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Analysis for strategies for combined coverage by NTN + B5G Final Version

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Abstract

This deliverable E11 presents a final version of comprehensive and advances analysis of the state of the art in the standardization of integrated terrestrial and non-terrestrial networks (TN–NTN), focused in the 6G ecosystem. It reviews the latest 3GPP releases, architectural frameworks, physical layer challenges, and emerging research directions toward 6G.

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List of Acronyms

ACB	Access Class Barring
AMF	Access and Mobility Management Function
DL	Downloading link
D-MIMO	Distributed Massive multiple-input multiple-output
DSSS	Direct-sequence spread spectrum
GEO	Geostationary Earth Orbit
HAPS	High Altitude Platform System
LEO	Low Earth Orbit
LMF	Location Management Function
LTE	Long Term Evolution
MEO	Medium Earth Orbit
MIMO	Massive multiple-input multiple-output
NTN	Non Terrestrial Networks
PRS	Positioning Reference Signals
RIS	Reconfigurable Intelligent Surfaces
TN	Terrestrial Networks
UAC	Unified Access Control
UL	Uploading Link

1. Introduction

The contributions of this deliverable are focused on the challengues in the adoption of 6G and NTN networks. Like its predecessors, 6G aims to deliver higher data rates, ultra-low latency, ubiquitous connectivity, and enhanced security [1]. The foundational enablers of 6G include both terrestrial networks and non-terrestrial networks. While TNs serve as the foundation of the global communication infrastructure, NTNs are set to complement TNs and extend connectivity into remote and rural areas. Thus, the integration of TNs and NTNs will create a robust three-dimensional (3D) network that is essential to achieve the ambitious goals of 6G communication. However, communications is not the only goal of future 6G networks. Over the past years, cellular communication systems have increasingly integrated positioning services, a trend that is becoming even more pronounced in 6G [2]. Positioning information is essential for a wide range of applications, including autonomous vehicles, smart cities, industrial internet of things (IoT), emergency response systems, and augmented reality. These applications impose rigorous requirements on positioning systems, demanding not only high accuracy, typically ranging from meters to centimeters, but also wide coverage, high reliability, low latency, and resilience in challenging environments. Generally, existing TNs and NTNs cannot fully meet these demanding requirements independently. For example, the coverage of TNs is constrained by the availability and density of infrastructure, whereas satellite signals in NTNs experience significant degradation due to obstruction and attenuation in dense urban areas [3]. Addressing these challenges requires *an integrated approach that leverages the strengths of both TNs and NTNs* to deliver precise and reliable positioning under diverse conditions.

To understand TN-NTN integration from technical and standardization perspectives, we begin by analyzing the characteristics of key 6G enablers in both networks and their interactions across various 6G frequency ranges (from FR1 to sub-THz frequencies). This analysis will help identify the most suitable combinations of enablers and frequency ranges for effective integration. We then review the latest 3GPP standardization efforts for TN and NTN positioning. Next, we highlight the challenges and opportunities of integrating TN and NTN, providing the research community with a list of key problems that require immediate attention. Finally, we present two numerical case studies of tightly integrated TN-NTN systems, further demonstrating the potential of this integration

