Holographic MIMO Aided Integrated User-Centric Cell-Free Terrestrial and Non-Terrestrial Networks

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***Abstract*—With the rapid growth of global communication demand, the limitations of traditional terrestrial networks (TNs) in terms of their coverage, reliability and resource utilization efficiency are becoming increasingly apparent. To address these challenges, this paper proposes a holographic multiple-input multiple-output (MIMO) user-centric cell-free integrated terrestrial and non-terrestrial network (TN-NTN). The proposed architecture is promising to achieve seamless global coverage, high spectral efficiency and robust performance in dynamic multi-user scenarios by combining holographic beamforming, distributed access points (APs) and satellite-ground collaboration. Based on the proposed holographic MIMO assisted user-centric cell-free TN-NTN, first we present the associated channel estimation and time synchronization methods conceived for these dynamic environments, and use statistical modeling as well as distributed optimization techniques for improving the adaptability and synchronization accuracy of the system. Then, we analyze the hybrid beamforming design proposed for this architecture, which combines holographic and digital beamforming for optimizing both signal directionality and interference suppression. We harness statistical modeling and real-time feedback for prompt dynamic adaptation to the violently fluctuating channel conditions. We demonstrate that our system significantly outperforms traditional TN-NTNs in terms of its spectral efficiency and system adaptability. We conclude with the challenges faced by practical hardware limitations, time synchronization and resource allocation, and propose promising future research directions such as hardware optimization, quantum enhanced security, and advanced modulation.**

I. Introduction

Given the rapid growth of the global communication demands, conventional terrestrial networks (TNs) exhibit limitations in terms of their coverage range, service reliability and resource utilization efficiency, which have to be improved for next-generation systems [1]. To deal with the above limitations, integrated terrestrial and non-terrestrial networks (TN-NTNs) have been proposed for next-generation networks [2]. By the integration of the terrestrial infrastructure, high-altitude platforms (HAPs) and low Earth orbit (LEO) satellites, TN-NTNs become capable of realizing seamless global connectivity. Furthermore, TN-NTNs have also seen increasing commercial interest, with notable examples including SpaceX Starlink, OneWeb and Amazon's Project Kuiper, aiming to deliver global broadband connectivity through large-scale LEO satellite constellations.

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To fully harness the potential of TN-NTNs and address the challenges of dynamic environments, advanced technologies and innovative architectures must be explored. Among these, the holographic MIMO and user-centric cell-free architecture have emerged as promising solutions.

Specifically, the holographic multiple-input multiple-output (MIMO) is composed of densely packed tunable elements harnessed for pencil-like precise beamforming and spatial multiplexing, providing high spectral efficiency, high energy efficiency and dynamic beamforming capabilities [3]. These features make the holographic MIMO particularly effective for multi-user and multi-layered communication systems like TN-NTNs, significantly enhancing their performance. By dynamically configuring the sub-wave length meta-surface elements for efficient beamforming and directivity control, holographic MIMOs become capable of system optimization, including interference management and resource allocation. Furthermore, the holographic MIMO's capability to dynamically shape the wavefronts in real time allows the system to respond promptly to time-varying channel conditions, user mobility and to traffic demands, making them eminently suitable for large-scale distributed networks [4].

Additionally, the introduction of a user-centric cell-free architecture enhances both the network's flexibility and the user experience [5]. User-centric cell-free networks can significantly improve the service capabilities in multi-user scenarios by relying on the tight coordination of distributed access points (APs) for eliminating the deleterious cell-boundary effects. This architecture leads to an improved spectral efficiency, uniform service quality, and seamless mobility across large geographic areas.

Given the benefits of the aforementioned techniques, this paper proposes a holographic MIMO-aided user-centric cell-free TN-NTN framework, delivering innovative solutions by harnessing performance optimization. By addressing key challenges in the practical deployment of the proposed holographic MIMO-assisted user-centric cell-free TN-NTN architecture, we tackle challenging issues, including precise channel estimation under Doppler frequency shifts, time synchronization in high-dynamic environments, and interference suppression in high user-density scenarios. Specifically, the contributions of this paper are as following:

- **Architecture Design:** A novel user-centric cell-free TN-NTN system integrating holographic MIMO technology is proposed. By leveraging distributed APs and holographic beamforming, the system mitigates both the severe signal attenuation and the inter-user interference in dynamic TN-NTN environments.

- **Channel Estimation and Synchronization:** We propose robust methods for precise channel modeling under Doppler frequency shifts and for high-accuracy time synchronization in dynamic TN-NTN settings, ensuring reliable communication.
- **Hybrid Beamforming Design:** We design an advanced hybrid beamforming mechanism tailored for holographic MIMO-assisted cell-free TN-NTNs, effectively managing both the channel gain and the interference suppression, while achieving scalability in multi-user TN-NTN scenarios.

In contrast to existing studies addressing holographic MIMO schemes, cell-free architectures, or TN-NTNs in isolation, this paper presents a unified system-level framework. The proposed design jointly tackles the key challenges of channel estimation, time synchronization and beamforming design in dynamic non-terrestrial environments. To the best of our knowledge, such an integrated implementation-aware approach has not been explored in prior studies.

The rest of this paper is organized as follows. We introduce the trends and architectures of TN-NTNs in Section II. Section III discusses the key technical methodology of the proposed holographic MIMO-assisted cell-free TN-NTN. Our case study is presented in Section IV, while Section V presents open challenges and their solutions. Section VI outlines some future directions. Finally, we conclude in Section VI.

