A Survey on Direct-to-Device Satellite Communications: Advances, Challenges, and Prospects

Hannaneh B Pasandi, Juan A Fraire, Sylvia Ratnasamy, Herve Rivano

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Hannaneh B. Pasandi
University of California, Berkeley and Inria, INSA Lyon, CITI, UR3720
h.pasandi@berkeley.edu

Juan A. Fraire
Inria, INSA Lyon, CITI, UR3720
juan.fraire@inria.fr

Sylvia Ratnasamy
University of California, Berkeley
sylvia@cs.berkeley.edu

Herve Rivano
Inria, INSA Lyon, CITI, UR3720
herve.rivano@inria.fr

ABSTRACT

Direct-to-Device (D2D) communication in satellite networks represents a significant advance in telecommunications, enabling seamless connectivity without relying on terrestrial infrastructure. This survey aims to provide a detailed overview of D2D communication technologies, protocols, applications, and recent advances based on the current state of D2D. We categorize the literature on D2D into a new taxonomy. This taxonomy covers technological foundations, protocols and algorithms, use cases, challenges, and future trends. We emphasize the key challenges and pinpoint research gaps within each category, offering a well-structured domain overview.

CCS CONCEPTS

• **Networks** → *Mobile networks.*

KEYWORDS

direct-to-device; direct-to-cell; direct-to-smartphone communication; satellite IoT; Low Earth Orbit (LEO) satellite.

1 INTRODUCTION

Direct-to-Device (D2D) satellite communication enables our smartphones and IoT devices to connect directly to satellites in space using cellular technology (4G, 5G, and beyond). This capability moves us ever closer to ubiquitous and reliable connectivity and is especially valuable in remote and underserved areas. While 93.3% of the world's adult population enjoys mobile coverage today, the remaining 520+ million people still lack access to consistent cellular service [31]. Even for those within serviced regions, coverage reliability is geographically constrained by terrestrial infrastructure. However, decreasing satellite manufacturing and deployment costs have accelerated the launch of vast constellations into Low Earth Orbit (LEO), offering improved signal quality, higher data speeds, and more cost-effective terminal hardware. By leveraging LEO satellite constellations, D2D technology can enable communication without terrestrial infrastructure, overcoming coverage limitations in remote areas.

Several critical technological innovations have enabled D2D communication. Advanced beamforming techniques [26] allow precise signal focusing on specific geographic areas, enhancing signal quality and reducing interference. Software-defined payloads [25] provide dynamic spectrum allocation, adapting to varying user demands and regulatory requirements in real time. Enhanced power management systems [33] have extended satellite lifespans and improved energy efficiency. Component miniaturization and terminal technology advancements have enabled standard smartphones and IoT devices to communicate directly with satellites. These innovations collectively overcome traditional barriers such as signal attenuation and device compatibility, facilitating seamless D2D communication and advancing global connectivity.

In addition to technological advances, regulatory progress has played a crucial role. The FCC has advanced Mobile Network Operator-Satellite Network Operator (MNO-SNO) spectrum sharing frameworks, enabling better integration between terrestrial and satellite networks [29]. By allowing satellite operators to lease spectrum from MNOs, the FCC's framework facilitates dynamic and competitive satellite services, driving harmony between MNOs and SNOs and fostering multi-tenant LEO satellite networks [39]. Such spectrum-sharing policies enable greater flexibility and coverage for end users.

Table 1 summarizes the state of key D2D deployments in the commercial arena. We define the "type" of D2D communication based on Direct-to-X where X takes the form of a

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Table 1: Summary view of LEO Satellite Technologies and Deployments for D2D Communication.

Company	Key Achievements	Type	Status	Target Constellation Size	Partnerships
Starlink	Satellite-to-cell service	DTC, DTS	Active	4,425 satellites (planned)	T-Mobile
OneWeb	Global LEO constellation deployment	DTC, IoT	Active	648 satellites (planned)	AT&T, Eutelsat
Telesat	Developing Lightspeed constellation	DTC, IoT	In development	298 satellites (planned)	Microsoft Azure
AST SpaceMobile	First 5G call from space to a smartphone	DTS	Active	168 satellites (planned)	AT&T, Rakuten
Apple & Globalstar	Emergency SOS for iPhone 14	DTS	Active	24 satellites (operational)	N/A
Lynk Global	FCC approval for satellite-to-phone service	DTS	Active	10 satellites (planned)	Vodafone

Cellular ground station (DTC), Smartphone (DTS), or IoT device, also known as Direct-to-Satellite (DtS)-IoT. We note that partnerships between satellite companies (e.g., Starlink, AST SpaceMobile) and terrestrial operators (e.g., T-Mobile, AT&T) have enabled rapid progress in D2D services. Recently, Starlink successfully launched 90 DTC satellites [8], demonstrating their ability to support video calls [10] and provide download speeds of up to 17 Mbps for regular smartphones [9]. The commercialization of DTC satellite technology is also progressing rapidly [5–7]. At the same time, 3GPP continues to fast-track the standardization of non-terrestrial networks (NTN) for seamless satellite-based communication [11–18][1].

