IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received March 28, 2022, accepted April 14, 2022, date of publication April 22, 2022, date of current version May 3, 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3169499

Architectures and Synchronization Techniques for Distributed Satellite Systems: A Survey

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This work was supported by the Luxembourg National Research Fund (FNR), through the CORE Project COHEsive SATellite (COHESAT): Cognitive Cohesive Networks of Distributed Units for Active and Passive Space Applications, under Grant FNR11689919.

ABSTRACT Cohesive Distributed Satellite Systems (CDSSs) is a key enabling technology for the future of remote sensing and communication missions. However, they have to meet strict synchronization requirements before their use is generalized. When clock or local oscillator signals are generated locally at each of the distributed nodes, achieving exact synchronization in absolute phase, frequency, and time is a complex problem. In addition, satellite systems have significant resource constraints, especially for small satellites, which are envisioned to be part of the future CDSSs. Thus, the development of precise, robust, and resource-efficient synchronization techniques is essential for the advancement of future CDSSs. In this context, this survey aims to summarize and categorize the most relevant results on synchronization techniques for Distributed Satellite Systems (DSSs). First, some important architecture and system concepts are defined. Then, the synchronization methods reported in the literature are reviewed and categorized. This article also provides an extensive list of applications and examples of synchronization techniques for DSSs in addition to the most significant advances in other operations closely related to synchronization, such as inter-satellite ranging and relative position. The survey also provides a discussion on emerging data-driven synchronization techniques based on Machine Learning (ML). Finally, a compilation of current research activities and potential research topics is proposed, identifying problems and open challenges that can be useful for researchers in the field.

INDEX TERMS Synchronization, distributed satellite systems, distributed beamforming, remote sensing, satellite communications.

I. INTRODUCTION

Distributed Satellite Systems is a very promising architecture for future remote sensing and communication missions [1], [2]. The term DSS refers to satellite systems with two or more spacecraft communicating to accomplish the mission goal. Nowadays, most missions are DSSs, in part influenced by the space industry's paradigm shift toward smaller and cheaper satellites [2]. Its potential increases with the use of signal coherent processing methods from different platforms, especially coherent transmission and reception, which implies that the system behaves as a single unit with collocated transceivers, also known as Distributed Beamforming (DBF). This entails the improvement of several DSS applications such as Earth observation, geolocation, navigation, imaging, communications, among others. However, it requires strict time, frequency, and phase synchronization among the distributed nodes.

For example, deep space communications could be accomplished by DSSs applying distributed multiple-input and multiple-output (MIMO) techniques [3] if the terminals at each end of the link are synchronized at symbol level.

The associate editor coordinating the review of this manuscript and approving it for publication was Fei Chen.

This implies that the stations need to maintain synchronized clocks with sub-nanosecond accuracy to guarantee a bandwidth of a few hundred MHz [4]. Another example can be Earth observation applications based on distributed Synthetic aperture radar (SAR) interferometry. In this case, the final resolution depends on the accuracy of the phase synchronization achieved between the satellites [5]. For some applications, the synchronization requirement is the critical limiting factor in making practical implementations possible [6]. In those cases, the level of effort, power consumption, and complexity required for the synchronization algorithm may be higher than those needed for the mission itself.

Achieving exact phase, frequency, and time synchronization is a complex problem when the clock reference signals are generated locally at each distributed node. It is significantly more challenging when the distance between the distributed nodes is much larger than the signal wavelength, and especially when this distance varies over time due to the relative movement of the nodes, as it typically happens in DSSs [7]. Furthermore, the electrical distance, determined by the inter-satellite channels and the Radio frequency (RF) chains at each spacecraft, is not constant either. In these cases, it is not possible to rely on network backhaul links or to use the exact location of the collaborating nodes as it can be done in some terrestrial networks [8], [9].

The synchronization of distributed wireless systems is highly challenging and has received plenty of attention in the literature. For example, [10] summarizes some of the timing and carrier synchronization techniques proposed for wireless communication systems. Another survey on the synchronization in wireless systems is given in [11], where the authors summarize the clock synchronization protocols in Wireless Sensor Networks (WSNs). However, both articles are limited to terrestrial systems, and they do not address synchronization for DSSs.

On the other hand, the opportunities and challenges of DSSs have been explored in many publications. For example, [12] summarizes the use of WSNs for planetary exploration. In this article, the authors mentioned synchronization as one of the problems encountered in distributed systems design. Besides, [13] provided a comprehensive assessment of modern concepts and technologies of DSSs and analyzed the technical barriers to DSSs implementation. In addition, [14] stated the revolutionary strength of DSSs such as satellite swarms and the limitations in its implementation due to synchronization requirements.

However, the synchronization of DSSs is still an open and challenging research question that has attracted the attention of the scientific community in the last few years. This has resulted in a large body of work appearing in conferences and journals from different fields. To the best of authors' knowledge, a comprehensive survey document to cover topics on synchronization applied to DSSs is still missing. This article intends to fill this gap. With this idea in mind, this paper summarizes and categorizes the most relevant publications on synchronization techniques for DSSs. The result is a comprehensive survey that can be used as a guide for researchers and developers working in this field.

A. CONTRIBUTIONS OF THIS PAPER

This survey describes the most relevant results on synchronization for DSS and the strict requirements and new technologies related to distributed satellite missions. For the sake of clarity, the main contributions of this paper can be summarized as:

- A brief survey of the DSSs architectures is provided, classifying them into five general groups: Constellations, Clusters, Swarms, Fractionated and Federated spacecraft, for which the main features are identified.
- The distributed time, phase, and frequency wireless synchronization methods reported in the literature are summarized and compared, analyzing their feasibility for DSSs.
- Other operations, closely related to synchronization in DSSs such as inter-satellite ranging and relative positioning are also analyzed.
- It is offered an extensive compilation of the missions and Proof of Concepts (PoCs) implementations reported up to the present.
- Some of the most relevant current research activities and potential research topics are presented, identifying problems and open challenges.

B. PAPER ORGANIZATION

The paper is organized as follows: After the Introduction, some important concepts on the architectures and system models for DSSs are defined in Section II. The synchronization methods reported in the literature are presented and categorized in Section III. Section IV deals with other operations closely related to the synchronization in DSSs such as: inter-satellite ranging and relative position. Sections V and VI comment examples of synchronization methods in DSSs, whereas Section V lists some ideas and new methods that have not been implemented yet. Section VI provides to the reader examples of PoCs and launched missions of DSSs with special emphasis on the synchronization methods implemented. Section VII presents the use of ML for synchronization purposes. The most relevant open questions and future research directions are highlighted in Section VIII. Finally, the reader can find the general conclusions in Section IX. The list of acronyms is provided in Section I-C to make the reading more accessible.

C. ACRONYMS

ADC	Analog-to-digital converter
AP	Access Point
ARNS	Augmented Relative Navigation System
ASP	Adaptive Synchronous Parallel
BioRARSA	Robust Adaptive Random Search Algorithm
BS	Base station
BSP	Bulk Synchronous Parallel

CDSS	Cohesive Distributed Satellite System
CF	Cell-free
CFO	Carrier frequency offset
CNN	Convolutional Neural Network
CoMP	Coordinated Multipoint
COTS	Commercial Off-The-Shelf
CPU	Central processing unit
CRLB	Cramer-Rao lower bound
CSI	Channel State Information
DBF	Distributed Beamforming
DCA	Distributed Consensus Algorithm
DOWR	Dual One-Way Ranging
DOWT	Dual One-Way Time
DRT	Dehop-Rehop transponder
DSP	Digital Signal Processor
DSS	Distributed Satellite System
DSSS	Direct Sequence Spread Spectrum Signal
DTB	Distributed Transmit Beamforming
D1BF	Deterministic One-bit Feedback
EKF	Extended Kalman filter (KF)
E1BF	Enhanced One-Bit Feedback
FDD	Frequency Division Duplex
FFT	Fast Fourier transform
FH-FDMA	Frequency Hopping-Frequency Division Multiple Access
FPGA	Field Programmable Gate Arrays
F-RT	Frequency-slotted round-trip
FSS	Federated Satellite System
FTSP	Flooding Time Synchronization Protocol
GEO	Geostationary Orbit
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
GRAIL	Gravity Recovery and Interior Laboratory
IoSat	Internet of Satellites
INS	Inertial navigation system
InSAR	Interferometric Synthetic Aperture Radar
ISL	Inter-satellite link
KBR	K-Band Microwave Ranging
KF	Kalman filter
LAMBDA	Least-squares Ambiguity Decorrelation Adjustment
LEO	Low-Earth Orbit
LISA	Laser Interferometer Space Antenna
LO	Local oscillator
LOS	Line of sight
LSTM	Long short-term memory
MANET	MobileAd-hoc Network
MEO	Medium-Earth Orbit
MIMO	multiple-input and multiple-output
ML	Machine Learning
MMSE	Minimum mean square error
MSE	Mean square error
NTP	Network Time Protocol
OCB	Opportunistic Collaborative Beamforming
OFDM	Orthogonal Frequency Division Multiplexing
OLFAR	Orbiting Low Frequency Antennas for Radio Astronomy
OPLL	Optical Phase-Locked Loop (PLL)
OTA	Over-the-air
PA	Pairwise Algorithm
PBS	Pairwise Broadcast Synchronization
PLL	Phase-Locked Loop
PoC	Proof of Concept
POD	Precise orbit determination
PRISMA	Prototype Research Instruments and Space Mission technology Advancement
PRN	Pseudo-random noise
PTP	Precision Time Protocol
RBS	Reference broadcast synchronization
RF	Radio frequency
RMS	Root mean square
R-RT	Robust round-trip
RSS	Received signal strength
SAR	Synthetic aperture radar
SDDB	Successive Deterministic Distributed Beamforming
SDR	Software-Defined Radio
SIN	Space Information Network
SNR	Signal-to-Noise Ratio
SSP	Stale Synchronous Parallel
TDD	Time Division Duplex
TOA	Time of arrival
TOF	Time of flight
TPSN	Timing Synchronization Protocol for Sensor Networks
T-RT	Time-slotted round trip
TWTT	Two-way time transfer
TWR	Two-Way Ranging
UE	User Equipment
USRP	Universal Software Radio Peripherals
UAV	Unmanned Aerial Vehicles
UWB	Ultrawideband
WSN	Wireless Sensor Network
0F	Zero feedback
1BF	One-bit Feedback
2BF	Two-bits Feedback
2WS	Two-way Synchronization
3D	3-Dimensional

II. ARCHITECTURES AND SYSTEM MODEL FOR DISTRIBUTED SATELLITE SYSTEMS

A. OVERVIEW OF EXISTING ARCHITECTURES

DSSs can be classified into five general groups: Constellations, Clusters, Swarms, Fractionated, and Federated spacecraft. Table 1 summarizes the main characteristics of these groups.

- **Constellations** refer to a traditional approach where tens of medium to large satellites (over 500 kg each) are distributed around Earth to guarantee global or regional coverage of a service. Some of the most famous satellite constellations are: the Global Navigation Satellite

System (GNSS) constellations, such as Global Positioning System (GPS) and Galileo and; the satellite communication constellations, such as Globalstar [15], Iridium [16], and OneWeb [17]. Inter-satellite communication in these networks is scarce or null, except in the Iridium constellation where each satellite can have four Ka-band Inter-satellite links (ISLs) [16].

- A **cluster** is a group of at least two mini or micro satellites (from 10 to 500 kg each) deliberately positioned closely together to enhance or create new system capabilities. These DSSs cover a smaller portion of the Earth and mainly require inter-satellite communications to keep a close flying formation. Some satellite clusters are Gravity Recovery and Climate Experiment (GRACE) [18], Laser Interferometer Space Antenna (LISA) [19], Prototype Research Instruments and Space Mission technology Advancement (PRISMA) [20], PROBA-3 [21], and TanDEM-X [22].
- Satellite **swarms** are similar to clusters, except they contain a significantly higher number of satellites, often smaller and less expensive (less than 10 kg each). They are envisioned to contain hundreds and even thousands of nanosatellites operating together in a loose flying formation. They will require inter-satellite communications, as each member determines and controls relative positions to the others. Unlike previous DSSs that have several examples, satellite swarms are a new concept yet to be demonstrated. Examples of satellite swarms projects are QB-50 [23] and Orbiting Low Frequency Antennas for Radio Astronomy (OLFAR) [24].
- **Fractionated spacecraft** is a revolutionary satellite architecture that distributes the functions of a single large satellite into numerous modules that communicate by ISL in a highly dynamic topology [25]. Among the multiple advantages of this concept can be mentioned the flexibility, robustness, and the significant decrease in the required time to launch and deploy a satellite mission. Fractionated satellite systems is a very recent concept that have not yet been implemented.
- Finally, the **Federated Satellite System (FSS)** paradigm visualizes opportunistic collaboration among fully independent and heterogeneous spacecraft [26]. This is one of the most recent DSS concepts and is inspired by the current peer-to-peer networks and cloud computing. The main idea is to benefit from the potential of under-utilized space commodities by trading and sharing previously unused resources available in space assets at any given time. It is worth noting that much of Federated Satellite System (FSS)'s potential relies on the spacecraft capabilities to establish communications through ISL. The recently launched FSSCat mission [27] is an example of FSS.

In addition to this classification, CDSSs can be categorized according to their synchronization scheme as centralized or distributed. The former refers to distributed systems where all the nodes adjust their carriers to follow one controller node, which has the most stable oscillator in the system. This synchronization scheme has a relatively simple implementation, but it may have robustness drawbacks. On the other hand, distributed synchronization satellite systems do not rely on a single node but try to find a common carrier considering all the oscillators in the system. This characteristic overcomes the robustness drawback of the former group but makes the synchronization algorithms more complex. The synchronization methods suitable for CDSSs will be addressed in detail in the following sections.

Moreover, considering the communication links between the nodes of the DSS, the space segment can be classified as:

- **Ring**, in which each node connects to two other nodes, forming a single continuous path through all the elements of the DSS. This topology is not suitable for centralized synchronization algorithms.
- **Star**, in which each node connects to a central node that performs specific tasks ranging from communications with the ground segment to leading the synchronization. This topology generally uses centralized synchronization methods.
- **Mesh**, in which each node is connected to every other node in the distributed system. This topology can be implemented fully or partially depending on the complexity of the DSS, and it accepts the implementation of both distributed and centralized synchronization algorithms.
- **Hybrid** topologies combine two or more of the previous ones.

These topologies are shown in Fig. 1, where the arrows represent the ISLs.

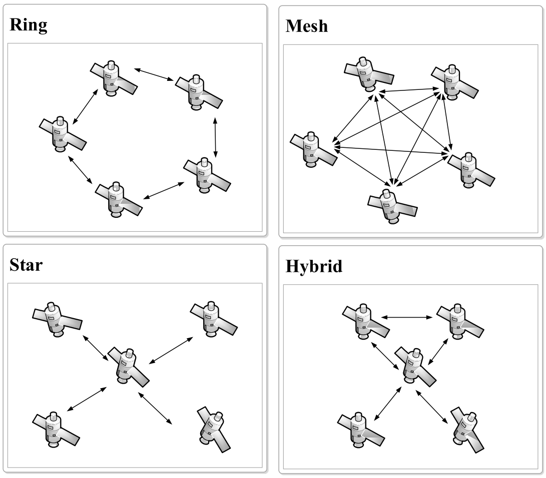

FIGURE 1. Classification of DSS considering the ISLs.

B. GENERALIZED SYSTEM MODEL

The general DSS considered in this article is a distributed array of autonomous nodes which collaborate to perform distributed beamforming towards an intended target node outside the array. From a general perspective, the nodes of

TABLE 1. **Main characteristics of the DSS groups.**

Classification	Number of Satellites	Satellites Weight	Inter-satellite Comm	Examples
Constellation	tens	> 500 kg	scarce or null	GNSS, Globalstar, Iridium
Cluster	at least 2 satellites	10 to 500 kg	required to keep a close flying formation	GRACE, LISA, PRISMA, PROBA-3, TanDEM-X
Swarm	hundreds in a loose flying formation	< 10 kg	required to determine and control relative position	QB-50, OLFAR
Fractionated spacecraft	at least 2 satellites	< 500 kg	required to achieve the mission objectives	not implemented yet
FSS	dynamic	any	required to share unused resources	FSSCat

the distributed arrays considered in this survey can be moving while the whole system tries to stay at a fixed position, or the entire array can be following a trajectory or orbit.

For both cases, the nodes require transmission and reception capabilities to synchronize the distributed system. For the general DSS, no specific geometric distribution of the nodes is assumed, none of the previously mentioned classes neither. However, each of them can be described by a state variable $\overrightarrow{x_n} = (\overrightarrow{p_n}, \overrightarrow{v_n})$ where $\overrightarrow{p_n}$ and $\overrightarrow{v_n} \triangleq \mathrm{d}\overrightarrow{p_n}\mathrm{d}t$ represent position and speed of the node n, respectively.

Besides, it is assumed the existence of RF-ISLs between all the elements of the DSS, which implies a Mesh configuration, even if all the links are not activated at the same time. The complex transfer function of these ISLs is formally represented as complex coefficients h_{nm}, where n and m are the node subscripts. The matrix $\mathbf{H}$, containing all the h_{nm}, can be used to describe the DSS. It determines the most suitable synchronization procedure. Fig. 2 shows the general DSS considered in the next sections to analyze the synchronization techniques.

The quality of the ISL is considered variable as a function of the position and orientation of the nodes, given that omnidirectional antennas are not assumed. Besides, the frequency responses of the RF chains are considered different for each node.

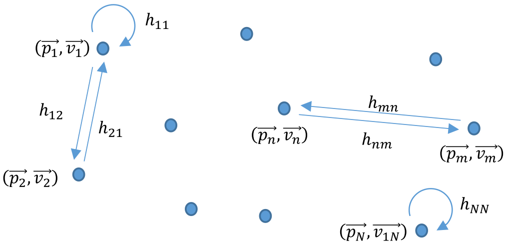

FIGURE 2. **General scheme of the DSS performing the required synchronization for a DBF transmission.**

For synchronization purposes, each of the distributed nodes generates its own initial reference signal, the stability of which depends on the available hardware at each satellite. The objective of the synchronization algorithm is to make all of those initial reference signals converge to a common reference with the best possible accuracy.

C. SUMMARY AND LESSONS LEARNT

- DSS can be classified as Constellations, Clusters, Satellite swarms, Fractionated spacecraft, and, FSS.
- Distributed synchronization algorithms are more robust than centralized synchronization algorithms, but more complex.
- According to the ISL, there are four types of DSS: Ring, Star, Mesh, or Hybrid topology.
- The general DSS model considered in this article is a distributed array of autonomous spacecraft which collaborate to perform distributed beamforming towards an intended target node outside the array.
- The general model assumes a Mesh configuration with the reference signals locally generated at each distributed satellite.

III. OVERVIEW OF SYNCHRONIZATION METHODS

A critical aspect of the synchronization of distributed radio systems, in general, is the clock or time synchronization in addition to the phase synchronization. This section summarizes the most significant synchronization methods reported in the state of art. These algorithms can be classified as Closed-loop or Open-loop methods based on the use of feedback from a node external to the DSS. The external node can be another satellite, an anchor point, or the intended communication target. The Closed-loop methods require a communication channel to transmit the feedback information between the external node and the DSS. Whereas in Open-loop, the synchronization is achieved without the participation of any node other than the distributed satellites.

Another way to classify the synchronization methods considers the communication between the elements of the DSS. In order to achieve synchronization, some algorithms require the exchange of information among the distributed satellites. This can be done as a two-way message exchange or closed loops, which requires a duplex channel between the nodes of the DSS, or as a broadcast or one-way communication. Another option is to synchronize without any communication among the elements of the DSS. In this case, it is possible to achieve coherence using the feedback from a node out of the DSS. Both classifications can be superimposed, as it is represented in Fig. 3. In this figure, some of the missions analyzed in the following sections were included as examples.

A. TIME SYNCHRONIZATION

Time synchronization is critical in the application of many DSS. The coherent transmission in communication applications, as an instance, requires aligned signals at the symbol level to achieve the full potential of the beamforming gains. The tight clock and timing synchronization is achieved with different levels of accuracy in other areas, such as wired and optical networks and wireless sensor networks. For example, some distributed applications such as computer networking, distributed signal processing, instrumentation, and earth observation applications require accurate timing or clock synchronization. The purpose of this section is to explain those timing synchronization methods used in other areas and give advice on how to translate them into DSS, in particular for communications applications.

Previous studies have identified the time or clock synchronization challenge for clock frequencies in the order of tens to thousands of MHz and accuracies ranging between orders of one fractional digit relative to the clock frequency. Recently, it has been studied for multi-static and MIMO radar and distributed beamforming applications where the required precision is orders of magnitude more stringent [28]. Additionally, these systems require what is known as absolute time synchronization, which is different from relative time synchronization on which the timing of an impingent signal is tracked. The problem of absolute time synchronization was first formally defined by Poincaré and Einstein in 1898 [29], and 1905 [30] respectively. The formal definition of this problem and the Two-way time transfer (TWTT) concept was provided in the framework of relativistic-event-simultaneity.

Fig. 4 depicts the basic idea of the TWTT concept. Here, an initiating or source node sends a signal (or packet) at time T_1. A slave (or follower node) receives the signal at time T_2 after a delay of $\Delta t_1 = T_2 - T_1$ and responds (or reflects) after a known delay at time T_3. The source node receives the response signal at time T_4. The time offset of the clocks is then $((T_2 - T_1) - (T_4 - T_3))/2 = (\Delta t_1 - \Delta t_2)/2$, and the propagation delay is $((T_2 - T_1) + (T_4 - T_3))/2 = (\Delta t_1 + \Delta t_2)/2$. Therefore, proper knowledge of this propagation time offset will be used to achieve absolute synchronization.

The TWTT concept created the foundations for clock synchronization of twenty-century networks and complex systems, such as satellites and the Internet [31]. This general concept can be applied to diverse kinds of systems and networks, including DSS. This section will emphasize the case of DSS. The following subsections describe timing synchronization methods that have been developed in different communications areas and could be extrapolated to DSSs. An example of the use of TWTT in DSS is presented in [32], where the authors compared the performance of three clocks offset prediction algorithms based on this method for a master-slave architecture. In addition, the authors in [7] used TWTT to synchronize four spacecraft in a distributed satellite formation flying, achieving time synchronization simulation errors smaller than ± 10 ns. The work in [33] analyzed the effect of the motion of the satellite on the two-way time synchronization accuracy. Another example based on TWTT calculates the time difference between two satellite clocks by measuring the phase difference of a pseudo-random noise code in a master-slave architecture [34]. The method is proposed to achieve on-orbit synchronization in a micro-satellite cluster [34]. Other authors combined RF carrier ranging methods with TWTT to obtain inter-satellite range and time synchronization simultaneously [35]–[37].

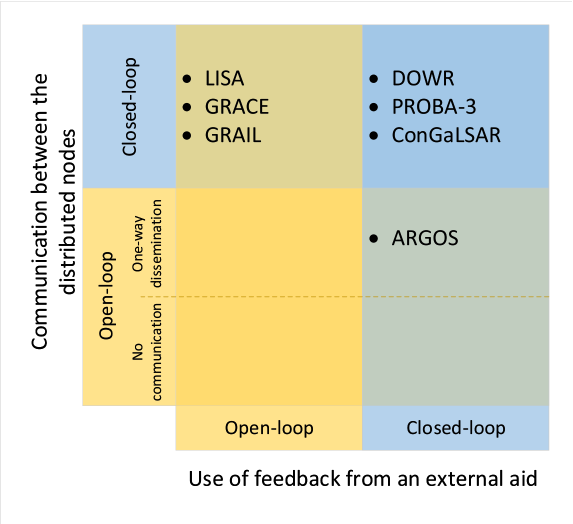

FIGURE 3. Classification of the synchronization methods.