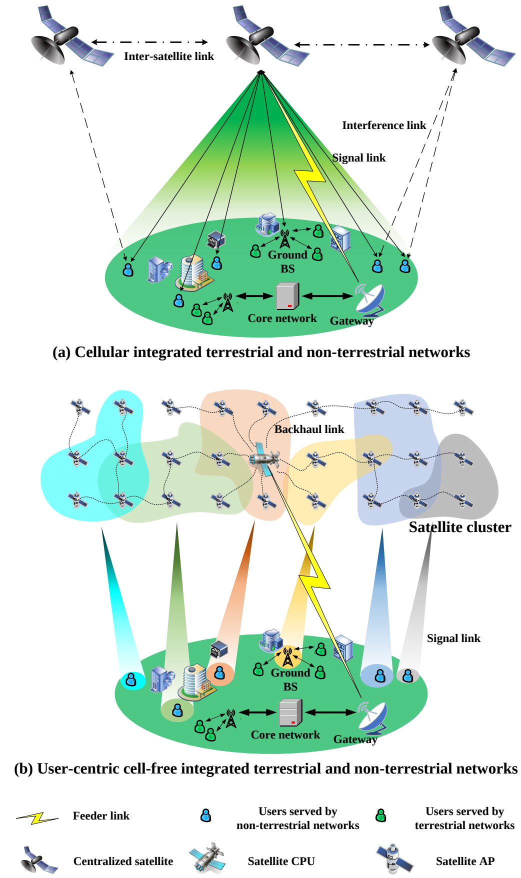

Fig. 1. System model of the cellular and user centric cell-free integrated TN-NTNs.

II. Trends and Architectures of TN-NTNs

This section first introduces the development trends of TN-NTNs, including its technical driving force and progress. Then, the architectures of both cellular and cell-free TN-NTN are introduced. Finally, the implementation method, advantages and potential applications of holographic MIMOs in TN-NTNs are outlined in detail, and analyzed in combination with the advantages of the cell-free architecture.

A. *Trends in TN-NTNs*

TN-NTNs provide important technical support for sixth-generation (6G) wireless systems by integrating the terrestrial infrastructures and non-terrestrial nodes. The development of TN-NTNs is driven by the following key drivers:

- ***Rapid development of LEO satellite technology***: The LEO technology is the core driving force for the evolution of TN-NTNs. At a low orbital altitude of 300 kilometers, the one-way propagation delay is as low as 1 milliseconds. The development of satellite constellation optimization and inter-satellite links has enabled LEO satellites to support dynamic routing and multi-hop communications, hence significantly reducing the reliance on terrestrial gateways [2]. In addition, the advances in Doppler shift management technology, such as orthogonal time frequency space (OTFS) modulation, has improved the adaptability of LEO satellites in high-speed dynamic scenarios, providing reliable guarantees for communications in high-dynamic scenarios.
- ***Tight integration of terrestrial and non-terrestrial networks***: Through 3GPP's NTN standardization work, the collaborative operation of terrestrial and non-terrestrial networks has been gradually progressing. This inherent integration enhances the resource scheduling flexibility of TN-NTNs, especially in high-density dynamic multi-user scenarios, and facilitates the unified scheduling and optimization of cross-domain user needs.

Although TN-NTN technologies have made significant progress, their actual deployment still faces challenges in terms of spectrum sharing, dynamic channel management and high-precision synchronization. Solving these problems requires deeper architecture design and holistic system optimization, especially in holographic MIMO-aided collaborative cell-free architectures.

B. *Architectures of TN-NTNs*

LEO satellites play a pivotal role in supporting low-latency high-speed global communications, particularly in remote regions, significantly improving the coverage and connectivity, of TN-NTNs. Fig. 1 contrasts the architecture of integrated TN-NTNs supported by LEO satellites in both cellular and cell-free scenarios.

Briefly, the conventional integrated TN-NTN cellular network is illustrated in Fig. 1 (a), where data from the core network is transmitted to terrestrial base stations (BSs) within the terrestrial network. To extend coverage beyond terrestrial limitations, the non-terrestrial network leverages satellite links. Specifically, data gleaned from the core network is relayed to LEO satellites, which act similarly to cell towers. Each LEO satellite covers a specific footprint on Earth via its beam, transmitting data to both ground BSs and terrestrial users within the coverage area. Owing to their low orbits, LEO satellites are capable of providing lower latency and higher data rates than geostationary (GEO) satellites, facilitating seamless handovers. However, these networks inherit numerous challenges from the traditional terrestrial cellular architecture. As illustrated in Fig. 1 (a), users roaming at the edge of a satellite beam often experience inter-satellite interference from adjacent beams, hence suffering from a degraded service quality. Furthermore, allocating network resources and balancing dynamic loads becomes more challenging due to the complex environmental factors, such as weather changes and infrastructure obstructions, leading to signal degradation and service interruptions.

To overcome these limitations in satellite-based cellular networks, we conceive the integrated TN-NTN user-centric cell-free network, concept of Fig. 1 (b). Explicitly, instead of relying on a single satellite beam, the terrestrial users are dynamically served by a cluster of satellite APs, supporting seamless service. In this architecture, data is transmitted from the gateway to the satellite's central processing unit (CPU), which then shares the data with the satellite APs via backhaul links. Each centralized satellite is effectively decomposed into multiple satellite APs that cooperatively serve users. This user-centric approach provides flexible resource allocation for individual users, enhancing their service quality and mitigating the inter-satellite interference. By distributing the load across multiple satellite APs, the cell-free satellite network ensures consistent and uniform communication performance, effectively overcoming the constraints of traditional satellite networks. The distributed architecture can also improve network resilience, since multiple satellite links can compensate for potential disruptions in individual connections, thereby further enhancing the system's reliability and scalability. Furthermore, user-centric clustering enhances the connectivity and performance by leveraging the cooperation among the distributed satellite APs.

