Distributed Approach to Satellite Direct-to-Cell Connectivity in 6G Non-Terrestrial Networks

Diego Tuzi, Estephania Flores Aguilar, Thomas Delamotte, Gunes Karabulut-Kurt, and Andreas Knopp

Abstract

Satellite direct-to-cell (D2C) connectivity considers the communication between satellites and low-cost handheld devices on Earth. It represents one of the most challenging aspects of the integration between terrestrial and non-terrestrial networks. Low Earth orbit (LEO), sub-6GHz bands, and large aperture satellite antennas are the key to enable D2C connectivity. The industry is tackling the problem with a conventional approach, consisting of the design of very large reflectors or phased arrays. This article proposes a new way to face the problem: the distributed approach. A satellite base station (BS) is decomposed into several small platforms in a so-called swarm configuration to form a sparse phased array. The use of small satellites promises cost-effective solutions, while distributed satellite systems (DSSs) increase the fault tolerance, and thus the reliability, of the entire constellation. This article compares the performance of conventional and distributed approaches under different conditions. It shows that distributed approaches outperform conventional ones even under unfavorable conditions and pessimistic assumptions. Important tradeoffs are derived showing the flexibility of distributed approaches. Finally, major research aspects for exploiting the full potential of the distributed approach are highlighted.

Introduction

Anywhere and anytime connectivity is one of the promises of 6G. This challenging goal cannot be achieved using only one network infrastructure. This explains why 6G is seen as a convergence point for all space, air, and ground network infrastructures which, until now, have mainly been operated as completely isolated silos. Connectivity will be guaranteed not only via classical fiber/copper networks and terrestrial wireless base stations (BSs) but via a multilayered hierarchical network. The zero-altitude components, the terrestrial networks (TNs), will be complemented by higher altitude networks, the non-terrestrial networks (NTNs). NTNs in turn will comprise multiple components, but satellite networks are undoubtedly the key component for ubiquitous connectivity.

One of the most challenging aspects of integrating satellite networks into terrestrial networks is the direct connectivity between satellites and terrestrial devices. The term direct connectivity generally refers to two main use cases, depending on the user terminal on Earth. Terrestrial terminals can be very small aperture terminals (VSATs) or common handheld devices (Handheld) such as smartphones. The latter have smaller antennas and limited power resources. For this reason, satellite networks for VSAT can benefit from higher frequencies (Ku/Ka bands), while satellite networks for Handheld use lower frequencies (L/S bands) to cope with link budget limitations, but the scarcity of bandwidth resources is even more critical in these lower bands. Despite the differences between satellite networks for VSAT and Handheld, low Earth orbit (LEO) altitudes are privileged for the direct connectivity scenario to limit the latency gap with terrestrial networks. Nevertheless, they have several disadvantages, one of which is the increase in the number of satellites to cover the entire globe, from hundreds to tens of thousands depending on the level of performance required. In recent years, the industry has provided several examples of LEO constellations for VSAT (e.g., Starlink, OneWeb, and Kruiper) and, more recently, constellations for Handheld (e.g., Lynk Global and AST SpaceMobile). This article focuses on direct connectivity for Handheld, referred to as satellite direct-to-cell (D2C) connectivity.

Despite the reduction of distance between endpoints using LEO altitudes and the reduction of path loss using L/S bands, the formulation of the link budget for satellite D2C connectivity requires a great effort on the satellite side. This explains why D2C connectivity solutions are considering a *conventional approach* based on medium to large phased arrays or phased feed arrays with large reflectors (left-hand side of Fig. 1). This trend leads to an increase in the production cost of individual satellites, especially for large platforms, for which complex materials and structures are required to fit them into the launch vehicle. In addition, the increase in satellite size increases the weight and thus the launch costs.