Table 1 also shows that current deployments vary in their target constellation size. Companies like Starlink target 1000s of satellites, while others such as Telesat have almost an order of magnitude fewer. The deployment of Apple's Emergency SOS with Globalstar and the entry of Lynk Global's satellite-to-phone services, supported by FCC approval, further illustrate the role of partnerships in enabling new *applications*.

In this paper, we provide a holistic overview of the D2D ecosystem based on a survey of the publicly available research and commercial literature; we provide detailed citations in later sections.

2 D2D SATELLITE COMMUNICATION

This section highlights some of the enabling technologies and trends that are driving D2D communication.

Efficient data transmission. Modern LEO constellations enable D2D connectivity using advanced modulation and error correction. Examples of such techniques include low-density parity-check (LDPC) codes [19] and multi-user detection (MUD) algorithms [36]. These techniques are critical because D2D faces specific challenges due to the long signal propagation distance, high Doppler shifts, and variable channel conditions. LDPC codes provide robust error correction, effectively mitigating signal attenuation over long distances and improving link reliability. MUD algorithms, on the other hand, enhance spectral efficiency by allowing multiple users to share the same frequency resources, thus combating interference in the congested space-to-ground link.

Spectrum Allocation and Regulatory Framework. Spectrum sharing between satellite and terrestrial services is essential to prevent interference. Regulatory bodies like the FCC and ITU allocate critical bands (e.g., n25, n256) for D2D services, ensuring seamless connectivity for standard smartphones without extensive hardware changes [28, 43].

Diverse Use-cases. The various forms of DTX enable different usages. For example, DTC allows standard phones (i.e., not necessarily smartphones) to connect in areas without coverage. DTS services, from players like Globalstar and SpaceX, provide broadband to unmodified smartphones [22], while DTS-IoT connects IoT devices in sectors like agriculture and logistics via NTN bands in remote areas [43].

New antenna and link technologies. LEO satellites equipped with multibeam antennas and advanced transceivers support simultaneous communication with thousands of devices[52]. Inter-satellite links (ISLs) allow data to move between satellites without ground relay, ensuring resilience and flexibility [37]. Advanced antenna technologies, such as multibeam systems, ensure efficient frequency reuse and boost capacity by dynamically focusing on demand-heavy areas [26].

3 D2D COMMUNICATION: TAXONOMY, CHALLENGES, GAPS

To systematically categorize D2D, we developed a taxonomy separating them into seven dimensions. For each category,

[1]NTN is 3GPP terminology for all non-terrestrial networks, including the LEO satellite networks that we consider here.

we identify the core challenges in the relevant work, summarize efforts to date, and offer our critical assessment of their analysis. Table 2 provides an overview of these categories, which we then discuss in detail.

• **Category 1: Type of Direct Communication.** As mentioned earlier, D2D communication can be classified into three sub-categories based on the end device type: DTS, IoT (DtS-IoT), and DTC. Each sub-category has unique requirements, including latency, signal reliability, and seamless handover in high-mobility environments. A significant challenge for DTC is ensuring reliable smartphone connectivity in remote areas, while DtS-IoT faces hurdles in achieving scalability and energy efficiency. Real-world deployments of mega-constellations like Starlink and OneWeb have demonstrated the potential of these technologies. However, based on our assessment, advancements in dynamic routing protocols are crucial due to the frequent handover events in LEO satellites caused by their high orbital velocity, which leads to changing network topologies. Current protocols, optimized for terrestrial networks, face challenges with maintaining connections, resulting in latency and packet loss. In addition, spectrum management is vital because of limited bandwidth and increasing congestion and interference. Efficient allocation is necessary to prevent collisions and ensure fair access, which directly affects the scalability of IoT and smartphone connectivity. Network reliability and service quality will remain compromised without resolving these issues, especially in high-density scenarios.

Based on our assessment, DTC is a crucial enabler for smartphones and IoT devices, particularly in underserved areas. Despite progress, challenges like latency, seamless handovers, and signal reliability in high-mobility environments remain. For IoT, achieving scalability and energy efficiency in DtS-IoT applications is vital, while dedicated terminals must overcome issues of cost-effectiveness and connectivity in difficult environments. Advances in dynamic routing protocols, spectrum management, and protocol innovations will be essential to fully realize the potential of DTC in D2D communications.