C. Holographic MIMO Aided Cell-Free Architecture

Holographic MIMOs support efficient beamforming, interference management, and channel optimization by dynamically controlling electromagnetic signals. Intrinsically amalgamated with the cell-free architecture, the potential of this holographic MIMO technology is further improved. The following are the main implementations of holographic MIMOs and their applications in cell-free TN-NTNs:

- ***Dynamic Metasurface Antenna (DMA)***: As shown in Fig. 2 (a), the DMA consists of multiple microstrips, each connected to a dedicated radio frequency (RF) chain. Each microstrip includes three core components: a feed, a waveguide, and a series of sub-wavelength metamaterial elements [6]. These metamaterial elements composed of artificial materials can dynamically adjust the phase shift of electromagnetic (EM) waves via a software controller, following a Lorentzian-constrained phase configuration for precise wavefront control. The waveguide propagates the EM waves to the feed Fig. 2 (a), which converts them into high-frequency currents for the RF chain. Finally, the RF chain processes the signals, converting them to the baseband for additional digital beamforming. DMA achieves highly directional signal transmission based on dynamically controlling the phase shift of metamaterial elements. Its distributed design can significantly reduce hardware complexity, while attaining high spectral efficiency. In the cell-free architecture, DMA can improve the channel gain and reduce multi-user interference through distributed metasurfaces deployed between multiple APs, providing strong support for user-centric services.
- ***Reconfigurable Holographic Surfaces (RHS)***: The RHS is a special leaky-wave antenna, where the information is beamformed based on a wave circuit generating excitation and a radiating element configuration controller [7]. Specifically, as shown in Fig. 2 (b), the RHS comprises a feed, a waveguide, and numerous sub-wavelength metamaterial radiation elements, all integrated on a planar surface. When the feed generates an EM wave, referred to as the reference wave, the wave propagates along the waveguide and interacts with the radiation elements. Each radiation element adjusts the amplitude of the reference wave according to the pre-configured holographic pattern, which is based on the interference between the reference wave and the desired object wave. By tuning the radiation amplitude of each radiation element, the RHS forms highly directional beams that are steered towards target users for holographic beamforming. This beamforming mechanism avoids the need for complex phase-shifting circuits, thus reducing power consumption and hardware complexity. This design makes the RHS a promising solution for scenarios requiring energy efficiency and lightweight hardware. Its dynamic control capability is particularly effective in the complex multipath propagation environment of the cell-free TN-NTNs considered. By generating customized beams for each user, a RHS can further improve the network performance, especially in high-dynamic multi-user environments.
- ***Stacked Intelligent Metasurface (SIM)***: As depicted in Fig. 2 (c), the SIM architecture leverages its multi-layer design for enhancing signal processing directly in the EM wave domain, without relying on complex digital beamformers [8]. By utilizing the waveband beamformer, the SIM manipulates the phase shifts of the EM waves across multiple frequency bands. Each layer of the metasurface contains reconfigurable meta-atoms that provide additional degrees of freedom for controlling the wave propagation. In the SIM architecture, creating parallel sub-channels between the transmitter and the receiver

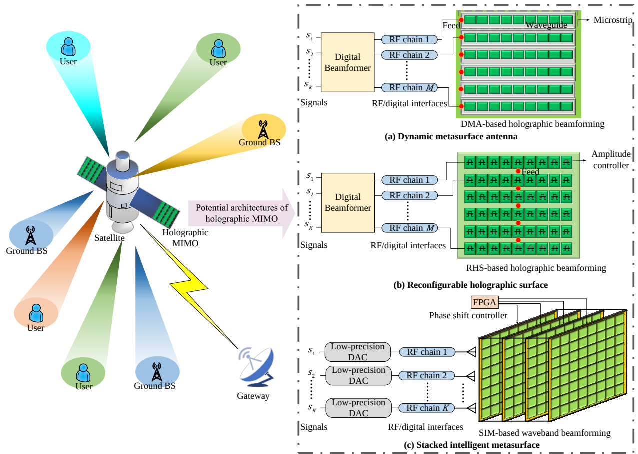

Fig. 2. Potential implementation architectures of the holographic MIMO, including dynamic metasurface antenna, reconfigurable holographic surface and stacked intelligent metasurface.

further boosts its efficiency, supporting interference-free communications and maximizing the system capacity. Furthermore, unlike conventional systems that require multiple RF chains and digital-to-analog conversions (DACs), the SIM supports high-performance beamforming by directly processing waves, which significantly reduces the hardware complexity. These features make SIMs an ideal solution for satellite networks, enabling low-latency communication and maximizing multiplexing gain. Compared to DMA and RHS, SIM is more compact and can provide more efficient beamforming capabilities under low-power conditions. This makes it particularly suitable for miniaturized devices in cell-free TN-NTNs, such as satellite and drone communications, improving user experience while optimizing energy efficiency.

By combining holographic MIMO technology with the cell-free architecture, distributed collaboration between APs is strengthened, while mitigating cell boundary effects and spectrum contention, hence providing a new path for the deployment of TN-NTNs.

In addition to the above architectural benefits, practical deployment on non-terrestrial APs requires addressing installation, power, and thermal challenges. Specifically, holographic metasurfaces are typically mounted on the satellites' outer structure for unobstructed beamforming powered by onboard solar energy, while heat dissipation is managed through passive thermal control techniques such as heat sinks or phase change materials ensuring reliable operation in TN-NTN environments.