An alternative to the previous approach is the decomposition of the single satellite into a distributed satellite system (DSS) with several small platforms. The *distributed approach* organizes platforms in a swarm configuration, coordinated to achieve a common goal (right-hand side of Fig. 1). The common goal is the coherent transmission/

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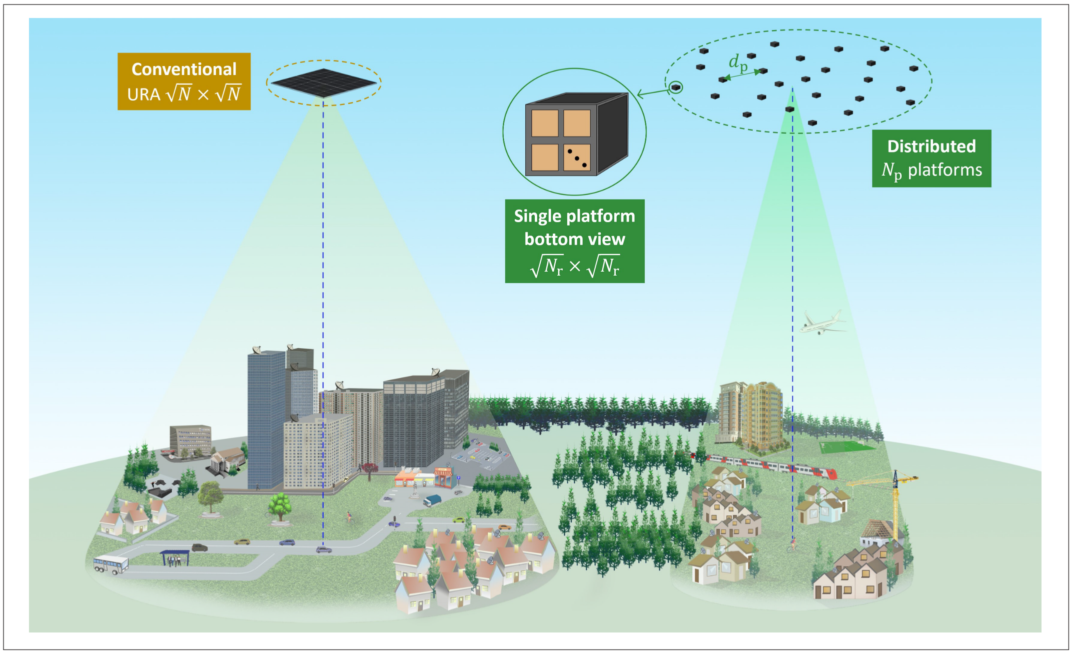

FIGURE 1. Use case example of D2C connectivity with a BS in space (conventional and distributed). A BS can provide service to a variety of users in different environments.

reception of the signals creating a distributed phase antenna array. The swarm can be implemented in different ways, but a common implementation considers a formation flying (FF)[1] consisting of one or more leaders with enhanced capabilities and several followers with limited capabilities. Platforms communicate with each other via a wireless or wired connection. This approach uses small and lightweight satellite platforms (e.g., CubeSats) that can facilitate the fabrication process and reduce the total weight. This can lead to a twofold reduction of production and launch costs. Furthermore, the distributed nature of the system introduces other positive aspects, such as fault tolerance, as the failure of a single platform in the distributed system can only produce a graceful degradation in performance, avoiding service interruption.

Swarms of small satellites organized in an FF is a research topic in various fields of application. Numerous research and space flight demonstrations have been conducted in astronomy, deep-space communications, meteorology, and environmental uses [1]. Swarms have also been considered in unmanned aerial vehicles (UAVs) [2]. Other works applied distributed approaches to LEO satellites but used a limited number of more powerful satellites, higher frequency ranges, and more powerful terminals on Earth [3, 4]. Nevertheless, swarms of small satellites for D2C connectivity have received limited attention. The paper in [5] presented a formation of sub-arrays in geostationary Earth orbit (GEO) and LEO scenarios, but the LEO performance derived is similar to the conventional approach. The paper in [6] considered a swarm creating a distributed phased array for D2C connectivity, emphasizing the importance of swarm geometry in antenna performance, but considering only one radiating element per small satellite.

