→ THE EUROPEAN SPACE AGENCY

CONVERGING EARTH AND SPACE: DIRECT-TO-DEVICE CONNECTIVITY VIA SATELLITE

By ESA CSC (Connectivity and Secure Communications)
Space for 5G/6G and Sustainable Connectivity

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FOREWORD

In today's rapidly evolving digital landscape, connectivity is no longer a luxury—it is a necessity. From global logistics and emergency response to education and inclusion, the ability to communicate and access information from anywhere is fundamental to societal and economic resilience. Yet, billions of people and devices remain outside the effective reach of terrestrial mobile networks.

Direct-to-Device (D2D) connectivity via satellite stands at the frontier of closing this gap. For the first time, standard consumer devices—smartphones, wearables, Internet of Things (IoT) sensors—can connect directly to satellites in orbit, delivering ubiquitous coverage and unprecedented continuity. What was once viewed as speculative or niche is now rapidly becoming a global priority.

This transformation is being driven by a convergence of technologies: advanced satellite constellations, standardised Non-Terrestrial Network (NTN) protocols in 3rd Generation Partnership Projects (3GPP), miniaturised chipsets, and stronger collaboration between space and mobile industries. At the same time, the demand is growing—from consumers, governments, and enterprises alike—for resilient, secure, and globally available communications.

As Europe's space agency, the European Space Agency (ESA) is committed to enabling this future. Through the 5G/6G Strategic Programme Line, we support technical innovation, industrial competitiveness, and the integration of non-terrestrial systems into next-generation networks. Our facilities, funding mechanisms, and strategic partnerships—including the ESA 5G/6G Hub—offer a platform for collaboration across sectors and across borders.

This whitepaper presents a comprehensive overview of the D2D landscape. It sets out the use cases, technological enablers, standardisation progress, and strategic choices ahead. Most importantly, it outlines a call to action: to join forces—public and private, terrestrial and space, national and international—and shape a European-led path forward.

We invite stakeholders across industry, academia, and government to engage with us. Together, we can make seamless, global, space-enabled connectivity not only possible, but real.

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LIST OF ACRONYMS

Acronym	Definition
3GPP	3rd Generation Partnership Project, responsible for mobile network standardisation.
CAMARA	GSMA-led initiative to standardise open APIs for exposure of network capabilities.
D2D	Direct-to-Device communication, where a standard consumer device connects directly to a satellite.
ESA 5G/6G Hub	ESA's facility in Harwell enabling integration and testing of TN/NTN solutions.
HARQ	Hybrid Automatic Repeat reQuest, a protocol used to ensure reliable data transmission.
IoT	Internet of Things
ISL	Inter-Satellite Link
JOINER	UK's federated testbed initiative for telecom R&D, including 6G and emerging technologies.
LEO/MEO/GEO	Satellite orbits: Low Earth Orbit, Medium Earth Orbit, Geostationary Orbit.
NB-IoT	Narrowband IoT, a low-power wide-area standard defined by 3GPP.
NR	New Radio
NTN	Non-Terrestrial Network, typically satellite-based, integrated with terrestrial mobile infrastructure.
RedCap	Reduced Capability device class introduced in 3GPP Release 17/18 for lightweight IoT.
TN	Terrestrial Network, standard ground-based mobile and broadband infrastructure.
UE	User Equipment

1. EXECUTIVE SUMMARY

Direct-to-Device (D2D) communications via satellite are rapidly transforming from a niche emergency capability into a mainstream enabler of global connectivity. With increasing momentum in the telecom and space sectors, D2D services are set to become a cornerstone of both 5G and 6G architectures—bridging coverage gaps, enhancing resilience, and unlocking new services directly to everyday devices such as smartphones, wearables, and Internet of Things (IoT) sensors.

This white paper explores the strategic potential of D2D over Non-Terrestrial Networks (NTN), highlighting how recent advances in standardisation (e.g., 3GPP Release 17/18) and satellite technology are converging to enable seamless global reach. It reviews the growing ecosystem of players—from mobile network operators and satellite providers to chipset developers and regulatory bodies—working to integrate D2D into future mobile networks.

Beyond technical enablers, the paper identifies a wide range of use cases, from emergency messaging and remote broadband access to global roaming, direct-to-IoT communication, and mobility applications across maritime, aviation, and automotive sectors. It also outlines key challenges, including power consumption, waveform optimisation, terminal integration, and regulatory constraints.

Europe is well positioned to lead this transformation. The European Space Agency (ESA), through its 5G/6G Strategic Programme Line and the NTN-focused 5G/6G Hub, is already enabling the development and demonstration of D2D technologies in collaboration with its Member States and industry. This includes support for chipset and terminal integration, hybrid TN/NTN experimentation, and advanced in-orbit validation facilities.

As 6G moves from vision to deployment, D2D via NTN will be critical to achieving universal and resilient connectivity. This paper concludes with a proposed roadmap for Europe and ESA—focused on accelerating innovation, supporting standards, fostering public-private collaboration, and ensuring that European capabilities remain at the forefront of this emerging global frontier.

2. INTRODUCTION

The global drive toward seamless, universal connectivity has brought renewed attention to **Direct-to-Device (D2D)** communications via **Non-Terrestrial Networks (NTN)**. D2D in this context refers to the ability of **standard consumer devices**—smartphones, wearables, and lightweight IoT terminals—to connect **directly to satellites**, without the need for specialised ground equipment or terminals. This represents a fundamental shift in the way mobile connectivity is extended across the globe, especially in areas that remain underserved or completely unconnected by terrestrial networks.

The evolution of D2D via satellite is unfolding in parallel with the expansion of **5G and the early definition of 6G**, supported by the convergence of several factors:

- The standardisation of **NTN within 3GPP** (starting with Release 17) has opened the door for seamless integration between terrestrial and space-based networks.
- **LEO satellite constellations** with improved link budgets and lower latency are becoming increasingly viable for handheld connectivity.
- **Miniaturisation of satellite-capable chipsets** and improvements in antenna and RF design are making it possible to embed NTN support into mass-market devices.
- Mobile network operators are seeking cost-effective solutions to **extend coverage** to rural, remote, and maritime areas without additional terrestrial infrastructure.