III. Key Technical Methodology

In the holographic MIMO-based user-centeric cell-free TN-NTN architecture, multiple technical improvements are required. High-precision channel estimation supports accurate beamforming, while stable time synchronization is the basis of conducive multi-AP collaboration. We propose a series of innovative solutions relying on dynamic feedback from the holographic surface and on a novel distributed optimization strategy for the overall improvement of the system's performance.

A. *Channel Estimation*

Accurate channel estimation is critical for TN-NTNs, as it directly impacts beamforming performance and resource allocation. Due to the highly dynamic nature of satellite communications, channel estimation in TN-NTNs faces several challenges, including high Doppler frequency shifts, fast fading, and interference. In this section, we propose a *multi-layer channel estimation method* that integrates the characteristics of the holographic surface and distributed AP architecture.

1) Channel estimation error modeling: The accuracy of channel estimation is affected by various factors. In high-mobility environments, the received signal experiences a frequency shift, leading to violently time-varying channel state information (CSI). The Doppler shift can be expressed as $f_{\text{doppler}} = \frac{v f_c \cos\theta}{c}$, where v is the relative velocity, f_c is the carrier frequency, θ is the angle of arrival, and c is the speed of light. Additionally, the multi-path effect in TN-NTNs inflicts rapid fading, where the received signal is given by $h(t) = \sum_{l=1}^{L} \alpha_l e^{j(2\pi f_l t + \theta_l)}$, with L representing the number of paths, α_l as the path gain, f_l as the Doppler shift for each path, and θ_l as the phase offset. Reception is further corrupted by additive white Gaussian noise (AWGN), modeled as $h_{\text{obs}}(t) = h(t) + n(t)$, where $n(t) \sim \mathcal{CN}(0, \sigma^2)$.

2) Holographic MIMO channel modeling and sparse representation: To improve estimation accuracy, we leverage the inherent sparsity of holographic MIMO channels. Given the fine-resolution wavefront shaping capability of holographic surfaces, the channel response can be expressed using a sparse model. Hence the holographic MIMO channel is modeled as a sparse representation in the angular domain, given by $\mathbf{h} = \mathbf{\Psi}\mathbf{x} + \mathbf{n}$, where $\mathbf{h}$ is the channel vector observed, $\mathbf{\Psi}$ is the basis matrix formed by the steering vectors of the holographic surface, $\mathbf{x}$ is the sparse channel coefficient vector, and $\mathbf{n}$ represents the noise term.

Due to the sparsity of the channel coefficient vector $\mathbf{x}$, we employ orthogonal matching pursuit (OMP) to estimate the channel, where the estimated channel coefficient vector is given by $\hat{\mathbf{x}} = \arg\min_{\mathbf{x}} \|\mathbf{h} - \mathbf{\Psi}\mathbf{x}\|_2^2$ subject to $\|\mathbf{x}\|_0 \leq K$. The OMP algorithm iteratively selects the best matching atoms from $\mathbf{\Psi}$ for reconstructing the channel coefficient vector $\mathbf{x}$, thereby improving estimation accuracy in sparse environments.

3) Distributed cooperative channel estimation: Given the distributed nature of the cell-free TN-NTNs, multiple APs collaborate for enhancing channel estimation accuracy. Each AP obtains a local estimate $\hat{h}_n$, and a global estimate is formed as $\hat{h}_{\text{global}} = \sum_{n=1}^{N} w_n \hat{h}_n$, where N is the number of APs, w_n represents the weight assigned to each AP based on its channel quality. The weights are dynamically adjusted using $w_n = \gamma_n / \sum_{m=1}^{N} \gamma_m$, where γ_n is the channel gain at AP-n, ensuring that APs having stronger signals contribute more to the final channel estimation.

4) Dynamic channel updates using RMMSE: To maintain accurate CSI in time-varying environments, we employ a recursive minimum mean square error (RMMSE) approach.

The estimated channel vector is updated as $\hat{h}_{k+1} = \hat{h}_k + K_k(y_k - H_k\hat{h}_k)$, where y_k is the received signal vector, H_k is the channel matrix that characterizes the propagation conditions between the satelite APs and the terrestrial nodes, including path loss, fading, interference, and Doppler shifts. Furthermore, K_k is the Kalman gain that determines the weighting between the prior estimate and the newly received measurement, computed as $K_k = P_k H_k^T (H_k P_k H_k^T + R_k)^{-1}$. Here, P_k is the estimation error covariance matrix, and R_k represents the noise covariance. This method enhances dynamic channel tracking by continuously updating the channel estimate, thereby reducing estimation errors over time.

B. *Time Synchronization*

Time synchronization is essential for ensuring coordinated AP collaboration and efficient beamforming in user-centric cell-free TN-NTNs. Due to the high mobility of non-terrestrial nodes, synchronization errors arise from clock drift, Doppler shifts, and propagation delays. In this section, we introduce a holographic surface-assisted synchronization mechanism and a distributed multi-node synchronization algorithm for mitigating these issues.

1) Time Synchronization Error Modeling: Synchronization errors in TN-NTNs can be attributed to the following three primary factors:

- ***Clock drift***: Each AP and satellite maintains an internal clock that drifts over time due to oscillator imperfections. The drift follows $T_{\text{drift}}(t) = T_0 + \alpha t + \epsilon(t)$, where T_0 is the initial offset, α is the drift rate, and $\epsilon(t)$ represents stochastic noise.
- ***Doppler frequency shift***: High mobility in non-terrestrial nodes results in frequency shifts, introducing synchronization errors, which can be expressed as $\Delta T_{\text{doppler}} = \frac{\Delta f \cdot T_{\text{transmission}}}{f_c}$. Here, $T_{\text{transmission}}$ represents the symbol duration and Δf represents the frequency shift.
- ***Propagation delay variation***: As satellites move along different orbits, the distance between users and APs varies, causing dynamic delays given by $T_{\text{propagation}} = \frac{d}{c}$, where d is the transmission distance.