This article extends the concept of [6] by considering more than one element on a single platform. It provides an overview of the satellite D2C connectivity use case. Moreover, it compares conventional and distributed approaches by analyzing the performance of a single beam, providing insights into the performance of multiple beams, and deriving important trade-offs for system design. It demonstrates that distributed approaches, in the presence of pessimistic assumptions and unfavorable conditions, can still outperform the conventional approach. Finally, it defines major research aspects of the distributed approach, such as FF stability, synchronization accuracy, multibeam coverage optimization, and constellation design aspects. The numerical results presented can be reproduced using code available on a public repository (https://github.com/diegotuzi/Distributed-Approach-to-Satellite-Direct-to-Cell-Connectivity-in-6G-Non-Terrestrial-Networks)

Direct-to-Cell Connectivity in NTN

D2C connectivity consists of direct two-way communication between satellites and mobile terminals, such as smartphones, operating in the L/S frequency band. This communication model addresses two of the fundamental problems of the digital divide: the broadband access gap and terminal costs. End users in rural and remote areas around the world will be able to benefit from high-speed Internet access with low-cost end devices.

In recent years, major technology companies have been working to make D2C connectivity a reality, adapting their products to enable connection with existing satellite systems. For example, Apple made a huge investment to upgrade Globalstar's satellite network, consisting of 24 LEO satellites and several ground stations that provide the critical infrastructure to support the emergency SOS function for iPhone 14 models. Another example is the Huawei Mate 50 smartphone that allows users to send text messages and their location using the Beidou navigation constellation. Additionally, MediaTek, Qualcomm, and Samsung are developing chips to support satellite D2C connectivity features.

[1] The term formation flying is usually referred to the problem of keeping a desired relative separation, orientation, or position between or among platforms.

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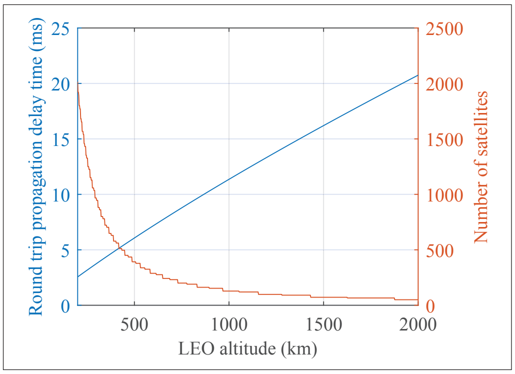

FIGURE 2. Trade-off between round-trip propagation delay time and number of satellites for a Walker constellation with 30° minimum elevation angle. An increase of the LEO altitude reduces the size of the constellation but the round-trip propagation delay time increases.

The interest of these large players testifies to the potential of this use case for a profitable future, but these first examples can only provide initial services far from the expected performance of 6G NTN. The future of NTNs is based on new LEO constellations. LEO altitudes range between 200 and 2000 km above the Earth's surface. LEO satellites have several advantages: lower path loss and lower latency. Figure 2 (left y-axis) shows the round-trip propagation delay time as a function of the different altitudes. The round-trip propagation delay ranges between a few ms to around tens of ms, which is considerably less than the latency of GEO satellites. Figure 2 (right y-axis) shows the required number of satellites to achieve the global coverage with a Walker constellation, calculated through the simple equations in [7] and using a minimum elevation angle[2] of 30° (as in [8]). There is an indirect relationship between the propagation delay and the number of satellites. Lower propagation delays require lower altitudes but larger constellations and vice versa. Later analysis will consider an intermediate altitude of 500 km that represents a trade-off between the two quantities in Fig. 2.

The first examples of new LEO constellations for D2C connectivity come from the industry. SpaceX requested spectrum to upgrade Starlink mobile services and a modular payload will be added to future Starlink satellites to support frequencies around 2 GHz. The feature should come with T-Mobile phones in 2024/2025. Other companies, such as Lynk Global and AST SpaceMobile have already achieved tangible results. Lynk Global is the first company to demonstrate the technical feasibility of sending a text message via satellite communications to unmodified mobile phones. The planned constellation comprises more than 5.000 medium size satellites. On the other hand, AST SpaceMobile launched a prototype LEO satellite called BlueWalker 3, a large deployable phased array with a massive aperture of about 64 m^2. In this case, the planned size of the constellation is around 170 large satellites with an aperture of 128 m^2 [9].

The examples above show that companies are planning different strategies to offer D2C connectivity but following a conventional approach. This article presents an alternative distributed approach.