This new wave of satellite-enabled connectivity has already entered the public consciousness through consumer-oriented emergency messaging services and upcoming broadband services, mainly from the United States and China. What was once considered niche or futuristic is now a fast-evolving frontier.

As the need for **resilience, global reach, and ubiquitous access** grows—particularly in the face of climate change, humanitarian crises, and global security challenges—D2D via NTN offers a compelling, scalable, and complementary solution to terrestrial coverage.

The European Space Agency (ESA), through its 5G/6G Strategic Programme Line and 5G/6G Hub in Harwell, recognises this potential. ESA is already working with industry to explore, demonstrate, and accelerate D2D capabilities that leverage the unique strengths of satellite systems, while being tightly integrated with terrestrial mobile infrastructure.

This white paper introduces the **current state and future trajectory of D2D communications via NTN**, highlighting the **technology enablers**, **market drivers**, and **strategic implications** for Europe. It outlines ESA's ongoing role in supporting industry innovation, collaboration, and standardisation, and provides a roadmap for ensuring Europe's leadership in this transformational domain.

3. MARKET AND TECHNOLOGY DRIVERS

The growing momentum behind Direct-to-Device (D2D) communication via satellite is being driven by a convergence of market needs, technology advances, and ecosystem alignment. As the demand for ubiquitous, resilient, and cost-effective connectivity intensifies, D2D has emerged as a practical and scalable solution to reach users beyond the limits of terrestrial networks.

3.1 MARKET DEMAND FOR UBIQUITOUS COVERAGE

Despite massive investments in terrestrial infrastructure, **an estimated 2.6 billion people** still lack reliable mobile broadband coverage, particularly in rural, remote, and maritime regions. Traditional expansion models are increasingly constrained by cost, geography, and infrastructure availability. D2D over satellite offers an attractive alternative—**leveraging space-based assets to extend mobile coverage directly to standard user equipment (UE)**.

This unmet demand extends beyond consumer access:

- **Emergency services and civil protection** require always-available connectivity for coordination and crisis response.
- **Enterprises operating in remote areas**—from energy and mining to logistics and maritime—need mobile-grade services without fixed networks.
- **IoT applications** in agriculture, infrastructure, and environment monitoring require low-cost, global device reachability.
- **Travelers, hikers, and outdoor users** increasingly expect seamless smartphone functionality in coverage gaps.
- **Automotive connectivity**, enabling vehicle-to-everything (V2X) communications, over-the-air updates, and enhanced safety services in areas lacking terrestrial coverage.

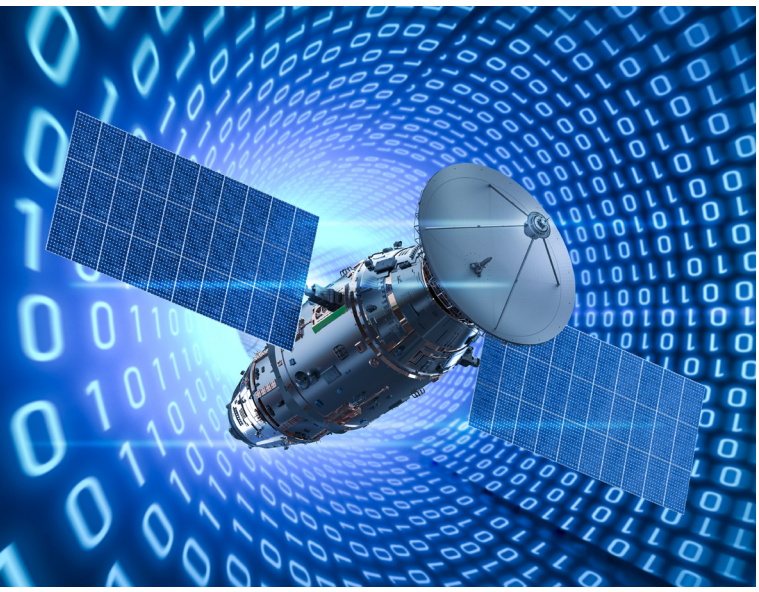
The consumer market has also been primed by the entry of high-profile players (e.g., Apple, Starlink) and the inclusion of satellite messaging in commercial smartphones, bringing D2D into public awareness.

3.2 SATELLITE ECOSYSTEM READINESS

The satellite industry has rapidly matured to meet these new market demands. Key technology enablers include:

- **Proliferation of LEO constellations** with improved link budgets and round-trip latencies below 50 ms, enabling mobile-like user experiences.
- **Flexible payloads and software-defined satellites** capable of dynamically adjusting to user density and frequency allocations.
- **Multi-orbit architectures** combining LEO, MEO, and GEO to support a range of latency, coverage, and cost trade-offs.
- **Standardisation of protocols and waveforms** aligned with terrestrial mobile technologies (see Section 6).

These advancements have unlocked opportunities to support not only messaging and IoT, but also **broadband-grade access directly to handheld devices**.



3.3 MOBILE INDUSTRY CONVERGENCE

The mobile telecom industry is also shifting toward hybrid network models. Several trends support the rise of D2D:

- **3GPP integration of NTN** starting from Release 17 has paved the way for satellite and mobile operators to work on a common technology base.
- **CAMARA API development** enables service exposure across network types, including satellite links.
- Terrestrial Mobile Operators are exploring **roaming partnerships with satellite providers**, aiming to deliver global continuity of service.
- Interest in **spectrum sharing and regulatory coordination** (e.g., use of S/L/Ku/Ka bands for hybrid NTN-TN access) is growing.
- **Device manufacturers** are increasingly open to integrating satellite-capable chipsets, as mass-market interest rises.

The result is a growing ecosystem—satellite operators, MNOs, chipset vendors, phone OEMs, and regulators—aligning on D2D as a mainstream capability.

3.4 STRATEGIC OPPORTUNITY FOR EUROPE

European institutions and industry are uniquely positioned to benefit from these trends. Europe has strong assets in satellite manufacturing, a rising NTN industry, and an ambitious digital sovereignty agenda. By accelerating investment and standardisation leadership in D2D, Europe can play a defining role in the future of global connectivity.