These uncorrected errors degrade signal coherence, leading to inefficient beamforming and resource allocation.

2) Holographic Surface Assisted Synchronization: To mitigate the impact of Doppler shift and propagation delay jitter, we propose a holographic surface-assisted synchronization mechanism. The holographic surface continuously tracks channel phase variations and dynamically adjusts signal timing through adaptive beamforming. Specifically, the steps of the holographic surface-assisted synchronization mechanism can be described as follows:

- ***Real-time feedback correction***: The holographic surface detects and compensates for synchronization errors by adjusting phase offsets, where the corrected synchronization time is $\hat{T}_{\text{sync}} = T_{\text{observed}} - \Delta T_{\text{doppler}}$, where T_{observed} represents the initially measured synchronization time before applying feedback corrections.
- ***Interference suppression***: By dynamically shaping wavefronts, the holographic surface reduces synchronization jitter caused by multipath fading.
- ***Distributed AP coordination***: The APs use feedback from the holographic surface to maintain global timing consistency across the network.

By leveraging ultra-precise wavefront control, the holographic surface significantly reduces synchronization errors, improving system stability.

3) Multi-Node Distributed Synchronization: Given the distributed nature of user-centric cell-free TN-NTNs, APs must synchronize their clocks collaboratively. We adopt a consensus-based synchronization strategy, where each AP shares its time offset with neighboring nodes, and a weighted averaging algorithm is applied as $\Delta T_{\text{global}} = \frac{1}{N}\sum_{n=1}^{N} w_n \Delta T_n$. Here, ΔT_n denotes the time offset of the n-th AP, and w_n represents a dynamic weighting factor that depends on the signal-to-noise ratio (SNR) of synchronization signals, stability of each AP's local oscillator and holographic surface feedback on phase variations. This approach ensures network-wide clock alignment, while adapting to dynamic environmental changes.

4) Kalman filtering for dynamic time correction: To further enhance synchronization accuracy, we employ Kalman filtering for dynamically refining time estimates. The system updates the estimated time offset as $T_k = AT_{k-1} + Bu_k + w_k$, where A models time drift, u_k represents synchronization reference inputs, w_k accounts for noise, and B is the control matrix which determines the effect of the input of u_k on the state of time offset. By iteratively refining time estimates, Kalman filtering reduces error accumulation and adapts to high-mobility environments, ensuring stable synchronization performance.

The Kalman filter typically converges within 5-10 iterations under typical initialization, ensuring rapid adaptation in dynamic TN-NTN environments. Moreover, as a benefit of its recursive structure, the filter maintains robustness under high-Doppler mobility by dynamically adjusting its prediction-correction process. In cases of intermittent feedback, the filter continues predicting based on the prior model and performs corrections opportunistically when new synchronization references become available. Furthermore, to reduce the network overhead caused by distributed synchronization, each AP shares only its local time offset estimates, rather than full CSI, with neighboring nodes. These exchanges are performed using low-rate feedback and the consensus update mechanism is localized within the AP clusters, ensuring that the overhead remains manageable even in large-scale deployments.

C. *Beamforming Design*

Beamforming design is crucial in TN-NTN systems for achieving inter-beam interference suppression and efficient resource utilization in multi-user communications by optimizing signal directivity and channel gain. Hence we propose a hybrid strategy combining holographic and digital beamforming as follows:

- ***Holographic beamforming***: By controlling the coefficients of the sub-wavelength units of the holographic surface, a high-gain directional beam is generated for the target user. The holographic beamforming process can be mathematically expressed as adjusting the phase shift ϕ_n of each metasurface element for beneficially aligning the incoming signals. This leads to an equivalent channel gain of $h_{\text{eff}} = \sum_{n=1}^{N} q_n \mathrm{e}^{j\phi_n} f_n$, where q_n represents the adjustable coefficient of the n-th metasurface element, and f_n is the propagation coefficient of the received signal. Explicitly, the phase shifts are optimized for maximizing the received signal power.

- ***Digital beamforming***: At the baseband, the minimum mean square error (MMSE) criterion is used for optimizing the signal direction and for suppressing interference. Given the estimated CSI, the digital beamforming vector is given by $\mathbf{v} = (\mathbf{H}^{\mathrm{H}}\mathbf{H}+\alpha\mathbf{I})^{-1}\mathbf{H}^{\mathrm{H}}\mathbf{s}$, where $\mathbf{H}$ represents the equivalent channel matrix, $\mathbf{s}$ is the transmitted signal vector, and α is a regularization parameter that controls interference suppression. Then, a low-complexity algorithm based on statistical channel information can be designed, leveraging the statistical distribution of interfering satellites in TN-NTNs.