[2] The elevation angle is the vertical angle formed between the Earth's surface and the line of sight direction between the Handheld and the swarm. The introduction of a minimum elevation angle reduces the service area of the BS in space and increases the size of the constellation required to provide global coverage.

Distributed Approach to Enable Direct-to-Cell Connectivity

The goal of each component of a LEO constellation for D2C connectivity is to reproduce from space the service provided by a typical terrestrial BS. A BS in space can be a single satellite with a conventional phased array (an approach followed in most of the current constellations) or a swarm of small satellites creating a distributed phased array, which is the approach proposed in this article.

The conventional approach consists of a single satellite platform with a phased array with N radiating elements (left-hand side of Fig. 1). The most common implementation of phased arrays is the rectangular one, where the vertical and horizontal distance between the elements is the same (d_r) and usually around half the wavelength. In this article, this architecture is referred to as a conventional uniform rectangular array (c-URA).

The distributed approach consists of a swarm of N_p small satellites (right-hand side of Fig. 1), where each platform is equipped with N_r radiating elements (zoom in on the bottom of the single platform, in the center of Fig. 1). The total number of radiating elements of the swarm is N, equal to the product of N_p and N_r. Also in this case, every single small satellite of the swarm is equipped with a rectangular phased array with uniform inter-element distance (d_r) of about half the wavelength. However, the distance between platforms, d_p, is much higher than half the wavelength. Swarm platforms can be organized in different architectures, this article considers two alternatives: the distributed uniform rectangular array (d-URA), and distributed enhanced logarithmic spiral array (d-ELSA) with a spatial tapering coefficient equal to one, defined in [6]. The first organizes the platforms in a rectangular formation, the latter according to a geometry based on Fermat's spiral. The swarm forms a close formation in space, where each platform follows a collision-free orbit at the same altitude. Swarm platforms can use a wireless (free-flying) or wired (tethered) connection to achieve the required level of coordination. Free-flying swarms use RF/optical links that require complex solutions to synchronize and control the formation. Tethered swarms consider physical connections between platforms using space tethers [10]. A tethered alternative can provide greater formation stability and a wired data connection, but it introduces mechanical challenges to realize compact deployable structures to fit into the launch vehicle.

Single Beam Channel Capacity Without Interference

The BS in space (conventional or distributed) has to communicate with a single user that is placed at the nadir position (Fig. 1). The BS must generate a beam in the direction of the user. The resulting beam pattern of a phased array (conventional or distributed) is the combined effect of the beam pattern of the single radiating element and the array factor, which depends on the position of the radiating elements, and the beamforming coefficients. The following analysis focuses on the array factor, where the precoding/beamforming coefficients are calculated assuming the knowledge of the user's exact position. Thanks to this choice, the resulting main lobe is centered at the user position.

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The performance of the conventional approach is compared with different instances of the distributed approach under several degrees of freedom. The total number of radiating elements (N) increases up to about a thousand. The number of radiating elements on a single platform (N_r) is 4 or 16, limiting the size of the platform and allowing the use of CubeSats. The distance between the platforms (d_p) is ten or twenty times the wavelength, so that a target beam footprint under 5 km of coverage radius is achieved, similar to terrestrial BSs. The number of platforms, N_p, is impacted by the previous parameters and can simply be derived by dividing the total number of elements (N) by the number of radiating elements on a single platform (N_r). The BS considers N radiating elements with 8 dBi gain and power (P_r) set at 0.35 W.[3] The total power of the BS is the product between P_r and N. The center frequency is 2 GHz (S-band) and the bandwidth is 30 MHz, assumptions consistent with NTN satellite bands in frequency range 1 (FR1), operating in frequency division duplexing (FDD). The LEO altitude of the BS is 500 km. The Handheld has a 0 dBi antenna gain, such as a terrestrial smartphone. Other parameters for the link budget are selected according to the analysis in [8].

