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Technical Feasibility and Application Prospects of LEO Satellite Communication for Smartphones

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Abstract. As an important component of future communication systems, Non-Terrestrial Networks (NTN) provide a new technological pathway for achieving wide-area continuous and highly reliable communication by introducing Low Earth Orbit (LEO) satellites. In recent years, with the standardization of satellite direct-to-device communication in 3GPP Release 17, direct connectivity between LEO satellites and smartphones has gradually become a major research focus in the communication field. This paper analyzes the feasibility and key challenges of applying LEO satellite communication technology to smartphones. Based on several representative application scenarios, the potential value of this technology in emergency communications, remote area coverage, and basic messaging services is examined. Subsequently, the main technical challenges faced during practical deployment are systematically summarized, including terminal hardware constraints, dynamic channel characteristics, spectrum resource management, network handover, and latency control. On this basis, potential technological development directions are further discussed, including low-power terminal design, channel compensation and adaptive modulation, dynamic spectrum allocation mechanisms, and collaborative networking strategies between satellite and terrestrial cellular networks. The study indicates that direct LEO satellite communication for smartphones is more suitable for low-data-rate and delay-tolerant communication services in the short term, while its large-scale deployment still depends on the continued evolution of communication standards, terminal technologies, and system architectures. The analysis presented in this paper may provide useful insights for future research and engineering practice on the deep integration of satellite and terrestrial communications in the 6G era.

Keywords: Low Earth Orbit (LEO) satellites, satellite direct-to-smartphone communication, spectrum management, channel characteristics, network integration

1. Introduction

The rapid development of mobile communication networks has significantly transformed modern society, enabling ubiquitous connectivity for individuals, industries, and public services. Despite remarkable progress in terrestrial cellular technologies, including the global deployment of 4G and the ongoing rollout of 5G networks, achieving truly universal coverage remains a persistent challenge [1,2]. Terrestrial networks are inherently vulnerable to large-scale disruptions caused by

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natural disasters, power outages, and infrastructure failures, which can severely affect emergency communication and disaster relief operations [3].

Satellite communication systems have long been considered a promising complement to terrestrial networks due to their wide coverage capability and independence from ground infrastructure [4]. Recent advancements in satellite technology, particularly the deployment of large-scale Low Earth Orbit (LEO) satellite constellations, have renewed interest in integrating satellite communication directly into the cellular ecosystem [5,6]. Compared with geostationary satellites, LEO satellites significantly reduce propagation delay and path loss, making them more suitable for delay-sensitive mobile services and power-constrained user devices [3].

Meanwhile, the concept of Non-Terrestrial Networks (NTN) has been formally incorporated into the 5G standardization framework by the 3rd Generation Partnership Project (3GPP) and is expected to play an even more prominent role in the evolution toward 6G networks [7,8]. NTN aims to extend traditional cellular networks beyond terrestrial infrastructure by integrating satellite systems and high-altitude platform components. Within this framework, direct communication between satellites and conventional smartphones—commonly referred to as Direct-to-Device (D2D) or Direct-to-Cell (D2C) satellite communication—has emerged as a particularly attractive paradigm [9,10].

However, enabling direct satellite connectivity on smartphones introduces a series of fundamental technical challenges that distinguish it from both traditional satellite communication systems and conventional terrestrial cellular networks. Smartphones are subject to strict constraints in terms of antenna size, transmission power, and energy consumption, which significantly limit the achievable link budget [9,11]. In LEO-based satellite systems, the high mobility of satellites introduces additional challenges, including severe Doppler shifts, rapidly changing propagation conditions, and frequent handovers [7]. Furthermore, spectrum sharing and interference management between satellite and terrestrial networks introduce new complexities, particularly when satellite systems reuse frequency bands allocated to cellular services [12]. These challenges are further compounded by the need to maintain acceptable quality of service, latency, and reliability within a unified satellite–terrestrial network architecture [13,14].

Although a growing body of research has investigated various aspects of satellite–terrestrial integration, existing studies are often fragmented across different layers and perspectives. Some studies focus primarily on satellite system design and constellation optimization, while others address specific physical-layer techniques or protocol adaptations for NTN [6]. In contrast, evaluating the practical feasibility of direct satellite communication on ordinary smartphones requires a system-level understanding that simultaneously considers terminal constraints, channel impairments, network integration, and standardization issues.

2. Background

2.1. Non-Terrestrial Networks and satellite–terrestrial integration

Non-Terrestrial Networks (NTN) have emerged as an important extension of traditional cellular systems, aiming to address the inherent coverage limitations of terrestrial infrastructure [13]. In the context of mobile communications, NTN is not intended to replace terrestrial cellular networks but rather to complement them. The fundamental design principle of NTN is to integrate non-terrestrial components into the existing cellular architecture, enabling seamless service continuity between terrestrial and non-terrestrial segments [15].