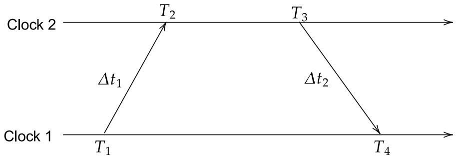

FIGURE 4. Operating principle of the TWTT clock synchronization [28].

1) TIME SYNCHRONIZATION IN WIRED NETWORKS

The TWTT concept is the basis of most synchronizations protocols in the literature. The Network Time Protocol (NTP) and Precision Time Protocol (PTP) are extensively used in large-scale modern computer networks, and both operate with a TWTT approach. The network nodes exchange timestamps employing (UDP) packets to measure the round-trip propagation latency. NTP generates software timestamps with non-deterministic time offsets and achieves clock accuracies in the order of $\sim$ 10 μs [38]. The PTP (IEEE-1588) is an evolution of the NTP, which generates hardware timestamps using the waveforms of the associated clock. This protocol achieves clock alignment by exchanging synchronization packets among the involved nodes. The IEEE-1588 standard limits the maximum rate for the timestamp counters to 125 MHz, providing accuracies of $\sim$ 10 ns [39], [40]. The performance of these systems, such as NTP and PTP, rely directly on the clock rates used, and the achieved accuracy is given by the granularity associated with an integer counter.

Further refinements of the time synchronization mechanism use the clock phase information. A salient example is the White Rabbit project of the European Organization for Nuclear Research (CERN). White Rabbit operates with Ethernet frames to detect the phase difference between the local clock and a clock extracted from the received Ethernet signal.

Across large wired networks, White Rabbit operates under specially designed network switches to measure and compensate fractional clock phase differences achieving ∼ 10 ps accuracy [41].

Even though these time synchronization mechanisms can not be used directly on DSS, the main concepts can be extrapolated to DSS scenarios. In the DSSs, the coarse synchronization methods such as NTP and PTP can be used to eliminate the ambiguity in the total channel delay. Then, the time synchronization can be refined with differential time mechanisms at the waveform level, using White Rabbit or similar approaches.

2) TIME SYNCHRONIZATION IN WIRELESS SENSOR NETWORKS

In wireless communications, absolute time synchronization is also frequently desired, and the wireless channel is typically used to exchange the synchronization messages. The algorithms for absolute time synchronization in wireless networks can be classified as sender-to-receiver and receiver-to-receiver synchronization methods. The former is based on the TWTT between couples of nodes, whereas receiver-to-receiver methods use time readings of a standard signal broadcasted to a set of nodes from a common sender [42].

Some receiver-to-receiver solutions include Reference broadcast synchronization (RBS) [43] and Pairwise Broadcast Synchronization (PBS) [44]. The RBS protocol implements a Time of arrival (TOA) exchange between the distributed nodes disregarding the signal Time of flight (TOF) over the physical medium [43]. PBS is a well-known timing synchronization scheme for WSNs, which is based on sets of node-pairs for network-wide synchronization. PBS operates under the assumption that all the participating nodes will receive and detect the pairwise synchronization frames exchanged between two master/reference nodes. This approach assumes a hierarchically distributed structure [44] and assumes that distances between nodes and their associated delays (TOFs) are identified in advance.

The most well-known sender-to-receiver synchronization methods are Timing Synchronization Protocol for Sensor Networks (TPSN) [45] and Flooding Time Synchronization Protocol (FTSP) [46]. TPSN implements TWTT between pairs of nodes preceded by a discovery phase from where each node obtains a level. In FTSP and its variations [47], the distributed nodes synchronize to a signal broadcasted from the root node or a previously synchronized node.

For these protocols to work, synchronization must be performed several times. Additionally, the nature of the WSN, in which the network observes a physical phenomenon (temperature, pressure, etc.), determines synchronization requirements in the order of microseconds. However, this level of accuracy is inadequate to perform distributed coherent (beamforming) radio applications.

For example, the required time synchronization to achieve beamforming maintaining the performance at acceptable levels is around ± 7.5 percent of a symbol duration. For single-carrier communication baud rates of a hundred MHz, this represents a required accuracy of ± 0.75 ns. This accuracy could be achieved with a refinement of the methods mentioned above, such as the work in [48]. This article proposes a step forward into the timing accuracy increase by using frequency-modulated continuous-wave (FMCW) signals with relatively high bandwidth of 150-MHz. The method performs the synchronization between two stations using a TWTT approach (similar to the one proposed in [49]). It uses the aforementioned radar-like waveform to provide a joint carrier-phase and timing synchronization with an accuracy of 66 ps.

3) ULTRAWIDEBAND PULSE SYNCHRONIZATION

Wireless synchronization approaches using Ultrawideband (UWB) pulses instead of exchanges of a network packet have recently caught researchers' interest. To estimate the TOA at sub-nanosecond levels, UWB approaches take advantage of high-speed hardware, generally at sampling rates higher than 1 GHz.

Several applications have exploited UWB signaling using high speeds clocks and Analog-to-digital converters (ADCs). Some examples are the sets of multiple active receivers locked, and synchronous to a single transmitter [50], distributed consensus techniques [51], and distributed sensor positioning [52]. The works in [53] propose a propagation-aware TOF protocol and provide validation for the system using an atomic clock integrated on a chip and a 64 GHz hardware clock timestamp counter [54]. As a result, these experiments achieved a distributed timing accuracy of 5 ns between two sensors. It is essential to mention that the transmission of UWB pulses is not feasible for small satellites such as CubeSats due to power constraints. However, its advantages can be considered for DSS with less strict power consumption requirements.

Nevertheless, it is worth pointing out that increasing clock frequencies is not the only alternative to increase the timing accuracy in synchronization mechanisms. A common misconception in the literature regarding UWB synchronization systems is that the ADC frequency bounds the time resolution. As specified by the Cramer-Rao lower bound (CRLB) [55], accurate TOA measurements within minuscule fractions of a sampling period is attainable, specially in Line of sight (LOS) scenarios. The measurement of these time offsets, fractional to the sampling time, can be achieved by time offset mechanisms, also known as timing-error-detectors, such as the Gardner method [56], and the Early-Late-Gate method [57] among others.

B. FREQUENCY AND PHASE SYNCHRONIZATION

As previously stated, considering the use of feedback from an external node, frequency, and phase synchronization methods can be classified as:

- Closed-loop methods, where the feedback from the target nodes could be either a single bit or a few bits or

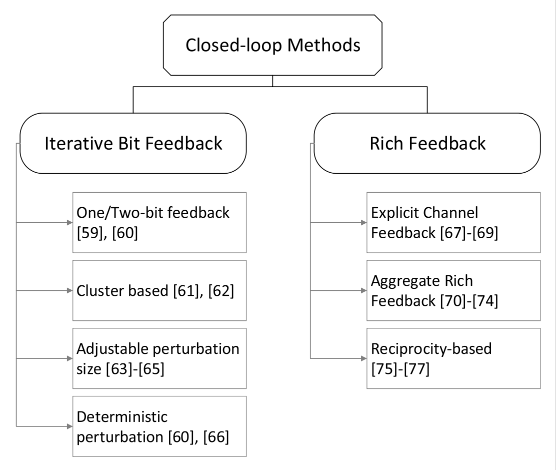

FIGURE 5. Classification of the Closed-loop synchronization methods.

could have the form of rich feedback with limited or full Channel State Information (CSI) [58].

- Open-loop methods that require either intra-node communication or blind beamforming, also known as Zero feedback (0F) [58].

In the following sections, some of the most notable examples from each category are discussed.

1) CLOSED-LOOP SYNCHRONIZATION METHODS

Fig. 5 lists the closed-loop synchronization methods found in the literature. They are classified into different groups according to the feedback type for a better understanding, although more detailed information is provided in this section.

The group Iterative Bit Feedback includes the algorithms where the distributed nodes modify their signals according to one or more decision bits received from the target node. Among them, the most well-known algorithm is the classical One-bit Feedback (1BF), proposed in [59]. This method considers the beamforming nodes synchronized in time and frequency and achieves phase synchronization by applying independent random phase rotations in each beamforming node. At each time slot, transmitter nodes add a random perturbation to their signals. The target node measures the Received signal strength (RSS) and sends one bit indicating if the RSS is better than the previous value. Depending on this bit, the transmitters keep or update the phase rotation. The process is repeated during the next time slot until each node's phase has been adjusted to its optimal value. The primary constraint of this algorithm is its convergence time, which was improved in [60] using Two-bits Feedback (2BF).

Other approaches improve convergence time by reducing the number of collaborative nodes. For example, [61] proposed to separate the distributed nodes in clusters and perform the phase synchronization in two stages. The outcome of this algorithm with respect to 1BF is more evident as the number of nodes increases, when, for $N \approx 100$ nodes, it can decrease to half the required iterations. However, comparing both techniques only by the number of iterations is not fair since the epoch in [61] is more complex and therefore takes a longer convergence time. Another iterative bit feedback method for phase synchronization named Opportunistic Collaborative Beamforming (OCB) was proposed in [62]. In this case, the destination node selects a subset of the distributed nodes whose transmitted signals produce the higher coherence gain at the destination.

Further enhancement of the 1BF is proposed in [63] by emulating the bacterial foraging techniques. In this algorithm which is called the Robust Adaptive Random Search Algorithm (BioRARSA), the "swim" mechanism, along with the step size adjustment, enables the beamforming nodes to decrease convergence time as well as improve robustness against variation of initial conditions. A comprehensive explanation of this method and its performance can be found in [64]. Another synchronization method that increases the convergence speed by adjusting the perturbation size was presented in [65], where the authors proposed to exploit the cumulative positive feedback information additionally.

The methods discussed above are based on random disturbances of the transmitted signal phase. However, Deterministic One-bit Feedback (D1BF) [60], and its improved version, Successive Deterministic Distributed Beamforming (SDDB) [66] proposed to limit the possible phase perturbations to a set of discrete values from where choose the one that allows achieving the maximum RSS possible. The number of elements in the perturbation set is proportional to the convergence time and determines the performance in terms of maximum achieved RSS. Even though SDDB shows steeper growth rates than D1BF, both deterministic algorithms have limited performance due to the digitization of the perturbation set. Some combinations of deterministic and random methods were considered in [60], where the hybrid methods obtained allow prioritizing the convergence time or the beamforming performance depending on the specific requirements of the network.

Iterative Bit Feedback algorithms are unsuited for DSS due to their slow convergence characteristic. Generally, the long distance between the DSS and the receiver implies a delay in the communication that, combined with the slow convergence of these methods, makes it not suitable to synchronize the system by Iterative Feedback algorithms.

The rich feedback methods use more information instead of just a few feedback bits to achieve synchronization. They can be classified in three categories according to the way the distributed nodes obtain the channel estimation:

- Explicit Channel Feedback method, where each distributed node transmits a known sequence of training symbols to estimate the channel response.
- Aggregate Rich Feedback methods, where the transmitters simultaneously send uncorrelated training sequences used to estimate each channel gain.
- Reciprocity-based methods, where the transmitters observe the uplink feedback signals sent by the target nodes and use reciprocity to estimate their downlink channel gains automatically.

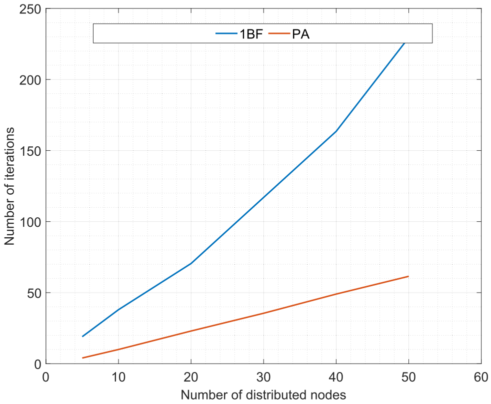

FIGURE 6. Convergence time comparison between 1BF and PA [68].

These algorithms have proven to be more robust than the Iterative Bit Feedback methods at the price of considerable feedback overhead. For instance, the Enhanced One-Bit Feedback (E1BF) [67], which is an Explicit Channel Feedback algorithm, compensates for the effect of the average time-varying channel by combining explicit phase information with the 1BF method to provide better convergence and scalability as compared to 1BF. A comprehensive description of this algorithm can be found in [67]. Another Explicit Channel Feedback algorithm that outperforms 1BF for convergence time is the Pairwise Algorithm (PA) for Distributed Transmit Beamforming (DTB) presented in [68], which is also more energetically efficient. Fig. 6 shows the number of iterations required to achieve 90% of the maximum coherent gain for PA and 1BF.

Generally, nullforming requires far tighter synchronization than beamforming. For that reason, it mainly uses rich feedback approaches. For example, in [69], a distributed gradient-descent algorithm is used to modify the signals' power and phase in consecutive time slots achieving beamforming and nullforming simultaneously. The method works in a time-scheduled way to estimate the CSI and perform the collaborative transmission [69].

In general, Aggregate Rich Feedback methods are more scalable than Explicit ones. For example, the algorithm proposed in [70] is an Aggregate Rich Feedback method based in 1BF that allows each collaborating node to estimate its channel response to the receiver. Similarly, in the scheme proposed in [71], all the distributed nodes simultaneously transmit, and the receiver sends a phase compensation vector to achieve distributed transmit nullforming. However, in this method, the transmitter nodes use Code Division Multiple Access (CDMA) to facilitate signal separation at the receiver. The receiver uses an Extended KF (EKF) to generate state estimations for each transmitter, which implies some scalability limitations for this scheme. An improved version of the previous algorithm was proposed in [72].

The Reciprocity-based methods were first introduced as Frequency-slotted round-trip (F-RT) synchronization method in [73]. In this work, a distributed network of two nodes, each of them equipped with two PLLs, achieves frequency and phase synchronization by continuously transmitting three unmodulated beacons in a round-trip way. This strategy is effective in highly dynamic networks. Another example of F-RT synchronization is described in [74], where the system perform precise electrical-distance measurement and supplies a phase-synchronous signal to a remote location simultaneously. The round-trip phase synchronization method implemented in the article is represented in Fig. 7. However, in typical multipath channels, the frequency division duplexing intrinsic of F-RT generates non-reciprocal phase shifts, which reduce the performance. To overcome the problem, in [75] it is proposed a Time-slotted round trip (T-RT) algorithm, which is equivalent to the F-RT but using the same frequency for all beacons. Frequency interference is avoided by time division duplexing. Even when this method gives the advantage of simultaneous frequency and phase synchronization, F-RT and T-RT schemes have as a drawback the extreme power consumption due to the extensive signaling.

All the works listed in this section aim that all carriers arrive with the same initial phase at the destination based on perfect time alignment. Nevertheless, Mañosa-Caballu and Seco-Granados proposed a Robust round-trip (R-RT) synchronization protocol to achieve frequency, phase, and timing synchronization [76]. This algorithm is based on the T-RT method mentioned above. The robustness of the protocol allows it to work in dynamic environments in the sense that nodes can disappear without severely affecting the system's performance. Other approaches [10] addressed joint time delay and Carrier frequency offset (CFO) synchronization in closed-loop systems. For example, [77] covers maximum likelihood synchronization in multi-node decode-and-forward cooperative relaying networks considering time-varying channels. In [78], the same goal was approached through a weighted consensus algorithm to reach synchronization in a dense wireless network.

2) OPEN-LOOP SYNCHRONIZATION METHODS

Whereas rich feedback may give faster and better convergence than bit feedback, the signaling overhead is substantially more significant. The overhead implies latency problems in real-time applications, which can represent a considerable challenge for its implementation in cases such as satellite communications systems. In such scenarios where quick and reliable feedback from the target nodes is not possible, Open-loop synchronization methods are the recommended schemes. Fig. 8 shows the Open-loop synchronization methods analyzed in this section.

One of the simplest ways to do open-loop synchronization is through Master-slaves architectures, where one primary node broadcasts a beacon, and the secondary nodes lock their oscillators to this reference [6]. This algorithm can be considered as a closed-loop method if the primary node is not part of the DSS [79]. For instance, in [80] all nodes acquire their relative locations from the beacon of a nearby reference point that doesn't have to be the destination node. This allows open-loop synchronization, but each node requires knowledge of

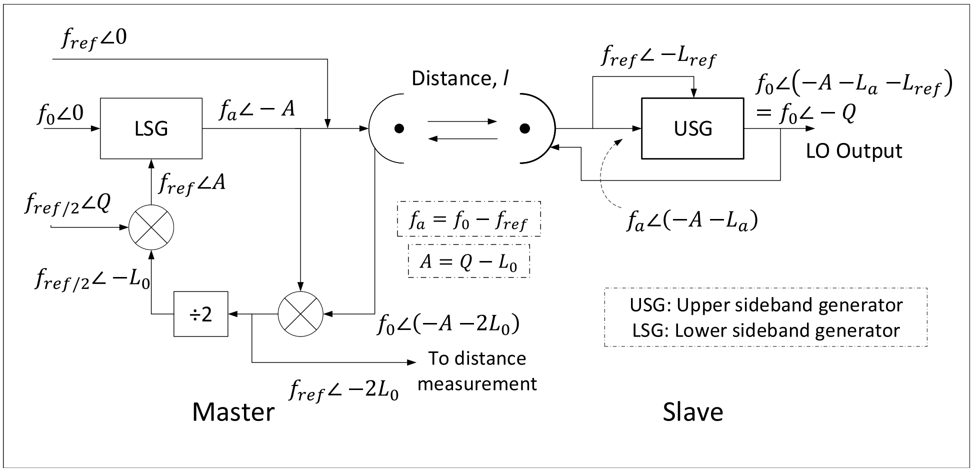

FIGURE 7. Transmission of a phase stabilized LO signal using a round-trip phase synchronization method [74].

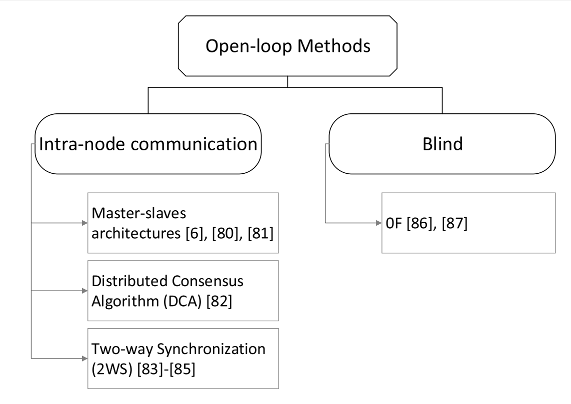

FIGURE 8. Classification of the Open-loop synchronization methods.

its relative position from a predetermined reference point within the cluster. In [81], frequency and phase synchronization is achieved by locking the secondaries' oscillators to the reference beacon sent by the controller node after pre-compensating the phase mismatch and the propagation delay.

A solution more robust to link and node failures than Master-slave architectures is the Distributed Consensus Algorithm (DCA) proposed in [82], where each node broadcasts its carrier signal to all of its neighbors. Thus, the total received signal at any node is the superposition of its neighbors' carrier signals distorted by the channel. The goal of the DCA is to use this received signal to adjust the instantaneous frequency at each distributed node in such a way that all the distributed nodes eventually become frequency locked to a common carrier [82].

Another Open-loop algorithm based on the retrodirective principle is Two-way Synchronization (2WS), proposed in [83]. The main idea of this method is to implement a retrodirective beamforming between the base stations in a mobile network without the need of CSI or feedback from the mobiles. To this end, a sinusoidal beacon is transmitted in a forward and backward propagation through all the base stations allowing them to compute a common carrier frequency and phase used to perform beamforming. The most significant drawback of retrodirective beamforming methods is that generally, the channel and the RF chains at each transceiver are not reciprocal. A relative calibration method to compensate for this drawback is proposed in [84]. In [85], it is proposed a faster version of 2WS by exploiting the broadcast nature of the wireless links. The difference with [83] is that in the Fast Open-loop protocol, each base station only considers the signal from its adjacent two neighbors and ignores any signal from other base stations. In this way, the algorithm minimizes the latency by reducing the required non-overlapping time slots.

Finally, the blind method or 0F is a synchronization algorithm that intends to synchronize the network without any feedback from the target or the rest of the distributed nodes. According to [86], the offsets of the oscillator drift cause intermittent coherent addition of signals at the receiver, which can result in significant beamforming gains. Even though the complexity of the 0F algorithm is simple, the data rate that can be achieved with this method is very low as the coherent beamforming is not stable. In addition, the statistical analysis reported in [87] shows that 0F only works efficiently for a small network.

Table 2 provides a summary of the synchronization algorithms analyzed during this section. It includes the target parameter synchronized by the method: Time, Frequency or Phase; the original application and; the the feasibility to use it for thhe synchronization of DSSs.

C. SUMMARY AND LESSONS LEARNT

- The synchronization algorithms can be classified as Closed-loop or Open-loop methods based on the use of feedback from a node external to the DSS.
- Another classification considers the communication between the elements of the DSS. It can be Closed-loop when the exchange of information among the distributed satellites is done as a two-way message exchange or; Open-loop when it is done as a broadcast or one-way communication.

- The time synchronization of DSS is mainly based on the TWTT algorithm. However, recent publications refer to the use of pseudo-random noise code and other techniques to achieve time synchronization and inter-satellite ranging simultaneously.
- The time synchronization methods used in WSN do not guarantee the accuracy required by communications applications. However, they could be applied to DSS after some refinement.
- Some of the methods used for time synchronization in terrestrial distributed wireless networks can be applied to synchronize DSS.
- Among the Closed-loop synchronization algorithms that use the feedback from a node external to the DSS, the rich feedback methods are more suitable to implement in DSS. Specifically, the PA algorithm for DTB and the reciprocity-based methods are the most recommended.
- Most Open-loop synchronization algorithms without any external aid, but with intra-node communication in the form of two-way message exchange are suitable for the synchronization of DSS.
- Higher synchronization accuracy could be achieved by combining the use of intra-node communication in the form of two-way message exchange and the feedback from a node external to the DSS. However, this configuration is not feasible for all applications.

IV. RANGING AND RELATIVE POSITIONING IN DSSs

There are other operations closely related to the synchronization in DSSs, such as the inter-node ranging and relative position. For these operations, the requirements and accuracy of the coherent operation depend on the performance of the ranging and relative positioning algorithms. Several synchronization methods are based on these measurements [88]–[90]. For example, in [88], a dynamic model describes the stochastic kinematics and the clock evolution of each distributed node relative to the frame of the receiver of a DTB system. Other examples are the remote sensing DSSs missions, such as GRACE and PROBA-3, where knowing the relative position among the distributed nodes is fundamental to combining their measurements. For that reason, this section compiles recent advances in inter-node ranging and relative positioning for DSSs.

A. INTER-SATELLITE RANGING

For many DSSs, inter-satellite relative range measurement is a requirement for cooperative tasks. Generally, autonomous inter-satellite measurements and communications can reduce the dependence on ground stations, signal transmission delays, and improve the resilience and maneuverability of the DSS. To this end, the distributed nodes must have the capability of inter-satellite ranging.

The methods to do inter-satellite ranging can be classified into two main groups represented in Fig. 9: those based on RF and those based on optical signals. Measurements made using radio signals are the most mature technology, but optical measurements can achieve better ranging performance. However, the higher directivity of the laser beam, in comparison with the RF antenna's patterns, can represent a limitation for specific applications. Besides, the sunshine can blind optical sensors.