Holographic beamforming provides coarse-grained directional control, while digital beamforming achieves refined optimization, and combines statistical modeling with real-time feedback for adapting to dynamically fluctuating channel conditions. This hybrid beamforming scheme effectively combines the benefits of holographic metasurface control and digital optimization for improving the spectral efficiency and robustness in dynamic TN-NTN environments. In terms of hardware feasibility, the analog part of the hybrid beamforming can be realized using programmable metamaterials, which allow dynamic control of the electromagnetic wavefronts at a low power consumption. By contrast, the digital beamforming layer only requires a limited number of RF chains, as most of the spatial processing is handled in the analog domain. This significantly reduces the hardware complexity and makes the architecture suitable for non-terrestrial platforms with stringent size, weight and power constraints. In particular, the SIM-based holographic MIMO architecture enables wave-based analog computing, where signal transformations are physically realized through programmable electromagnetic interactions. Functionally analogous to fully connected neural networks, this structure supports low-power, low-latency processing without relying on graphics processing unit (GPU)-based digital computation, which is especially beneficial for satellite systems with constrained onboard resources [9]. Furthermore, holographic MIMO systems enable rapid beam steering through near-real-time reconfiguration of metasurfaces, with typical switching delays in the range of 100 ns depending on the hardware implementation. Even under control and synchronization constraints in TN-NTN scenarios, the overall delay remains below 1 μs, supporting agile link adaptation in dynamic environments.

IV. Case Study

In this section, we numerically evaluate the throughput of holographic MIMO assisted user-centric cell-free integrated TN-NTNs. We consider the uplink, where satellite APs are randomly distributed at the altitude of $H = 300$ km within a 1000-kilometer radius to support a typical terrestrial user. We adopt the DMA architecture at the satellite APs. The channel link spanning from the terrestrial user to each metamaterial element follows a shadowed-Rician distribution, denoted as $\mathcal{SR}(\omega, b_0, \upsilon)$. Unless otherwise specified, the simulation parameters are as follows: the carrier frequency is 30 GHz; the transmit power of the terrestrial user is 30 dBm; the bandwidth is 10 MHz; the noise power density is -174 dBm/Hz; the number of microstrips is 8; the number of metamaterial elements in each microstrip is 128; the metamaterial element spacing is $\lambda = \frac{1}{16}\lambda$; the antenna gain of each satellite AP is 60 dBi; the number of satellite APs is 8; and the parameters of the shadowed-Rician fading model are $\omega = 0.4$, $b_0 = 0.3$, and $\upsilon = 3$.

Fig. 3 shows the cumulative distribution function (CDF) of the throughput R for both the cell-free and the cellular integrated TN-NTNs. At lower throughput levels R, the cell-free network significantly outperforms the cellular network, especially as the number of satellite APs increases. For example, for $L = 64$ APs, the cell-free network reaches a throughput of approximately 3 bit/s/Hz at the 90% likelihood level, while the cellular network only achieves around 1 bit/s/Hz. This is because the cell-free network leverages the cooperation of multiple satellite APs, reducing the interference and enhancing the spectral efficiency, particularly for users found in challenging locations. By contrast, as we move to higher throughput values, the cellular network begins to outperform the cell-free network. This indicates that, while cell-free networks excel in providing more consistent throughput across a wide range of users, cellular networks may offer better peak performance for the user located in beneficial positions relative to the satellite. Furthermore, as the number of satellite APs in the cell-free network increases from $L = 2$ to $L = 64$, the performance improves steadily, particularly low throughput. This emphasizes the scalability of cell-free architectures, where multiple satellite APs collaboratively serve each user, thereby improving performance consistency and spectral efficiency across different user locations. Conversely, the cellular network suffers from higher variability in throughput due to the inter-cell interference and the limitations of the single-beam coverage. In summary, the simulation results demonstrate that cell-free networks offer more consistent and reliable throughput for a larger portion of users in integrated TN-NTNs.

To reduce the load of backhaul links in cell-free TN-NTNs, a subset of satellite APs are selected to support each user. We assume that the terrestrial user is supported by a cluster of L' satellite APs with the highest channel gain among all L satellite APs. Fig. 4 presents the throughput R as a function of the number of serving satellites L' selected in cell-free networks, with comparisons made across different satellite orbit altitudes H. Observe from Fig. 4 that for the cell-free network, the throughput generally improves as the number of the selected serving satellites increases. This shows that the cell-free network can outperform the cellular network by harnessing more serving satellites at all orbital altitudes. For example, at the orbital altitude of $H = 300$ km, the throughput of the cell-free network exceeds that of the cellular network

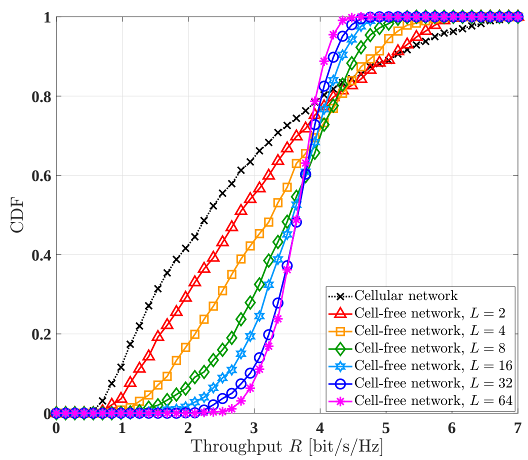

Fig. 3. The CDF of the throughput R in the cellular LEO satellite network and the cell-free LEO satellite network, with different number of satellite APs. To ensure a fair comparison, the cellular network employs 64 microstrips at the satellite, while the cell-free network has a total of 64 microstrips distributed across all satellite APs.

