ranges. In this context, synchronization and beam-finding techniques are relevant to carry out reliable communication within the aforementioned scenario. Based on these considerations, in the following we discuss state-of-the-art methods to perform such tasks. Current systems for communication in LEO satellites utilize Orthogonal Frequency Division Multiplexing (OFDM), which is a modulation strategy very sensitive to Doppler effects [1-2]. An alternative that has demonstrated promising results when using Multiple Input, Multiple Output (MIMO) systems is the Orthogonal Time Frequency Space (OTFS) modulation scheme [3]. In contrast to OFDM, which yields a signal representation in the time-frequency domain, OTFS is done in the delay-Doppler domain, consequently being more resilient to Doppler shifts [4]. In addition to that, OTFS makes it possible for a more sparse channel representation in the delay-Doppler domain than in time-frequency. This enables a reduction of complexity in receiver design and channel estimation [5]. Furthermore, OTFS can be implemented by applying 2D transforms over different available modulation schemes. Moreover, OTFS provides an improved spectrum usage in comparison to OFDM-based systems [2].

In addition to OTFS as a synchronization alternative, state-space approaches can be applied for this task [6]. In [6], an extended Kalman filter is developed which can also be used when a mobile receiver (in space or on Earth) is connected to multiple transmitter satellites. Simulations including 2 or 3 transmitter satellites show, in respect to a decision-feedback loop strategy, better performance in terms of bit error rate versus Signal-to-Noise Ratio (SNR). This approach has even demonstrated a behavior very close to the optimal case, namely without Doppler. In terms of Mean Squared Error (MSE), the extended Kalman filter showed good capability for tracking the Doppler shifts, even with relatively low SNR values. Lastly, with a sufficiently high SNR, the respective MSE is relatively close to the respective Cramer-Rao lower bound. Current mmWave-enabled LEO satellite systems apply MIMO-based strategies for beamforming and they take advantage of Line-of-Sight (LOS) conditions [7]. One strategy that has been studied in this scenario is the determining dynamic beam positions for beam-hopping techniques in order to reduce the transmission delay due to data package queueing [8]. It has been found that the number of beams is negatively correlated to the queueing delay and the beam position division problem is formulated to cover all users with the least amount of beams. This problem is solved taking into consideration the user and traffic distribution. Simulation results that the queueing delay can be considerably reduced.

Other techniques can be applied for beam-finding in LEO systems. For example, tensor-based operations for array signal processing have been investigated and have potential to be used in the discussed scenario [9]. Furthermore, quaternion-valued processing can be used to address problems involving, for instance, antennas whose directions are orthogonally polarized being employed transmitter and receiver sides with a 4D modulation scheme across these two polarization diversity channels [7]. With quaternion-value adaptive algorithms, it is even possible to recover interference suppression to recover the original 2D signals.

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Non-terrestrial networks (NTNs) are poised to revolutionize the telecommunication landscape, providing global connectivity with potentially lower latency and improved reliability. Two fundamental challenges faced by NTNs are efficient synchronization and beam-finding. This review aims to summarize the state-of-the-art solutions proposed in these two areas, i.e., synchronization and beam-finding.

Synchronization in NTNs

Synchronization in NTNs is critical due to their high mobility and dynamic topology. The study of [1] presents a novel approach to addressing the challenges posed by the conventional random access (RA) preamble design in the framework of 5G New Radio (NR) enabled low earth orbit (LEO) non-terrestrial networks (NTNs). Traditional RA preamble designs are unable to satisfy the link budget in NTNs due to the considerable distance separating terrestrial terminals and satellites, resulting in subpar performance in areas such as Physical Random-Access Channel (PRACH) detection and timing estimations for uplink synchronization. Moreover, the relatively high-speed motion between the satellite and the terminal can exacerbate the frequency offset, further impeding PRACH detection. Hence, the authors introduce an innovative RA preamble format that leverages a multi-length Zadoff-Chu (ZC) sequence. This adaptation is geared towards mitigating the inherent ambiguity in RA preamble estimations, with the study delving into an analysis of symmetric transmission of the proposed preamble. The paper further contributes to this field by proposing two novel algorithms for the detection of PRACH, showcasing their functionality through simulation results. These simulations indicate that the proposed RA preamble is capable of fulfilling the rigorous performance demands of LEO-based NTNs. Importantly, the study highlights the superior robustness of the second proposed algorithm in terms of handling timing error and frequency offset.