This integration allows user equipment (UE) to access satellites or aerial platforms through cellular protocols while maintaining compatibility with existing mobile devices and core network

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functions [3,13]. The integration of satellite systems into cellular networks introduces fundamental differences compared with traditional satellite communication paradigms. Satellite communication based on NTN adopts cellular design principles, such as standardized air interfaces, centralized network control, and interoperability with terrestrial infrastructure, rather than relying on proprietary waveforms and dedicated terminals [8].

This transition lays the foundation for enabling satellite access on conventional mobile devices. At the same time, it introduces new technical constraints and design trade-offs that must be carefully addressed [14].

2.2. 3GPP NTN architecture and standardization

To enable the practical deployment of NTN within the cellular ecosystem, the 3rd Generation Partnership Project (3GPP) has incorporated satellite components into the 5G system through a series of standardization efforts. Starting from Release 17, 3GPP defined the fundamental architecture, use cases, and technical requirements for supporting 5G New Radio (NR) non-terrestrial access, with further enhancements expected in subsequent releases [3].

From the perspective of user equipment (UE), a key assumption in the 3GPP NTN standardization process is to maintain compatibility with existing cellular devices [3,8]. This design choice significantly reduces the barrier to adoption but imposes strict constraints on transmission power, antenna characteristics, and protocol behavior [9].

In addition, the standardized NTN framework emphasizes spectrum reuse and coexistence with terrestrial networks, typically operating within frequency bands already allocated to cellular services [7]. While this approach improves spectrum efficiency, it also introduces challenges related to interference management and regulatory compliance.

2.3. Characteristics of Low Earth Orbit satellite systems

Among the various satellite orbital regimes, Low Earth Orbit (LEO) satellite systems are widely regarded as the most suitable candidates for enabling direct communication with smartphones [5]. LEO satellites typically operate at altitudes ranging from several hundred to a few thousand kilometers above the Earth's surface. Compared with Geostationary Earth Orbit (GEO) and Medium Earth Orbit (MEO) systems, LEO satellites offer significantly lower propagation delay and free-space path loss [12].

These characteristics are particularly important for delay-sensitive applications and communication with power-constrained mobile devices [9].

However, the advantages of LEO systems come at the cost of increased system dynamics. Due to their high orbital velocity relative to the Earth's surface, LEO satellites exhibit rapid apparent motion with respect to ground users. This mobility results in significant Doppler shifts and time-varying channel conditions, which can severely affect synchronization and link reliability if not properly compensated [3,7].

Furthermore, a single LEO satellite covers only a limited geographic area. As satellites move in and out of the user's field of view, frequent handovers are required, increasing the complexity of mobility management and network control [13].

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2.4. Direct-to-Device satellite communication paradigm

Direct-to-Device (D2D) satellite communication represents a paradigm shift in satellite connectivity, enabling ordinary smartphones to communicate directly with satellites without requiring dedicated satellite terminals [16]. The term "ordinary smartphone" refers to commercial mobile devices that remain unchanged or require only minimal modifications compared with conventional cellular communication devices.

This paradigm significantly lowers the barrier to satellite access and enables existing mobile hardware to support a wide range of application scenarios [15].

Compared with traditional satellite communication systems, which typically rely on large antennas and high transmission power, D2D satellite communication must operate under the strict physical and energy constraints of smartphones [9]. As a result, current D2D implementations are generally limited to low-data-rate services, such as short message transmission and emergency signaling.

The D2D paradigm also differs fundamentally from terrestrial cellular communication. Unlike terrestrial base stations, satellites exhibit high mobility relative to users, resulting in rapidly changing link conditions and limited contact durations [3,7]. In addition, smartphones typically employ omnidirectional or weakly directional antennas that are not optimized for long-distance space-to-ground links.

These factors shift the primary system bottleneck from infrastructure capacity to terminal capability and link reliability [10,11].

3. Application prospects of satellite communication in smartphones

Satellite communication integrated into smartphones provides application opportunities that differ significantly from those of traditional terrestrial cellular networks.

3.1. Emergency and disaster communications

Emergency and disaster scenarios represent one of the most promising application areas for satellite communication on smartphones. Smartphones are typically the most widely available and easily accessible communication devices among affected populations. Enabling satellite connectivity on conventional smartphones allows users to transmit critical information—such as emergency messages, location data, and basic status updates—even when terrestrial networks are unavailable.

Importantly, these services do not require high data rates or continuous connectivity. Instead, they emphasize reliability, accessibility, and stable operation under harsh conditions [16]. Consequently, emergency and disaster communications are widely regarded as the most realistic and socially impactful short-term application of satellite-enabled smartphones [16].