4. USE CASES AND APPLICATIONS

Direct-to-Device (D2D) connectivity via satellite unlocks a wide range of impactful applications, from **lifesaving emergency communications** to **broadband access in remote regions**, and **industrial-grade IoT services**. These use cases reflect a growing need for **ubiquity, mobility, and resilience**—needs that cannot be fully met by terrestrial infrastructure alone.

This chapter outlines the most relevant application domains where D2D via Non-Terrestrial Networks (NTN) brings immediate and long-term value, supporting both commercial and governmental objectives.

4.1 EMERGENCY COMMUNICATIONS AND PUBLIC SAFETY

In disaster or crisis scenarios, terrestrial networks are often **damaged, congested, or entirely unavailable**. D2D via satellite offers:

- **Backup connectivity** for first responders and civil protection teams
- **Direct-to-smartphone emergency alerts and SOS services** (e.g., earthquake or wildfire warnings)
- **Secure messaging fallback** in case of network failure or overload
- **Support for blue-light services** and cross-border emergency coordination

Examples: Apple Emergency SOS, Starlink-D2D, BeiDou satellite messaging, Tiantong satellite calling pilot programmes

4.2 REMOTE AND RURAL BROADBAND

Millions of people in rural or geographically challenging regions lack reliable mobile coverage. D2D offers a scalable way to connect them:

- **Direct-to-handset data services** for consumers and micro-enterprises
- **Education and health services** for remote communities
- **Connectivity for nomadic and semi-permanent populations** (e.g., seasonal workers, travellers)

This use case aligns strongly with **UN SDG** goals and EU ambitions for digital inclusion.

4.3 MARITIME, AVIATION, AND MOBILITY

Transport systems operate in areas with little or no terrestrial coverage. D2D can offer:

- **Passenger messaging and voice fallback** on ships and aircraft
- **Operational data exchange** for logistics and crew communications
- **Personal connectivity** for vehicle users in terrestrial areas lacking cellular coverage, as well as across oceans and airspace
- **NTN roaming services** during border crossings or transnational routes

Direct-to-Device satellite connectivity offers transformative capabilities across mobility domains:

- **Maritime:** Ensuring continuity of service across shipping lanes, cruise ships, and fishing vessels.
- **Aviation:** Supporting crew and passenger connectivity, airline operations, and emerging UAM platforms.
- **Rail:** Offering coverage in rural and trans-border routes for passengers and onboard systems.
- **Automotive:** Enabling resilient vehicle connectivity for telematics, safety services, over-the-air (OTA) updates, and future autonomous vehicle systems, especially in areas without terrestrial coverage.

These use cases reflect how D2D can augment mobile coverage for passengers and vehicles across geographies and industries.

4.4 IOT AND MACHINE-TYPE COMMUNICATION (MTC)

The proliferation of IoT requires **low-cost, low-power, low-maintenance** connectivity even in remote, harsh environments. D2D via satellite enables:

- **Direct-to-sensor connectivity** for agriculture, energy, environment
- **Smart infrastructure monitoring** (e.g., dams, roads, pipelines)
- **Wildlife and environmental tracking**
- **Low-data, wide-area telemetry** for logistics and industrial assets

Standards such as NB-IoT over NTN and 5G RedCap (Release 18/19) support these use cases.

4.5 DEFENCE, SECURITY, AND GOVERNMENT USE

D2D supports strategic needs where resilience and autonomy are critical:

- **Military mobility and tactical communications** without infrastructure
- **Border surveillance and patrolling support**
- **Connectivity for diplomats and aid workers** in fragile regions
- **Secure fallback for critical infrastructure operators**

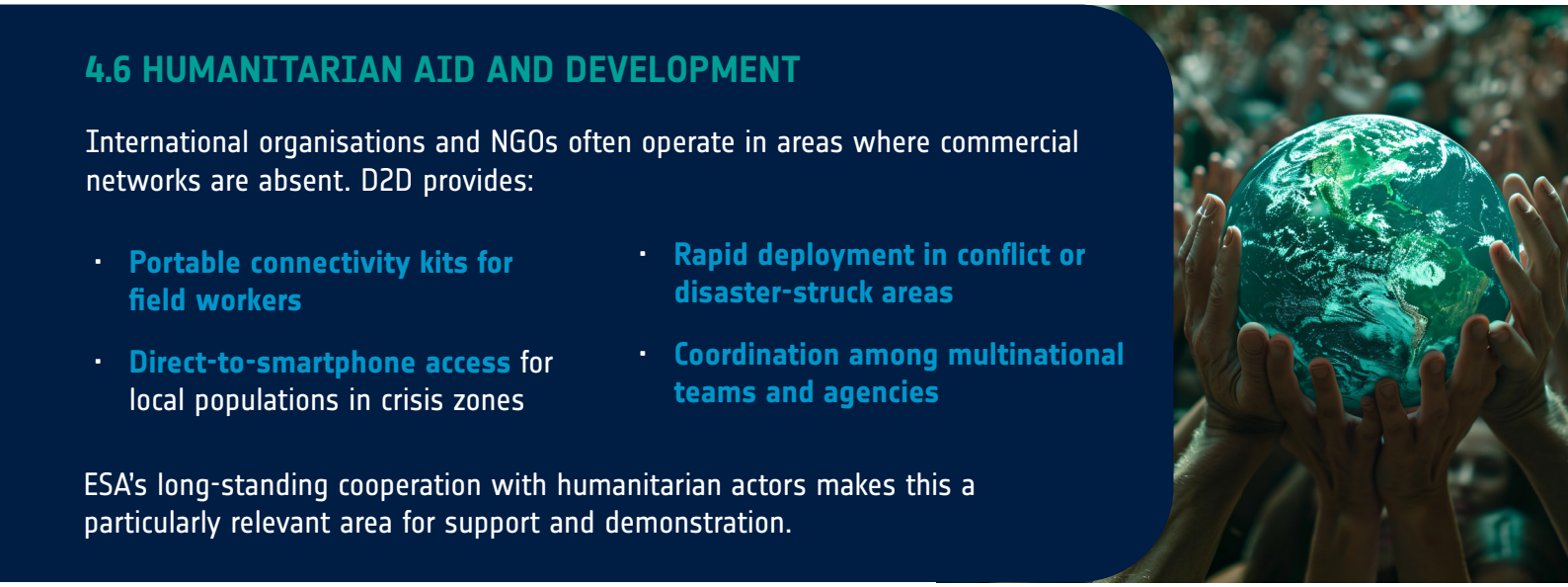
Such applications may leverage dual-use assets and align with sovereign satellite communications initiatives (e.g., IRIS²).