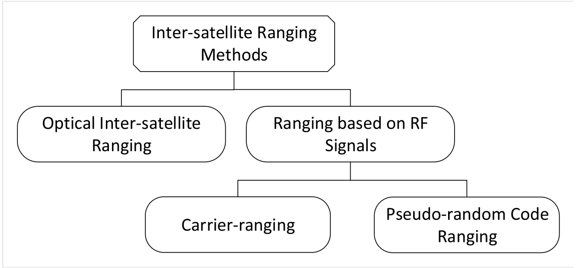

FIGURE 9. **Classification of the inter-satellite ranging methods.**

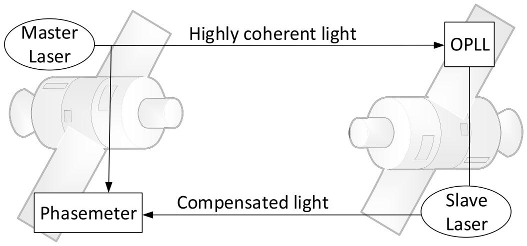

FIGURE 10. **Basic principle of optical inter-satellite ranging measurement.**

1) OPTICAL INTER-SATELLITE RANGING

The basic principle of optical inter-satellite ranging measurement, also known as transponder laser interferometry, is represented in Fig. 10 as explained in [91]. The frequency-stabilized and power-stabilized master laser provides a highly coherent light source to meet interference requirements between the local and receiver laser lights. First, the master's laser light travels through the inter-satellite space and arrives at the slave satellite, where the Optical PLL (OPLL) locks the phase of the slave laser to that of the weak light received. Then, the compensated slave laser light points and propagates back to the master satellite. The precision phasemeter measures the phase difference between the master laser and the received light to calculate the inter-satellite distance.

The authors in [91] discussed the state of the art of inter-satellite laser interferometer technologies for space-borne gravitational-wave detection. However, inter-satellite interferometric ranging has been previously implemented in missions such as GRACE follow-on, where the ranging performance of the former mission was improved by a factor of 10 by including an interferometric laser ranging system [92]. This improvement is due to the laser wavelength being 10,000 times shorter than the microwave wavelength.

As a variant to the methods mentioned before, which required two phase-synchronized lasers on both satellites, a single-laser design was proposed in [93]. This solution included a Mach-Zehnder interferometer on one of the satellites and a secondary satellite equipped with a retro-reflector. The work in [94] overcame the need for highly stable lasers

TABLE 2. Summary of synchronization methods.

Classification	Method	Sync target	Proposed application	Feasibility of its use in DSS
Closed-loop: Iterative Bit Feedback	1BF [59] / 2BF [60]	Phase	Terrestrial wireless networks	Not suitable for synchronization of DSS due to their slow convergence.
	OCB [62]	Phase	WSN	
	[61]	Phase	WSN	
	BioRARSA [63]	Phase	Wireless sensor/relay network	
	D1BF [60] / SDDB [66]	Phase	WSN	
Closed-loop: Rich Feedback	TPSN [45] and FTSP [46], [47]	Time	WSN	The basic ideas of these methods can be applied in DSS, specially for large distributed networks. However, some refinement should be considered in order to achieve the accuracy needed for communication applications.
	E1BF [67]	Frequency and phase	Wireless networks	It could be used in some scenarios, depending on the distance between the DSS and the receiver. However, the convergence time, 50% smaller in this method than the original 1BF, can still be an problem. An advantage of this algorithm is that only one element of the DSS processes the feedback from the receiver.
	[69]	Phase	Wireless networks	Even, when the possibility to jointly achieve null and beamforming is a very desirable characteristic in satellite systems, the slow convergence of this method may make it unsuitable for synchronization of DSS
	PA [68]	Frequency and phase	Wireless communication networks	It can be used in a DSS as long as a feedback channel is guarantee. This method presents scalability limitations.
	[70]	Phase	Wireless networks	This method allows simultaneously null and beamforming, which a desirable characteristic in satellite system. However, some limitations could be that (1) most of the calculation are performed by the distributed nodes and, (2) it can produce some latency for large DSS.
	[71] [72]	Frequency and phase	Wireless networks	Allows beam and null-forming considering significant feedback latency, which implies that this method could be used for long baseline communications. However, it can present scalability problems.
	F-RT [73] and T-RT [75]	Frequency and phase	Wireless communication networks	These methods can be used to synchronize DSSs as long as a feedback channel is guarantee. Another constraint related to these methods is that all the satellites in the distributed system have to receive the reference signal broadcasted by the destination node.
	R-RT [76]	Phase, frequency and time	WSN	
	[77]	Phase, frequency and time	Cooperative decode-and-forward communication system	To implement this method in a DSS, all the spacecraft have to simultaneously receive a common training sequence broadcasted by the destination node. In addition, some latency constraints must be taken into account.
Open-loop: Intra-node communication	RBS [43] and PBS [44]	Time	WSN	The basic ideas of these methods can be applied in DSS, specially for large distributed networks. However, some refinement should be considered in order to achieve the accuracy needed for communication applications.
	TWTT [7], [31]–[37]	Time	Satellite communications	It is used in DSS
	Master-Slave [80], [81]	Frequency and phase	WSN	Suitable for DSS with the constraint that it requires accurate inter-satellite ranging.
	DCA [82]	Frequency	Wireless networks	This method can be used to synchronize DSS as long as all the distributed nodes are inside the range of the rest.
	2WS [83]–[85]	Frequency and phase	Mobile networks	Despite some scalability problems, it can be used to synchronize DSS.
	[78]	Phase, frequency and time	Dense and compact wireless networks	This method is suitable for DSSs, where each node transmission can be received by almost all the satellites in the distributed system. However, algorithms with a central coordinator node acting as a reference for the delay compensation can be a more straightforward solution for less-dense networks.
Open-loop: Blind synchronization	0F [86], [87]	Frequency and phase	Wireless networks	Not recommended for DSSs, since it is limited to small networks, and it allows very low data rate.

and complex phase-locking solutions of the previous ones. Though, it is required to maintain the coherence properties of the laser light in the reference arm, which is very technologically challenging for distances more significant than 500 km, i.e., twice the expected inter-satellite distance. However, simulations results in [93] showed similar ranging resolution to the two phase-synchronized lasers method.

Recent publications proposed the use of a single optical ISL for ranging and communications simultaneously [95], [96]. For instance, [96] addressed the development of the optical transceivers to transmit ranging and frequency synchronization information through a coherent optical link between the spacecraft of the Kepler constellation. The Kepler system is based on a constellation of 24 Galileo-like Medium-Earth Orbit (MEO) and six Low-Earth Orbit (LEO) satellites carrying stabilized lasers as optical frequency references and equipped with terminals for two-way optical links. This provides a means for broadcasting synchronization, and navigation messages across the DSS without any communication with the ground segment [96]. A ranging precision of 300 μm and 10^{-15} s/s stability (Allan deviation at 1 s) is achieved through an OPLL locked to a Pseudo-random noise (PRN) sequence with a chip rate of 25.6 GChip/s. An additional data channel at 50 Mbit/s is multiplexed with the ranging signal to transmit timestamps in a known repetition rate. This allows time alignment of both satellites with the resolution of the Field Programmable Gate Arrayss (FPGAs)' clock rate used at both ends. Furthermore, the data link can be used for communication purposes by the constellation. Each MEO satellite has four bidirectional transceivers, two for connecting to neighboring satellites in the same orbit, and two for connecting to LEO satellites. The terminal aperture size is constrained to 75 mm due to the satellite's weight and size considered. However, to calculate the absolute ranging between terminals with an accuracy of 0.3 mm, the system requires aligning precision of 2.5% the chip length or better [96].

Another example of simultaneous ranging and communications inter-satellite optical link is the coherent optical receiver implemented in [95]. In this article, the authors presented an FPGA-based feedback-homodyne scheme as an alternative to the OPLL to obtain a more flexible coherent optical receiver. Besides, a parallel Fast Fourier transform (FFT) wavelength drift estimation algorithm was proposed, aiming to improve the speed and range of wavelength drift tracking simultaneously. Simulation results showed that the wavelength drift tracking performance depends on the number of FFT estimators used in parallel. However, using a real-time FPGA implementation, the authors demonstrated that the design meets the needs of phase offset compensation when three FFT estimators are used in parallel [95].

2) INTER-SATELLITE RANGING BASED ON RF SIGNALS

The use of RF for inter-satellite ranging is not a new concept. Articles such as [97], published in 1985, already proposed a design to measure satellite-to-satellite range-rate with a precision smaller than 1 μm/s in distances between 100 km and 300 km. However, further analyses included the frequency instability of the oscillators [98], the channel noise conditions [99], and the requirements of low-cost small satellites [100] among other specifications. Distances can be determined from either the signal's modulation (PRN codes) or the carrier phase.

One of the most popular carrier-phase based ranging methods is the Dual One-Way Ranging (DOWR) [7], [98], [99]. By combining the one-way range measurements from two microwave-ranging devices, the method minimizes the effect of oscillator phase noise. Each satellite uses identical transmission and reception subsystems to send a carrier signal to the other. The recorded measurements are transmitted to a control segment for processing and calculating the inter-satellite range. DOWR method is represented in Fig. 11.

Some variations of this method have been proposed. For example, in [7] the authors addressed the use of Dual One-Way Time (DOWT) synchronization and ranging (DOWT&DOWR) in DSSs. Simulation results indicated less than 0.2 m and 0.5 ns precise ranging and time synchronization accuracy and error time synchronization smaller than ±10 ns for inter-satellite distances up to 200 km in satellite formation flying [7]. Another example is the Random Access Inter-satellite Ranging (RAISSR) system proposed in [101]. In this system, each satellite transmits a signal to allow other satellites to perform a one-way distance measurement with respect to it. Even when the authors claimed no strict time synchronization, the method requires all the satellites to share a common time reference.

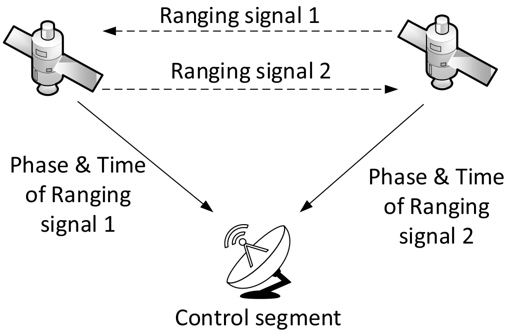

FIGURE 11. Basic principle of RF carrier-ranging by DOWR.

In [102], an approach to solving the problem of autonomous timing is proposed. This method aims to achieve time synchronization and high precision ranging between onboard oscillators and clocks on Earth, with only scarce information exchange. The main idea is to calculate the satellites CFO using a frequency tracking loop. Then, the inter-satellite range and the satellites' relative radial velocity are estimated on the ground [102]. The reported results showed a precision of 0.1 ns for inter-satellite baseline measurements and the accuracy of velocity measurement around 10^{-3} m/s, for approximately 0.01 Hz carrier frequency tracking error [102].

An essential aspect of DOWR that limits its performance is its synchronization requirements. As this method requires the transmitter and receiver to be synchronized, its accuracy is directly related to the performance of the synchronization algorithm. Clock drifts and offsets between nodes can introduce errors in the order of microseconds which can be too large for specific applications. On the other hand, the Two-Way Ranging (TWR) method does not have this drawback. In TWR, introduced in [100], one satellite sends the ranging signal and activates a counter to calculate the elapsed time until the reception of the other satellite replies. In this way, there is no need to synchronize both satellites' clocks [100]. The evaluation of the algorithm on a Software-Defined Radio (SDR) platform is reported in [100], showing an accuracy of a few centimeters.

Another hardware demonstration was presented in [89]. In this case, the authors developed a coherent distributed transmission system based on high-accuracy microwave ranging to perform DTB for mobile platforms. The Two-tone ranging method used for the indoor and outdoor experiments was introduced in [90].

The most well-known example of pseudo-random code ranging is the method applied by GNSS constellations. A variation of this method to measure the inter-satellite range in deep-space missions, where the navigation constellation is not available, was suggested in [103]. The design combines the typical GPS receiver with a RF transceiver to use when the satellite does not receive the GPS constellation' signals. The GPS module is a flight-qualified design that performs orbit determination using a EKF and the inter-satellite distance measurement is obtained by differencing both filtered absolute GPS solutions. The core of the whole system is a Central processing unit (CPU) core which controls the switch and coordination of the two ranging units [103]. Similarly, an Augmented Relative Navigation System (ARNS) for autonomous satellite formation flying in LEO is proposed in [104]. The idea of this article is that inter-satellite ranging systems can provide additional observation information, which can be used to increase the GPS stand-alone observation dimension. Reported results indicated that the ARNS improved the relative positioning accuracy by one order of magnitude in comparison to the GPS stand-alone solution [104].

In addition, other authors addressed ranging methods based on PRN codes. For instance, in [105] it is presented an algorithm to determine the initial value of smooth pseudo-range for the smoothing method proposed by Hatch [106]. The algorithm uses the least-squares straight line fitting technique to decrease the convergence time and improve the ranging accuracy [105]. On the other hand, the authors of [107] analyzed how it is affected the accuracy of inter-satellite ranging in a Direct Sequence Spread Spectrum Signal (DSSS) by the used bandwidth and [108] introduced a new ranging scheme combining continuous phase modulation and a PRN ranging code. The chip pulse used in this method is based on a normally distributed signal, which improves the ranging accuracy and reliability of the system.

Another example of a RF ranging technique using the signal's modulation was proposed in [109]. This paper analyzed a hybrid Orthogonal Frequency Division Multiplexing (OFDM) communication-metrology system for a two satellites formation flying. The system uses OFDM signals for ISL communications and measurements functions. The inter-satellite distance is estimated using a training symbol, which is also used for time and frequency synchronizations and estimation of the channel impulse response. The accuracy of the technique depends mainly on the bandwidth of the transmitted signal [109].

Most recent works focus on carrier ranging methods assisted by pseudo-random code ranging, which allows higher precision range values. For example, [110] proposed a pseudo-code-assisted carrier ranging algorithm, which is the combination of pseudo-range and dual-frequency carrier phase ranging methods. In [111], the impact of the frequency selection on the ranging accuracy was analyzed. Too high frequency leads to problems in the resolution of integer ambiguity, but too low frequency impacts ranging accuracy. Both articles reported range errors on the order of 1 cm for inter-satellite distances around 100 km [110], [111].

Even though the accuracy of carrier-ranging methods is higher than pseudo-random code ranging methods, the integer ambiguity is more difficult to resolve for the former ones. The solution of the phase integer ambiguity problem has been dealt in [104], [112] and [113]. For instance, [112] presents a robust integer-cycle ambiguity resolution method by modifying the well-known Least-squares Ambiguity Decorrelation Adjustment (LAMBDA) method [114]. The authors derived the validation threshold in closed-form as a function of the phase noise variance and the antenna baseline geometry. As a result, the success rate of the original LAMBDA is improved. However, the method requires that the spacecraft of which the LOS will be estimated is equipped with a body-fixed array of at least three antennas in different planes [112]. This could be a limitation for small satellites missions. Another procedure based on the LAMBDA method was proposed in [104]. This paper contains two approaches to combine the inter-satellite ranging measurements with GPS. Besides, it proposes a feedback scheme to convert the ambiguity float solutions obtained from the EKF into pseudo-perfect measurements through the LAMBDA method. After the possible integer solutions are verified, they are adopted as pseudo-perfect measurements to update the EKF for the next epoch.

Another approach to the phase integer ambiguity problem was proposed in [113]. In this case, the authors used the simplified time-differenced technique [115] to eliminate the influence of ambiguity in a GPS/Inertial navigation system (INS) integrated navigation algorithm [113]. The simplified time-differenced method consists of processing time differences of successive carrier phase measurements at a GPS base station, which increases the velocity and attitude accuracy. It reduces noise in the position information compared to the traditional tightly coupled systems. Unfortunately, the time-differenced carrier phase measurements do not fit easily in the framework of a KF measurement equation, which has adverse effects on the derivation of an appropriate measurement matrix [115].

B. RELATIVE POSITIONING

Spacecraft relative positioning in formation flying is a crucial enabler of new space missions and of paramount importance for distributed satellites architectures. Clearly, two subcategories can be distinguished: in-orbit autonomous and assisted from the ground. Relative positioning can be seen as a coordinated operation of the ranging systems described in the section above, which can occur either in-orbit or on-ground.

1) IN-ORBIT AUTONOMOUS

The primary technology used for precise relative positioning of autonomous formation flying satellites is GNSSs.

If the relative position between two GNSS receivers is required, the GNSS data differences from two receivers can be used. This method reduces common data errors, such as the GPS satellite clock offset. The difference is typically calculated using the pseudo-range estimation between the receivers and a GNSS satellite or more. Once resolved the code ambiguity, sub-metric precision is obtained by using this method [116].

In order to enable, cm to mm positioning accuracy levels, the handling of carrier differential GNSS (CDGNSS) estimations needs to happen [117]. Within the setting of the GRACE formation flying mission, the possibility of 1 mm level relative navigation over a 200 km separation has been illustrated by utilizing carrier GPS estimations from a high-grade dual-frequency BlackJack receiver [118].

A major problem in using CDGNSS is tackling for the unknown integer number of cycles (integer ambiguity) [119]. Especially when the resilience and precision of the integer solution are affected by variations in the number of common-in-view satellites, and ephemeris and ionospheric differential errors. This is enhanced when the inter-satellite distances are highly variable due to the relative orbital trajectory.

A few strategies based on arrays of GNSS sensors have been proposed to unravel the phase ambiguity problem. Since antennas are unbendingly mounted on the stage, the relative antenna position within the local body frame is known in advance. It can be used to improve the accuracy of the estimated integer ambiguity. In [120], the use of the Multivariate Constrained Least-squares AMBiguity Decorrelation Adjustment (MC-LAMBDA) strategy [121] successfully utilizing nonlinear geometrical constraints. By consolidating the known antenna geometry into its ambiguity objective function, this strategy has been appeared to illustrate reliable and immediate single-frequency integer ambiguity determination.

DSSs operating above LEO loses coverage of the GNSSs infrastructure and has to rely on other means for tracking and navigation. For those missions, a trilateration scheme is proposed in [122] that evaluates the 3-Dimensional (3D) relative position between a reference spacecraft and a target spacecraft using raw-range measurements from a distance baseline of known locations, which is called “anchors”. The anchors can be antennas of a ground-based network or satellites of a space-based network (e.g., GPS). The method assumes the clocks of the anchors to be perfectly synchronized and requires some synchronization between the anchors and the reference spacecraft. However, the synchronization errors between the reference spacecraft and the rest of the satellites in the DSS is compensated by using an additional anchor. This method achieves sub-meter accuracy for a Geostationary Orbit (GEO) DSS with two spacecraft, using a baseline network of three ground stations as anchors.

Another example of very accurate tracking and control of the relative position is the PROBA-3 mission. PROBA-3 is a European Space Agency (ESA) mission to obtain highly accurate formation flying. A couple of satellites, the Coronagraph Spacecraft (CSC) and the Occulter Spacecraft (OSC) will work together as an externally occulted solar coronagraph. The CSC hosts the optical assembly of the coronagraph as the primary payload, while the OSC carries the coronagraph external occulter disk. The mission requirements are a longitudinal accuracy better than 1 mm for the inter-satellite distance of 144 m [21]. To make this feasible, the formation flight system is distributed between both spacecraft: the CSC hosts the formation flying sensors, while the OSC performs the data processing [123]. The formation flight task requires the use of several metrology subsystems, from coarse accuracy and large scale range determination to very accurate and shorter scale range measurement and absolute positioning. All the data generated by these subsystems are processed in real-time by the Guidance and Navigation Control system, obtaining an unprecedented accuracy [124].

IRASSI is an interferometry-based mission concept composed of five free-flying telescopes orbiting the Sun-Earth/Moon second Lagrangian point, L2. It focuses on observing specific regions of the sky to study star formation, evolution processes, and early planetary origins. The study of these processes requires a telescope with angular resolution lower than 0.1 arcsec [125]. The interferometer relies on dynamically changing baselines obtained through the physical separation during scientific observations to achieve such strict resolution values. For example, the baseline vectors between the telescope reference points must be determined with an accuracy of 5μm to guarantee the precise correlation of the detected signals. The navigation concept capable of achieving these strict requirements consist of two components: the absolute position estimation concerning Earth and the relative position estimation, which determines the satellite’s positions to each other [126]. The description of two autonomous relative positioning algorithms based on a geometric snapshot approach can be found in [127].

For formation flying missions, in addition to the inter-satellites position, it is imperative to estimate and control the satellites’ attitudes accurately. In [128], the relationship between the precision estimation against the ranging accuracy, ranging distance, and satellite relative position were analyzed. As a result, it was concluded that obtaining accurate measurements required a balanced number of transmitting and receiving antennas with suitable configurations. It is a necessity to install more antennas to improve the precision estimation of the attitude angles [128].

Another critical requirement of formation flying is accurate relative navigation. Significant research results have been published about this topic. For example, [129] used the nonlinear dynamics describing the relative positioning of multiple spacecraft for formation flying trajectory tracking control. Using Lyapunov-based control design and stability analysis techniques, the authors developed a nonlinear adaptive higher-order sliding mode control commonly known as adaptive super twisting sliding mode control. On the other hand, [130] develops an efficient approach of autonomous relative orbit determination for satellite formation flying. The proposed solution uses the inter-satellite local measurements by the microwave radar and laser devices on board the satellites to perform the relative navigation. The design uses a decentralized Schmidt KF [130] to estimate the state of relative orbit between the satellites and proves that this approach is immune to the single satellite failure. Simulation results showed that the relative position estimation might achieve centimeter-level accuracy, and relative velocity estimation may achieve mm/s-level accuracy for a circular spatial formation consisting of three satellites where the chief satellite is at the center. The radius is about 1 km [130]. Similarly, in [131] a method for autonomous orbit determination combining X-ray pulsar measurements and inter-satellite ranging during

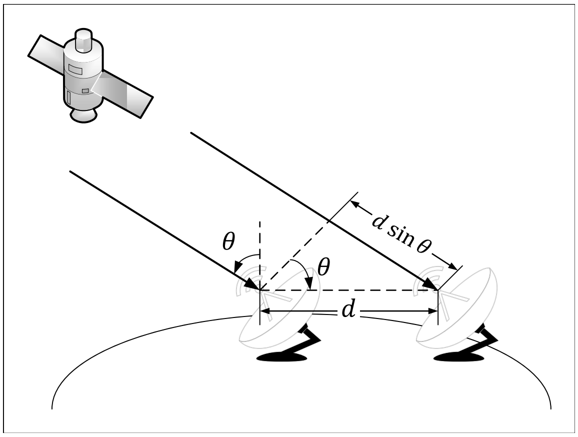

FIGURE 12. **Orbit determination by Interferometry.**

Mars orbiting phase was presented. The method calculates an observability index reflecting the measurement information quality and optimizes the observable target selection and the observation scheduling. Then, the Unscented KF is used to estimate the autonomous pulsar assisted orbit determination [131].

2) ASSISTED FROM GROUND

Determining the orbital position of satellites from the ground requires obtaining azimuth and elevation view angles of the satellite and the distance from the ground station to the satellite (range).