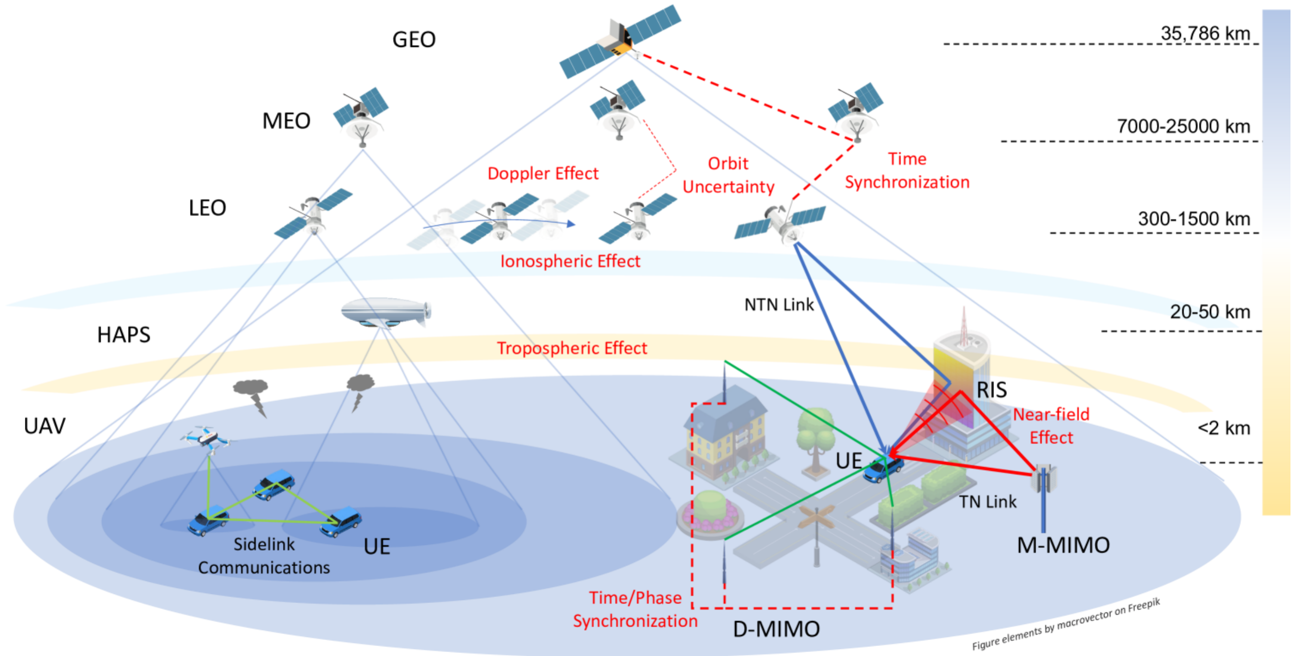

Figure 1. NTN (GEO, MEO, LEO, HAPS, and UAV) and TN enablers (M-MIMO, D-MIMO, RIS, and sideline communications)

1. 6G enablers

The 6G native enablers in both TN and NTN bring complementary characteristics, offering unique opportunities and challenges. These characteristics are shaped by the fundamental properties of these technologies, their operational frequency bands, and the localization environment. For example, the high altitudes of NTN systems enable extensive coverage but introduce latency and propagation challenges, distinguishing them from TN systems. Similarly, the envisioned operation of 6G across a broad frequency spectrum further diversifies the behavior and performance of these technologies across various scenarios. This section explores the characteristics of each 6G enabler, emphasizing their interplay with different frequency ranges and environmental conditions.

Terrestrial Networks

Massive multiple-input multiple-output (MIMO), distributed MIMO (D-MIMO), reconfigurable intelligent surfaces, and sidelink communications play a central role in enabling 6G TN-based localization. Each technology involves specific hardware requirements, algorithmic challenges, and benefits, as well as mobility considerations across various frequency bands under unique propagation conditions. The following sections will explore their distinct characteristics.

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- Massive MIMO

M-MIMO employs large antenna arrays at the base station (BS) to simultaneously serve multiple users over the same time-frequency resource, significantly increasing spectral efficiency through spatial multiplexing. Large antenna arrays also enable high-resolution angle estimation, making M-MIMO fundamental for achieving high-accuracy 6G localization. At FR1 (and likely FR3), digital arrays with dedicated RF chains per antenna element provide accurate angle estimation and robust multipath separation in dense propagation environments, avoiding the time-consuming beam sweeping required by hybrid and analog arrays. However, challenges include high hardware complexity and power consumption from the large number of RF chains, intricate multipath propagation (e.g., multi-bounce reflections and diffraction) and limited bandwidth, resulting in poor range resolution [4]. At FR2 (and likely FR4), M-MIMO accommodates denser antenna arrays under half-wavelength spacing and broader bandwidths, enabling narrow, high-gain beams that boost signal-to-noise ratio (SNR) and improve delay and angular resolution. The beam squint effect at these frequencies may also offer additional spatial cues for localization by illuminating different spatial regions at varying frequencies. However, localization with M-MIMO at FR2 and FR4 suffers from hardware imperfections (e.g., power amplifier nonlinearity and phase noise), analog/hybrid array constraints limiting mobility support and angle estimation, and harsh propagation conditions including line-of-sight (LoS) blockage and diffuse scattering [5].