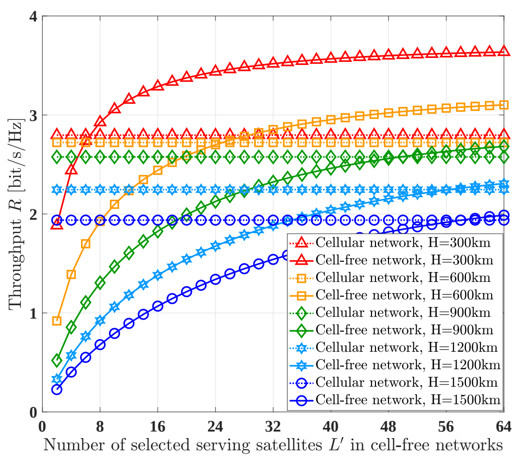

Fig. 4. The throughput R versus the number of the selected serving satellites L' in the cell-free network under different orbit altitudes H.

for $L' = 8$ serving satellites. This advantage of the cell-free network is due to the collaboration of multiple satellite APs serving the user, which mitigates the interference and enhances the spectral efficiency. Furthermore, we observe that the throughput in cell-free networks saturates beyond a certain number of selected satellites.

V. Challenges and Solutions

Although the TN-NTNs based on holographic MIMO and user-centric cell-free architecture proposed in the above case study have shown significant performance advantages, they still face numerous practical challenges. We detail them from three key perspectives: hardware limitations, synchronization and interference management, as well as dynamic optimization, followed by potential solutions.

A. Hardware Limitations

The hardware complexity of holographic MIMO systems is the main obstacle to their large-scale application. The implementation of DMA, RHS and SIM requires dynamic control of the phase, amplitude, and polarization of microstructure units, while current material science and micro-nano processing technologies still have significant limitations in controlling accuracy, stability, and manufacturing costs. In addition, energy consumption and heat dissipation issues in LEO satellites have increased the complexity of hardware design. The increased power consumption and heat dissipation requirements caused by high-frequency beamforming and dynamic beam switching make it difficult for traditional satellite batteries and heat dissipation technologies to meet the requirements of holographic MIMO systems. At the same time, although the compact design of the holographic surface is suitable for miniaturized devices, the matching of the antenna array arrangement to the satellite shape still faces challenges.

To address these issues, the response speed and durability of the metasurface can be improved and the production cost can be reduced by developing high-performance dynamic control materials, such as liquid crystal polymers, micro electro mechanical systems (MEMS) technology and phase change materials [10]. In addition, the modular design concept can be used for flexibly configuring the holographic surface for different mission scenarios, which can improve the adaptability and scalability of the hardware. In low-orbit satellites, the combination of efficient dynamic power control algorithms and advanced heat dissipation designs, such as heat pipe technology or phase change material heat dissipation, can further optimize the energy efficiency and heat dissipation performance, hence supporting the widespread deployment of distributed architectures.

B. Synchronization and Interference Management

It is crucial to realize time synchronization and interference management in TN-NTN systems for achieving high-performance communications, but they become particularly complex in high-dynamic and multi-user scenarios. In terms of time synchronization, high-precision clock alignment is required between high-velocity low-orbit satellites and ground nodes, but traditional Global Positioning System (GPS)-based synchronization schemes are susceptible to interference from delay fluctuations and Doppler frequency shifts. In multi-user scenarios, the spectrum overlap of inter-satellite links and terrestrial user signals further exacerbates the interference problem, and real-time updating of the interference covariance matrix requires substantial computing resources.

To this end, we propose an auxiliary time synchronization scheme based on holographic surfaces. Upon exploiting the dynamic channel feedback provided by the holographic surface, the clock offset can be adjusted in real time, thereby reducing the impact of delay-jitter and Doppler-shift. In addition, the time synchronization correction method combined with Kalman filtering can further improve the synchronization accuracy. In terms of interference management, coarse-grained holographic beamforming can achieve preliminary interference suppression, while digital beamforming relying on the CSI can perform fine-grained optimization. The multi-node based distributed collaboration mechanism can delegate the interference management task to multiple APs, thereby reducing the computational burden of a single node. Furthermore, the use of spectrum sensing and dynamic spectrum allocation algorithms can maximize the exploitation of spectral resources, while reducing the interference caused by spectral overlap.

C. *Dynamic Optimization*

The dynamic optimization of TN-NTNs faces the dual challenge of environmental fluctuations and computational complexity. The rapid changes in user distribution, channel status, and resource requirements impose severe challenges on the real-time adaptability of traditional optimization algorithms. Furthermore, the nonlinear constraints of multi-objective optimization problems significantly increase the computational complexity, especially in multi-node collaboration scenarios.

To solve the above problems, artificial intelligence (AI)-driven dynamic optimization methods provide an effective way. Forward through reinforcement learning algorithms, historical data and real-time feedback can be combined for dynamically adjusting the network parameters to adapt to rapidly fluctuating environments [11]. For example, deep reinforcement learning methods can be used to optimize resource allocation, beamforming, and user scheduling, thereby improving both the adaptability and robustness of the system.

VI. Future Directions

Although the cell-free TN-NTN architecture based on holographic MIMO has shown great potential in theoretical and simulation studies, it still faces countless unresolved issues in actual deployment and complex application scenarios. Future research has to focus on sensing and localization, modulation innovation, security improvement, multi-objective optimization, specific scenario adaptability and other aspects to promote the comprehensive application of this architecture.

A. *Integrated Sensing and Communications*

Integrated sensing and communication (ISAC) accommodates both communication and sensing functionalities on a single hardware platform, which improves system efficiency by reducing hardware redundancy and optimizing the spectrum usage. Holographic MIMOs, combined with the user-centric cell-free architecture, significantly enhance the benefits of ISAC in TN-NTNs. Holographic MIMO enables precise beamforming, facilitating simultaneous communication and sensing [12], while the distributed cell-free network improves the coverage and adaptability. AI-driven algorithms, particularly deep learning, optimize the system by processing large volumes of sensing data in real time. They dynamically adjust beam patterns and seamlessly switch between satellite and terrestrial links, which ensures both efficient communication and accurate environmental sensing.