4.6 HUMANITARIAN AID AND DEVELOPMENT

International organisations and NGOs often operate in areas where commercial networks are absent. D2D provides:

- **Portable connectivity kits for field workers**
- **Direct-to-smartphone access** for local populations in crisis zones
- **Rapid deployment in conflict or disaster-struck areas**
- **Coordination among multinational teams and agencies**

ESA's long-standing cooperation with humanitarian actors makes this a particularly relevant area for support and demonstration.



4.7 CONSUMER-DRIVEN INNOVATION AND SERVICES

As D2D becomes embedded in commercial smartphones and wearables, new services will emerge:

- **Global messaging plans for frequent travellers**
- **Roaming-free, always-on satellite service tiers**
- **Integrated location and navigation services** in remote areas
- **D2D gaming, media or social applications** during off-grid experiences

These services will gain traction as device manufacturers and operators bundle NTN capabilities into mainstream offerings.

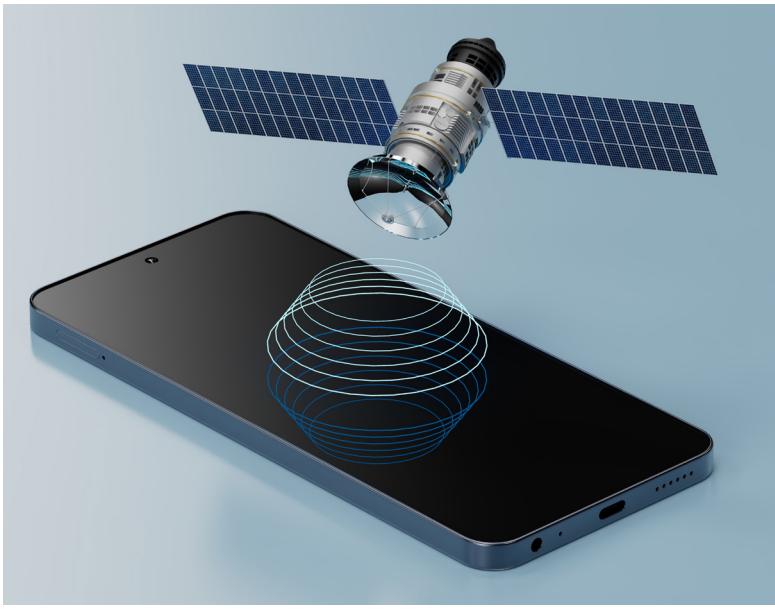
4.8 SUMMARY TABLE: D2D APPLICATION DOMAINS

Sector	Use Case	User
Public Safety	Emergency alerts, fallback comms	First responders, citizens
Rural Inclusion	Broadband access, education/ health support	Local users, schools
Transport	Passenger messaging, fleet comms	Airlines, maritime operators, automotive OEMs, Rail operators
IoT	Environmental data, asset tracking	Farmers, utilities, logistics
Defence/Gov	Tactical fallback, secure comms	Armed forces, gov agencies
Humanitarian	Crisis response, field connectivity	NGOs, UN agencies
Consumer	Travel roaming, off-grid access, adventure use	Tourists, outdoor users

5. TECHNOLOGY ENABLERS AND CHALLENGES

Delivering reliable **Direct-to-Device (D2D)** connectivity via satellites requires solving a number of complex technical problems. Unlike traditional satellite terminals—often equipped with large antennas, fixed orientation, and stable power—consumer devices like smartphones and wearables operate with stringent constraints on **size, power, mobility, and cost**. As a result, enabling D2D via Non-Terrestrial Networks (NTN) demands careful coordination between satellite system design, terrestrial network integration, chipset capabilities, and standardisation.

This section outlines the key **enabling technologies** making D2D viable, as well as the **technical challenges** that must be overcome to scale deployment and adoption.



5.1 SATELLITE SYSTEM INNOVATIONS

Recent progress in satellite technologies underpins the feasibility of D2D:

- **LEO constellations** enable low-latency links (20–50 ms), sufficient for messaging and emerging broadband.
- **Advanced link budgets** made possible by frequency reuse, spot beam shaping, and power control tailored to handheld-class devices.
- **Flexible, software-defined payloads** with onboard gNodeB capability, enabling dynamic beam management and seamless integration with terrestrial networks.
- **Inter-satellite links (ISLs)** improving backhaul, routing, and load balancing in D2D scenarios.

These innovations shift the paradigm from static satellite access to dynamic, user-centric service delivery.

5.2 TERMINAL AND DEVICE CONSIDERATIONS

Consumer devices are not designed with satellite connectivity in mind. To enable D2D, several device-side innovations are required:

- **Antenna design:** Compact, low-profile antennas must provide adequate gain and directional performance under mobility and orientation changes.
- **Power management:** Satellite reception and transmission require more power; efficient duty cycling and receive-only modes are critical.
- **RF front-end and filtering:** Support for non-terrestrial frequencies (e.g., S/L bands) alongside terrestrial bands in the same hardware.
- **Modem integration**: Dual-mode or multi-mode modems capable of switching between TN and NTN connectivity seamlessly.

Chipsets by companies such as Qualcomm, MediaTek, and Apple have started to integrate these features, but performanceand standardisation remain in flux.

5.3 WAVEFORM AND PROTOCOL ADAPTATIONS

To support D2D, standard cellular protocols have been adapted to cope with:

- **Large Doppler shifts** caused by fast-moving LEO satellites
- **Longer round-trip delays**, even in LEO (~20–50 ms), and much higher in MEO/GEO
- **Variable link conditions**, including shadowing, fade, and blockage due to buildings or topography
- **Intermittent connectivity**, with frequent handovers between satellites and variable visibility

3GPP has introduced enhancements in **Release 17 and Release 18**, including:

- NTN NR for 5G and RedCap (Reduced Capability) UEs
- NB-IoT over NTN
- HARQ timing adaptations
- Satellite ephemeris and GNSS-based location support

5.4 SPECTRUM AND FREQUENCY BANDS

D2D services can operate in multiple frequency bands, each with trade-offs:

- **L-band (~1 GHz):** Good penetration and low Doppler, suited for messaging and IoT
- **S-band (~2 GHz):** Compromise between performance and form factor
- **Ku-band (~11–14 GHz):** Moderate throughput, widely used in satellite systems, offering a good balance of antenna size and coverage
- **Ka-band (~20–30 GHz):** High throughput but sensitive to weather and blockage
- **Terrestrial spectrum reuse:** Future options may include shared or supplemental spectrum with terrestrial MNOs

ESA's initial focus for D2D is on FR1 (sub-6 GHz), particularly L- and S-band, as the most practical near-term path for direct-to-handset services. Coordinating frequency use between NTN and TN actors—especially across jurisdictions—remains a challenge.