- Distributed MIMO

D-MIMO technology employs multiple geographically distributed access points, coordinated to function as a unified system, providing improved SNR, increased uniformity of service quality, and superior interference management compared to M-MIMO systems. The benefits of D-MIMO in 6G localization include extended coverage through spatial diversity and enhanced multipath resolvability via phase-coherent processing in rich propagation environments [6]. At FR1 and FR3, D-MIMO systems can operate in phase-coherent mode, which transforms the entire network into an extremely large sparse array, substantially improving angular resolution. Due to relatively small bandwidths available at FR1 and FR3, phase coherence among distributed APs is crucial for high-accuracy localization as geometric information is conveyed through phase measurements [6]. Conversely, small phase and positional misalignment can severely deteriorate localization performance, placing stringent requirements on synchronization and geometry calibration. Moving higher up in frequency, phase-coherence across distributed nodes becomes more challenging. Therefore, at FR2 and FR4, D-MIMO typically shifts from phase-coherent to time-coherent mode and offers favorable delay resolution through large available bandwidths. Although time synchronization is less demanding than phase synchronization from both hardware and algorithmic perspectives, which benefits localization at FR2 and FR4, worsening hardware impairments can still degrade localization accuracy compared to that observed at FR1 and FR3.

- Reconfigurable Intelligent Surfaces.

RIS can dynamically control wireless signal propagation, enhancing coverage and signal quality in complex environments [7]. RIS technology includes various types, such as passive (low cost), active (high SNR), and simultaneously transmitting and reflecting (STAR)-RIS (wider coverage), each with unique operational characteristics. In all RIS types, out-of-band control can be exploited to share geometric information, which can aid in coordinating multiple RIS units and dynamically adjust their phase shifts. Acting as an extra anchor (i.e., a location reference node), a RIS can significantly improve localization by offering additional reference points for positioning, especially in non-line-of-sight (NLoS) scenarios. However, calibration of the surveyed position and orientation of RIS, non-ideal beam patterns, and variations in reflection coefficients are essential to achieve high-precision positioning. In addition to RIS calibration, the key challenges to be addressed include the computational complexity of optimizing RIS configurations in real-time and the high path loss caused by the RIS's multiplicative/cascaded double-fading channel.

- Sidelink Communications.

By leveraging sidelink communication, nodes, such as vehicles and unmanned aerial vehicles, can share absolute or relative measurements to achieve higher positioning accuracy and robustness [8]. This approach allows for both explicit cooperation (sharing exact location information) and implicit cooperation (using relative geometric measurements between nodes), enhancing localization accuracy. However, cooperative localization requires an increased demand for bandwidth and efficient resource allocation to handle the extra data exchange. Privacy and security are also concerns, as sharing location or relevant measurement data can expose sensitive information. Advanced solutions like federated learning can address these privacy issues, while decentralized scheduling can reduce the data load and energy consumption to ensure scalability.

Non-terrestrial Networks

NTNs come in many variants and can be broadly categorized into space-based and aerial-based segments. In the former category, we count geosynchronous Earth orbit (GEO) satellites, medium Earth orbit (MEO) satellites, and low Earth orbit (LEO) satellites. In the latter category, we count high-altitude platform stations and UAVs. In the following, we will discuss the technologies in each segment, highlighting their characteristics, opportunities, and challenges.