3.2. Coverage extension in remote and infrastructure-limited areas

Another important application prospect of satellite communication for smartphones is the extension of connectivity to remote and infrastructure-limited regions. In such scenarios, satellite connectivity acts as a complementary access mechanism rather than a replacement for terrestrial cellular networks.

Satellite-enabled smartphones can provide baseline connectivity, allowing users to access essential communication services even when terrestrial signals are absent or intermittent [17]. The

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value of satellite communication in coverage extension lies in its ability to bridge the remaining coverage gaps without requiring large-scale deployment of ground infrastructure [6].

3.3. Maritime, aviation, and high-mobility scenarios

Maritime, aviation, and other high-mobility environments constitute another important area where satellite communication for smartphones demonstrates strong potential. For maritime and aviation users, smartphones equipped with satellite communication capabilities can support basic services such as safety notifications, operational messages, and emergency alerts [16].

High-mobility scenarios also highlight the complementary nature of satellite connectivity. Satellite-enabled smartphones are not intended to replace onboard communication systems or dedicated satellite terminals. Instead, they can function as auxiliary communication devices, enhancing redundancy and improving user accessibility [16].

3.4. Internet of things and low-data-rate services

Satellite-enabled smartphones also create opportunities in Internet of Things (IoT) applications and low-data-rate services [17]. Typical application scenarios include environmental monitoring, agriculture, asset tracking, and infrastructure inspection in remote regions.

In these scenarios, data transmission requirements are usually limited and involve intermittent transmission of small payloads. By allowing smartphones to function as intermediary gateways rather than primary data consumers, satellite communication can support a wider range of applications under strict energy and bandwidth constraints [14].

The above application prospects demonstrate the practical value of integrating satellite communication into smartphones, particularly in scenarios where coverage availability and communication reliability are critical [16]. Across these application domains, several common characteristics emerge: low data rate requirements, tolerance for intermittent connectivity, and a stronger emphasis on robustness rather than throughput [9].

However, realizing these application prospects is constrained by several technical challenges related to smartphone limitations, channel dynamics, spectrum coexistence, and network integration [7].

4. Key technical challenges

The realization of direct-to-device satellite communication is still constrained by numerous technical challenges, including energy limitations, channel dynamics, and spectrum coexistence. These challenges arise from the inherent mismatch between the satellite communication environment and the design assumptions of conventional smartphones and terrestrial cellular networks.

4.1. Smartphone terminal constraints

One of the most fundamental challenges in enabling satellite communication on smartphones lies in the limitations of terminal hardware. Unlike dedicated satellite terminals, smartphones are not designed to support long-distance space-to-ground communication links. Their compact physical size imposes strict constraints on antenna dimensions, radiation efficiency, and directivity, resulting in low antenna gain and limited link margins [9].

In addition to size constraints, smartphone antennas are typically optimized for terrestrial cellular frequencies and propagation environments. The radiation patterns of smartphone antennas are highly

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dependent on user behavior, such as hand grip and device orientation, which can lead to significant and unpredictable performance degradation [9]. From a system perspective, these terminal constraints fundamentally limit the achievable communication performance [9].

4.2. Power consumption and link budget constraints

Energy efficiency represents another major challenge for satellite communication on smartphones. Smartphones operate under strict power budgets due to limited battery capacity, thermal constraints, and user experience requirements. Unlike terrestrial cellular communication, satellite links generally involve significantly higher path loss, particularly in the uplink direction, which creates additional demands on transmission power.

In addition to data transmission, satellite connectivity also incurs considerable energy consumption associated with satellite discovery, synchronization, and tracking processes [7].

4.3. Channel impairments and mobility effects

The propagation environment of satellite-to-smartphone links differs fundamentally from that of terrestrial cellular channels. In LEO satellite systems, the high relative velocity between satellites and ground users produces significant Doppler shifts, which may be orders of magnitude larger than those typically encountered in conventional cellular scenarios. These Doppler effects complicate carrier synchronization, channel estimation, and signal detection, particularly for smartphones with limited processing and tracking capabilities [3,7].

In addition to Doppler effects, LEO satellite links exhibit rapidly time-varying visibility and non-stationary channel conditions. The contact duration between a satellite and a specific user is limited, leading to frequent changes in link geometry, path loss, and propagation delay [3].

4.4. Spectrum sharing and interference management

Spectrum availability and interference management constitute another critical challenge for satellite communication on smartphones. Many satellite–smartphone communication solutions do not operate exclusively in dedicated satellite frequency bands but instead rely on spectrum sharing with terrestrial cellular networks. This approach improves spectrum efficiency and regulatory feasibility but introduces complex interference scenarios [7,12].