One of the most accurate Precise orbit determination (POD) measurements assisted from the ground can be achieved by Radio Interferometry methods. Interferometry is a technique for passive tracking. A simple interferometer consists of two receivers represented in Fig. 12. Using the phase difference between the signals received by the two antennas, the direction of the target can be determined. Connected-Element Interferometry (CEI) is a technique for determining the phase offset from the TOA difference of a downlink radio signal to two antennas on a short baseline. In [132], the authors used a small-scale CEI system of two orthogonal baselines (75 m × 35 m) to track a GEO satellite. Reported results showed accuracies smaller than 1 km in the radial and the cross-track directions, and 3D position accuracy in the order of 2 km. Another example of the positioning of GEO satellites by Radio Interferometry was proposed in [133]. In this case, the authors focused on determining the view angles of GEO satellites with an estimation accuracy of 0.001° in Ku band.

In addition, ISLs can improve the accuracy of orbit determination for GNSSs constellations. One example of this was presented in [134], where it was demonstrated that the POD of the Kepler system could be performed with just one ground station achieving orbit accuracies of 5 cm in 3D and 0.24 cm in radial direction [134]. On the other hand, in [135], it was proven that the use of ISL ranging measurements could reduce the first positioning time about six times in conventional navigation receivers.

C. SUMMARY AND LESSONS LEARNT

- In a DSS, the inter-node ranging and relative position are closely related to the synchronization algorithm. Generally, the requirements and accuracy of the coherent operation depend on the performance of the ranging and relative positioning algorithms as much as the synchronization itself.
- Optical inter-satellite ranging methods can achieve higher accuracy, but the higher directivity of the laser beam can represent a limitation for specific applications.
- The use of a single optical ISL to simultaneously perform ranging and communication is a trending topic in this field.
- Inter-satellite ranging based on RF can use measurements of the carrier's phase or use the signal modulation. Recent publications considered the combination of both: carrier ranging assisted by pseudo-random code ranging methods.
- Both optical and RF-based ranging algorithms have to deal with the phase integer ambiguity problem.
- Spacecraft relative positioning can be seen as a coordinated operation of the ranging systems described above, which can take place either in-orbit autonomous or assisted from the ground.
- The leading technology used for precise relative positioning of autonomous formation flying satellites is GNSSs.
- DSSs operating above LEO loses coverage of the GNSS infrastructure and has to rely on more complex schemes. Examples of these schemes were analyzed in this section.
- One of the most precise POD measurements assisted from the ground can be achieved by Radio Interferometry methods.

V. APPLICATIONS OF DSSs SYNCHRONIZATION

As stated above, carrier and time synchronization are critical and very challenging requirements for CDSS. Consequently, the research in the area is very prolific. In this section, the most significant articles about synchronization for DSS found in the literature are summarized. They are arranged in two groups attending to its application: Communications or Remote Sensing.

A. COMMUNICATIONS

Small satellites, organized in distributed systems, are envisioned to be the future of space communications [14]. Forming a dynamic phased array in space with the nodes of a DSS can improve the communications capabilities between the network and the Earth. However, implementing such an array requires effective open-loop carrier synchronization [2]. In [8], the phase synchronization constraints of a DSS of very simple, resource-limited femto-satellites communicating with Earth were derived and discussed [8]. Fig. 13 from [8] shows the normalized amplitude of the received signal as a function of the number of transmitters for different

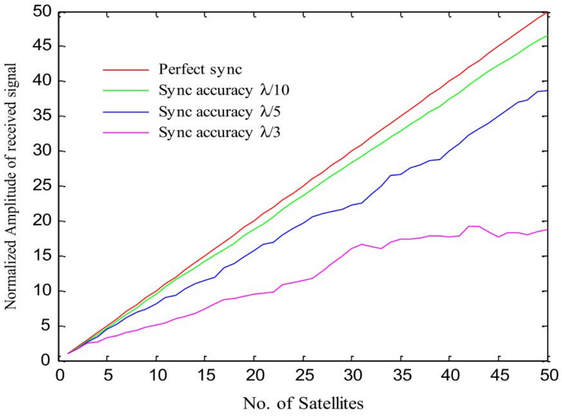

FIGURE 13. Normalized amplitude of the received signal vs. the number of satellites for different values of phase synchronization accuracy [8].

accuracies of phase synchronization. As can be appreciated in the figure for a high number of nodes, the effects of phase synchronization inaccuracies are more evident.

In [9], a time and phase synchronization solution to perform beamforming in a LEO-DSS is proposed. The mathematical framework and analysis of the synchronization scheme is developed, which relays in an external beacon transmitted from a GEO spacecraft above the intended ground receiver. This open-loop method achieves subcentimeter-level (subnanosecond-level) phase synchronization with localization accuracy on the order of meters [9]. However, these results are restrained to a particular array geometry, which is not always feasible.

In [7], the simulation and performance evaluation of the two-way range and time synchronization method for a DSS were presented. The DSS consisted of four satellites in a formation flying mission, with 50 km of inter-satellite distance and a carrier frequency of 400 MHz simulated in the Systems Tool Kit (STK) platform from Analytical Graphics, Inc. According to the simulation results, the error of the time synchronization was less than 10 ns [7].

B. REMOTE SENSING

Remote sensing and Earth observation from DSSs have become attractive for the community in the last years. New concepts, like distributed synthetic aperture radiometers or fractionated radars, offer the potential to significantly reduce the costs of future multistatic SAR missions [136], [137]. Besides, the low radar power budget and high spatial resolution requirements of future remote sensing satellite missions seem to be only possible to achieve through multistatic configurations [138]. However, the frequency, phase, and time synchronization is still the major challenge that slows down the launch of new missions. For that reason, new synchronization methods for Remote Sensing DSSs are published daily.

For instance, an inter-satellite time synchronization algorithm for a micro-satellite cluster was proposed in [34]. The authors proposed a time control loop that dynamically adjusts each satellite reference frequency according to the time difference with the time benchmark of the cluster. Consequently, time synchronization is achieved by locking the clocks of all the satellites to a chosen one. Similarly, [139] presents a method to relatively synchronize the clocks in a DSSs without the use of GNSS signals. A reference pulse transmitted by a master satellite is received and time-tamped by all the secondary satellites in its broadcast domain. The method estimates the clock offsets relative to the other secondary satellites by calculating the receive-time differences between two secondary satellites. Simulation results reported in [139] showed excellent convergence rates. However, this method requires that all the distributed nodes are in the same broadcast domain of a single master satellite, and the LOS from one satellite to all others must always be available. Besides, the algorithm is affected by the difference in propagation time between two receivers. This is not a problem for relatively small networks but, for DSSs with longer inter-satellite distances, these propagation delays have to be compensated.

Other authors have studied the effects of time and frequency synchronization on DSS SARs [140], [141]. In [140], a model considering the time and frequency synchronization errors in Interferometric Synthetic Aperture Radar (InSAR) were presented. The performance of the range and azimuth compression with the synchronization errors was analyzed to obtain the time and frequency synchronization requirements for parasitic InSAR system design. On the other hand, [141] studied the performance degradation in bi-static and multi-static SARs due to the oscillators' phase noise. Using a dedicated synchronization link to quantify and compensate the oscillators phase noise was proposed considering three different synchronization schemes: continuous duplex, pulsed duplex and, pulsed alternated. The analysis included additional factors such as receiver noise and the Doppler effect and contributions known from sampling theory like aliasing and interpolation errors. According to the reported results, successful oscillator phase noise compensation is possible if the compensation algorithm and the signal timing are adapted to the link hardware and SAR parameters [141].

More advanced works have reached the implementation and test steps, which are fundamental to using a synchronization method in a mission. For example, [142] proposed a hardware-in-the-loop simulation and evaluation approach for DSSs SAR. The proposal was used to model a typical bi-satellite formation spaceborne distributed SAR system in the X band. The SARs' central electronic equipment was implemented in hardware, whereas the echo generation and the processing and evaluation of the results were performed in software. In [143], a phase synchronization scheme based on F-RT for the operation of the airborne based bistatic SAR receiver, SABRINA-UAV was prototyped and tested in the laboratory. Another example is the testbed for coherent distributed remote sensing systems proposed in [138]. This platform is composed of two satellites, the channel emulator, and two targets, all implemented in Universal Software Radio Peripherals (USRP). The authors proposed and validated a dual carrier point-to-point synchronization loop through the testbed. The synchronization algorithm is based on a Master-Slave architecture to autonomously synchronize both satellite clocks with a common reference using ISLs [138]. Generally, the hardware simulations include features that can not be easily or accurately considered with computer-based simulations. First, there are coupling relationships among the channel mismatch, the time and phase synchronization errors, and other error sources. The single error analysis method used in the computer-based simulation can't meet this requirement. Besides, the hardware implementation of the synchronization algorithm gives a more accurate description of its performance. Computer-based simulations cannot precisely measure features like processing time and resources. On the other hand, the error source characteristic has to be known for data analysis and evaluation, which is more complicated for hardware simulations.

Several remote sensing distributed satellite missions have been proposed and deployed during the last years. Section VI will refer to already deployed missions, but the proposed synchronization algorithms for future missions are of interest to this section.

1) ARGOS: The Advanced Radar Geosynchronous Observation System (ARGOS) will be a MIMO SAR system hosted on a swarm of mini-satellites in quasi-geostationary orbits [144]. It consists of: a swarm of active and passive spacecraft in a zero inclination quasi-GEO orbit; a data-link to a telecommunication satellite that is used for both data download and synchronization; a ground segment and; a network of active calibrators for precise estimation of sensors clocks and orbits. According to [145], the link with the telecommunication satellite can be used to synchronize the DSS to a common clock and support the estimation of the precise orbits, in a similar way to a cloud PLL. Besides, the oscillators' phase noise can be compensated by exploiting a network of Compact Active Transponders or through an on-ground synchronization scheme capable of estimating the phase on very bright point targets.
2) LuTan-1: LuTan-1 (LT-1), also known as TwinSAR-L mission, is an innovative spaceborne bistatic SAR mission based on the use of two radar satellites operating in the L-band with flexible formation flying, to generate the global digital terrain models in the bistatic interferometry mode [146]. Several articles about the LT-1 phase synchronization scheme have been published [146]–[149]. The algorithm, proposed in [147], considers the time multiplexing of the synchronization pulses with the radar pulse-repetition intervals avoiding any interference in the SAR data acquisition. Besides, [146] proposed a KF phase-error estimation and compensation method, which improves the synchronization accuracy for low Signal-to-Noise Ratio (SNR). On the other hand, [148] evaluated the performance of the LT-1's synchronization scheme for multipath effects, and [149] presents its experimental verification.
3) ConGaLSAR: A Constellation of Geostationary and LEO SAR (ConGaLSAR) radars has been proposed in [137]. The phase and time synchronization of this constellation would be supported by a novel transponding mode known as MirrorSAR, where the LEO satellites work as relay nodes for the ground echoes to the illuminating GEO satellite. The key idea of MirrorSAR is to redirect the radar echoes to the spacecraft, where they can be coherently demodulated with the same clock references previously used to generate the radar pulses [136]. The authors introduce two alternatives for synchronization. In the most simple one, the LEO subsystem functionality is limited to amplify and forward the received RF signal. The second possible configuration, named Double Mirror Synchronization, requires the transmission of a very stable reference signal from the illuminator to the LEO-satellites by using a dedicated low-gain antenna. Even though this method increases the synchronization processing considerably and requires more complex LEO-satellites, it still assumes that the distance between the transmitter and receiver satellites is almost constant, and it can be accurately estimated [136].

C. SUMMARY AND LESSONS LEARNT

- Not many publications consider CDSS for communications applications. However, there are some simulations for LEO DSS, synchronized with the aid of a GEO spacecraft. In addition, the two-way time and range synchronization method has been considered for the synchronization of a DSS of four satellites in a formation flying mission.
- Remote sensing and Earth observation from DSSs has become attractive for the community in the last years. However, the frequency, phase, and time synchronization is still the major challenge that slows down the launch of new missions. For that reason, new synchronization methods for Remote Sensing DSSs are published constantly.
- Time and phase synchronization by master-slave architecture using intra-node communications are the preferred methods for remote sensing DSSs. However, the complexity of the system increases with the number of distributed nodes to be synchronized due to the increment of ISLs required.
- Information about the synchronization algorithms for future remote sensing distributed satellites missions was discussed in this section, specifically ARGOS, LuTan-1, and ConGaLSAR missions.

VI. EXAMPLES OF SYNCHRONIZATION FOR DSSs

The development of new synchronization techniques in DSSs as in any other wireless network requires three main steps: design, prototyping, and deployment. The new

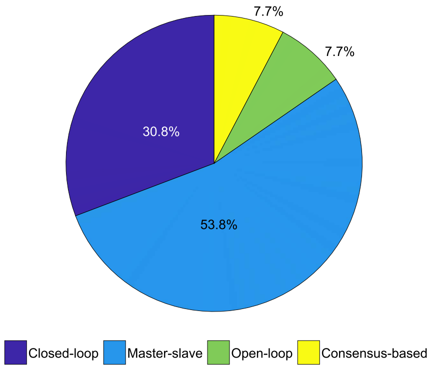

FIGURE 14. **Distribution of prototypes per synchronization method.**

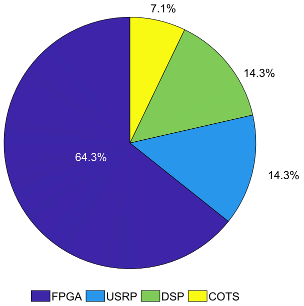

FIGURE 15. **Distribution of hardware platforms used to implement the synchronization methods.**

synchronization methods are theoretically analyzed, tested, and improved using software simulators during the design step. However, no matter how thorough the design step, new algorithms should comply with the prototyping before deployment. Theoretical design - software simulation - prototyping is a closed-loop that must be executed repeatedly to improve a synchronization technique before its deployment in DSSs. Theoretical design and simulation of synchronization algorithms suitable for DSS were already covered in previous sections. This section summarizes the most relevant hardware implementations and prototyping of such algorithms.

The most relevant and advanced examples of synchronization techniques for cohesive distributed systems are analyzed in the following. Unlike the previous section, where concepts and theoretical methods were discussed, this section presents synchronization algorithms that have been implemented and tested at least as a hardware PoC. Similar to the previous section, the examples are classified according to their application as Synchronization Examples in Distributed Communications Systems and Synchronization Examples in Remote Sensing DSSs.

A. SYNCHRONIZATION EXAMPLES IN DISTRIBUTED COMMUNICATIONS SYSTEMS

Hardware development for communication satellite systems has been pointing toward reconfigurable SDR System-on-a-Chip ground receivers, and to the ultimate extreme of Satellite-on-a-chip during the last years, [14]. In general, recent trends on prototyping and deployment of spacecraft are based on Commercial Off-The-Shelf (COTS) [150], FPGA [151] and SDR [152] designs. Mostly due to its reconfigurable characteristics and because they allow less expensive and faster development processes. Several examples of the use of SDR for inter-satellite communication in small satellite systems can be found in [2]. Fig. 14 and 15 show a graphic representation of the synchronization methods and the hardware platforms analyzed in this section.

However, there are not many publications about the hardware prototypes of synchronization algorithms, specifically in Communications CDSS. Mainly because the use of CDSSs for communications is a very recent topic that does not have any launched missions yet. Nevertheless, it is helpful to analyze the PoC of the synchronization algorithms used in distributed terrestrial communications that DSSs could apply. This can support the selection of the synchronization technique and the hardware platform during the design of a prototype for Communications CDSS. The examples are presented in order of increasing complexity, and some technical details are listed in Table 3 at the end of the section.

1) MOBILE COMMUNICATIONS NETWORKS

One example of distributed coherent radio system that shows some similarities with the DSSs is the recently proposed Cell-free (CF) massive MIMO concept. In CF operation, the network infrastructure performs beamforming towards the User Equipments (UEs) using multiple distributed radio nodes. The beamforming coordination relies on the Time Division Duplex (TDD) operation and uses a densely distributed network topology [153], [154]. Although there is a CPU in CF Massive MIMO system, the exchange of information happens only in the form of payload data while the power control coefficients change slowly. Neither is there a provision of sharing the instantaneous CSI among the Access Point (AP) or the CPU. Channel estimation is performed only at the AP using uplink pilot signals and further used for decoding uplink symbols and precoding the downlink symbols. [155].

A crucial requirement of the CF Massive MIMO is the global synchronization of RF carriers and information symbols across the geographically distributed service nodes network. In [156], CFO estimation for Distributed Massive MIMO and CF Massive MIMO is studied. Specifically, the article evaluates the performance of distributed large-scale MIMO systems with two collaborative (successive and joint), and one non-collaborative (independent) CFO estimation techniques [156]. According to [157], the global synchronization of RF carriers and information symbols across a distributed MIMO network can be done with a common 1 pps (pulse per second) GPS timing signal used to provide GPS disciplined oscillators [157]. This solution was demonstrated for two 50 MHz carriers tracked by frequency lock loops implemented on FPGA development platforms. Results showed a locking time of 500 s and a coherence time of 10 s, which is enough for the MIMO processing [157].

The TDD operation implemented in CF Massive MIMO is not very appealing for a DSSs used for communication applications due to the long latency of the satellite orbits. However, an extrapolation of the method to Frequency Division Duplex (FDD) scenarios can be applied. In such a case, more robust synchronization in time and phase is required between the distributed satellite nodes. One example of FDD standardized technology in mobile networks is the Coordinated Multipoint (CoMP) transmission and/or reception used in Long Term Evolution Advanced (LTE-A) standard.

In CoMP operation, multiple transmission points coordinate to combine the user's information signal from neighboring evolved Node B (eNB) to improve the received signal quality. To this end, CoMP transmission requires sharing coordination information, usually consisting of user's feedback CSI, through the backhaul links [158]. It can be implemented in four different types depending on the degree of coordination among cells: (1) Coordinated Scheduling and Beamforming and, (2) Joint Processing, both in the downlink; (3) Coordinated Scheduling and, (4) Joint Reception and Processing, both in the uplink. Even though multiple types of CoMP can be used together [158]. For example, in [159] proposed to switch the CoMP transmission mode between Coordinated Beamforming and Joint Processing adaptively to maximize the average achievable rate, considering that the last one is more sensitive to phase synchronization errors than Coordinated Beamforming [159].

CoMP requires the transmission points to be tight time and frequency synchronized. This constraint mostly affects coordination between Base stations (BSs) because some additional solution is needed to provide accurate phase synchronization. Large distances between the BSs result in unavoidable differences in TOA between the users' signals which in turn lead to inter-symbol interference in OFDM systems if the cyclic prefix length is exceeded. Moreover, CFOs which are caused by imperfect oscillators, lead to inter-carrier interference and are a problem, particularly in the downlink due to the feedback delay of the measured CSI. The most extended approach to synchronization in CoMP at outdoor BSs is to obtain a precise clock reference from GNSS [160]. This could be extended to DSS in LEO MEO. However, indoor BSs require to be synchronized over the backhaul network using standard protocols such as PTP or proprietary solutions like synchronous Ethernet [161], [162] [163].

In any typical cellular system, the users perform synchronization with a single BS where the BS transmits predefined signals to the UEs to adjust their transmit timings so that signals received from many UEss to the BS are time-aligned. However, a concern in CoMP is that the UEs needs to be synchronized to multiple BS simultaneously. Hence, the previously discussed technique is not going to work in the CoMP case. Due to this, the usage of CoMP becomes limited to deployments where the inter-site distances between BSs are small [164].

Different approaches to the time synchronization problem stated before have been proposed. The most straightforward is to use a larger cyclic prefix, but it reduces the system's throughput. Another widely used approach is adjusting the time advance based on the nearest BS. However, such a solution is not capable of fully solving the problem since some of the users may not be able to use the CoMP. In [164], the authors propose a linear combination of samples corresponding to the two consecutively received OFDM symbols to identify multiple transmitted signals. Such a scheme enables the mitigation of Multi-user Interference by applying Successive Interference Cancellation, as also proposed in [165] and [166]. Another approach considers the positions of the serving and interfering BSs and the estimated location of the UE to timely relate the synchronization signals received from adjacent BSs [167]. Several other approaches which consider asynchronous interference mitigation are discussed in [168] and [169]. All these methods could be extrapolated to time synchronization in DSS.

Joint processing of the carrier phase (along-with frequency) is one of the significant challenges in CoMP as in DSS. The time difference of arrivals imposes a phase offset on the transmit covariance matrix leading to improper precoding matrix index selection and therefore limiting the promised performance of CoMP [170]. It is a two-fold problem: (a) The RF-LO of the participating BS in CoMP are required to be synchronized among them, (b) the LO of the UEs are also required to be synchronized with the corresponding BS. Since the phase noise of the oscillator evolves quickly and only with the help of backhaul information, it becomes challenging to establish synchronization between the participating BSs. For achieving an acceptable level of synchronization, the phase noise needs to be very low in the LOs, which makes such deployment cost-inefficient. In another approach, the UE can also keep tracking the phase noise. The effect of BSs coordination and synchronization on the phase noise estimation at the user receiver was studied in [171], where it is derived the data-aided and non-data-aided CRLB for the phase noise estimation in a CoMP system. Another approach presented in [172] addresses the data-aided joint synchronization and channel estimation for the uplink of CoMP systems based on the Minimum mean square error (MMSE) criterion. This proposal considers an alternating minimization method to simplify the MMSE cost function such that the multiuser CFO, sampling timing offset, and channel frequency response can be estimated in an iterative approach more feasible for practical systems. Another method that addresses the estimation and compensation of time and frequency offsets in CoMP was proposed in [173]. In this case, the authors compare two solutions to the time-frequency offset estimation problem, one in which the UE is not aware of the transmitting point, and one in which the UE is provided with assistance information.

2) IMPLEMENTATION EXAMPLES OF CLOSED-LOOP SYNCHRONIZATION METHODS

- **One Bit Feedback**: In [59], an FPGA (Spartan-3) based hardware prototype was developed to demonstrate 1BF. Phase synchronization is achieved Over-the-air (OTA) whereas the frequency synchronization is attained via RF cables, and a frequency distribution source Octoclock [174]. The implementation used three single transmitters (beam-formers) and a single antenna receiver. At a feedback rate of 300 ms, convergence within 90% of the theoretical limit is achieved after 60 iterations. The experiments were performed inside the laboratory, i.e., static environment. Hence, the performance under the realistic time-varying channels was not investigated. Besides, frequency synchronization was also required to be achieved OTA.

A hardware prototype of the 1BF method, using USRP SDR [175] was presented in [176]. This prototype functionality is ''all-wireless'', i.e., no wired connections are used to attain frequency and timing synchronization. This experimental setup used three single-antenna transmitters and one single antenna receiver. With a feedback interval of 50 ms, nine times beamforming gain was achieved. However, like the implementation in [59], the experiments were performed indoors. Then, the performance of the system against the time-varying channel was not investigated. Besides, only phase synchronization is achieved OTA whereas frequency synchronization is achieved through coaxial cables and frequency distribution source.

Another prototype described in [177] performs both frequency and phase synchronization using 1BF, which has been derived from [59]. Individual components of the hardware prototype have been developed by the authors themselves and the beamforming algorithms have been programmed on Digital Signal Processor (DSP) cores. At a test frequency of 60 GHz, using three elements distributed phased array, 9.2 dB of distributed beamforming gain is achieved. In contrast to the methods discussed previously, i.e., [59] and [176], both frequency and phase synchronization are achieved OTA. However, the feedback interval of 0.5 ms is excessively high as compared to the other 1BF methods discussed ([59] and [176]). Besides, the prototype was tested against static channel environments; hence the performance of the system against the time-varying channel was not investigated.