- Space-based NTNs

Satellites share common traits such as high altitude above ground, susceptibility to atmospheric effects, and orbital state uncertainty. GEO satellites orbit at 35,786 km, MEO satellites at 7,000–25,000 km, and LEO satellites at 300–1,500 km above sea level. Their altitudes impact latency, path loss, beam footprint size, and LoS/NLoS characteristics, influencing link budgets, SNR, and susceptibility to jamming and spoofing. In addition, high satellite altitude results in poor positioning information gained from angle-based measurements. Hence, positioning with an independent satellite system requires access to multiple satellites to perform positioning, which might not be feasible in all scenarios. Next, atmospheric effects include ionospheric (more prominent in S and L bands, similar to FR1) and tropospheric effects (more prominent in Ku/FR3 and Ka/FR2 bands). These effects, categorized as fast (e.g., scintillation) or slow (e.g., absorption), can distort signal phases and must be modeled, estimated, and compensated to avoid positioning errors. Finally, orbital state uncertainty arises from factors like gravitational forces, atmospheric drag, and solar radiation pressure, which disturb satellite trajectories and require correction to enhance positioning accuracy.

A key distinction among these anchors is orbital mobility. GEO satellites, geosynchronous with Earth, experience minimal Doppler effects. On the other hand, MEO satellites, with approximately 12-hour orbital periods, exhibit moderate Doppler shifts, while LEO satellites, which typically take between 90 minutes and 2 hours to complete one full orbit, experience significant shifts. These Doppler shifts aid positioning but necessitate advanced estimation techniques. Differences in satellite footprints also matter. LEO systems require mega-constellations for global coverage, MEO constellations need fewer satellites, and GEO satellites, fixed above the equator, provide wider coverage. LEO and MEO constellations, offering diverse geographic observations, improve geometric dilution of precision (GDoP) and positioning accuracy but introduce coordination challenges that will be discussed later. Lastly, satellites are equipped with clocks that vary in quality and stability. For instance, GEO and MEO satellites, being less numerous and typically heavier, are equipped with atomic clocks, which are far more stable then the clocks in the more abundant and smaller LEO satellites. Hence, extra attention must be directed towards modeling of these clocks and estimating their biases to avoid loss in localization accuracy [9].

- Aerial-based NTNs

Aerial nodes, encompassing HAPSs and UAVs, operate at lower altitudes than space-based systems, typically between 20−50 km for HAPSs and a few hundred meters to several kilometers for UAVs, depending on the local regulations. Their proximity to Earth results in lower signal delays, transmission power, and path losses compared to satellites. HAPSs offer quasi-stationary wide-area coverage, similar to GEO satellites, making them suitable for remote and rural areas, while UAVs provide flexible and dynamic coverage in urban or emergency scenarios. Both systems primarily contend with tropospheric effects like rain attenuation and fog, as well as state uncertainties due to wind drift, affecting positioning accuracy. Furthermore, mobility varies between these systems. For instance, HAPSs are relatively stable, experiencing minimal Doppler shifts, whereas UAVs can introduce moderate Doppler effects due to their rapid movements, providing additional positioning information and adding complexity to using them as anchors. Despite these challenges, HAPSs and UAVs enhance localization performance by increasing the number of anchor points, enhancing the vertical GDoP, offering adaptable coverage, and bridging coverage gaps. However, they also introduce complexities in terms of real-time coordination, power management, interference handling, and path planning (in the case of UAVs), which must be carefully addressed to realize their full localization potential [9].

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Frequency Dependencies

In general, TN and NTN networks operating at lower frequency ranges are more mature, have higher coverage, are less affected by hardware impairments, environmental effects, and user mobility, and can achieve low to medium levels of positioning accuracy. On the other hand, operating at higher frequencies holds the potential of achieving higher positioning accuracy but at the cost of complexity of addressing high signal attenuation, LoS blockage, environmental effects, user equipment (UE) mobility issues, and hardware impairments. Hence, more research work needs be done to tackle these aspects in order to achieve the highest potential of these 6G enabler technologies.