In the study of [2], the authors delve into the topic of non-terrestrial networks (NTN) as they extend the reach of coverage. Though current 5G new radio (NR) techniques largely focus on terrestrial networks, the exploration of NTN support through 5G NR is being tackled by the 3rd Generation Partnership Project (3GPP) as of Release 15. The study delves into the advancements achieved by the first release of NR NTN, completed in Release 17. A critical issue in both terrestrial networks and NTN is uplink time synchronization. In its absence, interference among multiple users can occur, as well as misalignment between uplink and downlink. Notably, the NR NTN introduces an open-loop timing advance (TA) system, including common TA and UE-specific TA, a significant divergence from the 5G NR method. In this regard, authors of [2] outlines the latest developments in Release 17, offering detailed solutions, procedures, and evaluation results concerning uplink synchronization in NR NTN. This research significantly contributes to the understanding of time synchronization within the context of NR NTN, thereby providing vital insights into tackling the unique challenges it presents.

On the other hand, the authors in [3] delves into the evolving sphere of Non-Terrestrial Networks (NTNs), shedding light on their significance for upcoming generations of mobile communication systems. While NTNs present exciting market prospects and innovative use cases for the future, signal propagation over the NTN channel introduces new challenges that compromise various procedures of current deployed standards, e.g., the fourth and fifth generation of mobile communication (4G & 5G) and narrowband internet of things (NB-IoT). One of the critical procedures affected is the random access (RA) procedure, which is instrumental for acquiring isochronous uplink synchronization among different users in various deployed scenarios. The authors additionally analyze how the considerable increase in the communication link delays resultantly affects the RA procedure. Thus, proposing new solutions to surmount the incurred challenges. In their examination of various existing solutions and new proposals, the authors provide a nuanced trade-off analysis, maintaining a broad scope by targeting 4G, 5G, and NB-IoT systems. The paper's unique contribution comes with its practical validation through an experimental setup against a selected KPIs for RA procedure, i.e., the time required for a single user (UE) to establish a connection with the base station (BS) over an NTN channel, all implemented in an open-air interface. The study uses hardware that emulates signal propagation delay. This experimental laboratory testbed validates various solutions while also uncovering fresh challenges that are not previously considered in the literature. A key performance indicator (KPI) for the RA procedure over NTN is shared – the time required for a single user to establish a connection with the base station. This research is instrumental in deepening the understanding of synchronization issues in NTN, taking a step further by translating theory into practice.

Beam-finding in NTNs

Beam-finding is crucial in NTN, especially with the prospects of introducing cell-free massive MIMO systems operating in Frequency-Range-2 (FR-2), i.e., mmWave bands. Moreover, beam-finding in harsh multipath environments requires solutions that are fast, robust, and efficient in terms of power and spectral efficiency. The study of [4] presents an innovative approach to manage capacity and radio spectrum in the context of sixth-generation (6G) Non-Terrestrial Networks (NTNs), particularly when there's a substantial number of devices requiring access to different broadcast services concurrently. The authors propose a move from traditional single-beam satellite systems to a high throughput satellite system, utilizing multibeam transmissions to augment the capacity, enhance spectrum utilization, and curtail interbeam interference. The study presented a dynamic multicast/broadcast single-frequency network (MBSFN) beam area formation (D-MBAF) algorithm. This approach clusters beams into dedicated MBSFN beam areas (MBAs). This method is geared towards boosting the overall data rate (ADR) of the multibeam NTN system while simultaneously serving the varying video content requirements of the NTN terminals involved. This dynamic algorithm applies multicast subgrouping to cluster NTN terminals into separate MBAs, each served at varying data rates. In this manner, the algorithm ensures efficient allocation of radio resources, mitigating interference among beams from different MBAs. The presented simulations performed under a variety of conditions attest to the proficiency of the D-MBAF algorithm, which are evident from the results KPIS such as average throughput, total data rate, utilization of resource blocks, and the count of transmitted layers. The outcomes show that their D-MBAF has a superior performance compared to both single-frequency multibeam transmission and multilayer video delivery strategies.