The first analysis focuses on the performance considering an additional white Gaussian noise (AWGN). Figure 3a shows one of the basic antenna design trade-offs. By increasing the equivalent antenna array aperture, the HPBW of the main lobe is reduced and consequently, the coverage on Earth is reduced. Distributed approaches increase the distance between platforms, resulting in a larger equivalent antenna aperture than the conventional case. Figure 3b shows another basic antenna design trade-off. The maximum gain of an antenna array mainly depends on the number of radiating elements. Furthermore, the total BS power increases with the number of elements. As a result, the signal-to-noise ratio (SNR) increases similarly for all architectures, showing comparable throughput.

An interesting parameter to combine the previous results is the throughput area density (TAD). It represents the ratio between the throughput (Mb/s) and the area covered with the main beam (km^2) and it is expressed in Mb/s/km^2. Figure 3c shows an interesting result. Distributed approaches have a higher TAD than the conventional approach thanks to the reduced coverage.

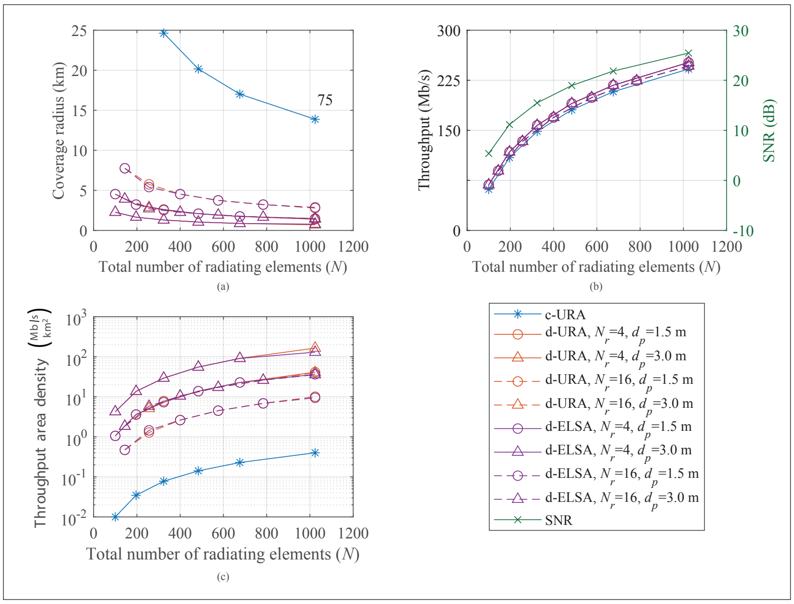

FIGURE 3. Single beam performance with AWGN channel and without interference: a) Distributed approaches achieve larger equivalent antenna aperture reducing the HPBW and thus the coverage on Earth; b) All architectures have the same number of elements, which leads to similar performance in terms of single beam throughput; c) Distributed approaches outperform conventional ones by spreading the same throughput over a smaller area.

Single Beam Channel Capacity With Interference

In a multi-beam scenario with full frequency reuse (FFR), the single beam performance is severely degraded by interference from all other beams in the same BS (intra-beam). Intra-beam interference is characterized by the beam pattern outside the HPBW of the main lobe. Figure 4 shows a normalized gain cut for the different architectures considered with the same number of elements equal to 1024 (normalization is based on the maximum gain among the three architectures). In conventional phased arrays, the isolation level between the main lobe and the other lobes can be controlled through tapering techniques. These can provide a high isolation level at the expense of maximum gain degradation and increased HPBW. Figure 4a shows the normalized beam pattern of the c-URA architecture without and with tapering (using a Taylor window). On the other hand, as known from classical antenna array theory, increasing the distance between radiating elements beyond a certain threshold, as in the case of distributed architectures, leads to the problem of grating lobes (GLs). Figure 4b shows the d-URA architecture with a uniform distance between platforms of 3m (twenty times the wavelength). As expected, the beam pattern is affected by the GL problem. An alternative to mitigate the GLs is to control the geometry of the array. Interesting are geometries based on Fermat's spiral [11].

Figure 4c shows the beam pattern of the d-ELSA architecture that achieves a certain level of mitigation of the GLs. However, unlike the conventional approach, the application of known tapering techniques does not promise the same increase in isolation. Therefore, multi-beam solutions for distributed architectures must take this into account.