3. Standardization

While 6G standardization has started with 3GPP's Release 20 by 2025, the groundwork for TN and NTN localization enablers has already been laid in 5G and 5G-Advanced standards (Releases 16 to 19). Additionally, proprietary industrial solutions, such as Starlink, have emerged over the past decade, offering valuable insights and lessons for the development of the next-generation cellular NTN. Hence, this section explores these standardization efforts and industrial advancements in TN and NTN positioning.

3GPP Standardization Activities

Although 3GPP positioning standardization has focused on TN over the past decades, NTN standardization started to gain traction and is envisioned to continue in 6G. In this section, we review 3GPP's 5G positioning standards in TN and NTN, and our vision for 3GPP's 6G TN-NTN integration standardization.

• 5G TN Standardization

Positioning services have been supported in all generations of cellular networks, starting from supporting emergency services and evolving the 5G system to also support commercial services with tighter positioning requirements. In terms of technology, one of the major innovations occurred in the 4G era, where dedicated reference signals for positioning, such as downlink (DL) positioning reference signals (PRS) and uplink (UL) sounding reference signals (SRS), were introduced. These came along with various positioning techniques, such as the DL- time difference of arrival (TDOA), UL-TDOA, and enhanced cell-ID (e-CID) [10]. In 5G, further enhancements were introduced, such as the usage of higher frequency (FR2) and M-MIMO to enable beamforming-based transmission and reception, which together with other enhancements, allowed new target requirements of 20 cm in accuracy and less than 10 ms in latency to be achieved. Furthermore, challenging scenarios where NLoS becomes dominant were also investigated. These resulted in enhancements and new positioning techniques being introduced in 3GPP Release 17 [11]. In 3GPP Release 18, even further positioning enhancements, such as the use of carrier phase measurements, and device-to-device positioning were introduced [11]. In the current 3GPP Release 19, a new feature on the usage of artificial intelligence/machine learning (AI/ML) for positioning enhancements is being specified.

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• 5G NTN Standardization

NTN was first studied in 3GPP Release 16 and then specified in Release 17. Although positioning procedures and solutions are still primarily developed for the TN, NTN still continuously evolves with new features for NR and IoT devices. Among these features, there is a limited positioning operation in NTN that was introduced in 3GPP Rel-18 with the purpose of supporting network-verified UE location with extremely coarse positioning accuracy (i.e., of the order of 10 km) [11]. This is to ensure that the UE is connected to the appropriate core network, particularly for a UE close to country borders. For this purpose, the method uses multiple satellite-UE round-trip time (RTT) measurements at different time instances as described in [12].

• 6G NTN and TN Standardization

In the 6G time frame, NTN positioning is expected to have tighter requirements to support more use cases. The legacy positioning measurements in TN positioning, such as angle-based measurement (e.g., angle-of-arrival (AoA) and angle-of-departure (AoD)) and timing-based measurement (e.g., DL-TDOA, UL-TDOA, and multi-RTT), can be extended to NTN positioning. In NTN positioning, deployment scenarios where the UE sees either one or multiple satellites need to be considered. This significantly affects how the positioning measurements are performed and on how the final location is estimated. The positioning measurement/estimation can differ depending on the aforementioned deployment scenarios. NTN positioning with only one satellite can be challenging in order to achieve accurate positioning. At the start of 6G, there is an opportunity to investigate new reference signals/waveforms for positioning. Such new signals could be adopted, especially when they prove beneficial in comparison to the legacy PRS or SRS. The network architecture to support NTN positioning is expected to be developed based on the legacy TN positioning architecture, by involving the location management function (LMF). However, it is expected that there will be some enhancements through adding new features/functions and also in the signaling mechanism between network nodes. Although TN and NTN positioning have operated independently and have been used for different purposes in 5G, we envision that 6G TN and NTN will be co-designed from the start. This will facilitate a common signal design and network architecture, enabling a smooth integration of TN and NTN.