B. *Localization*

Despite their propagation delay, LEO-based localization schemes still suffer from more significant latency than terrestrial systems, which degrades the inaccuracy. Specifically, the longer propagation distances result in more errors in the estimation of time-of-arrival (ToA) and angle-of-arrival (AoA) [13]. On the other hand, the signal obstruction reduces the reliability of localization, particularly when the line-of-sight (LoS) path between LEO satellites and users is blocked. Furthermore, the reflected signals proliferate the multi-path effects, which also distorts the estimation of the time and angle information, hence degrading the localization performance. The devices should be capable of supporting TN-NTNs, and localization relies on accurately synchronized nodes, which increases the cost and complexity.

One of the most significant advantages of TN-NTNs is their improved localization coverage, where the terrestrial network fails. This improves the robustness of localization, including conventional GPS.

C. *Advanced Modulation Techniques*

As TN-NTNs introduce human-perceivable delay and high path-loss due to the long propagation path, while excessive Doppler-shifts distort the communication channel. OTFS schemes constitute a promising solution for high-mobility NTNs [14]. With the aid of their Delay-Doppler (DD) domain matrix design, they are capable of outperforming conventional orthogonal frequency division multiplexing (OFDM) in high-mobility channels. In recently years, index modulation (IM) has also been considered as a beneficial candidate for NTNs [15]. However, both OTFS and OFDM suffer from high peak-to-average power ratio (PAPR), even while using IM. Reliable detection of IM in high-mobility channels requires extra resources for channel estimation, but the satellite resources are limited. Again, AI-based techniques can be used for mitigating these drawbacks at a modest complexity. Machine learning methods, such as deep neural networks, convolutional neural networks, and graph neural networks offer significant potential, when integrated with index modulation techniques in NTNs, including inter-satellite and satellite-to-ground communications, where AI can be harnessed for developing intelligent receivers that adaptively learn the complex mappings between received signals and transmitted data in real time. These models effectively handle nonlinearities and compensate for hardware imperfections common in satellite systems.

D. *Security Relying on Quantum Technologies*

Quantum communication promises ultimate security for TN-NTNs, because the quantum signal collapses back into the classical domain in the presence of eavesdropping. If eavesdropping is detected, the quantum key negotiation has to be permitted [15]. However, since the quantum signal must not be amplified, either trusted quantum relays or satellite-based relaying are required for long-distance transmission. Future research has to explore the application of QKD between distributed access points, especially in collaborative TN-NTN scenarios, where the establishment and maintenance of quantum links still faces technical challenges. Their keyrate and coverage distance may be readily improved by holographic MIMO systems.

E. System Robustness and Multi-Objective Optimization

The robustness of the system in a dynamic environment is one of the keys to the successful application of TN-NTNs. Future research has to focus on maintaining the performance in a dynamic environment, counteracting the impact of Doppler shift, fast fading channels, and changes in user distribution. The robustness of the system can be further improved by designing adaptive beamforming and agile resource allocation algorithms, combined with a recursive optimization mechanism to respond to external perturbations in real time. In addition, under a challenging multi-objective optimization framework, Pareto optimization may harnessed, where an optimal configuration in terms of throughput, latency, and energy consumption are determined. Specifically, Pareto optimization generates a set of non-dominated solutions, where none of the performance indicators may be improved without degrading at least one of the others. Combining the needs of different scenarios and dynamically adjusting the indicator weights can improve the efficiency of system's resource utilization, as well as optimize the overall performance of the system for specific applications.

F. Adaptation to Specific Scenarios and Global Coverage

The cell-free TN-NTN architecture based on holographic MIMO exhibits compelling application prospects in extreme environments and dynamic high-velocity scenarios. Future research needs to further optimize the coverage performance and communication quality of the system in remote areas in support of telemedicine, disaster monitoring, and drone communications. By combining holographic beamforming with dynamic resource allocation, the system can more efficiently adapt to user needs in complex scenarios. In addition, in high-velocity mobile scenarios, such as high-speed trains and drone networks, investigating robust channel estimation and time synchronization algorithms can significantly improve the stability of the system under high-Doppler shift. In order to achieve truly seamless global coverage, future research has to further explore cross-domain network collaboration mechanisms, especially resource coordination and access management between TN and NTN nodes.

G. Experimental Validation and Commercial Deployment

Experimental validation is an important step for holographic MIMO assisted cell-free TN-NTNs to move from theory to practical applications. Future research should focus on developing hardware platforms for real communication environments, while simulating extreme environments, such as multipath interference and high-velocity mobile scenarios. Furthermore, combined with commercial needs, a feasibility analysis of large-scale deployment can be carried out, including issues such as hardware cost, spectrum allocation, and hand-over efficiency. Research on how to reduce the deployment and maintenance costs and optimize resource allocation efficiency provides technical support and guidance for the practical application of holographic MIMO assisted cell-free TN-NTNs in 6G networks.

VII. Summary and Conclusions

Given the increased momentum in 6G research, the cell-free TN-NTN architecture based on holographic MIMO provides an innovative solution for future wireless communications. We reviewed the progress in TN-NTNs and holographic MIMO research, and proposed innovative cell-free TN-NTNs concepts based on holographic beamforming and distributed collaboration. Subsequently, some key technologies such as channel estimation, time synchronization and beamforming design were detailed. Despite the progress made, substantial further research is required for actual deployment.

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