- **Full-feedback**: Very few PoC demonstrators are available for Full-Feedback implementations. For example, in [178] a notable range extension by performing outdoor OTA tests was shown using COTS handheld radio (based on FPGA and DSP) equipment. Also, the KF is used to predict the offset in frequency and phase, which further assists in tackling the time variation of the channels. Thus making the system perform satisfactorily even when the nodes are mobile. It is shown that as compared to a COTS radio transmitter (approximate range 2 km), by performing distributed beamforming, the range can be extended up to 6 km using ten such radio nodes. Further extension of range up to 10 km can be achieved by using 30 such radio nodes. In [179], using the same experimental setup and beamforming method, 0.1 dB distributed beamforming gain was demonstrated using ten COTS radio nodes. OTA operation and application of KF for prediction makes this implementation suitable for DSS scenarios.

3) IMPLEMENTATION EXAMPLES OF OPEN-LOOP SYNCHRONIZATION METHODS

Among the open-loop algorithms, in [180] an SDR implementation (USRP X310 [181]) using transmitter nodes was demonstrated. OTA tests confirmed reliable frequency lock even at very low power. In another open-loop SDR implementation (USRP N210 [182]), a solution for OFDM based frames is developed by designing specific preambles to estimate the frequency and timing offset. The system is capable to operate reliably under frequency selective and slow fading channels. OTA showed performance gains from 2.5 dB to 2.8 dB.

4) IMPLEMENTATION EXAMPLES OF MASTER-SLAVE SYNCHRONIZATION METHODS

In [183], an SDR implementation of Master-Slave closed-loop synchronization procedure named as NetBeam was demonstrated. NetBeam involves a network of radios that broadcast information locally and jointly transmit it to a remote receiver. This is equivalent to a Master-Slave closed-loop synchronization. The performance is further enhanced by the creation of a cluster of beamformers based on CSI. As for the hardware implementation: a dual antenna configuration of USRP X310 is used as a receiver, and a single antenna configuration of USRP B210 is used as transmitters. A significant aspect of this implementation is that the 3D distribution of radio nodes is considered, which is crucial for DSSs (full-dimensional beamforming). Besides, a faster convergence is attained through machine learning techniques.

A SDR (USRP) implementation for parallel frequency and phase synchronization was demonstrated in [184]. In this case, the Master-Slave method was used for frequency synchronization whereas 1BF was used for phase synchronization. This is an all wireless implementation, where no wired medium is used for CSI feedback or clock/frequency distribution. Convergence time for the beamforming is of the order of several milliseconds. Another example of frequency and phase synchronization by the Master-Slave method is described in [185] using a SDR (USRP X310). In this case, coherent pulses are received with more than 90% of the ideal coherent energy. Similarly, [186] provided a comparison between wired and wireless clock distribution to achieve frequency and phase synchronization by Master-Slave. OTA tests showed a near-ideal 6 dB gain from a two-transmitter system at a distance of 85 m and coherent gain up to 90% of the ideal signal summation is achieved.

On the other hand, in [187] a SDR (USRP N210) implementation of a Master-Slave architecture for phase synchronization is presented. The external frequency source is used for stable clock distribution whereas phase synchronization is achieved through the Master-Slave method. Channel reciprocity is exploited to obtain CSI without the need for feedback. Besides, the nodes cooperate in disseminating the CSI.

Beamforming gain as close as 90% to the ideal beamforming gain is achieved.

Besides, in [188] the authors analyze the wireless carrier frequency and sample timing synchronization by performing an exchange of RF signals between the master and slave nodes. Further, the proposed solution was implemented in GNU Radio, and wireless tests were performed using Ettus USRP N210 SDRs. Besides, the estimation of the fractional clock phase was performed using matched filter bank consisting of sixteen fractionally delayed Zadoff-Chu sequences [189] which were capable of estimating residual timing offsets as small as 1/16 of the sample duration. However, the system did not address propagation delays, and also the system bandwidth was limited to only 1 MHz. The method yields a residual timing precision of approximately 500 ns which exceeds the expectation of CRLB.

In addition, authors in [190] used a SDR implementation (using USRP-E312) to perform synchronization, which did not require time-stamps. The observed accuracy of the method was less than 1 μs (0.8 μs) for 150 kHz sampling rate with precision limited to 1/10 of the sample rate. The authors reported the limited real-time processing capability of the USRP-E312 as the reason behind using such a low sampling rate. Three E310s were used in the over-the-wire setting: one as the master node, a second as the slave node, and a third as the measurement device for determining the resulting clock offset.

5) IMPLEMENTATION EXAMPLES OF CONSENSUS-BASED SYNCHRONIZATION METHODS

The PoC presented in [191] demonstrates consensus-based synchronization through SDR (USRP N210) implementation. GNU Radio was used for software-based signal processing. Both time delay and CFO estimation, as well as tracking, are addressed in the implementation. Convergence time is of the order of seconds when different nodes have different CFO. OTA tests showed carrier frequency offsets to be within 100 parts per billion (ppb) while timing offset were correctly estimated. Besides, the implementation also showed tracking capabilities.

Another notable consensus-based implementation can be found in [188]. For OFDM type frames, a specific frame structure was designed to facilitate frequency synchronization. A residual timing offset within 1/16 of symbol duration and a residual frequency offset of 5 Hz is achieved. With such residual frequency and timing offset, a near-optimal received signal power gain is shown when distributed beamforming is performed.

B. SYNCHRONIZATION EXAMPLES IN REMOTE SENSING DSSs

This section analyzes the synchronization methods used by DSSs missions to perform Earth observation and remote sensing tasks. At the end of the section, Table 4 summarizes the technical details of these missions.

1) GRACE

The Gravity Recovery and Climate Experiment (GRACE) was a mission devoted to monitoring changes of the Earth's gravity field irregularities from its dispatch in March 2002 to the conclusion of its science mission in October 2017 [18]. GRACE comprised of two equal satellites in near-circular orbits at $\sim$ 500 km elevation and 89.5° inclination, detached from each other by around 220 km along-track, and connected by an exceedingly precise inter-satellite, K-Band Microwave Ranging (KBR) system. The satellites were nominally held in a 3-axis stabilized, nearly Earth-pointed orientation, such that the KBR antennas were pointed accurately at each other. The KBR gives a micron-level precision (10 μm) using carrier phase estimations within the K (26 GHz) and Ka (32 GHz) frequencies [192]. A single horn serves as the K/Ka antenna for both transmitting and receiving the inter-satellite dual-band wave signals [193]. Each satellite transmits two sinusoidal signals (at K and Ka bands) with a frequency offset (nominally set to 0.5 MHz). The two 0.5 MHz down-converted RF signals are sampled at approximately 19 MHz and passed to the digital signal processing part of the receiver. Dedicated digital signal processing channels are used to digitally counter-rotate the phase of each down-converted signal, track phase with a digital phase-locked loop, and extract phase.

2) LISA

LISA stands for Laser Interferometer Space Antenna [194]. It is a distributed satellite mission formed of three spacecraft operating in formation flying at a 5,000,000 km distance, being the three peaks of an equilateral triangle. This arrangement composes a huge interferometer to monitor the gravitational waves coming from galactic and out of the galaxy sources. Each spacecraft contains two verification masses and laser bars that measure the separation between its masses and those from the other nodes with a required precision of 20 pm. This is the most extreme example of accurate ranging between flying payloads ever seen before. The spacecraft use inertial sensors and micro-newton thrusters to determine and control their orbits, whereas laser interferometry is used to measure the distance with the required accuracy.

3) OLFAR

The Orbiting Low Frequency Antennas for Radio Astronomy (OLFAR) is a space-based low-frequency radio telescope that investigates the universe's so-called dark ages, maps the interstellar medium, and finds planetary and sun-powered bursts in other solar systems. The telescope, which is composed of a swarm of fifty satellites, was sent to an area distant from Earth to maintain a strategic distance from the high Radio Frequency Interference found at frequencies underneath 30 MHz, coming from Earth [195]. The satellites can be maintained in a 3D configuration with a maximum diameter of 100 km [196] by using round-trip pulse-based synchronization.

TABLE 3. Summary of PoC hardware implementations of distributed synchronization techniques.

	Synch. Method	Frequency Synch	Phase Synch.	Feedback rate (ms)	Beamforming Gain / Convergence	Static / Time-Varying	Platform
[59]	Closed-Loop	Wired	Wireless	300	90% of theoretical limit	Static	FPGA
[176]	Closed-Loop	Wired	Wireless	50	9x	Static	FPGA
[177]	Closed-Loop	Wireless	Wireless	0.5	9.2 dB	Static	DSP
[178]	Closed-Loop	Wireless	Wireless	NA	0.1 dB	Time varying	FPGA and DSP
[180]	Open-Loop	Wireless	Wireless	NA	2.5 - 2.8 dB	Time Varying	FPGA
[183]	Master-Slave	Wireless	Wireless	NA	10x	Time Varying	FPGA
[184]	Master-Slave	Wireless	Wireless	NA	NA	Static	FPGA
[186]	Master-Slave	Wireless	NA	NA	90% of theoretical limit	Time Varying	COTS
[187]	Master-Slave	Wireless	Wireless	NA	90% of theoretical limit	Static	FPGA
[185]	Master-Slave	NA	Wireless	NA	90% of theoretical limit	Time Varying	FPGA
[188]	Master-Slave	Wireless	Wireless	NA	NA	Static	USRP
[190]	Master-Slave	Wired	Wired	NA	NA	Static	USRP
[191]	Consensus-Based	Wired	Wireless	NA	NA	Time Varying	FPGA

4) TanDEM-X

TanDEM-X was a scientific mission that comprised of two X-band SAR satellites following an orbit in near arrangement, with variable separation between them between 500 and 1100 m [49]. The mission produces high accuracy SAR snapshots at X-band in both monostatic and bistatic setups. For the bistatic design, one of the two satellites works as a transmitter and the other one as a receiver, and the mission performs a closed-loop synchronization scheme to get the required coherence.

5) GRAIL

The Gravity Recovery and Interior Laboratory (GRAIL) was a NASA mission to outline the gravity field of the Moon to a remarkable level of detail [197]. Twin shuttles were propelled on 10 September 2012 and were embedded into lunar orbit on 31 December 2011 and 01 January 2012 [198] correspondingly. The instrument for this mission was based on GRACE. Nevertheless, there were a few contrasts between both missions. The principal difference between the GRAIL and GRACE instruments emerged because GRAIL was not suffering the Earth's atmosphere drag, nor GPS navigation system was accessible. GRACE compensated for air disturbance basically by having an accelerometer to measure non-gravitational speed variations and by using two independent microwave ranging frequencies instead of only a single one.

GRAIL was streamlined by excluding the K-Band frequency (26 GHz) as well as the accelerometer (non-gravitational strengths are small enough to be modeled rather than measured). Furthermore, for GRACE, GPS was utilized to estimate the relative delay between the two spacecraft, calibrate on-board ultra-stable oscillators, and track the two satellite orbits. Without GPS accessible at the Moon, GRAIL included an extra S-Band (2 GHz) Time Transfer System to supplant the GPS timing measurements, and an extra X-Band (8 GHz) Radio Science Signal used for Doppler following of the shuttle and ultra-stable oscillator frequency calibrations through the Deep Space Network [197].

C. SUMMARY AND LESSONS LEARNT

- Hardware development for communication satellite systems has been pointing toward re-configurable SDR System-on-a-Chip ground receivers and to the ultimate extreme of Satellite-on-a-chip during the last years. In general, recent trends for prototyping and deployment of spacecraft are based on COTS, FPGA and SDR designs.
- Synchronization algorithms from Mobile Networks performing cohesive distributed communications, such as CF Massive MIMO and CoMP, can be extrapolated to synchronize CDSSs.
- Most prototypes of synchronization methods for distributed wireless communication networks implemented Master-Slave architecture and FPGA platforms.
- DSSs missions performing Earth observation and remote sensing tasks were discussed in this section. Most of them do not include more than three distributed nodes, and the synchronization is achieved using RF signals. Missions included in the section are: GRACE, LISA, OLFAR, TanDEM-X and, GRAIL.

VII. SYNCHRONIZATION USING MACHINE LEARNING

ML techniques can be significantly useful to address various synchronization problems associated with the end-to-end communication system. Some applications of ML in facilitating the synchronization process include frame synchronization, compensation of the errors caused by sampling frequency/time offsets, carrier synchronization, and characterization of phase noise. While modeling an end-to-end communication system, there may arise synchronization problems between transmitter and receiver due to various reasons including, sampling frequency offset, sampling timing error, and mismatch about the beginning of each frame, i.e., frame header, at the receiver. To address these problems, a Convolutional Neural Network (CNN) could be promising to build an additional synchronization model in order to achieve better frame synchronization and also to compensate for the impairments caused due to sampling timing error and sampling time offset. To this end, a CNN-based synchronization model with softmax activation function proposed in [199] has demonstrated 2 dB better detection than the direct correlation detection in terms of correctly detecting the actual position of a frame header. Furthermore, the traditional frame synchronization techniques based on maximum likelihood

TABLE 4. Summary of synchronization requirements for Remote Sensing DSSs missions.

Mission	Application	Distance between nodes	Band of operation	Required accuracy	Number of nodes	Synch. signal	Phase (P) Timing (T) Ranging (R)
GRACE [18] [192], [193]	Gravity	220 km	K (26 GHz) Ka (32 GHz)	10 μm	2	CW	R
LISA [194]	Gravitational waves	$5 \cdot 10^6$ km	Optical	20 pm	3	CW	R
OLFAR [195], [196]	Radio telescope	100 km	TBD	< 1 m	10 - 50	Pulsed	PT
TanDEM-X [49]	SAR	0.5 - 1.1 km	X	$\pm 0.1°$	2	Pulsed chirp	PT
GRAIL [197]	Lunar gravity	50 - 225 km	S (2 GHz) X (8 GHz) Ka (32 GHz)	1 μm	2	CW	PTR

and correlation may fail due to hardware implementation constraints or frequency deviation problems. To address this, ML techniques such as multi-instance learning can be used to solve the frame synchronization problem under different frequency ranges without additional modifications [200].

Moreover, ML techniques can be used to accurately characterize amplitude and phase noises, which are essential parameters in the synchronization process of distributed satellite systems. In this regard, in [201] a Bayesian filtering-based framework was used in combination with the expectation-maximization to characterize the amplitude and phase noise characterization of the lasers. The carrier synchronization has been experimentally demonstrated using the proposed framework, and the Bayesian filtering has been shown as an efficient method to estimate laser phase noise even in the presence of low SNR.

Due to limited computing power, the complexity of the ML model, and the increased data volume, a single learning node/machine is generally not able to execute an ML model, and this will require the distributed implementation of ML models across several distributed nodes in a network. In distributed learning, a local node computes a data subset's local updates/models. It updates the local updates/model parameters to the centralized server, which then calculates the global parameters [202]. The computed global parameters are then distributed to the local nodes to all distributed nodes. This distributed approach significantly reduces the communication burden required to communicate all the local raw data to the centralized server and utilize the local computational power to generate local models.

However, the application of ML techniques in distributed systems may result in relatively low accuracies and poor convergence rate due to differences in the transmission delays and computational capabilities of distributed nodes/clusters. Therefore, it is crucial to have a proper synchronization among different nodes/clusters of distributed systems to enhance the accuracy of the ML training model and to accelerate the training time. The synchronization cost may result in a significant performance loss of a distributed ML model [203]. In general, to parallelize the data across distributed clusters, ML techniques utilize Bulk Synchronous Parallel (BSP) strategy [204], in which all computational nodes need to commit and receive new global parameters before starting the next iteration, resulting in a load imbalance problem. This load imbalance problem can be addressed with an asynchronous strategy as it enables the distributed learning nodes to utilize local model parameters for the next iteration [205]. The main problem with this asynchronous method is that the model may not provide the accuracy guarantee since the model can be trapped in a local optimum without converging to a globally optimum solution. Another approach is Stale Synchronous Parallel (SSP) strategy [206], in which the modes can utilize the stale global parameters to train the local model; however, this may not guarantee convergence due to the limitations of stale global parameters. A promising approach to address the drawbacks of the methods above is to dynamically adapt the communications method between the centralized/parameter server and the distributed nodes based on the performance of each node. In this regard, the Adaptive Synchronous Parallel (ASP) strategy proposed in [203] has been shown to achieve higher convergence speed and provide better accuracy than the SSP methods. However, the applicability of the ASP method in a large-size distributed ML framework remains an open problem.

The emerging cyber-physical systems requiring time synchronization are vulnerable to the threat of time synchronization attacks, which mainly focus on modifying the measurements' sampling time/time stamps without modifying the system measurements. Such time synchronization attacks may lead to serious consequences in cyber-physical systems, such as incorrect voltage stabilization in smart grid networks. The existing attack detection techniques such as residual-based bad data detection and the conventional supervised ML-based detectors may not be able to effectively detect such attacks, leading to the need for innovative ML-based solutions [207]. In this regard, "first difference aware" ML classifier proposed in [207] could be promising to detect two types of time synchronization attacks, namely, direct time synchronization, which only modifies some time stamps, and stealth time synchronization attack, which modifies all the timestamps at a certain time. The First Difference ML (FDML) techniques utilize the backward first difference of the time-series data in order to process the input data stream before employing an ML method.

For a satellite system with a Dehop-Rehop transponder (DRT) working in the Frequency Hopping-Frequency Division Multiple Access (FH-FDMA) mode, it is common to use different hopping sequences for the uplink and downlink communications to avoid possible jamming or interference in both the links [208]. However, the synchronization between DRT and ground equipment with different hopping sequences becomes very complicated, and it is a crucial challenge to investigate an efficient synchronization method. In this regard, authors in [209] proposed an ML-based novel method to carry out synchronization with the Frequency Hopping signal for tactical SatCom system by utilizing serial search for coarse acquisition and Long short-term memory (LSTM) network for fine acquisition. The main objective of the proposed work is to reduce the synchronization time. It has been shown that the proposed LSTM-based method enables the fast and quick fine acquisition in comparison to the existing methods in the literature and provides benefits in saving the overall synchronization time by allowing the fine acquisitions for both downlink and uplink and learning the temporal trend of the signal.

In the context of 5G integrated SatCom utilizing OFDM, authors in [210] proposed a Cyclic Prefix based multi-symbol merging blind timing algorithm to enhance the timing accuracy. Also, an improved synchronization method has been submitted to realize more accurate time-frequency error correction in the considered 5G integrated SatCom system. With the help of simulations results, it has been depicted that the proposed multi-symbol merging method provides better performance than the single-symbol method in low SNR conditions, and the proposed synchronization method can provide a good Bit Error Ratio (BER) performance.

Due to the availability of massive volumes of high-resolution videos and images taken by LEO satellites and Unmanned Aerial Vehicless (UAVs), many data sources have become available for Space Information Networks (SINs). However, the application of ML becomes challenging due to limited computing and communication resources and also the low frequency and orbit resources in SINs. Also, the unstable connections of SINs further create the challenges of employing ML among a swarm of satellites and UAVs. To address this, authors in [211] considered the application of distributed ML in SINs, called SpaceDML, to effectively reduce the communication overhead among the SIN devices. The proposed SpaceDML utilizes adaptive loss-aware quantization and partial weight averaging algorithms to compress models without sacrificing their quality and selectively average the active agents' partial model updates, respectively. The evaluation with public dataset and realistic model presented in [211] has demonstrated that the proposed SpaceDML can enhance the model accuracy by about 2-3 % and reduce the communication burden among SIN devices can be up to 60 % as compared to the baseline algorithm.

A. SUMMARY AND LESSONS LEARNT

- ML can be considered as a promising technique to address several synchronization problems related to frame synchronization, compensation of the errors caused due to sampling frequency/time offsets, carrier synchronization, and characterization of phase noise in communication systems, including a SatCom network.
- For distributed satellite systems, ML techniques can be used to accurately characterize amplitude and phase noises, which are essential parameters in the synchronization process of a distributed satellite system.
- Distributed learning techniques find significant importance in distributed satellite systems as they enable the distributed implementation of ML models across several distributed nodes in a network.
- Synchronization cost may result in a significant performance loss in a distributed ML implementation, and it is imperative to have a proper synchronization among different nodes/clusters of a distributed system to enhance the accuracy of the ML training model and to accelerate the training time.
- Time synchronization attack is one important problem to be considered in the emerging cyber-physical systems involving a distributed satellite system as it may lead to severe consequences in the overall system operation. The conventional supervised ML-based detectors may not be able to effectively detect such attacks, leading to the need for innovative ML-based solutions such as ''first difference aware'' ML classifier proposed in [207].
- Synchronization between DRT and ground equipment with different hopping sequences in an FH-FDMA-based satellite system becomes very complicated, and ML-based synchronization techniques such as LSTM seem to be promising as illustrated in [209].
- ML techniques could also be promising to enhance timing accuracy in 5G integrated satellite system [210] and to reduce the communication burden among different distributed SIN nodes in emerging SINs with the help of distributed ML [211].

VIII. RESEARCH CHALLENGES AND OPPORTUNITIES

This section summarizes some of the critical research challenges and opportunities identified while conducting this survey.

A. SYNCHRONIZATION THROUGH ISLs IN NEXT GENERATION GNSSs

Multiple research results have indicated significant performance improvements on navigation constellations, thanks to the introduction of inter-satellite ranging and communication links [108], [212]. At the same time, a consolidation of the technologies enabling this improvement is essential to reduce further the complexity of the inter-satellite ranging and communication payload and simplify the ground-based orbit determination and clock synchronization algorithms. ISLs currently perform navigation and communication functions through independent low-rate telemetry and high-rate data channels, respectively. The integration of both functionalities into one common channel would simplify the onboard equipment and improve the electromagnetic compatibility, which implies the reduction of power consumption and the required frequency resources.

Current GNSSs employ a network of ground stations to track the satellite clocks and estimate their deviations for a single time scale. The estimated time offsets are included in the navigation messages sent to the final user, which use the information to correct the satellite clock delays in the received signals. This procedure would be simplified if the satellites of the GNSSs could synchronize their carriers without the intervention of the ground segment. The use of optical ISLs could be a viable solution to achieve this goal enabling a novel GNSS architecture in which, rather than independently maintaining a time scale, each navigation satellite would synchronize the emitted broadcast navigation signals to a common system time [213], [214].

B. FEDERATED SATELLITE SYSTEM (FSS)

To fully achieve the potential that FSS represents for space systems, several challenges need to be addressed to achieve its successful implementation, and operation [215]. Some of the technical challenges that need to be considered in the development of FSSs are [216]:

- Coordination/cooperation between heterogenous satellites belonging to the same network. This requires the definition of **compatible communication standards**, including allocation of the appropriate frequency bands, bandwidths, and the definition of the modulations. Inter-satellite links can be either radio or optical. Both impose different requirements on the spacecraft in terms of pointing accuracy and jitter and have different ranges and transmission speeds.
- The different layers of the **protocol stack** also need to be defined. Routing protocols have to be able to properly manage the fast switches/handoffs and bottlenecks that for polar LEO satellites typically occur in the polar regions, where the satellite density is larger. Quality of service (QoS) must also be maintained to keep latency bounded. Some works have proposed the use of MobileAd-hoc Network (MANET) routing protocols to autonomously determine the optimum route in a context where all nodes are constantly moving. In the Internet of Satellites (IoSat) context MANETs can provide the self-organization, self-configuration, and flexibility required by FSS [215].
- Additionally, all the **backbone technologies** to support FSS operations so as to interconnect seamlessly in-situ sensors and user terminals from ground to/from the space infrastructure (e.g. [217]), to become the IoSat paradigm [218], will also have to be developed.
- Depending on the above requirements and technologies, this can be achieved by **multi-layer constellations** formed by LEO satellites at different heights and/or MEO satellites, and/or possibly GEO satellites.
- Last, but not least, **privacy and security problems** must be addressed to prevent potentially malicious users from operating and taking control of the FSS [47] or preventing third parties from sniffing the information gathered by or transmitted through the satellites forming the FSS. In this line, the use of distributed keys and blockchain offers a new field of research.