In shared-spectrum deployments, satellite transmissions may interfere with terrestrial networks, while terrestrial base stations may generate strong interference toward satellite receivers. Unlike traditional cellular interference, satellite-terrestrial interference spans significantly different link geometries and power levels, increasing the complexity of coordination and mitigation. Furthermore, due to satellite mobility, interference conditions may vary significantly across geographical regions and time [7,12].

4.5. Mobility management and network integration

Mobility management in satellite-enabled smartphone systems differs significantly from that in terrestrial cellular networks. In conventional terrestrial networks, user mobility is the primary factor triggering handover decisions. In contrast, in satellite communication systems, the serving nodes (satellites) are highly mobile relative to mostly stationary or slowly moving users. As a result, the network must handle frequent handovers caused by satellite orbital motion [3].

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Beyond handover management, integrating satellite access into the existing cellular network architecture also introduces broader network-level challenges.

5. Future trends

The aforementioned technical challenges highlight that enabling satellite communication on smartphones is not merely a matter of incremental improvement, but rather requires coordinated advancements across multiple layers of the system architecture.

5.1. Terminal- and antenna-aware system design

Given the strict physical constraints of smartphones, future research is expected to shift from relying solely on hardware enhancements to overcome terminal limitations toward terminal-aware system design. Satellite communication systems may increasingly incorporate explicit awareness of smartphone antenna patterns, orientation, and usage conditions into link adaptation and resource allocation mechanisms, rather than assuming idealized antenna characteristics [9].

Advances in compact multi-antenna configurations, reconfigurable antennas, and antenna diversity techniques may enable incremental performance improvements without significantly increasing device size or power consumption.

5.2. Energy-efficient communication and access strategies

Energy efficiency will remain a primary design objective for satellite communication on smartphones. Future research may prioritize communication paradigms that minimize energy consumption rather than maximize throughput. This shift could redefine traditional performance metrics and influence protocol design at both the physical and network layers [13].

5.3. Robust air interface and channel-aware technologies

The highly dynamic nature of satellite-to-smartphone channels requires air interface designs that differ from the assumptions commonly adopted in terrestrial cellular systems. Future research is expected to focus on enhancing robustness against Doppler effects, rapid channel variations, and intermittent satellite visibility, particularly in LEO satellite environments [7].

5.4. Intelligent spectrum sharing and interference coordination

As satellite smartphone services increasingly rely on spectrum sharing with terrestrial cellular networks, intelligent spectrum management will become indispensable. Future research directions are likely to explore dynamic and context-aware spectrum sharing mechanisms that account for both satellite and terrestrial network conditions [13].

5.5. Integrated mobility management and network intelligence

As satellite and terrestrial networks become more tightly integrated, mobility management is expected to evolve significantly. Future research will likely move beyond reactive handover mechanisms toward predictive and intelligence-driven mobility management frameworks.

By leveraging satellite orbital information, user mobility patterns, and network state awareness, communication systems can anticipate connectivity disruptions and proactively manage transitions

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between satellites as well as between terrestrial and non-terrestrial network segments [3,13].

Overall, the future development of smartphone satellite communication will be driven by the integration of terminal-aware system design, energy-efficient operation, robust air-interface mechanisms, intelligent spectrum management, and advanced mobility control techniques [14].

6. Conclusion

Through systematic analysis, satellite communication for smartphones is technically feasible; however, it is constrained by a combination of factors, including terminal limitations, energy budgets, dynamic channel conditions, spectrum coexistence requirements, and mobility management complexity. Unlike traditional satellite systems, the primary bottleneck of direct-to-device communication does not solely lie in satellite infrastructure, but also in the interaction between consumer-grade smartphones and the highly dynamic satellite communication environment. Therefore, the practical value of this paradigm lies not in delivering high-throughput service, but in enabling basic and reliable connectivity when terrestrial networks are unavailable or unreliable.

From an application perspective, satellite communication on smartphones is best positioned as a complementary access mechanism that enhances coverage, resilience, and accessibility, rather than replacing terrestrial cellular networks. In the short term, deployments are expected to focus on low-data-rate services, such as emergency messaging, coverage extension in remote regions, and support for high-mobility scenarios with low-rate data requirements. Consequently, expectations regarding seamless broadband connectivity through satellite-enabled smartphones should be approached with caution under current technological and regulatory constraints.

Looking ahead, the development of satellite communication for smartphones is likely to be gradual and driven by coordinated advancements in several areas, including terminal-aware system design, energy-efficient communication strategies, robust air-interface technologies, intelligent spectrum management, and deeper integration between satellite and terrestrial networks. Continued progress in these domains will be essential for achieving the long-term vision of resilient and globally inclusive mobile connectivity, in which satellite communication serves as an integral component of future wireless networks rather than a standalone solution.

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