5.5 NETWORK ARCHITECTURE AND INTEGRATION

D2D is not only about the satellite–device link. It must also **integrate seamlessly** with terrestrial mobile infrastructure:

- **Service continuity:** Handover between TN and NTN without service disruption
- **Roaming and billing integration** with MNOs
- **Security and authentication mechanisms** common to terrestrial networks
- **APIs (e.g., CAMARA)** for exposing D2D capabilities to developers and service providers

Hybrid network architectures are essential: satellites act as access nodes, backhauled to 5GC, often through satellite-ground gateways or edge nodes.

5.6 REMAINING TECHNICAL CHALLENGES

Despite rapid progress, several hurdles remain:

- **Limited UE availability:** Most current D2D services are proprietary and only support limited functions (e.g., SMS only).
- **Scalability:** Mass-market use could saturate limited satellite capacity, especially in emergency scenarios.
- **Mobility management:** Maintaining consistent links to moving satellites with devices in motion remains complex.
- **Battery impact:** Frequent satellite polling or tracking can drain smartphone batteries rapidly.
- **Testing and validation:** End-to-end systems need large-scale trials across orbits, terrains, and user conditions.

5.7 ESA'S TECHNICAL ROLE

ESA is uniquely positioned to support:

- Development and testing of NTN-compliant **chipsets, terminals, space segment, and ground segment technologies**
- Ground-based **validation platforms at the ESA 5G/6G Hub**
- In-orbit experimentation and **technology demonstration missions**
- System-level **TRL maturation from early studies to pilot deployments**
- Collaboration with 3GPP and industry to ensure satellite-specific challenges are addressed in future releases

6. STANDARDISATION LANDSCAPE

The success of Direct-to-Device (D2D) satellite communications depends heavily on **global standardisation**, ensuring interoperability, scalability, and adoption by the wider telecom and device ecosystem. Standardisation provides the technical, regulatory, and commercial foundation needed to enable D2D across networks, vendors, and geographies.

In this context, **3rd Generation Partnership Projects (3GPP)** play a central role, but other organisations—such as **ETSI, GSMA,** the **ITU**, and various national and regional bodies—also contribute to the evolving D2D framework. This section provides an overview of the current status and key ongoing efforts.

6.1 3GPP: THE CORE OF NTN/D2D STANDARDISATION

Since **Release 17**, 3GPP has introduced a systematic integration of **Non-Terrestrial Networks (NTN)** into the 5G ecosystem. This began with support for **Narrowband IoT (NB-IoT)** and **NR over satellite**, and continues to evolve in **Releases 18 and 19**, laying the foundation for D2D capabilities.

Key developments include (for an exhaustive list consult 3GPP):

Release	NTN Features Relevant to D2D
Release 17	· Initial support for NR NTN and NB-IoT over satellite · Enhancements for delay/Doppler
Release 18	· RedCap (Reduced Capability) UEs for NTN · Mobility handling and beam management
Release 19	· Further integration of NTN into core networks · Messaging and broadcast services over NTN

This work is being driven by multiple **Working Groups**, particularly:

- **SA1** (use cases and requirements),
- **SA2** (architecture),
- **RAN** (radio access adaptations),
- **SA3** (security), and
- **CT** (core network protocols).

Several **European industry actors and research institutions**, often with ESA support, serve as rapporteurs or contributors to these work items.

6.2 GSMA AND CAMARA APIS

While 3GPP defines the radio and core network standards, **GSMA** plays a key role in enabling **interoperability and service exposure**:

- The **CAMARA open API framework** allows D2D services to be exposed across networks, including satellite.
- CAMARA APIs under development include **location accuracy, quality on demand, and coverage fallback**, relevant for D2D use cases.
- GSMA's **Foundry initiative** and **NTN interest groups** provide a collaborative space to test and demonstrate multi-vendor D2D solutions.

ESA is already partnering with GSMA on NTN-related showcases and API integration.

6.3 ITU AND SPECTRUM COORDINATION

D2D via satellite touches upon **frequency bands that require international coordination**:

- The **ITU-R** (Radiocommunication Sector) defines spectrum allocations and compatibility guidelines for satellite and terrestrial services.
- Current D2D use cases involve **S-band, L-band, and potentially Ku-** and **Ka-band** allocations.
- The **World Radiocommunication Conference (WRC)** decisions, including those from **WRC-23** and future **WRC-27**, will influence availability and regulatory treatment of bands suitable for D2D.

Europe must remain proactive in shaping **harmonised spectrum policy** that supports integrated D2D services.

6.4 ETSI AND NATIONAL STANDARDISATION EFFORTS

ETSI plays an important role in:

- Publishing **technical reports and standards** on satellite-terrestrial integration,
- Supporting **pre-normative research**, and
- Coordinating with national regulatory authorities across ESA Member States.

Initiatives such as **ETSI ISG NTN** and **ETSI STF** projects complement 3GPP activities by addressing testing, simulation, and deployment guidance.