The second analysis in Fig. 5 shows the impact of intra-beam interference on the single beam performance of the d-ELSA architecture. The number of interfering beams in Fig. 5a is statistically derived to create a pessimistic operating condition with a signal-to-interference-plus-noise ratio (SINR) equal to −5 dB. Considering a typical BS service area and a uniform multi-beam coverage, the total intra-beam interference can be approximated by the average power level radiated outside the main lobe of the beams multiplied by the number of interfering beams. Figure 5b compares the TAD for d-ELSA architectures with SINR = −5 dB and c-URA under a favorable condition representing the maximum single beam performance, in which all power is used for one beam and performance is limited only by noise with no interference. Although the performance of the distributed architectures is drastically reduced compared with Fig. 3c, due to the amount of intra-beam interference and the reduced power allocated to the single beam, they still outperform the maximum single beam performance of the c-URA.

[3] The antenna element model of 3GPP TR 38.901 is used. The choice of low radiating power was made considering the smallest possible implementation of the CubeSat platform.

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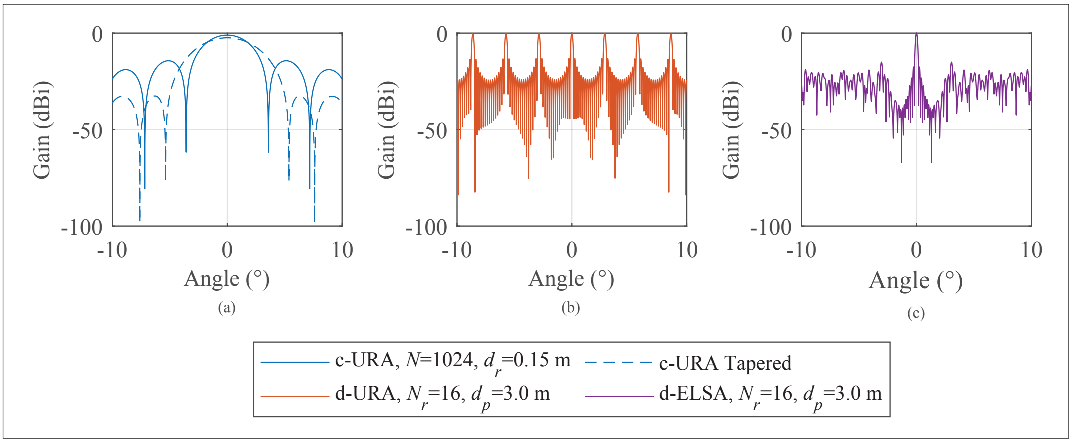

FIGURE 4. Normalized gain for different architectures (normalization to the gain of the c-URA): a) c-URA architecture without and with tapering windows to reduce the minor lobe levels; b) d-URA architecture with grating lobes problem due to the high spacing between the elements; c) d-ELSA architecture introduced in [6] capable of mitigating grating lobes in case of high element spacing.

Trade-Offs

The previous analyses show two important trade-offs of distributed architectures, summarized in Table 1. Firstly, considering the same number of radiating elements N, the same TAD performance can be achieved with different configurations of N_r, N_p, and d_p. A reduced number of platforms by increasing the number of elements on the single platforms (N_r) is advantageous in several important respects: fewer platforms to synchronize, and fewer platforms to maintain in the FF. On the other hand, platforms increase in size, making it difficult to use cost-effective platforms such as CubeSats. In addition, reducing the number of platforms also reduces the benefits of the distributed nature of the system, such as fault tolerance. Secondly, the results show that the TAD performance increases when increasing the distance between the platform (d_p). The TAD performance can be further improved by using larger distances, that is, by increasing the virtual antenna aperture and reducing the single beam coverage on Earth. In this case, the BS would need many more beams to cover the service area, but increasing the number of parallel beams would still increase the interference.

Open Issues and Future Research Directions

The main research aspects of the distributed approach, such as FF stability, synchronization accuracy, multi-beam coverage optimization, and constellation design aspects, are analyzed below.