C. DBF AS AN ENABLER FOR DSSs WITH SMALL SATELLITES

Despite the well-known advantages of small satellites over traditional ones, small satellites present some limitations in mass and volume that lead to restrictions in power consumption and the antennas' location. These constraints could be overcome by their use in DSSs configurations [138], [219]. Key challenges to achieving this potential benefit include distributed timing, carrier frequency, and phase synchronization [2]. Besides, the limited kinematic capabilities and the small cross-section of these satellites affect the accurate measurement of inter-satellite range and precise orbit determination and control, making the synchronization tasks even more difficult. However, several research results have proved the advantages of DBF for distributed wireless networks in terrestrial communications. Results such as the increment of the transmission range [220] and the SNR [221], as well as the experimental demonstration of DBF by a swarm of UAVs [222] could be extrapolated to DSSs. Future research in the field should focus on the synchronization algorithms to perform DBF with small satellites systems.

D. SYNCHRONIZATION ALGORITHMS SUITABLE FOR COMMUNICATIONS CDSSs

Generally, closed-loop synchronization methods are not the ideal solution for space-ground or long distances communication links due to the intrinsic delay between the DSS and the target nodes. In addition, other constraints such as the slow convergence of the iterative bit feedback algorithms [63]; the high power consumption and scalability problems of T-RT [75] and; the self-interference problem of F-RT algorithm [6] makes them not suitable for synchronization in CDSSs. Maybe the most promising solution among the closed-loop methods for CDSSs could be the consensus synchronization algorithm proposed in [78]. However, it is still required to analyze the effect on this algorithm of the transmission delay between the CDSS and the target node, especially when the design proposed in [78] considered the channel time invariant.

Unlike the previous group, open-loop methods do not require feedback from the target node. That makes them the preferable algorithms for CDSSs dedicated to communications and the only available solution for remote sensing applications. However, these algorithms require accurate inter-satellite ranging measurement [80], [81]. In most remote sensing missions, it is necessary to know precisely the exact position of each spacecraft in the CDSS for the primary mission goal. For that reason, using this measurement for synchronization purposes does not represent an additional cost. However, implementing these synchronization methods in Communications CDSSs would require including both subsystems: the accurate inter-satellite ranging and the synchronization algorithm, which may incur excessive resource consumption.

Therefore, a synchronization method suitable for Communications CDSSs using small satellites is still missing. The most promising solution seems to be related to the development of open-loop synchronization methods independent of the DSS geometry. Another possibility is the development of very efficient (in volume and resources consumption) ranging and synchronization methods.

E. HARDWARE IMPLEMENTATION OF SYNCHRONIZATION ALGORITHMS

As stated before, one of the most relevant open problems in Synchronization for DSSs is the development of algorithms capable of working in small satellites. To this end, the hardware implementation of these methods has to consider the low power, volume, and computational resources available in these spacecraft. Some general solutions could include distributed computation and wireless power transfer. However, the development of new hardware components for micro and nanosatellites is a critical research field that highly impacts the implementation of the synchronization algorithms for DSSs.

Another approach that has not been taken into account sufficiently is to consider the hardware limitations during the design of the synchronization algorithms. For example, the distortions produced by the power amplification and the phase noise introduced by the local oscillators are some of the hardware impairments that are obviated in most of the synchronization methods proposed. These physical phenomena are treated as random errors during the hardware implementation. However, including their description as part of the design can improve the performance of the synchronization method implemented.

Finally, there is another practical limitation related to the hardware implementation of F-RT synchronization algorithms. In this case, the accuracy of the method relies on the assumption that all the synchronization signals exchanged by the distributed nodes are in the same frequency band [73]. However, this assumption implies that the nodes should simultaneously transmit and receive signals in the same frequency band, which is not possible in practice due to self-interference. Assigning different frequencies affects the method's accuracy; performing time division multiple access introduces delays and scalability problems. The feasible solution to this problem can be the use of In-band Full Duplex techniques, as suggested in [138].

F. EFFICIENT INTER-SATELLITE RANGING METHODS

The methods for Inter-Satellite Ranging are still an open research topic. Advanced DSS will require an accurate inter-satellite ranging and baseline determination for sensing and communication applications. These accuracy requirements become ever stringent when no external or ground-based aids are used for synchronization.

The required accuracy also depends on the final mission goals. For instance, Remote Sensing DSSs missions without any feedback from external aids, as is the case of a spaceborne distributed radiometer or radio-telescopes, will require a stringent level of accuracy because the image quality will depend directly on the accuracy of the inter-satellite ranging [223]. The most promising advances in precise ranging methods for Remote Sensing missions point to using inter-satellite optical links as the most accurate alternatives [91]. However, solving the integer ambiguity problem remains an open research question for ranging methods based on optical or RF technologies either for communications or remote sensing applications [113].

On the other hand, Communications DSSs require more efficient algorithms in terms of resource consumption. In this case, one possible solution could be the implementation of methods to simultaneously perform range measurements and communications over ISLs in a similar way to the solutions proposed in [108], and [96].

G. ML-ENABLED SYNCHRONIZATION

As described in section VII, ML techniques could be promising in distributed satellite systems for various synchronization aspects such as frame synchronization carrier synchronization, characterization of phase noise, and the compensation of errors caused due to time/frequency offsets. The estimation of carrier frequency offset with low-resolution ADCs is necessary for the synchronization process as low-resolution ADCs can enable the operation of advanced MIMO operations with the help of full digital architectures. However, this becomes challenging at the higher carrier frequencies due to the higher channel bandwidth. To address this problem, ML techniques based on various deep Neural Network (NN) architectures could be used in finding the best estimate of the involved nonlinear function towards performing carrier frequency offset estimation [224]. Some of the critical design aspects to be considered in employing ML-based carrier frequency offset estimation include the sensitivity to noise, length of the training sequence, and computational complexity of the ML model. Also, the convergence rate and accuracy of the ML models should be carefully considered while employing ML techniques in distributed satellite systems due to differences in the propagation delays and heterogeneous capabilities of the distributed nodes.

Due to the distributed nature of the considered satellite applications, analyzing the feasibility of distributed ML techniques such as federated learning in distributed satellite systems could be a promising future research direction. One of the main problems to be considered while employing ML in distributed satellite systems is the synchronization cost. Although some synchronization techniques such as BSP [204], SSP [206], and ASP [203] have been proposed in the literature to deal with the performance loss caused due to distributed ML, application of distributed ML in large-scale distributed satellite systems remains an open problem. Moreover, another future research direction is to investigate suitable ML techniques to address time synchronization attacks [207] in distributed satellite systems caused by the modification of time/time stamps of the underlying measurements.

IX. CONCLUSION

The use of small satellites grouped as CDSSs is a new paradigm of the space industry. Many researchers worldwide are currently working to overcome the technical challenges that restrict their development. Among them, the synchronization of the distributed spacecraft is one of the most challenging open problems. For that reason, the volume of information about the synchronization of DSSs is already considerable and continues increasing by the day. In this context, this article has captured the latest advances in architectures and synchronization methods for DSSs. A brief survey of the DSSs architectures was provided, classifying them into five general groups: Constellations, Clusters, Swarms, Fractionated, and Federated spacecraft. Other parameters considered for the classification of DSS were the ISLs: Ring, Star, Mesh, or Hybrid topology and their synchronization scheme. Generally, Distributed synchronization algorithms are more robust than centralized synchronization algorithms but more complex.

The distributed time, phase, and frequency wireless synchronization methods reported in the literature were summarized and compared, analyzing their feasibility for DSSs. The synchronization algorithms were classified as Closed-loop or Open-loop methods based on the use of feedback from a node external to the DSS. In addition, another classification considered the communication between the elements of the DSS as Closed-loop, when the exchange of information among the distributed satellites was done as a two-way message exchange or; Open-loop when it was done as a broadcast or one-way communication.

The time synchronization of DSS is mainly based on the TWTT algorithm. However, recent publications refered to the use of pseudo-random noise code and other techniques to achieve time synchronization and inter-satellite ranging simultaneously. Among the Closed-loop synchronization algorithms that use the feedback from a node external to the DSS, the rich feedback methods are more suitable to implement in DSS. Specifically, the PA algorithm for DTB and the reciprocity-based methods are the most recommended. On the other hand, most of the Open-loop synchronization algorithms are suitable for the synchronization of DSS. As a conclusion, higher synchronization accuracy could be achieved by combining the use of intra-node communication in the form of two-way message exchange and the feedback from a node external to the DSS.

Other operations, closely related to synchronization in DSSs such as inter-satellite ranging and relative positioning were also analyzed. Generally, the requirements and accuracy of the coherent operation depend on the performance of the ranging and relative positioning algorithms as much as the synchronization itself. These operations can be performed by optical or RF inter-satellite ranging methods. The former one can achieve higher accuracy, but the higher directivity of the laser beam can represent a limitation for specific applications. The use of a single ISL to simultaneously perform ranging and communication and the solution to the phase integer ambiguity problem are trending topics in this field.

An extensive compilation of missions and proof of concept implementations have been included. Besides, the use of ML as a promising technique to address several synchronization problems was considered. For instance, frame synchronization, compensation of the errors caused due to sampling frequency/time offsets, carrier synchronization, and characterization of phase noise in communication systems, including a SatCom network. Distributed learning techniques as enablers of the distributed implementation of ML models across several distributed nodes in DSS was analyzed. Finally, a collection of current research activities and potential research topics was proposed, identifying problems and open challenges that can be useful for researchers in the field.

ACKNOWLEDGMENT

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REFERENCES

[1] M. D. Graziano, "Overview of distributed missions," in *Distributed Space Missions for Earth System Monitoring*. New York, NY, USA: Springer, 2013, pp. 375–386.
[2] R. Radhakrishnan, W. W. Edmonson, F. Afghah, R. M. Rodriguez-Osorio, F. Pinto, and S. C. Burleigh, "Survey of inter-satellite communication for small satellite systems: Physical layer to network layer view," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 4, pp. 2442–2473, 4th Quart., 2016.
[3] P. Savazzi and A. Vizziello, "Carrier synchronization in distributed MIMO satellite links," in *Proc. IEEE Int. Conf. Wireless Space Extreme Environ. (WiSEE)*, Dec. 2015, pp. 1–6.
[4] R. J. Barton, "Distributed MIMO communication using small satellite constellations," in *Proc. IEEE Int. Conf. Wireless Space Extreme Environ. (WiSEE)*, Oct. 2014, pp. 1–7.
[5] Y. Chen, D. Liang, H. Yue, D. Liu, X. Wu, H. Zhang, Y. Jiao, K. Liu, and R. Wang, "Implementation of a phase synchronization scheme based on pulsed signal at carrier frequency for bistatic SAR," *Sensors*, vol. 20, no. 11, pp. 1–14, 2020.
[6] J. C. Merlano-Duncan, L. Martinez-Marrero, J. Querol, S. Kumar, A. Camps, S. Chatzinotas, and B. Ottersten, "A remote carrier synchronization technique for coherent distributed remote sensing systems," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 14, pp. 1909–1922, 2021.
[7] L. Gun and H. Feijiang, "Precise two way time synchronization for distributed satellite system," in *Proc. IEEE Int. Freq. Control Symp. Joint With 22nd Eur. Freq. Time Forum*, Apr. 2009, pp. 1122–1126.

[8] P. P. Sundaramoorthy, E. Gill, and C. J. M. Verhoeven, "Enhancing ground communication of distributed space systems," *Acta Astronautica*, vol. 84, pp. 15–23, Mar. 2013.

[9] P. Sundaramoorthy, E. Gill, and C. Verhoeven, "Beamforming with spacecraft under reduced localization and clock constraints," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 52, no. 3, pp. 1197–1208, Jul. 2016.

[10] A. A. Nasir, S. Durrani, H. Mehrpouyan, S. D. Blostein, and R. A. Kennedy, "Timing and carrier synchronization in wireless communication systems: A survey and classification of research in the last 5 years," *EURASIP J. Wireless Commun. Netw.*, vol. 2016, no. 1, pp. 1–38, Dec. 2016.

[11] B. Sundararaman, U. Buy, and A. D. Kshemkalyani, "Clock synchronization for wireless sensor networks: A survey," *Ad Hoc Netw.*, vol. 3, no. 3, pp. 281–323, May 2005.

[12] R. Newman and M. Hammoudeh, "Pennies from heaven: A retrospective on the use of wireless sensor networks for planetary exploration," in *Proc. NASA/ESA Conf. Adapt. Hardw. Syst.*, Jun. 2008, pp. 263–270.

[13] D. Selva, A. Golkar, O. Korobova, I. L. I. Cruz, P. Collopy, and O. L. de Weck, "Distributed earth satellite systems: What is needed to move forward?" *J. Aerosp. Inf. Syst.*, vol. 14, no. 8, pp. 412–438, Aug. 2017.

[14] O. Kodheli, E. Lagunas, N. Maturo, S. K. Sharma, B. Shankar, J. F. M. Montoya, J. C. M. Duncan, D. Spano, S. Chatzinotas, S. Kisseleff, J. Querol, L. Lei, T. X. Vu, and G. Goussetis, "Satellite communications in the new space era: A survey and future challenges," *IEEE Commun. Surveys Tuts.* vol. 23, no. 1, pp. 70–109, 1st Quart., 2020.

[15] *Our Technology | CoNextions*. Accessed: Mar. 5, 2019. [Online]. Available: https://www.conextionsmed.com/technology/

[16] K. Maine, C. Devieux, and P. Swan, "Overview of IRIDIUM satellite network," in *Proc. WESCON*, 1995, pp. 483–490.

[17] *OneWeb—eoPortal Directory—Satellite Missions*. Accessed: Mar. 5, 2019. [Online]. Available: https://directory.eoportal.org/web/eoportal/satellite-missions/o/oneweb

[18] B. D. Tapley, S. Bettadpur, M. Watkins, and C. Reigber, "The gravity recovery and climate experiment: Mission overview and early results," *Geophys. Res. Lett.*, vol. 31, pp. 1–4, May 2004.

[19] G. D. Racca and P. W. McNamara, "The LISA pathfinder mission," *Space Sci. Rev.*, vol. 151, nos. 1–3, pp. 159–181, Mar. 2010.

[20] *PRISMA (Prototype)—eoPortal Directory—Satellite Missions*. Accessed: Mar. 5, 2019. [Online]. Available: https://directory.eoportal.org/web/eoportal/satellite-missions/p/prisma-prototype

[21] *Technologies/Proba Missions/Space Engineering and Technology/Our Activities/ESA*. Accessed: Mar. 5, 2019. [Online]. Available: http://www.esa.int/Our_Activities/Space_Engineering_Technology/Proba_Missions/Technologies2

[22] E. Maurer, R. Kahle, F. Mrowka, G. Morfill, A. Ohndorf, and S. Zimmermann, "Operational aspects of the TanDEM-X science phase," in *Proc. SpaceOps Conf.*, Reston, VA, USA, May 2016, p. 2459.

[23] *The von Karman Institute for Fluid Dynamics*. Accessed: Mar. 5, 2019. [Online]. Available: https://www.qb50.eu/index-2.html

[24] S. Engelen, C. Verhoeven, and M. Bentum, "OLFAR, a radio telescope based on nano-satellites in moon orbit," in *Proc. AIAA/USU Conf. Small Satell.*, Aug. 2010, pp. 1–7.

[25] O. Brown and P. Eremenko, "Fractionated space architectures: A vision for responsive space," Defense Adv. Res. Projects Agency, Arlington, VA, USA, Tech. Rep. 0704-0188, 2008.

[26] J. A. Ruiz-De-Azua, A. Calveras, and A. Camps, "A novel dissemination protocol to deploy opportunistic services in federated satellite systems," *IEEE Access*, vol. 8, pp. 142348–142365, 2020.

[27] A. Camps *et al.*, "FSSCat mission description and first scientific results of the FMPL-2 onboard 3CAT-5/A," in *Proc. IEEE Int. Geosci. Remote Sens. Symp. (IGARSS)*, Jul. 2021, pp. 1291–1294.

[28] S. Prager, M. S. Haynes, and M. Moghaddam, "Wireless subnanosecond RF synchronization for distributed ultrawideband software-defined radar networks," *IEEE Trans. Microw. Theory Techn.*, vol. 68, no. 11, pp. 4787–4804, Nov. 2020.

[29] H. Poincaré, "La mesure du temps," *Revue de Métaphysique et de Morale*, vol. 6, no. 1, pp. 1–13, 1898.

[30] A. Einstein, "Zur elektrodynamik bewegter körper," *Annalen der Physik*, vol. 322, no. 10, pp. 891–921, 1905.

[31] D. Kirchner, "Two-way time transfer via communication satellites," *Proc. IEEE*, vol. 79, no. 7, pp. 983–990, Jul. 1991.

[32] Z. Shengkang, Z. Li, and Y. Yujie, "Ultra-short term clock offset prediction for two-way satellite time synchronization," in *Proc. Joint Eur. Freq. Time Forum Int. Freq. Control Symp. (EFTF/IFC)*, Jul. 2013, pp. 335–338.

[33] F. Huang, X. Lu, G. Liu, Y. Wang, L. Sun, and Z. Li, "Autonomous time synchronization algorithm and time synchronization link performance analysis in the satellite constellation," in *Proc. 6th Int. Conf. Wireless Commun. Netw. Mobile Comput. (WiCOM)*, Sep. 2010, pp. 15–18.

[34] X. Jiuling, Z. Chaojie, W. Chunhui, and J. Xiaojun, "Approach to inter-satellite time synchronization for micro-satellite cluster," *J. Syst. Eng. Electron.*, vol. 29, no. 4, pp. 805–815, 2018.

[35] L. Pan, T. Jiang, L. Zhou, H. Xu, and W. Chen, "A research on high-precision time-synchronization and ranging system between satellites," in *Proc. Int. Conf. Microw. Millim. Wave Technol. (ICMMT)*, Apr. 2008, vol. 2, no. 1, pp. 926–929.

[36] H.-J. Ma, H. Wu, J. Wu, M. Li, K. Wang, Z. He, and D. Zhao, "Design and implementation of dual one-way precise ranging and time synchronization system," in *Proc. Joint Eur. Freq. Time Forum Int. Freq. Control Symp. (EFTF/IFC)*, vol. 3, Jul. 2013, pp. 831–834.

[37] Z. Yaowei, X. Zhaobin, J. Xiaojun, G. Xiaoxu, and J. Zhonghe, "Integrated method for measuring distance and time difference between small satellites," *J. Syst. Eng. Electron.*, vol. 32, no. 3, pp. 596–606, Jun. 2021.

[38] D. L. Mills, *Computer Network Time Synchronization: The Network Time Protocol on Earth and in Space*, 2nd ed. Boca Raton, FL, USA: CRC Press, 2006.

[39] *IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems*, IEEE Standard 1588-2008, 2008.

[40] B. Shi, D. Zhang, and J. Hu, "Preliminary investigation in wide area protection implementation using IEEE 1588 precision time protocol," in *Proc. IEEE Int. Symp. Precis. Clock Synchronization Meas., Control, Commun. (ISPCS)*, Oct. 2015, pp. 43–47.

[41] E. F. Dierikx, A. E. Wallin, T. Fordell, J. Myyry, P. Koponen, M. Merimaa, T. J. Pinkert, J. C. Koelemeij, H. Z. Peek, and R. Smets, "White rabbit precision time protocol on long-distance fiber links," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 63, no. 7, pp. 945–952, Jul. 2016.

[42] K. L. Noh, Q. M. Chaudhari, E. Serpedin, and B. W. Suter, "Novel clock phase offset and skew estimation using two-way timing message exchanges for wireless sensor networks," *IEEE Trans. Commun.*, vol. 55, no. 4, pp. 766–777, Apr. 2007.

[43] J. Elson, L. Girod, and D. Estrin, "Fine-grained network time synchronization using reference broadcasts," *ACM SIGOPS Oper. Syst. Rev.*, vol. 36, pp. 147–163, Dec. 2002.

[44] K.-L. Noh, E. Serpedin, and K. Qaraqe, "A new approach for time synchronization in wireless sensor networks: Pairwise broadcast synchronization," *IEEE Trans. Wireless Commun.*, vol. 7, no. 9, pp. 3318–3322, Sep. 2008.

[45] S. Rucksana, C. Babu, and S. Saranyabharathi, "Efficient timing-sync protocol in wireless sensor network," in *Proc. Int. Conf. Innov. Inf., Embedded Commun. Syst. (ICIIECS)*, Coimbatore, India, Mar. 2015, pp. 1–5.

[46] M. Maróti, B. Kusy, G. Simon, and A. Lédeczi, "The flooding time synchronization protocol," in *Proc. 2nd Int. Conf. Embedded Netw. Sensor Syst. (SenSys)*, Jan. 2004, pp. 39–49.

[47] F. Shi, X. Tuo, S. X. Yang, J. Lu, and H. Li, "Rapid-flooding time synchronization for large-scale wireless sensor networks," *IEEE Trans. Ind. Informat.*, vol. 16, no. 3, pp. 1581–1590, Mar. 2020.

[48] S. Roehr, P. Gulden, and M. Vossiek, "Method for high precision clock synchronization in wireless systems with application to radio navigation," in *Proc. IEEE Radio Wireless Symp. (RWS)*, Jan. 2007, pp. 551–554.

[49] H. Fiedler, G. Krieger, M. Zink, M. Younis, M. Bachmann, S. Huber, I. Hajnsek, and A. Moreira, "The TanDEM-X mission: An overview," in *Proc. Int. Conf. Radar*, Sep. 2008, pp. 60–64.

[50] D. Zachariah, S. Dwivedi, P. Händel, and P. Stoica, "Scalable and passive wireless network clock synchronization in LOS environments," *IEEE Trans. Wireless Commun.*, vol. 16, no. 6, pp. 3536–3546, Jun. 2017.

[51] M. Segura, S. Niranjayan, H. Hashemi, and A. F. Molisch, "Experimental demonstration of nanosecond-accuracy wireless network synchronization," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2015, pp. 6205–6210.

[52] B. Denis, J. B. Pierrot, and C. Abou-Rjeily, "Joint distributed synchronization and positioning in UWB ad hoc networks using TOA," *IEEE Trans. Microw. Theory Techn.*, vol. 54, no. 4, pp. 1896–1910, Apr. 2006.

[53] A. Dongare, P. Lazik, N. Rajagopal, and A. Rowe, "Pulsar: A wireless propagation-aware clock synchronization platform," in *Proc. IEEE Real-Time Embedded Technol. Appl. Symp. (RTAS)*, Apr. 2017, pp. 283–292.

[54] S. Knappe, V. Shah, P. D. D. Schwindt, L. Hollberg, J. Kitching, L.-A. Liew, and J. Moreland, "A microfabricated atomic clock," *Appl. Phys. Lett.*, vol. 85, no. 9, pp. 1460–1462, Aug. 2004.