6.5 CHALLENGES AND GAPS

Despite progress, several challenges remain:

- **Fragmentation in spectrum policies** between countries
- **Lack of standard D2D device certification pathways**
- **Latency and Doppler compensation** approaches differ across current systems
- **Limited support for NTN in mobile core network vendors**
- **Security models** need to evolve for mixed TN/NTN environments

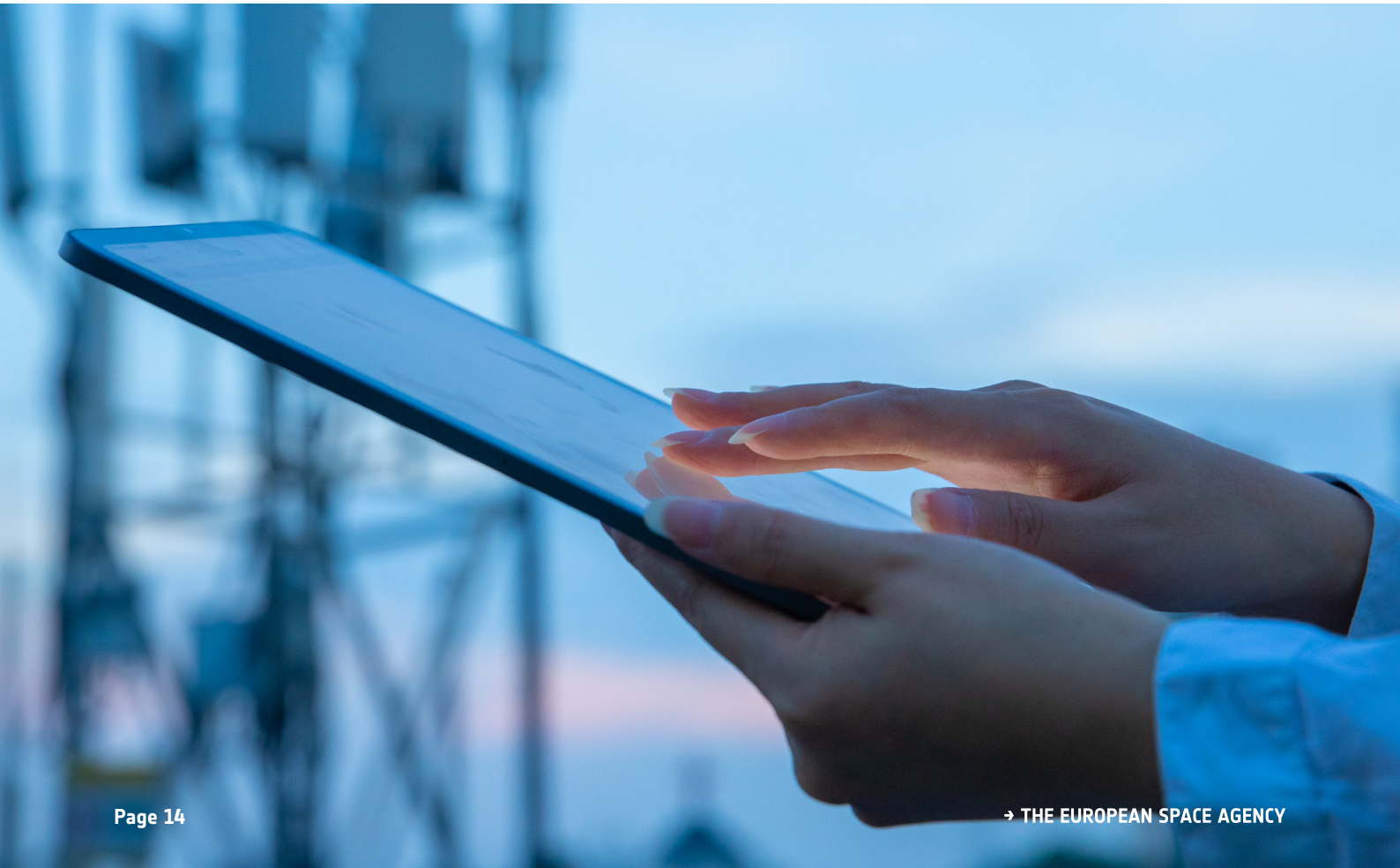
These gaps are opportunities for ESA and its partners to contribute meaningful technical input and steer standardisation priorities.

6.6 ESA'S ENGAGEMENT IN STANDARDS

ESA has historically played a bridging role between the space and telecom communities. In the context of D2D, ESA:

- Supports **European industry and academia** in contributing to 3GPP and ETSI
- Funds **proof-of-concept implementations** that validate standard features
- Partners with **GSMA and CAMARA** on interoperability testing and demonstrations
- Contributes to **WRC preparation and coordination** through relevant national delegations
- Develops **reference architectures and system models** that feed into standardisation inputs

By continuing this engagement, ESA ensures that space-based perspectives are reflected in global standards—protecting the interests of European industry and enabling long-term scalability for D2D services.



7. ESA'S ROLE AND ACTIVITIES

The European Space Agency (ESA) plays a pivotal role in enabling the **emergence and acceleration of Direct-to-Device (D2D) satellite communications**. With a mandate to support space-enabled innovation for both industry and society, ESA fosters the **development, validation, and deployment of advanced Non-Terrestrial Network (NTN) technologies**, particularly those that bridge the gap between the satellite and mobile sectors.

This chapter outlines how ESA is contributing to the D2D ecosystem through its programmes, partnerships, infrastructure, and strategic guidance.

7.1 SUPPORTING THE NTN AND D2D INNOVATION VALUE CHAIN

ESA supports the **full innovation value chain** for NTN and D2D, from early-stage concepts through to near-commercial pilots. This includes:

- **System studies and architecture design** (e.g. hybrid TN/NTN models, D2D system architectures)
- **Chipset, modem, and terminal development** for NB-IoT, RedCap, and NR-NTN compatibility, including low-profile, power-efficient antennas and optimized waveforms
- **Payload and satellite system innovations** such as large antenna aperture, digital beamforming networks (DBFN), onboard gNodeB, integrated into flat stackable satellites to enable direct handset communication
- **End-to-end integration and testing** with 5G/6G cores and radio networks
- **Lab and field validation platforms** for NTN/D2D trials, ensuring scalability and interoperability
- **Application-layer and protocol innovations** (e.g. APIs for NTN service integration)

Through its **ARTES programme**, and in particular the 5G/6G Strategic Programme, ESA co-funds R&D with European industry to de-risk critical technologies, accelerate time-to-market, and strengthen Europe's competitiveness in NTN and D2D. ESA also fosters open innovation by providing industry with access to funding mechanisms, advanced facilities, and technical expertise, while collaborating with 3GPP and global partners to ensure satellite-specific challenges are addressed in current and future standards.