• **Category 2: Satellite Constellation Topology.** In this category, we triage work based on the target number of satellites deployed and their constituent orbital parameters for D2D (see Table 1). The core challenge is optimizing the orbital parameters to fit D2D (number of orbital planes and satellites). Smaller constellations, like nano and micro (e.g., Kinéis [35]), offer more flexibility and are easier to deploy, making them ideal for niche applications and rapid deployment IoT scenarios. Larger constellations, such as mega-constellations (e.g., Starlink), provide extensive coverage and higher capacity, essential for global broadband communication networks and services. Jones et al. [33] analyze the emerging D2D market, examining how satellite constellations provide supplemental coverage to underserved areas. Their study offers insights into strategic partnerships and regulatory issues influencing the deployment of various constellation sizes but does not address the unique requirements of D2D-focused constellations. Our critical assessment is that today's constellations have only been designed for services other than D2D. This raises an important question: how should constellations be shaped if D2D is the primary service?

• **Category 3: Lower Layer Protocol Architecture.** The growing adoption of small IoT satellites in the "new space" era has driven advancements in DtS-IoT, with a focus on optimizing PHY and MAC layers for efficient communication. Small satellites, being easy to manufacture and deploy, have rapidly expanded the IoT satellite industry [1–4]. However, key challenges in satellite communication, including limited bandwidth, high latency, and Doppler shift management, must be addressed to ensure scalable deployments. Systems like Spectrumize [44] significantly improve spectral efficiency by utilizing predictable Doppler shifts to enable simultaneous transmissions and resolve packet collisions, making it highly effective in low SNR environments. While LTE and LPWAN protocols have been adapted for D2D communication [30, 47], further refinement is needed to address extended range, time correction, and power management in D2D links. The willingness of standardization bodies, such as 3GPP and LoRaWAN, to modify PHY/MAC protocols will be crucial for the future scalability and reliability of D2D communication.

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• **Category 4: Satellite-Specific Network Architecture and Protocols.** At the transport layer, the core challenge

Category	Sub-categories	Description	Reference
Type of Direct Communication	Smartphone; IoT; Dedicated Terminals	Classifies device types; different requirements for each.	[20, 30, 32]
Satellite Constellation Topology	Nano; Micro; Mega	Classifies satellite sizes; important for scalability and coverage.	[33, 35]
Lower Layer Protocol Architecture	PHY Layer; MAC Layer	Handles PHY/MAC layers; crucial for transmission and interference control.	[30, 47]
Upper Layer Protocol Architecture	Network Layer; Transport Layer	Optimizes network/transport layers; satellite link communication.	[38, 40]
Spectrum Management and Regulation	Licensed Bands; Unlicensed Bands; Dynamic Spectrum Sharing	Regulatory frameworks; spectrum allocation for D2D.	[21, 28, 34, 44]
Demonstrations and Applications for D2D	D2D Providers; Lockheed Martin 5G; CosmicBeats	Demos/tools; DtS-IoT and 5G evaluations	[41, 45, 48, 50]
Edge Computing in Satellite Networks	On-board Processing; Distributed Computing; Resource Allocation	Edge computing integration; enhances performance, lowers latency.	[27, 49]

Table 2: Taxonomy of D2D Communications and Satellite Technologies.

in satellite-specific network architecture is adapting traditional Internet and mobile protocols to the dynamic and high-latency environments introduced by satellite networks. D2D systems must address issues like frequent handovers and high Doppler shifts, particularly for LEO satellites. Existing terrestrial protocols lack the necessary resilience to high mobility and intermittent connectivity. Recent research focuses on designing robust transport layer protocols that can handle the dynamic topologies of satellite constellations [39]. Innovative systems such as SpaceCore [38] decouple core network functions from session states, minimizing signaling overhead and improving resilience to network failures, particularly in LEO constellations.