Similarly, in [5], authors explore the emerging field of integrated satellite-terrestrial communication networks (ISTCNs) within the context of sixth-generation mobile networks. ISTCNs are pivotal in addressing the communication needs for seamless global coverage and anytime access. The authors note that the sharing of spectrum resources between terrestrial and satellite terminals in ISTCNs leads to uneven and time-varying distribution of these resources for the satellite system. Existing beam scheduling algorithms that allocate satellite beams based on terminal demands fail to account for the dynamic changes in spectrum resources available for satellites, making them unsuitable for

ISTCNs. To address this issue, the authors propose a joint design of beam hopping and adaptive dynamic multiple access. This considered design integrates beam hopping, cognitive radio, and non-orthogonal multiple access technologies. Moreover, this proposed approach is adept at accommodating the fluctuating traffic demands and the variability of available spectrum resources in ISTCN, thus considerably enhancing the utilization of the spectrum. Through simulation results, the authors confirm the effectiveness of the proposed joint design scheme. They conclude the paper by discussing potential research directions and open challenges on the joint design scheme of beam scheduling and multiple access in ISTCN.

Overall, research of both articles signifies a substantial progression in the beam-finding methodologies for NTNs, i.e., 1) design of algorithms for managing beam formation and multicast subgrouping for improved data rate and spectrum utilization (c.f. [4]), and 2) introducing a novel approach that synergizes beam hopping, cognitive radio, and non-orthogonal multiple access technologies for efficient spectrum utilization (c.f. [5]).

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Synchronization is essential to ensure that the satellites' transmissions are coordinated and aligned properly. It is critical in inter-satellite communication systems to ensure proper coordination and timing alignment between satellites. When clock or local oscillator signals are generated locally at each of the distributed satellites, achieving exact synchronization in absolute phase, frequency, and time is a complex problem. That is why, the development of precise, robust, and resource-efficient synchronization techniques is essential for the advancement of ISLs.

Here are a few key aspects of synchronization in ISLs:

- Time Synchronization: Satellites in a network need to have synchronized clocks to establish precise timing for communication. This synchronization is typically achieved using highly accurate atomic clocks onboard each satellite. Time synchronization ensures that all satellites in the network operate on the same time scale, allowing coordinated communication.

- Frequency Synchronization: It ensures that the transmission and reception frequencies of the satellites are aligned. This alignment is necessary to avoid interference and enable proper reception of signals between satellites.

- Propagation Delays: Inter-satellite links involve signal propagation through space, which introduces delays. Satellites need to account for these propagation delays when synchronizing their transmissions and receptions. Precise calculations and adjustments are made to compensate for these delays and ensure accurate synchronization.

Literature review & State-of-the-art

The work presented in [1] provides a comprehensive overview of timing and carrier synchronization techniques specifically designed for wireless communication systems. It highlights the advancements and proposals in this area, focusing on terrestrial systems. Additionally, another survey [2] delves into synchronization protocols for clock synchronization in Wireless Sensor Networks (WSNs), offering valuable insights into the topic. However, it is important to note that both surveys primarily concentrate on terrestrial systems and do not cover the crucial aspect of synchronization in Distributed Satellite Systems (DSSs).