Industrial Advancements

Industrial players, such as SpaceX, play a crucial role in exploring alternative and complementary solutions that have not been addressed by 3GPP standardization. In particular, the use of LEO satellites for PNT has attracted significant attention in recent years. These efforts include the deployment of dedicated LEO constellations for PNT services, as well as leveraging signals of opportunity (SoOP) from constellations originally designed for communication purposes. In this section, we discuss advancements in both dedicated and opportunistic NTNs.

• LEO PNT with Dedicated Systems

LEO constellations specifically designed for PNT are being developed as complementary systems to GNSS or as standalone alternatives. Initiatives such as the European Space Agency's efforts to develop a dedicated LEO-PNT constellation highlight this trend. Companies like TrustPoint, Xona Space Systems, Geely, and Future Navigation are actively developing their own LEO satellite constellations, consisting of 288, 258, 240, and 160 satellites respectively, to deliver high-accuracy PNT services. These systems are required to transmit ephemeris data, clock bias, and drift corrections, and may include atmospheric effects, providing the essential information for precise PNT solutions. Different signal structures are under investigation for LEO-PNT applications, including orthogonal frequency division multiplexing (OFDM) signals, direct-sequence spread spectrum (DSSS) signals, and chirp spread spectrum (CSS) signals, each with specific advantages and challenges [13]. Direct-sequence spread spectrum (DSSS) signals, commonly employed in GNSS systems, can face challenges in acquisition and tracking due to the rapid motion of LEO satellites, necessitating modifications from standard GNSS receivers. In contrast, CSS signals can avoid the two-dimensional Doppler-delay search required for acquisition in the GNSS architecture, enabling lower complexity solutions in scenarios with large Doppler shifts. However, further investigation is required to achieve accurate ranging, access multiple satellites, and enable data transmission using CSS signals for LEO-PNT. Currently, many aspects of these dedicated LEO-PNT systems are still under development, with ongoing efforts to refine technology and deploy infrastructure.

- LEO PNT via SoOP

LEO satellites, originally designed for non-navigation purposes, can also serve as valuable resources for localization by opportunistically utilizing their signals. Existing LEO constellations suitable for PNT via SoOP include Starlink, Orbcomm, Argos, Iridium, Globalstar, and others, each operating with distinct frequency bands and modulation schemes [14]. Currently, thousands of satellites from multiple operators are in orbit, with tens of thousands anticipated in the near future. A key advantage of SoOP is its ability to utilize a wide variety of ambient satellite signals, increasing signal diversity and maximizing resource efficiency. However, the absence of signal specifications, often due to business security or privacy concerns, introduces considerable challenges in signal processing and synchronization. Currently, efforts are underway to develop advanced signal processing techniques and receiver architectures capable of extracting key observations for positioning applications, including Doppler shift, carrier phase, and pseudo-range. This can be achieved by leveraging the inherent characteristics of these signals, along with techniques such as blind beacon estimation, machine learning-based signal processing, and other advanced methods [14].

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4. Integration Challenges and Opportunities

While both TN and NTN offer advanced localization capabilities, their integration remains largely unexplored. Combining these networks promises higher accuracy and a seamless, globally unified localization service. Integration can occur at various stages of the localization pipeline, which includes designing the communication system, estimating geometric channel parameters, and fusing those parameters to determine the user's position. Hence, integration is typically categorized into three levels: loose, tight, and ultra-tight

Loose integration combines the final position estimates from each system. For instance, it requires independent multilateration from at least four non-terrestrial anchors, along with a positioning solution from one or more terrestrial BSs, which are then fused to enhance accuracy. *Tight integration*, by contrast, operates on geometric measurements, removing the need for independent multilateration from multiple non-terrestrial anchors. It can fuse a single range measurement from an NTN anchor with range and angle measurements from a BS or an RIS, offering greater flexibility and accuracy at the cost of increased system complexity. *Ultra-tight integration* takes this further by modifying both networks at earlier stages. These modifications, ranging from joint resource allocation to unified physical-layer design, significantly boost performance but also add complexity. Although every integration schemes has its pros and cons, all of them share a set of challenges to be solved and opportunities to be reaped. Hence, this section outlines the key challenges and opportunities of TN-NTN integration.