• **Category 5: Spectrum Management and Regulation.** An important decision differentiating between work on D2D is whether they operate in the licensed versus unlicensed bands on a global scale for D2D. The core question must be addressed in each case is how spectrum resources are shared. Research on spectrum sharing between small cells and satellites identifies significant challenges and opportunities, particularly in mitigating interference and ensuring coexistence between terrestrial and satellite systems [34]. The deployment of D2D services using terrestrial spectrum, such as those proposed by AST SpaceMobile and Lynk, presents a complex regulatory environment, contrasting with more established frameworks for satellite-allocated spectrum [24]. Studies have highlighted the necessity for novel dynamic spectrum-sharing mechanisms and the potential for regulatory updates to accommodate the integration of satellite and terrestrial networks [21, 51]. The ITU's evolving regulations and the ongoing work by national administrations illustrate the complexity of achieving global spectrum harmonization. Our assessment indicates that global spectrum harmonization is complex but necessary for the widespread adoption of D2D services. Thus, we believe that the following questions must be addressed for future progress: How will this global integration be achieved? What is the role of ISM bands for IoT? Effective spectrum management and regulatory frameworks are crucial to addressing these challenges and facilitating the successful deployment of D2D satellite systems.

• **Category 6: Demonstrations and Applications for D2D.** This category reviews key demonstrations and applications of D2D communication systems. Major industry players, such as Starlink, AST SpaceMobile, and Lynk, have showcased the feasibility of D2D technologies. Lockheed Martin's 5G demo demonstrated satellite-enabled 5G communication for smartphone and IoT applications. At the same time, the CosmicBeats Simulator offers critical insights into DtS-IoT performance, particularly for latency, scalability, and network stability [45, 48]. Providers like Starlink and AST SpaceMobile have proven direct-to-device connectivity with unmodified smartphones, and Lynk Global has enabled smartphone-to-satellite connections in remote areas [46]. Though these demonstrations validate the technology's potential, scalability remains a significant challenge. Tools like CosmicBeats help assess D2D network performance under high-traffic conditions, evaluating metrics like latency and throughput. Lockheed Martin's 5G demo highlights expanding D2D capabilities in real-world scenarios. D2D communication supports various applications, such as emergency services, remote connectivity, and IoT use cases. Apple's Emergency SOS feature, enabled by Globalstar, provides critical satellite connectivity for iPhone 14 users during emergencies [23]. Garmin Solutions also offers satellite services for remote areas, highlighting D2D's importance in enhancing connectivity and safety where terrestrial infrastructure is limited [42].

Category 7: Edge Computing in Satellite Networks. This category examines integrating edge computing in satellite networks to improve D2D performance and reduce latency. Managing limited on-board computational resources remains a key challenge. Denby et al. [27] address this by introducing *Kodan*, which prioritizes high-value data for on-board processing, reducing ground station reliance and optimizing bandwidth. Tao et al. [49] propose *Umbra*, a scheduling system that optimizes satellite traffic across spatial and temporal dimensions, reducing bottlenecks and improving resource allocation. While these solutions improve resource management and network performance, unresolved challenges include scalability and system reliability under satellite failure. Furthermore, international regulatory consistency is essential to mitigate spectrum conflicts and enable global deployment.

4 DISCUSSION & FUTURE OUTLOOK

In the following, we discuss other factors that could shape D2D's full potential.

• **Technological Considerations.** Future D2D constellations must prioritize lower latency, high throughput, and redundancy. However, current systems face challenges like low link budgets due to large distances and limited satellite antenna directionality. This results in frequent packet drops and suboptimal data rates. Identified gaps include inefficient inter-satellite links and the need for adaptive bit-rate protocols for satellite motion and fluctuating link quality. Additionally, packet collisions between overlapping satellite footprints reduce spectral efficiency, which must be addressed through dynamic spectrum allocation and enhanced interference management. Potential future solutions may include advanced beamforming techniques and AI-driven traffic management systems to dynamically optimize spectrum usage and link quality across satellite networks, improving both efficiency and resilience.

• **Business Models.** D2D adoption hinges on identifying key applications that drive demand, yet gaps remain in mainstream smartphone solutions. While emergency services and IoT show promise, D2D's potential for mass-market smartphone integration is unproven. A primary challenge is the high cost of deployment, particularly in regions with limited infrastructure. Achieving continuous coverage in remote areas without substantial investment also remains a hurdle [20, 30]. Scalable solutions should leverage MNO-Satellite synergies to reduce costs by sharing infrastructure. Dynamic spectrum sharing between terrestrial and satellite systems can enhance resource efficiency and lower expenses. Pay-as-you-go models and tiered pricing could encourage adoption in underserved markets.

• **Standardization and Collaboration.** Standardizing 3GPP radio interfaces for satellite constellations is crucial for broader adoption. Unified standards will ensure seamless cross-network compatibility and foster collaboration between MNOs, SNOs, and regulators, enabling more efficient spectrum sharing. Potential solutions include the development of multi-tenant satellite access protocols and global spectrum harmonization to enhance scalability and resource allocation. Future directions should focus on creating interoperability frameworks that allow diverse operators to innovate and compete within a shared satellite infrastructure.

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