Clock synchronization and frequency/phase synchronization are the main two essential aspects of synchronization. In [3], synchronization methods are classified into two categories. The first classification is based on the utilization of feedback from an external node, leading to two types of synchronization algorithms: closed-loop and open-loop methods. The closed-loop methods involve receiving feedback from an external node, while the open-loop methods achieve synchronization without the involvement of any external node. The second classification is based on communication between the network elements. Some synchronization algorithms require the exchange of information among the distributed satellites, and this can be accomplished through two-way message exchange. Alternatively, certain algorithms can achieve synchronization through broadcast or one-way communication, where information is transmitted from a single source to the network elements.

The concept of Two-way time transfer (TWTT) which is the basis of most synchronizations protocols in the literature has emerged as a significant approach for clock synchronization. Its utilization in the field of satellite communication was initially discussed by the authors in [4], highlighting its efficiency. Subsequently, in [5], the performance of three clock offset prediction algorithms based on TWTT was compared for a master-slave architecture. This study aimed to assess their effectiveness in achieving accurate synchronization. Expanding on the application of TWTT, [6] focused on synchronizing four spacecraft in a distributed satellite formation flying scenario. Through the utilization of TWTT, the work in [6] achieved remarkable time synchronization simulation errors of less than ± 10 ns. Additionally, an important contribution in the field of two-way time synchronization accuracy was made by the authors of [7]. Their work extensively analyzed the impact of satellite motion on the accuracy of TWTT, providing valuable insights into mitigating potential synchronization challenges caused by satellite movement.

Several researchers have exploited the use of Ultra-Wide Band (UWB) signaling, high speeds clocks and Analog-to-digital converters (ADCs). [8] [9] [10] discussed the sets of multiple active receivers locked, and synchronous to a single transmitter, distributed consensus techniques, and distributed sensor positioning. Furthermore, [11] [12] proposed a propagation- aware time of flight (TOF) protocol and provide validation for the system using an atomic clock integrated on a chip and a 64 GHz hardware clock timestamp counter.

The study detailed in [3] thoroughly examines various techniques for frequency and phase synchronization, providing a comprehensive overview of the field. These techniques are classified into open-loop and closed-loop methods based on the presence or absence of feedback mechanisms.

- Closed-loop methods are further divided into two groups. The first group includes Iterative Bit Feedback algorithms, such as the notable One-bit Feedback (1BF) proposed in [13]. These algorithms achieve phase synchronization by applying random phase rotations to beamforming nodes and updating them based on feedback received from the target node. However, it has been observed that Iterative Bit Feedback algorithms are not well-suited for satellite communication due to their slow convergence and the long distances between satellites. The second group of closed-loop methods comprises rich feedback algorithms, which utilize more information to achieve synchronization. These methods include Explicit Channel Feedback [14], where each distributed node transmits a known sequence of training symbols to estimate the channel response, Aggregate Rich Feedback [15], where transmitters simultaneously send uncorrelated training sequences for estimating individual channel gains, and Reciprocity-based methods [16], where the transmitters leverage reciprocity to estimate downlink channel gains by observing uplink feedback signals from target nodes. Rich feedback methods offer greater robustness in synchronization but come at the expense of increased feedback overhead.

- Open-loop methods, on the other hand, are divided into two groups. The first group involves intra-node communication, such as: First, the Master-slave architectures [17], where a master node coordinates synchronization among distributed nodes. Second, Distributed Consensus Algorithm (DCA) proposed in [18], where each node broadcasts its carrier signal to all its neighbors, thus, the total received signal at any node is the superposition of its neighbors' carrier signals distorted by the channel. Lastly, based on the retrodirective principle the Two-way Synchronization (2WS) method has been proposed in [19]. The second group, known as blind or Zero-Feedback algorithms, aims to achieve synchronization without any feedback from the target node or other distributed nodes [20] [21].

By exploring the various synchronization methods, the study sheds light on their strengths and limitations in different contexts. It provides valuable insights for researchers and practitioners in the field of synchronization, particularly in the context of satellite communication and distributed networks.

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