Challenges

Integrating TN and NTN for localization presents several technical challenges, including increased network overhead, higher processing latency, stronger signal interference, and greater signal processing complexity. These challenges need to be addressed before we are able to reap the benefits of the TN-NTN integration.

Network Overhead

The integration of TN and NTN requires frequent information exchange among terrestrial base stations, gateways, non-terrestrial anchors, and user terminals, leading to increased signaling overhead. This is particularly evident in managing handovers, synchronization, and control signaling across diverse links. Such overheads will be exacerbated as the TN-NTN integration becomes tighter.

Latency

Compared to TN, the long propagation distances inherent to NTN links introduce significant delays, which can impair time-sensitive applications such as vehicular networks and autonomous systems. Such latency is expected to increase due to the extra signaling needed for integration.

Signal Interference

The coexistence of terrestrial and non-terrestrial links creates complex interference scenarios, which can arise from overlapping frequency bands, multipath propagation, or inter-satellite, HAPS, and UAV links. Managing such interference in a dynamic environment adds further complexity to system design and operation.

Signal Processing

Achieving high localization accuracy in integrated systems requires advanced signal processing algorithms to address challenges, such as varying observations, non-stationary fading, fluctuating SNR levels, and coupled external factors (e.g., atmospheric effects, hardware impairments, mobility, and anchor state uncertainty). These factors collectively contribute to a significant increase in computational complexity.

Opportunities

Integrated TN-NTN systems will offer significant opportunities in terms of coverage, accuracy, integrity, and resilience.

• Coverage

Both TN and NTN have coverage limitations. NTN struggles in urban canyons, dense indoor areas, and regions with signal blockage, while TN faces challenges in remote or rural areas. The integration of TN and NTN overcomes these limitations by combining NTN's global coverage with TN's regional reach, ensuring seamless localization across all environments and providing ubiquitous coverage.

• Accuracy

TN-NTN integration can enhance localization accuracy for the following two reasons: (i) it leverages multi-source data fusion, and (ii) the dispersed localization anchors in ground, air, and space environments significantly improve the GDoP, leading to more accurate localization performance.

• Integrity

TN-NTN systems offer higher localization integrity, i.e., enhanced trustworthiness and reliability, by cross-validating information from multiple sources. This is critical for safety-sensitive applications such as aviation, maritime navigation, and autonomous driving.

- Resilience

TN-NTN integration improves resilience against jamming and spoofing by leveraging signal diversity and redundancy across terrestrial and non-terrestrial networks. Non-terrestrial anchors, being less vulnerable to ground-based jamming, provide an additional layer of robustness, while advanced signal processing techniques, like jammer localization, enable interference suppression and anomaly detection.

5. Conclusion

The integration of terrestrial and non-terrestrial networks offers a promising yet challenging path toward high-precision 6G localization. We examined the strengths and weaknesses of 6G enablers in both segments, demonstrating that by leveraging the complementary advantages of TN and NTN, 6G systems can provide seamless localization in various environments. However, significant challenges remain, including network interoperability, high overhead, Doppler effects, synchronization issues, and the need to mitigate overlapping sources of errors and hardware imperfections. Addressing these challenges requires the development of both innovative signal processing and networking techniques, along with aligned standardization and industrial solutions to ensure effective TN-NTN integration. Moving forward, the community should carefully study and decide on the optimal combination of integrated 6G enablers, the frequency of operation, and the level of integration for each application scenario to balance performance gains with solution complexity and operational constraints.

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