Formation Flying Stability

In the results previously shown, the perfect FF stability during the flight around the Earth has been assumed. However, in the real environment, Earth's oblateness, atmospheric drag, solar radiation pressure, and other effects perturb the positions of the platforms. Therefore, the study of orbit dynamics and the realization of autonomous guidance, navigation, and control algorithms are key aspects of FF stability. In particular, the deployment of the swarm in space is a crucial part, because platforms need different initial conditions to create collision-free trajectories. Particular deployment strategies promise great mitigation of the main perturbation effects, drastically reducing the probability of collision [12]. Thereafter, the propulsion system of each platform only has to perform periodic correction maneuvers to counteract residual trajectory degradation. Nevertheless, propulsion systems and fuel consumption can be limiting factors for small satellite implementations and mission lifetime. For this reason, electric propulsion and electromagnetic forces are other interesting fields of research in FF.

Fortunately, the beamforming results derived are quite robust against geometry imperfections, since the GLs mitigation lies in the aperiodicity of the geometry. The important aspect is the accurate estimation of the actual geometry through synchronization methods, which allow the beamforming coefficients to be calculated correctly.

Synchronization Accuracy

The results presented consider the coherent transmission/ reception of signals emitted/received by the distributed phased array, which requires the alignment of signals in frequency, phase, and time. In the distributed approach, signals are emitted/received by several platforms, each of which has its local oscillator that is subject to random frequency and phase offsets due to various factors and the quality of its components. If each platform used the local reference carrier as a reference signal without any means of synchronization, the coherent operation would be highly degraded. Therefore synchronization is an important research aspect for the distributed approach because the degradation of the beamforming depends on the level of synchronization error of the system, in other words, a certain level of accuracy is needed to keep the degradation of the performance under an acceptable threshold.

Although available literature and several experiments suggest methodologies to achieve the wireless synchronization of distributed phased arrays [13], the exact definition of the acceptable error level, the technology involved, and specific synchronization algorithms still require further research.

Multi-Beam Coverage Optimization

Reducing the size of the single beam (i.e., increasing the distance between the platforms) increases the TAD performance of distributed approaches, but impacts other important aspects. Although

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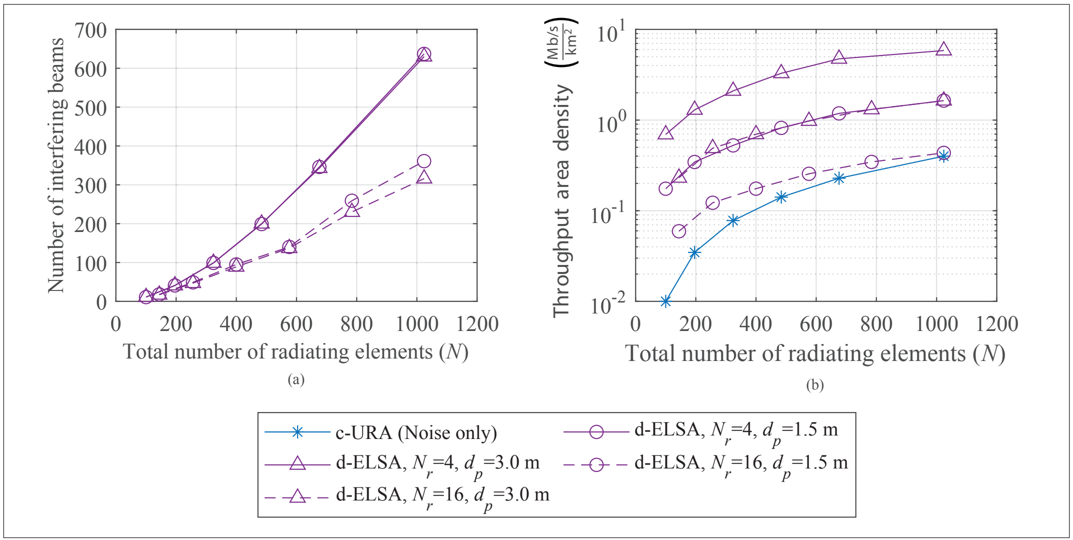

FIGURE 5. Single beam performance: c-URA under favorable conditions, only considering the effect of noise. Several instances of d-ELSA under unfavorable conditions, considering noise and a pessimistic interference condition (SINR = –5dB). Distributed approaches drastically reduce their performance, still outperforming the conventional ones with the same number of radiating elements.