7.2 THE ESA 5G/6G HUB AT HARWELL AND 5G/6G TELECOM LAB IN ESTEC

The **ESA 5G/6G Hub in Harwell (UK)** serves as a dedicated centre for **terrestrial and non-terrestrial network convergence**. The facility enables:

- **TRL 5–8 experimentation and demonstration** for NTN, including D2D use cases
- **Validation of standardised 3GPP features** in real-world testbeds
- **Integration with 5G Core and Open RAN solutions**
- **Collaboration with satellite operators and MNOs**

ESA's Hub is complemented by the Telecom Lab in ESTEC (NL) with similar features and capabilities.

7.3 IN-ORBIT DEMONSTRATIONS AND VALIDATION

ESA supports **in-orbit validation** of D2D technologies through:

- Participation in **public–private partnerships** with satellite operators
- Coordination of **multi-orbit demonstration missions**
- Planning of **dedicated in-orbit testbeds** for 5G and 6G NTN
- Potential use of ESA missions for protocol and terminal testing

This in-orbit capability complements ground-based infrastructure, enabling **end-to-end validation** of future D2D services.

7.4 STRATEGIC ENGAGEMENT AND ECOSYSTEM BUILDING

ESA acts as a **convener and catalyst**, bringing together stakeholders across space, telecom, and research:

- Partnering with **GSMA**, including joint exhibitions and demonstrations at Mobile World Congress
- Supporting the creation of the **NTN Forum,** which now includes over 400 members from industry and academia
- Aligning with European Commission programmes such as **IRIS², SNS JU,** and **EU Secure Connectivity**
- Coordinating with **national space agencies and ministries** to support member states' strategic priorities

Simulated image of ESA's 5G/6G Hub in Harwell UK: ESA 5G/6G Hub | ESA CSC

Through these efforts, ESA helps position Europe as a **global leader in NTN and D2D connectivity**.

7.5 CALL FOR COLLABORATION

ESA is actively inviting:

- **Satellite operators** to define payload and beam requirements for D2D
- **Chipset and device manufacturers** to integrate and test D2D features
- **SNOs, MNOs and infrastructure vendors** to support hybrid TN/NTN integration
- **Startups and SMEs** to explore niche applications and rapid deployment use cases
- **Regulatory bodies** to participate in spectrum and safety alignment

ESA's goal is to ensure that **European capabilities remain at the forefront** of D2D evolution—both technically and commercially.

8. STRATEGIC IMPLICATIONS FOR EUROPE

The emergence of Direct-to-Device (D2D) satellite connectivity marks a critical juncture for global communications—and a **strategic opportunity for Europe**. D2D sits at the crossroads of **space policy, digital sovereignty, industrial competitiveness, and societal resilience**. The successful development and deployment of D2D services will shape how Europe addresses its connectivity goals, competes in global markets, and ensures the autonomy of its infrastructure.

This chapter examines the broader implications of D2D for Europe's technological and strategic positioning.

8.1 DIGITAL SOVEREIGNTY AND CRITICAL INFRASTRUCTURE

Europe's dependence on foreign-owned mobile infrastructure, smartphone chipsets, and satellite constellations has raised concerns about **sovereignty in digital infrastructure**. D2D amplifies this issue: if key technologies—such as LEO constellations, D2D-capable chipsets, and associated protocols—are developed and controlled outside Europe, the continent risks being a **passive consumer** in a system it cannot influence or secure.

By investing in European-led D2D capabilities, Europe can:

- **Retain control over its critical communications assets**
- Build **redundancy and resilience** into emergency and defence networks
- Ensure that European values and regulations are embedded in global D2D architectures
- Prevent over-dependence on non-EU satellite and platform providers

8.2 SECURITY AND DUAL-USE POTENTIAL

D2D connectivity provides an inherently **resilient communications layer**, operating independently of terrestrial infrastructure. This has major implications for:

- **Civil protection and emergency response**
- **Military and defence mobility**
- **Border and infrastructure security**
- **Continuity of government and crisis coordination**

European governments increasingly seek **dual-use technologies**—civil capabilities with defence applicability—and D2D provides a compelling use case.

8.3 INDUSTRIAL COMPETITIVENESS AND INNOVATION

The D2D ecosystem spans satellite manufacturing, network infrastructure, device design, application development, and system integration. Europe is well-positioned in many of these domains, but faces competition from aggressive initiatives in the US, China, Korea, and beyond.

Strategic investment in D2D enables Europe to:

- Support its **space industry** and **chipset developers**
- Position **European satellite operators** as service providers to global MNOs
- Stimulate **SME and start-up innovation** in niche applications (e.g., direct-to-IoT, humanitarian tech, secure messaging)
- Build leadership in **standardisation and open platforms**

A vibrant European D2D ecosystem also creates **export opportunities** and contributes to the EU's competitiveness in the 6G landscape.

8.4 ALIGNMENT WITH EU AND MEMBER STATE PRIORITIES

D2D directly supports numerous European policy priorities:

Policy Goal	How D2D Supports It
Digital Decade 2030	Extends coverage to all citizens, closing the digital divide
Green Deal & Energy Efficiency	Reduces need for extensive terrestrial infrastructure in remote areas
Strategic Autonomy	Reduces reliance on foreign networks, satellites, and chipsets
Dual Use Capability	Enables dual-use capabilities through shared infrastructure and innovation

ESA can act as a **strategic enabler** by aligning its investments and partnerships with these wider European ambitions.