[55] R. Exel, "Receiver design for time-based ranging with IEEE 802.11b signals," *Int. J. Navigat. Observ.*, vol. 2012, pp. 1–15, Aug. 2012.
[56] F. Gardner, "A BPSK/QPSK timing-error detector for sampled receivers," *IEEE Trans. Commun.*, vol. COM-34, no. 5, pp. 423–429, May 1986.
[57] T. M. Schmidl and D. C. Cox, "Robust frequency and timing synchronization for OFDM," *IEEE Trans. Commun.*, vol. 45, no. 12, pp. 1613–1621, Dec. 1997.
[58] S. Jayaprakasam, S. K. A. Rahim, and C. Y. Leow, "Distributed and collaborative beamforming in wireless sensor networks: Classifications, trends, and research directions," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 4, pp. 2092–2116, 4th Quart., 2017.
[59] U. M. R. Mudumbai, B. Wild, and K. Ramchandran, "Distributed beamforming using 1 bit feedback: From concept to realization," in *Proc. 44th Allerton Conf. Commun., Control, Comp.*, Monticello, IL, USA, 2006, pp. 1020–1027.
[60] I. Thibault, G. E. Corazza, and L. Deambrogio, "Random, deterministic, and hybrid algorithms for distributed beamforming," in *Proc. 5th Adv. Satell. Multimedia Syst. Conf., 11th Signal Process. Space Commun. Workshop*, Sep. 2010, pp. 221–225.
[61] J. Lee, S. Lee, and J. Park, "Fast phase synchronization with clustering and one-bit feedback for distributed beamforming in a wireless sensor network," in *Proc. IEEE 87th Veh. Technol. Conf. (VTC Spring)*, Jun. 2018, pp. 1–4.
[62] M. O. Pun, D. R. Brown, and H. V. Poor, "Opportunistic collaborative beamforming with one-bit feedback," *IEEE Trans. Wireless Commun.*, vol. 8, no. 5, pp. 2629–2641, May 2009.
[63] C.-S. Tseng, J. Denis, and C. Lin, "On the robust design of adaptive distributed beamforming for wireless sensor/relay networks," *IEEE Trans. Signal Process.*, vol. 62, no. 13, pp. 3429–3441, Jul. 2014.
[64] S. Song, J. S. Thompson, P.-J. Chung, and P. M. Grant, "Exploiting negative feedback information for one-bit feedback beamforming algorithm," *IEEE Trans. Wireless Commun.*, vol. 11, no. 2, pp. 516–525, Feb. 2012.
[65] N. Xie, K. Xu, and J. Chen, "Exploiting cumulative positive feedback information for one-bit feedback synchronization algorithm," *IEEE Trans. Veh. Technol.*, vol. 67, no. 7, pp. 5821–5830, Jul. 2018.
[66] I. Thibault, A. Faridi, G. E. Corazza, A. V. Coralli, and A. Lozano, "Design and analysis of deterministic distributed beamforming algorithms in the presence of noise," *IEEE Trans. Commun.*, vol. 61, no. 4, pp. 1595–1607, Apr. 2013.
[67] W. Tushar, D. B. Smith, A. Zhang, T. A. Lamahewa, and T. Abhayapala, "Distributed transmit beamforming: Phase convergence improvement using enhanced one-bit feedback," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2012, pp. 528–532.
[68] P. Jeevan, S. Pollin, A. Bahai, and P. P. Varaiya, "Pairwise algorithm for distributed transmit beamforming," in *Proc. IEEE Int. Conf. Commun.*, May 2008, pp. 4245–4249.
[69] A. Kumar, R. Mudumbai, and S. Dasgupta, "Scalable algorithms for joint beam and null-forming using distributed antenna arrays," in *Proc. IEEE Global Commun. Conf.*, Dec. 2014, pp. 4042–4047.
[70] S. Goguri, B. Peiffer, R. Mudumbai, and S. Dasgupta, "A class of scalable feedback algorithms for beam and null-forming from distributed arrays," in *Proc. 50th Asilomar Conf. Signals, Syst. Comput.*, Nov. 2016, pp. 1447–1451.
[71] D. R. Brown, III, P. Bidigare, S. Dasgupta, and U. Madhow, "Receiver-coordinated zero-forcing distributed transmit nullforming," in *Proc. IEEE Statist. Signal Process. Workshop (SSP)*, Aug. 2012, pp. 269–272.
[72] D. R. Brown, R. David, and P. Bidigare, "Improving coherence in distributed MISO communication systems with local accelerometer measurements," in *Proc. 49th Annu. Conf. Inf. Sci. Syst. (CISS)*, Mar. 2015, pp. 1–6.
[73] D. R. Brown, G. B. Prince, and J. A. McNeill, "A method for carrier frequency and phase synchronization of two autonomous cooperative transmitters," in *Proc. IEEE 6th Workshop Signal Process. Adv. Wireless Commun.*, Jun. 2005, pp. 260–264.
[74] L. Belostotski, T. L. Landecker, and D. Routledge, "A technique for microwave ranging and remote phase synchronization," *IEEE Trans. Instrum. Meas.*, vol. 51, no. 3, pp. 551–559, Jun. 2002.
[75] D. R. Brown, III, and H. V. Poor, "Time-slotted round-trip carrier synchronization for distributed beamforming," *IEEE Trans. Signal Process.*, vol. 56, no. 11, pp. 5630–5643, Nov. 2008.
[76] M. Mañosas-Caballú and G. Seco-Granados, "Robust time-slotted round-trip carrier and timing synchronization for distributed beamforming," in *Proc. Eur. Signal Process. Conf. (EUSIPCO)*, Barcelona, Spain, 2011, pp. 1190–1194.
[77] S. B. Amor, S. Affes, F. Bellili, U. Vilaipornsawai, L. Zhang, and P. Zhu, "Multi-node ML time and frequency synchronization for distributed MIMO-relay beamforming over time-varying flat-fading channels," *IEEE Trans. Commun.*, vol. 67, no. 4, pp. 2702–2715, Apr. 2019.
[78] M. A. Alvarez and U. Spagnolini, "Distributed time and carrier frequency synchronization for dense wireless networks," *IEEE Trans. Signal Inf. Process. Netw.*, vol. 4, no. 4, pp. 683–696, Dec. 2018.
[79] Y.-S. Tu and G. J. Pottie, "Coherent cooperative transmission from multiple adjacent antennas to a distant stationary antenna through AWGN channels," in *Proc. Veh. Technol. Conf., IEEE 55th Veh. Technol. Conf. (VTC Spring)*, vol. 1, May 2002, pp. 130–134.
[80] H. Ochiai, P. Mitran, H. V. Poor, and V. Tarokh, "Collaborative beamforming for distributed wireless ad hoc sensor networks," *IEEE Trans. Signal Process.*, vol. 53, no. 11, pp. 4110–4124, Nov. 2005.
[81] G. Barriac, R. Mudumbai, and U. Madhow, "Distributed beamforming for information transfer in sensor networks," in *Proc. 3rd Int. Symp. Inf. Process. sensor Netw. (IPSN)*, Berkeley, CA, USA, 2004, p. 452.
[82] M. M. Rahman, S. Dasgupta, and R. Mudumbai, "A distributed consensus approach to synchronization of RF signals," in *Proc. IEEE Stat. Signal Process. Workshop (SSP)*, Aug. 2012, pp. 281–284.
[83] R. D. Preuss and D. R. Brown, "Two-way synchronization for coordinated multicell retrodirective downlink beamforming," *IEEE Trans. Signal Process.*, vol. 59, no. 11, pp. 5415–5427, Nov. 2011.
[84] T. P. Bidigare, U. Madhow, D. R. Brown, R. Mudumbai, A. Kumar, B. Peiffer, and S. Dasgupta, "Wideband distributed transmit beamforming using channel reciprocity and relative calibration," in *Proc. 49th Asilomar Conf. Signals, Syst. Comput.*, Nov. 2015, pp. 271–275.
[85] N. Xie, X. Bao, H. Wang, and X. Lin, "Fast open-loop synchronization for distributed downlink beamforming," in *Proc. 47th Annu. Conf. Inf. Sci. Syst. (CISS)*, Mar. 2013, pp. 1–6.
[86] A. Bletsas, A. Lippman, and J. Sahalos, "Simple, zero-feedback, distributed beamforming with unsynchronized carriers," *IEEE J. Sel. Areas Commun.*, vol. 28, no. 7, pp. 1046–1054, Sep. 2010.
[87] A. Bletsas, A. Lippman, and J. N. Sahalos, "Zero-feedback, collaborative beamforming for emergency radio: Asymptotic analysis," *Mobile Netw. Appl.*, vol. 16, no. 5, pp. 589–599, Oct. 2011.
[88] D. R. Brown, P. Bidigare, and U. Madhow, "Receiver-coordinated distributed transmit beamforming with kinematic tracking," in *Proc. IEEE Int. Conf. Acoust., Speech Signal Process. (ICASSP)*, Mar. 2012, pp. 5209–5212.
[89] T. M. Comberiate, K. S. Zilevu, J. E. Hodkin, and J. A. Nanzer, "Distributed transmit beamforming on mobile platforms using high-accuracy microwave wireless positioning," *Proc. SPIE*, vol. 9829, May 2016, Art. no. 98291S.
[90] J. E. Hodkin, K. S. Zilevu, M. D. Sharp, T. M. Comberiate, S. M. Hendrickson, M. J. Fitch, and J. A. Nanzer, "Microwave and millimeter-wave ranging for coherent distributed RF systems," in *Proc. IEEE Aerosp. Conf.*, Mar. 2015, pp. 1–7.
[91] M. Ming, Y. Luo, Y.-R. Liang, J.-Y. Zhang, H.-Z. Duan, H. Yan, Y.-Z. Jiang, L.-F. Lu, Q. Xiao, Z. Zhou, and H.-C. Yeh, "Ultraprecision intersatellite laser interferometry," *Int. J. Extreme Manuf.*, vol. 2, no. 2, May 2020, Art. no. 022003.
[92] F. Ales, P. F. Gath, U. Johann, and C. Braxmaier, "Modeling and simulation of a laser ranging interferometer acquisition and guidance algorithm," *J. Spacecraft Rockets*, vol. 51, no. 1, pp. 226–238, Jan. 2014.
[93] D. Bykhovsky, D. Kedar, and S. Arnon, "Fiber-ring delay line for high-resolution intersatellite ranging," *IEEE Photon. Technol. Lett.*, vol. 27, no. 6, pp. 673–676, Mar. 15, 2015.
[94] Y. Luo, H. Li, Y. Liang, H.-Z. Duan, J. Zhang, and H.-C. Yeh, "A preliminary prototype of laser frequency stabilization for spaceborne interferometry missions," in *Proc. Eur. Freq. Time Forum (EFTF)*, Apr. 2016, pp. 1–4.
[95] Y. Tian, J. Zhong, X. Lin, H. Yang, and D. Kang, "Inter-satellite integrated laser communication/ranging link with feedback-homodyne detection and fractional symbol ranging," in *Proc. IEEE Int. Conf. Space Opt. Syst. Appl. (ICSOS)*, Oct. 2019, pp. 1–5.
[96] R. M. Calvo, J. Poliak, J. Surof, and R. Wolf, "Evaluation of optical ranging and frequency transfer for the Kepler system: Preliminary laboratory tests," in *Proc. Eur. Navigat. Conf. (ENC)*, Nov. 2020, pp. 1–9.
[97] J. L. MacArthur and A. S. Posner, "Satellite-to-satellite range-rate measurement," *IEEE Trans. Geosci. Remote Sens.*, vol. GE-23, no. 4, pp. 517–523, Jul. 1985.
[98] J. Kim and B. D. Tapley, "Simulation of dual one-way ranging measurements," *J. Spacecraft Rockets*, vol. 40, no. 3, pp. 419–425, May 2003.

[99] Y. Jian, Y. Yikang, L. L. Fang, and L. Lei, "Research on digital phase-locked loop about K/Ka-band high precision receiver," in *Proc. Int. Conf. Intell. Syst. Design Eng. Appl. (ISDEA)*, vol. 2, Oct. 2010, pp. 185–188.

[100] M. Alawieh, N. Hadaschik, N. Franke, and C. Mutschler, "Inter-satellite ranging in the low earth orbit," in *Proc. 10th Int. Symp. Commun. Syst., Netw. Digit. Signal Process. (CSNDSP)*, Jul. 2016, pp. 1–6.

[101] X. Xiaoyi, W. Chunhui, and J. Zhonghe, "Design, analysis and optimization of random access inter-satellite ranging system," *J. Syst. Eng. Electron.*, vol. 31, no. 5, pp. 871–883, Oct. 2020.

[102] L. Wang, X. Li, Y. Yang, and L. Liu, "Research on inter-satellite ranging and velocity measurement method based on Doppler frequency measurement," in *Proc. 2nd Int. Conf. Consum. Electron., Commun. Netw. (CECNet)*, Apr. 2012, pp. 3446–3450.

[103] S. Rui, X. Guodong, and L. Shengchang, "Inter-satellite ranging system design in formation," in *Proc. 2nd Int. Symp. Syst. Control Aerosp. Astronaut. (ISSCAA)*, Dec. 2008, pp. 1–5.

[104] Y. Yang, Y. Li, C. Rizos, A. G. Dempster, and X. Yue, "Inter-satellite ranging augmented gps relative navigation for satellite formation flying," *J. Navigat.*, vol. 67, no. 3, pp. 437–449, May 2014.

[105] Z. Wang, H. Huan, and M. Wang, "Determining the initial value of carrier phase smoothing pseudorange by least squares straight line fitting technique," in *Proc. IEEE Int. Conf. Artif. Intell. Comput. Appl. (ICAICA)*, Mar. 2019, pp. 303–307.

[106] R. Hatch, "The synergism of GPS code and carrier measurements," in *Proc. 3rd Int. Geodetic Symp. Satell. Doppler Positioning*, Las Cruces, NM, USA, 1982, pp. 1213–1231.

[107] Y. Tang, Y. Wang, and J. Chen, "Impact of finite bandwidth for inter-satellite ranging using direct sequence spread spectrum signal," in *Proc. IEEE Int. Conf. Signal Image Process. (ICSIP)*, Aug. 2016, pp. 488–492.

[108] R. Xue, T. Wang, and H. Tang, "A novel chip pulse employed by ranging code based on simultaneous transmitting CPM modulation and PN ranging in inter-satellite links of GNSS," *IEEE Access*, vol. 8, pp. 132860–132870, 2020.

[109] A.-M. Crisan, A. Martian, and D. Coltuc, "Inter-satellite radio frequency ranging in a hybrid OFDM communication-metrology system," in *Proc. 15th Workshop Positioning, Navigat. Commun. (WPNC)*, Oct. 2018, pp. 3–7.

[110] B. Xiang, F. Yan, Y. Zhang, F. Shen, W. Xia, and L. Shen, "A new inter-satellite ranging method based on pseudo-range and dual-frequency carrier phase," in *Proc. 11th Int. Conf. Wireless Commun. Signal Process. (WCSP)*, Oct. 2019, pp. 1–5.

[111] B. Xiang, F. Yan, F. Shen, W. Xia, S. Xing, Y. Wu, and L. Shen, "Selection of frequency pairs and accuracy analysis in inter-satellite carrier ranging," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2019, p. 4.

[112] R. Sun, J. Guo, and E. Gill, "Antenna array based line-of-sight estimation using a GNSS-like inter-satellite ranging system," in *Proc. 6th ESA Workshop Satell. Navigat. Technol. (NAVITEC), Eur. Workshop GNSS Signals Signal Process.*, Dec. 2012, pp. 1–8.

[113] Z. Yue, B. Lian, and C. Tang, "GPS/INS integrated navigation algorithm based on the double-difference of time/inter-satellite with carrier phase," in *Proc. IEEE Int. Conf. Signal Process., Commun. Comput. (ICSPCC)*, Oct. 2017, pp. 1–6.

[114] P. J. G. Teunissen, "The least-squares ambiguity decorrelation adjustment: A method for fast GPS integer ambiguity estimation," *J. Geodesy*, vol. 70, no. 1, pp. 65–82, 1995.

[115] J. Wendel, O. Meister, R. Mönikes, and G. F. Trommer, "Time-differenced carrier phase measurements for tightly coupled GPS/INS integration," in *Proc. IEEE/ION Position, Location, Navigat. Symp.*, Apr. 2006, pp. 54–60.

[116] R. Kroes, "Precise relative positioning of formation flying spacecraft using GPS," Ph.D. dissertation, Fac. Aerosp. Eng., Technische Universiteit Delft, Delft, The Netherlands, 2006.

[117] S. D'Amico and O. Montenbruck, "Differential GPS: An enabling technology for formation flying satellites," in *Small Satellite Missions for Earth Observation*, R. Sandau, H.-P. Roeser, and A. Valenzuela, Eds. Berlin, Germany: Springer, 2010, pp. 457–465.

[118] R. Kroes, O. Montenbruck, W. Bertiger, and P. Visser, "Precise GRACE baseline determination using GPS," *GPS Solutions*, vol. 9, no. 1, pp. 21–31, Apr. 2005.

[119] A. Renga, M. Grassi, and U. Tancredi, "Relative navigation in LEO by carrier-phase differential GPS with intersatellite ranging augmentation," *Int. J. Aerosp. Eng.*, vol. 2013, pp. 1–11, Jan. 2013.

[120] N. Nandakumaran, P. J. G. Teunissen, and S. Verhagen, "Attitude determination and relative positioning for LEO satellites using arrays of GNSS sensors," in *Proc. IAG Years*, C. Rizos and P. Willis, Eds. Cham, Switzerland: Springer, 2016, pp. 743–749.

[121] P. Teunissen, "A general multivariate formulation of the multi-antenna GNSS attitude determination problem," *Artif. Satell.*, vol. 42, no. 2, pp. 97–111, Jan. 2007.

[122] K.-M. Cheung and C. Lee, "A trilateration scheme for relative positioning," in *Proc. IEEE Aerosp. Conf.*, Mar. 2017, pp. 1–10.

[123] M. Casti, S. Fineschi, A. Bemporad, G. Capobianco, F. Landini, D. Loreggia, V. Noce, M. Romoli, C. Thizy, and D. Galano, "Fine positioning algorithms for the ESA/PROBA-3 formation flying mission," in *Proc. IEEE Int. Workshop Metrol. Aerosp., MetroAeroSpace*, Jun. 2019, pp. 121–125.

[124] G. Capobianco, S. Fineschi, D. Loreggia, A. Bemporad, F. Landini, M. Casti, V. Noce, M. Romoli, D. Galano, and C. Thizy, "The in-flight calibration procedures of the shadow position sensors (SPS), a very accurate optical metrology system of the ESA/PROBA-3 formation flying mission," in *Proc. IEEE Int. Workshop Metrol. Aerosp. (MetroAeroSpace)*, Jun. 2019, pp. 479–483.

[125] L. Buinhas, E. Ferrer-Gil, and R. Forstner, "IRASSI: InfraRed astronomy satellite swarm interferometry—Mission concept and description," in *Proc. IEEE Aerosp. Conf.*, Jun. 2016, pp. 1–20.

[126] L. Buinhas, M. Philips-Blum, K. Frankl, T. Pany, B. Eissfeller, and R. Forstner, "Formation operations and navigation concept overview for the IRASSI space interferometer," in *Proc. IEEE Aerosp. Conf.*, Mar. 2018, pp. 1–16.

[127] H. Linz, D. Bhatia, L. Buinhas, M. Lezius, E. Ferrer, R. Förstner, K. Frankl, M. Philips-Blum, M. Steen, U. Bestmann, W. Hänsel, R. Holzwarth, O. Krause, and T. Pany, "InfraRed astronomy satellite swarm interferometry (IRASSI): Overview and study results," *Adv. Space Res.*, vol. 65, no. 2, pp. 831–849, Jan. 2020.

[128] M. Weiqing, R. Liu, Y. Xinxin, and E. Kamel, "Analysis of precision estimation of RF metrology in satellite formation flying," in *Proc. Int. Conf. Wireless Commun. Signal Process. (WCSP)*, Oct. 2015, p. 4.

[129] L. R. G. Carrillo, F. M. Palacios, E. S. E. Quesada, and K. Alexis, "Adaptive high order sliding mode control for relative positioning and trajectory tracking of spacecraft formation flying," in *Proc. 24th Medit. Conf. Control Automat. (MED)*, Jun. 2016, pp. 1095–1101.

[130] D. Xue, X. Cao, and Y. Wu, "Decentralized determination of relative orbit for formation flying satellite," in *Proc. 1st Int. Symp. Syst. Control Aerosp. Astronaut.*, 2006, pp. 338–343.

[131] S. Wang and P. Cui, "Autonomous orbit determination using pulsars and inter-satellite ranging for Mars orbiters," in *Proc. IEEE Aerosp. Conf.*, Big Sky, MT, USA, Mar. 2018, pp. 1–7.

[132] Z. Liu, L. Du, Y. Zhu, Z. Qian, J. Wang, and S. Liang, "Investigation on GEO satellite orbit determination based on CEI measurements of short baselines," *J. Navigat.*, vol. 72, no. 6, pp. 1585–1601, Nov. 2019.

[133] M. Sadeghi, F. Behnia, and H. Haghshenas, "Positioning of geostationary satellite by radio interferometry," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 55, no. 2, pp. 903–917, Apr. 2019.

[134] G. Michalak, K. H. Neumayer, and R. Konig, "Precise orbit determination of the Kepler navigation system—A simulation study," in *Proc. Eur. Navigat. Conf. (ENC)*, Nov. 2020, pp. 1–10.

[135] L. Chen, H. Lin, Z. Lu, J. Li, and G. Ou, "High orbital spacecraft fast positioning algorithm assisted by inter-satellite links," in *Proc. 2nd Int. Conf. Inf. Syst. Comput. Aided Educ. (ICISCAE)*, Sep. 2019, pp. 598–602.

[136] G. Krieger, M. Zonno, J. Mittermayer, A. Moreira, S. Huber, and M. Rodriguez-Cassola, "MirrorSAR: A fractionated space transponder concept for the implementation of low-cost multistatic SAR missions," in *Proc. Eur. Conf. Synth. Aperture Radar (EUSAR)*, Jun. 2018, pp. 1359–1364.

[137] P. Xiao, B. Liu, and W. Guo, "ConGaLSAR: A constellation of geostationary and low earth orbit synthetic aperture radar," *IEEE Geosci. Remote Sens. Lett.*, vol. 17, no. 12, pp. 2085–2089, Dec. 2020.

[138] J. C. Merlano-Duncan, J. Querol, L. Martinez-Marrero, J. Krivochiza, A. Camps, S. Chatzinotas, and B. Ottersten, "SDR implementation of a testbed for synchronization of coherent distributed remote sensing systems," in *Proc. IEEE Int. Geosci. Remote Sens. Symp. (IGARSS)*, Waikoloa, HI, USA, Sep. 2020, pp. 6588–6591.

[139] P. Ubolkosold, S. Knedlik, and O. Loffeld, "Clock synchronization protocol for distributed satellite networks," in *Proc. IEEE Int. Geosci. Remote Sens. Symp. (IGARSS)*, Seoul, South Korea, vol. 1, Jul. 2005, pp. 681–684.

[140] Z. Yongsheng, L. Diannong, and D. Zhen, "Analysis of time and frequency synchronization errors in spaceborne parasitic InSAR system," in *Proc. IEEE Int. Symp. Geosci. Remote Sens. (IGARSS)*, Jul. 2006, pp. 3047–3050.

[141] M. Younis, R. Metzig, and G. Krieger, "Performance prediction of a phase synchronization link for bistatic SAR," *IEEE Geosci. Remote Sens. Lett.*, vol. 3, no. 3, pp. 429–433, Jul. 2006.