Action	Pros	Cons
Reduction of the number of platforms (N_p) by increasing the number of elements on a single platform (N_r)	Complexity reduction for synchronization and FF stability	Increased size of the single platform, reduced opportunity to use CubeSats
Increment of the distance between platforms (d_p)	Complexity reduction for FF stability, TAD performance increment	Increased beamforming complexity (number of beams), or reduced service area (constellation size increment)

TABLE 1. Distributed approach trade-offs (considering the same total number of radiating elements).

a large number of active parallel beams can be tolerated (Fig. 5a), this may not be sufficient to achieve the same simultaneous coverage as a conventional implementation using the same number of radiating elements and the same power. Therefore, the number of parallel beams should be increased and/or the service area reduced.

The number of beams in Fig. 5a is derived by considering a beamforming scheme capable of directing the beam to different positions in the service area without altering the total beam pattern much (an assumption consistent with a simple scheme such as conjugate beamforming), and a FFR scheme. Therefore, advanced signal processing techniques can improve performance by reducing the amount of intra-beam interference and allowing more beams. Furthermore, less aggressive frequency reuse schemes can also increase the number of beams, but the impact on the performance must be evaluated. In addition, the use of beam hopping techniques could mitigate the required number of beams relative to the service area. Current technology makes it possible to go from one point to another on Earth up to 1,000 times per second [14], but even then, performance needs to be evaluated.

On the other hand, service area reduction would impact other important aspects. A reduced service area leads to a reduced BS service time, resulting in more frequent handovers, and most importantly, providing global coverage would require a larger constellation with more BSs.

Consequently, the degrees of freedom of the distributed approaches must be carefully optimized through a multi-beam coverage problem combining performance and service area.

High-Performance and Cost-Effective Constellation Design

A distributed BS constellation can be designed using the same conventional methods as the popular Walker design for global coverage.

Considering the plans of current LEO constellations for D2C there are several approaches. Lynk Global considers thousands of medium-aperture antennas with hundreds of radiating elements. The large number of satellites in the constellation provides a high minimum elevation angle, while the medium-aperture antenna limits the performance in terms of maximum throughput and TAD due to the large beams. On the other hand, AST SpaceMobile considers hundreds of huge-aperture antennas with thousands of radiating elements. The huge-aperture antenna increases performance in terms of maximum throughput and TAD due to the smaller and more powerful beams, but the smaller constellation provides a lower minimum elevation angle and a larger service area. Despite the differences, the analysis in [6] showed a similar total number of radiating elements (i.e., a similar total physical antenna aperture area in space for the two approaches). The easy choice from the performance standpoint would be a massive constellation of huge satellites, which would ensure high service availability and high performance, but costs would skyrocket.

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A distributed BS constellation can be designed using the same conventional methods as the popular Walker design for global coverage.

The flexibility of the distributed approach in generating a large virtual antenna aperture area with a small physical antenna aperture area, the use of small CubeSat platforms, and the availability of commercial off-the-shelf (COTS) components are promising aspects for a constellation of distributed BSs with a trade-off between service availability and performance, while reducing the overall cost. An initial cost analysis in [15] implied a significant cost reduction using distributed implementations for synthetic aperture applications. A full techno-economic analysis for a constellation of distributed BSs for D2C is needed to confirm the promised benefits.

Conclusion

This article emphasized the important role of satellite networks in D2C connectivity for 6G NTN. The goal of D2C connectivity is to create a BS in space to provide service to common terrestrial devices. A common technical trend for the implementation of a BS, called the conventional approach, has been identified. Subsequently, an alternative approach, the distributed approach, is presented. The distributed approach decomposes the conventional satellite platform into a swarm of smaller platforms, creating a distributed phased array. This article compared the single beam performance of conventional and distributed approaches under different conditions. Distributed approaches significantly outperform conventional ones even under unfavorable conditions and pessimistic assumptions. Important trade-offs were identified showing the flexibility of distributed approaches. Finally, the article presents several aspects that need further investigation to define the true potential of satellite swarms.

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