[142] Z. He, F. He, H. Huang, and D. Liang, "A hardware-in-loop simulation and evaluation approach for spaceborne distributed SAR," in *Proc. IEEE Int. Geosci. Remote Sens. Symp. (IGARSS)*, Jul. 2011, pp. 886–889.

[143] J. C. Merlano-Duncan, J. J. Mallorquí, and P. López-Dekker, "Carrier phase synchronisation scheme for very long baseline coherent arrays," *Electron. Lett.*, vol. 48, no. 15, pp. 950–951, 2012.

[144] A. M. Guarnieri, A. Broquetas, A. Recchia, F. Rocca, and J. Ruiz-Rodon, "Advanced radar geosynchronous observation system: ARGOS," *IEEE Geosci. Remote Sens. Lett.*, vol. 12, pp. 1406–1410, Jul. 2015.

[145] A. M. Guarnieri, A. Broquetas, F. López-Dekker, and F. Rocca, "A geostationary MIMO SAR swarm for quasi-continuous observation," in *Proc. IEEE Int. Geosci. Remote Sens. Symp. (IGARSS)*, Jul. 2015, pp. 2785–2788.

[146] D. Liang, K. Liu, H. Zhang, Y. Deng, D. Liu, Y. Chen, C. Li, H. Yue, and R. Wang, "A high-accuracy synchronization phase-compensation method based on Kalman filter for bistatic synthetic aperture radar," *IEEE Geosci. Remote Sens. Lett.*, vol. 17, no. 10, pp. 1722–1726, Oct. 2020.

[147] G. Jin, K. Liu, D. Liu, D. Liang, H. Zhang, N. Ou, Y. Zhang, Y. Deng, C. Li, and R. Wang, "An advanced phase synchronization scheme for LT-1," *IEEE Trans. Geosci. Remote Sens.*, vol. 58, no. 3, pp. 1735–1746, Mar. 2020.

[148] Y. Zhang, H. Zhang, N. Ou, K. Liu, D. Liang, Y. Deng, and R. Wang, "First demonstration of multipath effects on phase synchronization scheme for LT-1," *IEEE Trans. Geosci. Remote Sens.*, vol. 58, no. 4, pp. 2590–2604, Apr. 2020.

[149] D. Liang, K. Liu, H. Zhang, Y. Chen, H. Yue, D. Liu, Y. Deng, H. Lin, T. Fang, C. Li, and R. Wang, "The processing framework and experimental verification for the noninterrupted synchronization scheme of LuTan-1," *IEEE Trans. Geosci. Remote Sens.*, vol. 59, no. 7, pp. 5740–5750, Jul. 2021.

[150] A. Lovascio, A. D'Orazio, and V. Centonze, "Design of COTS-based radio-frequency receiver for cubesat applications," in *Proc. IEEE 5th Int. Workshop Metrol. Aerosp. (MetroAeroSpace)*, Jun. 2019, pp. 399–404.

[151] L. Yu, S. Zhang, N. Wu, and C. Yu, "FPGA-based hardware-in-the-loop simulation of user selection algorithms for cooperative transmission technology over LOS channel on geosynchronous satellites," *IEEE Access*, vol. 10, pp. 6071–6083, 2022.

[152] M. R. Maheshwarappa, M. Bowyer, and C. P. Bridges, "Software defined radio (SDR) architecture to support multi-satellite communications," in *Proc. IEEE Aerosp. Conf.*, Mar. 2015, pp. 1–10.

[153] G. Interdonato, E. Björnson, H. Q. Ngo, P. Frenger, and E. G. Larsson, "Ubiquitous cell-free massive MIMO communications," *EURASIP J. Wireless Commun. Netw.*, vol. 2019, no. 1, p. 197, 2019.

[154] O. T. Demir and E. Björnson, "Max-min fair wireless-powered cell-free massive MIMO for uncorrelated rician fading channels," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, May 2020, pp. 1–6.

[155] H. Q. Ngo, A. Ashikhmin, H. Yang, E. G. Larsson, and T. L. Marzetta, "Cell-free massive MIMO versus small cells," *IEEE Trans. Wireless Commun.*, vol. 16, no. 3, pp. 1834–1850, Mar. 2017.

[156] S. Jeong, A. Farhang, and M. Flanagan, "Collaborative vs. non-collaborative CFO estimation for distributed large-scale MIMO systems," in *Proc. IEEE 92nd Veh. Technol. Conf. (VTC-Fall)*, Nov. 2020, pp. 1–6.

[157] G. Borg, Z.-U.-D. Javaid, and A. Khandaker, "The physical and engineering requirements of scalable, decentralised, distributed, large-scale MIMO," in *Proc. 3rd Int. Conf. Informat. Comput. (ICIC)*, Oct. 2018, pp. 3–8.

[158] F. Qamar, K. B. Dimyati, M. N. Hindia, K. A. B. Noordin, and A. M. Al-Samman, "A comprehensive review on coordinated multi-point operation for LTE-A," *Comput. Netw.*, vol. 123, pp. 19–37, Aug. 2017.

[159] Z. Gu and Z. Zhang, "Mode selection for CoMP transmission with non-ideal synchronization," *China Commun.*, vol. 15, no. 12, pp. 132–146, 2018.

[160] Z. Chaloupka, L. Ries, A. Samperi, P. Waller, and M. Crisci, "Phase synchronization for 5G using mass market GNSS receivers," in *Proc. Eur. Freq. Time Forum (EFTF)*, Apr. 2018, pp. 192–196.

[161] V. Jungnickel, K. Manolakis, S. Jaeckel, M. Lossow, P. Farkas, M. Schlosser, and V. Braun, "Backhaul requirements for inter-site cooperation in heterogeneous LTE-advanced networks," in *Proc. IEEE Int. Conf. Commun. Workshops (ICC)*, Jun. 2013, pp. 905–910.

[162] Y. Tian, K.-L. Lee, C. Lim, and A. Nirmalathas, "Performance evaluation of CoMP for downlink 60-GHz radio-over-fiber fronthaul," in *Proc. Int. Topical Meeting Microw. Photon. (MWP)*, Oct. 2017, pp. 1–4.

[163] G. Song, W. Wang, D. Chen, and T. Jiang, "KPI/KQI-driven coordinated multipoint in 5G: Measurements, field trials, and technical solutions," *IEEE Wireless Commun.*, vol. 25, no. 5, pp. 23–29, Oct. 2018.

[164] A. M. Hamza and J. W. Mark, "A timing synchronization scheme in coordinated base-stations cooperative communications," in *Proc. Int. Conf. Wireless Commun. Signal Process. (WCSP)*, Oct. 2012, pp. 3–8.

[165] S.-Y. Huang, Y.-H. Lin, and J.-H. Deng, "Novel time offset preprocessing and interference cancellation for downlink OFDMA CoMP system," in *Proc. IEEE Asia Pacific Conf. Wireless Mobile (APWiMob)*, Aug. 2014, pp. 102–108.

[166] L. Zhao, K. Liang, G. Cao, R. Qian, and D. López-Pérez, "An enhanced signal-timing-offset compensation algorithm for coordinated multipoint-to-multiuser systems," *IEEE Commun. Lett.*, vol. 18, no. 6, pp. 983–986, Jun. 2014.

[167] A. Dammann and R. Raulefs, "Exploiting position information for synchronization in coordinated multipoint transmission," in *Proc. IEEE 77th Veh. Technol. Conf. (VTC Spring)*, Jun. 2013, pp. 1–5.

[168] H. Pilaram, M. Kiamari, and B. H. Khalaj, "Distributed synchronization and beamforming in uplink relay asynchronous OFDMA CoMP networks," *IEEE Trans. Wireless Commun.*, vol. 14, no. 6, pp. 3471–3480, Jun. 2015.

[169] A. M. Hamza, J. W. Mark, and E. A. Sourour, "Interference analysis and mitigation for time-asynchronous OFDM CoMP systems," *IEEE Trans. Wireless Commun.*, vol. 17, no. 7, pp. 4780–4791, Jul. 2018.

[170] S. Iwelski, B. Badic, Z. Bai, R. Balraj, C. Kuo, E. Majeed, T. Scholand, G. Bruck, and P. Jung, "Feedback generation for CoMP transmission in unsynchronized networks with timing offset," *IEEE Commun. Lett.*, vol. 18, no. 5, pp. 725–728, May 2014.

[171] M. R. Khanzadi, R. Krishnan, and T. Eriksson, "Effect of synchronizing coordinated base stations on phase noise estimation," in *Proc. IEEE Int. Conf. Acoust., Speech Signal Process. (ICASSP)*, May 2013, pp. 4938–4942.

[172] L. Chang, J. Zhang, X. Li, B. Liu, and K. Sun, "Joint synchronization and channel estimation for the uplink coordinated multi-point systems," in *Proc. 7th Int. Conf. Commun. Netw. China (CHINACOM)*, Aug. 2012, pp. 384–389.

[173] T. Koivisto, T. Kuosmanen, and T. Roman, "Estimation of time and frequency offsets in LTE coordinated multi-point transmission," in *Proc. IEEE 78th Veh. Technol. Conf. (VTC Fall)*, Sep. 2013, pp. 3–7.

[174] *OctoClock Clock Distribution Module With GPSDO—Ettus Research | Ettus Research, a National Instruments Brand | the Leader in Software Defined Radio (SDR)*. Accessed: May 25, 2020. [Online]. Available: https://www.ettus.com/all-products/octoclock-g/

[175] *USRP2—Ettus Knowledge Base*. Accessed: May 25, 2020. [Online]. Available: https://kb.ettus.com/USRP2

[176] F. Quitin, U. Madhow, M. M. U. Rahman, and R. Mudumbai, "Demonstrating distributed transmit beamforming with software-defined radios," in *Proc. IEEE Int. Symp. World Wireless, Mobile Multimedia Netw. (WoWMoM)*, Jun. 2012, pp. 1–3.

[177] M. Seo, M. Rodwell, and U. Madhow, "A feedback-based distributed phased array technique and its application to 60-GHz wireless sensor network," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 2008, pp. 683–686.

[178] D. Scherber, P. Bidigare, R. O'Donnell, M. Rebholz, M. Oyarzun, C. Obranovich, W. Kulp, D. Chang, and D. R. Brown, III, "Coherent distributed techniques for tactical radio networks: Enabling long range communications with reduced size, weight, power and cost," in *Proc. IEEE Mil. Commun. Conf. (MILCOM)*, Nov. 2013, pp. 655–660.

[179] P. Bidigare, M. Oyarzyn, D. Raeman, D. Chang, D. Cousins, R. O'Donnell, C. Obranovich, and D. R. Brown, "Implementation and demonstration of receiver-coordinated distributed transmit beamforming across an ad-hoc radio network," in *Proc. 46th Asilomar Conf. Signals, Syst. Comput. (ASILOMAR)*, Nov. 2012, pp. 222–226.

[180] S. Mghabghab, H. Ouassal, and J. A. Nanzer, "Wireless frequency synchronization for coherent distributed antenna arrays," in *Proc. IEEE Int. Symp. Antennas Propag., USNC-URSI Radio Sci. Meeting (APSURSI)*, Jul. 2019, pp. 1575–1576.

[181] *USRP X310 High Performance Software Defined Radio—Ettus Research | Ettus Research, a National Instruments Brand | the Leader in Software Defined Radio (SDR)*. Accessed: May 26, 2020. [Online]. Available: https://www.ettus.com/all-products/x310-kit/

[182] *USRP N210 Software Defined Radio (SDR)—Ettus Research | Ettus Research, a National Instruments Brand | the Leader in Software Defined Radio (SDR)*. Accessed: May 26, 2020. [Online]. Available: https://www.ettus.com/all-products/un210-kit/

[183] C. Bocanegra, K. Alemdar, S. Garcia, C. Singhal, and K. R. Chowdhury, "NetBeam: Networked and distributed 3-D beamforming for multi-user heterogeneous traffic," in *Proc. IEEE Int. Symp. Dyn. Spectr. Access Netw. (DySPAN)*, Newark, NJ, USA, Nov. 2019, pp. 1–10.

[184] M. M. Rahman, H. E. Baidoo-Williams, R. Mudumbai, and S. Dasgupta, "Fully wireless implementation of distributed beamforming on a software-defined radio platform," in *Proc. ACM/IEEE 11th Int. Conf. Inf. Process. Sensor Netw. (IPSN)*, Apr. 2012, pp. 305–315.

[185] R. K. Pooler, J. S. Sunderlin, R. H. Tillman, and R. L. Schmid, "A precise RF time transfer method for coherent distributed system applications," in *Proc. USNC-URSI Radio Sci. Meeting (Joint With AP-S Symp.)*, Jul. 2018, pp. 5–6.

[186] R. L. Schmid, T. M. Comberiate, J. E. Hodkin, and J. A. Nanzer, "A distributed RF transmitter using one-way wireless clock transfer," *IEEE Microw. Wireless Compon. Lett.*, vol. 27, no. 2, pp. 195–197, Feb. 2017.

[187] B. Peiffer, R. Mudumbai, A. Kruger, A. Kumar, and S. Dasgupta, "Experimental demonstration of a distributed antenna array pre-synchronized for retrodirective transmission," in *Proc. Annu. Conf. Inf. Sci. Syst. (CISS)*, Mar. 2016, pp. 460–465.

[188] H. Yan, S. Hanna, K. Balke, R. Gupta, and D. Cabric, "Software defined radio implementation of carrier and timing synchronization for distributed arrays," in *Proc. IEEE Aerosp. Conf.*, Nov. 2018, pp. 1–12.

[189] R. L. Frank and S. Zadoff, "Phase shift pulse codes with good periodic correlation properties," *IRE Trans. Inf. Theory*, vol. 8, no. 6, pp. 381–382, Oct. 1962.

[190] M. W. S. Overdick, J. E. Canfield, A. G. Klein, and D. R. Brown, "A software-defined radio implementation of timestamp-free network synchronization," in *Proc. IEEE Int. Conf. Acoust., Speech Signal Process. (ICASSP)*, New Orleans, LA, USA, Mar. 2017, pp. 1193–1197.

[191] M. A. Alvarez, W. Thompson, and U. Spagnolini, "Distributed time and frequency synchronization: USRP hardware implementation," in *Proc. IEEE Int. Conf. Commun. Workshop (ICCW)*, Jun. 2015, pp. 2157–2162.

[192] J. Kim and S. W. Lee, "Flight performance analysis of GRACE K-band ranging instrument with simulation data," *Acta Astronautica*, vol. 65, nos. 11–12, pp. 1571–1581, Dec. 2009.

[193] J. B. Thomas, "An analysis of gravity-field estimation based on intersatellite dual-1-way biased ranging," Nat. Aeronaut. Space Admin. (NASA), Pasadena, CA, USA, Tech. Rep. AD-A410563 JPL-98-15, May 1999, p. 196.

[194] *LISA—Laser Interferometer Space Antenna—NASA Home Page*. Accessed: Jan. 7, 2019. [Online]. Available: https://lisa.nasa.gov/

[195] A. Budianu, R. T. Rajan, S. Engelen, A. Meijerink, C. J. Verhoeven, and M. J. Bentum, "OLFAR: Adaptive topology for satellite swarms," in *Proc. 62nd Int. Astron. Congr. (IAC)*, vol. 9, Oct. 2011, pp. 7086–7094.

[196] R. T. Rajan, G. Leus, and A.-J. van der Veen, "Joint relative position and velocity estimation for an anchorless network of mobile nodes," *Signal Process.*, vol. 115, pp. 66–78, Oct. 2015.

[197] D. G. Enzer, R. T. Wang, and W. M. Klipstein, "GRAIL—A microwave ranging instrument to map out the lunar gravity field," in *Proc. IEEE Int. Freq. Control Symp. (FCS)*, Jun. 2010, pp. 572–577.

[198] K. Oudrhiri, S. Asmar, S. Esterhuizen, C. Goodhart, N. Harvey, D. Kahan, G. Kruizinga, M. Paik, D. Shin, and L. White, "An innovative direct measurement of the GRAIL absolute timing of science data," in *Proc. IEEE Aerosp. Conf.*, Mar. 2014, pp. 1–9.

[199] H. Wu, Z. Sun, and X. Zhou, "Deep learning-based frame and timing synchronization for end-to-end communications," *J. Phys., Conf. Ser.*, vol. 1169, pp. 12–60, Feb. 2019.

[200] Y. Wang, C. Zhang, Q. Peng, and Z. Wang, "Learning to detect frame synchronization," in *Neural Information Processing*, M. Lee, A. Hirose, Z.-G. Hou, and R. M. Kil, Eds. Berlin, Germany: Springer, 2013, pp. 570–578.

[201] D. Zibar, L. H. H. de Carvalho, M. Piels, A. Doberstein, J. Diniz, B. Nebendahl, C. Franciscangelis, J. Estaran, H. Haisch, N. G. Gonzalez, J. C. R. F. de Oliveira, and I. T. Monroy, "Application of machine learning techniques for amplitude and phase noise characterization," *J. Lightw. Technol.*, vol. 33, no. 7, pp. 1333–1343, Apr. 1, 2015.

[202] V.-D. Nguyen, S. K. Sharma, T. X. Vu, S. Chatzinotas, and B. Ottersten, "Efficient federated learning algorithm for resource allocation in wireless IoT networks," *IEEE Internet Things J.*, vol. 8, no. 5, pp. 3394–3409, Mar. 2021.

[203] J. Zhang, H. Tu, Y. Ren, J. Wan, L. Zhou, M. Li, and J. Wang, "An adaptive synchronous parallel strategy for distributed machine learning," *IEEE Access*, vol. 6, pp. 19222–19230, 2018.

[204] A. V. Gerbessiotis and L. G. Valiant, "Direct bulk-synchronous parallel algorithms," *J. Parallel Distrib. Comput.*, vol. 22, no. 2, pp. 251–267, 1994.

[205] V. Mnih, A. P. Badia, M. Mirza, A. Graves, T. Lillicrap, T. Harley, D. Silver, and K. Kavukcuoglu, "Asynchronous methods for deep reinforcement learning," in *Proc. 33rd Int. Conf. Mach. Learn.*, in Proceedings of Machine Learning Research, vol. 48, M. F. Balcan and K. Q. Weinberger, Eds., New York, NY, USA, Jun. 2016, pp. 1928–1937.

[206] Q. Ho, J. Cipar, H. Cui, J. K. Kim, S. Lee, P. B. Gibbons, G. A. Gibson, G. R. Ganger, and E. P. Xing, "More effective distributed ML via a stale synchronous parallel parameter server," in *Proc. 26th Int. Conf. Neural Inf. Process. Syst. (NIPS)*, vol. 1. Red Hook, NY, USA: Curran Associates, 2013, pp. 1223–1231.

[207] J. Wang, W. Tu, L. C. K. Hui, S. M. Yiu, and E. K. Wang, "Detecting time synchronization attacks in cyber-physical systems with machine learning techniques," in *Proc. IEEE 37th Int. Conf. Distrib. Comput. Syst. (ICDCS)*, Jun. 2017, pp. 2246–2251.

[208] S. Bae, S. Kim, and J. Kim, "Efficient frequency-hopping synchronization for satellite communications using dehop-rehop transponders," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 52, no. 1, pp. 261–274, Feb. 2016.

[209] S. Lee, S. Kim, M. Seo, and D. Har, "Synchronization of frequency hopping by LSTM network for satellite communication system," *IEEE Commun. Lett.*, vol. 23, no. 11, pp. 2054–2058, Nov. 2019.

[210] J. Tong, R. Song, Y. Liu, C. Wang, Q. Zhou, and W. Wang, "Enhanced synchronization of 5G integrated satellite systems in multipath channels," in *Proc. Int. Conf. Comput. Vis., Image Deep Learn. (CVIDL)*, Jul. 2020, pp. 617–621.

[211] H. Guo, Q. Yang, H. Wang, Y. Hua, T. Song, R. Ma, and H. Guan, "SpaceDML: Enabling distributed machine learning in space information networks," *IEEE Netw.*, vol. 35, no. 4, pp. 82–87, Jul. 2021.

[212] L. Sun, Y. Gao, W. Huang, P. Li, Y. Zhou, and J. Yang, "Autonomous time synchronization using BeiDou inter-satellite link ranging," in *Proc. IEEE Int. Conf. Signal, Inf. Data Process. (ICSIDP)*, Dec. 2019, pp. 1–5.

[213] G. Giorgi, B. Kroese, and G. Michalak, "Future GNSS constellations with optical inter-satellite links. Preliminary space segment analyses," in *Proc. IEEE Aerosp. Conf.*, Mar. 2019, pp. 1–13.

[214] P. Henkel, "Precise point positioning for next-generation GNSS," in *Proc. Eur. Navigat. Conf. (ENC)*, Nov. 2020, pp. 1–11.

[215] J. A. Ruiz-De-Azua, A. Camps, and A. C. Auge, "Benefits of using mobile ad-hoc network protocols in federated satellite systems for polar satellite missions," *IEEE Access*, vol. 6, pp. 56356–56367, 2018.

[216] J. A. R. de Azua, A. Calveras, and A. Camps, "From monolithic satellites to the internet of satellites paradigm: When space, air, and ground networks become interconnected," in *Computer-Mediated Communication*, I. Dey, Ed. Rijeka, Croatia: IntechOpen, 2022, ch. 2.

[217] L. Fernandez, J. A. Ruiz-de-Azua, A. Calveras, and A. Camps, "On-demand satellite payload execution strategy for natural disasters monitoring using LoRa: Observation requirements and optimum medium access layer mechanisms," *Remote Sens.*, vol. 13, no. 19, p. 4014, Oct. 2021.

[218] J. A. R. de Azua, A. Calveras, and A. Camps, "Internet of satellites (IoSat): Analysis of network models and routing protocol requirements," *IEEE Access*, vol. 6, pp. 20390–20411, 2018.

[219] A. Ghasempour and S. K. Jayaweera, "Data synchronization for throughput maximization in distributed transmit beamforming," in *Proc. Cognit. Commun. Aerosp. Appl. Workshop (CCAA)*, Jun. 2017, pp. 1–4.

[220] P. Sriploy and T. Chanpuek, "The enhancement of wireless sensor network in smart farming using distributed beamforming," in *Proc. Int. ECTI Northern Sect. Conf. Electr., Electron., Comput. Telecommun. Eng. (ECTI-NCON)*, Feb. 2018, pp. 5–9.

[221] J. Diao, M. Hedayati, and Y. E. Wang, "Experimental demonstration of distributed beamforming on two flying mini-drones," in *Proc. United States Nat. Committee URSI Nat. Radio Sci. Meeting (USNC-URSI NRSM)*, Boulder, CO, USA, 2019, pp. 97–98.

[222] S. Mohanti, C. Bocanegra, J. Meyer, G. Secinti, M. Diddi, H. Singh, and K. Chowdhury, "AirBeam: Experimental demonstration of distributed beamforming by a swarm of UAVs," in *Proc. IEEE 16th Int. Conf. Mobile Ad Hoc Sensor Syst. (MASS)*, Monterey, CA, USA, Nov. 2019, pp. 162–170.

[223] A. Lan, J. Yan, L. Wu, F. Zhao, and J. Wu, "A study on in-orbit calibration fora spaceborne distributed interferometer," in *Proc. IEEE Int. Geosci. Remote Sens. Symp. (IGARSS)*, Jul. 2018, pp. 1043–1046.

[224] R. M. Dreifuerst, R. W. Heath, Jr., M. N. Kulkarni, and J. Charlie, "Deep learning-based carrier frequency offset estimation with one-bit ADCs," in *IEEE Workshop Signal Process. Adv. Wireless Commun. (SPAWC)*, May 2020, pp. 1–5.

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