8.5 RISKS OF INACTION

Failing to act on D2D carries significant risks:

- **Loss of technological relevance** in an area where others are moving fast
- **Dependency on non-European constellations and modems**
- **Missed opportunities for European industry** to shape global standards and ecosystems
- **Reduced negotiating power** in international regulatory and spectrum frameworks

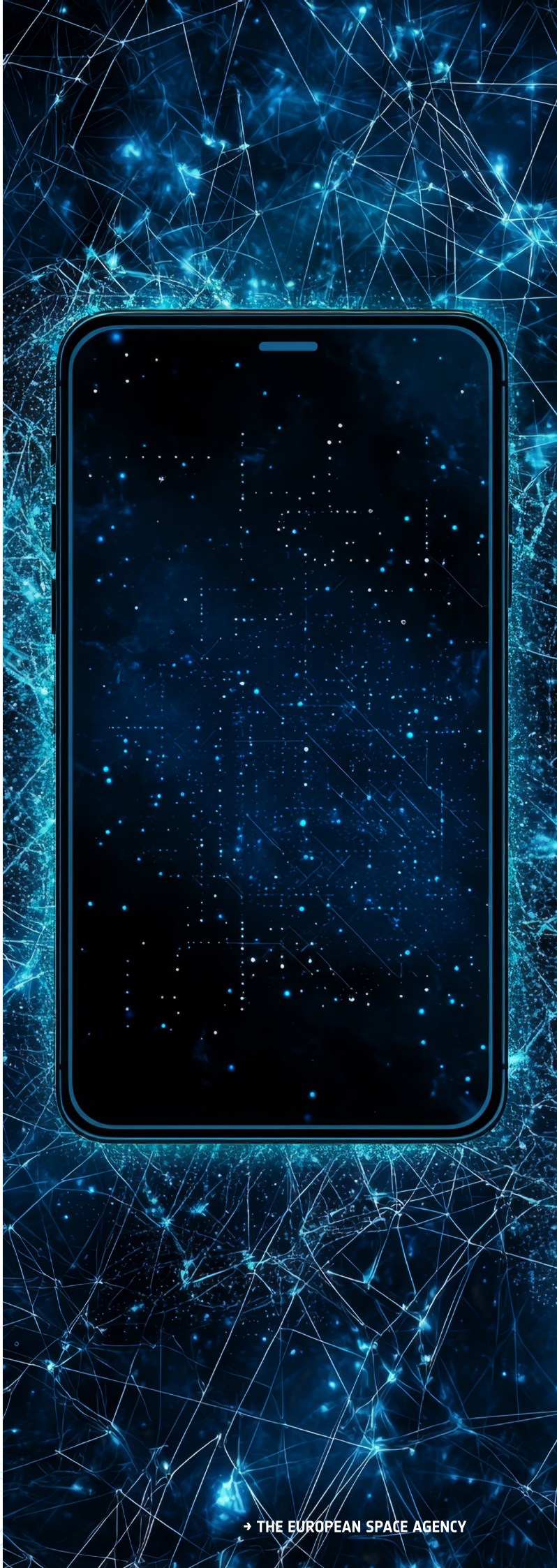
Europe must avoid repeating past patterns of innovation fragmentation and undercapitalisation.

8.6 STRATEGIC RECOMMENDATIONS

To maximise its D2D potential, Europe should:

1. **Coordinate across space, telecom, and defence sectors** to create unified priorities and funding instruments.
2. **Support industrial development of D2D components:** chipsets, terminals, antennas, payloads, satellite platforms, ground gateways.
3. **Invest in system-level demonstrations** that validate D2D services in real-world conditions.
4. **Align national and EU funding programmes** to avoid duplication and fragmentation.
5. **Ensure regulatory support**, including spectrum harmonisation and NTN-friendly licensing frameworks.
6. **Promote D2D in 3GPP, ETSI, and ITU** with strong European leadership.

ESA, together with its Member States and EU institutions, can play a critical role in translating these recommendations into coordinated, impactful action.



9. ROADMAP AND RECOMMENDATIONS

To realise the full potential of Direct-to-Device (D2D) satellite connectivity, Europe must act decisively and collaboratively across its institutional, industrial, and academic ecosystems. The D2D opportunity spans multiple timelines—from short-term demonstrations and standards evolution to long-term service deployments integrated into 6G and beyond.

This chapter outlines a proposed **phased roadmap** and sets out **strategic recommendations** for the European Space Agency (ESA), industry, Member States, and policy stakeholders to accelerate D2D progress and secure European leadership.

9.1 PHASED ROADMAP FOR D2D DEVELOPMENT

2024–2026: FOUNDATION AND EARLY VALIDATION

- **Demonstrate key use cases** (e.g. emergency messaging, direct-to-IoT) through ESA-supported pilots
- **Engage device and chipset vendors** to accelerate integration of NTN compatibility in consumer-grade hardware
- **Connect ESA's 5G/6G Hub** to federated testbeds for ground validation and enable a distributed in-orbit laboratory for experimentation
- **Support industry development** of D2D early commercial systems
- **Study and validate advanced system concepts** with innovative space and ground technologies through early pathfinders demonstrators for future post 2030 D2D solutions

Output: Functional end-to-end D2D demos, European NTN test capabilities, ecosystem mobilisation, and a roadmap towards next-generation space segment solutions.

2026–2028: MATURATION AND PRE-COMMERCIAL PILOTS

- **Validate commercial and dual-use D2D architectures** through in-orbit demonstration missions.
- **Coordinate EU/ESA/Member State funding** to accelerate industry-readiness of European D2D offerings.
- **Promote European contributions** in 3GPP Release 20+ and CAMARA API integration.
- **Fund roadmap implementation for future D2D systems**
- **Support roaming agreements and TN/NTN interworking** with operators and regulatory frameworks.

Output: standard-compliant, interoperable D2D pilots; aligned public-private roadmap; growing commercial interest

2028–2030+: DEPLOYMENT AND GLOBAL POSITIONING

- **Deploy first operational D2D services,** particularly in rural inclusion, maritime, and government sectors.
- **Establish European D2D ecosystem** with domestic supply chain and service offerings.
- **Expand international cooperation** for D2D-enabled roaming, spectrum harmonisation, and emergency services.
- **Position D2D as a pillar of 6G** infrastructure, including NTN-native architectures.

Output: European commercial deployments; dual-use public-private services; global standard and policy influence

9.2 STRATEGIC RECOMMENDATIONS

FOR ESA

- **Continue supporting D2D through ARTES 5G/6G Strategic Programme Line (5G/6G SPL)** and related open tenders, including chipsets, terminals, satellite platforms and system integration.
- **Strengthen the ESA 5G/6G Hub as a D2D test and demonstration platform**, linked to national and EU facilities.
- **Coordinate in-orbit validation opportunities** with satellite operators and payload providers.
- **Lead joint actions with GSMA, ITU, and ETSI** to represent satellite-sector needs in standardisation.
- **Mobilise Member States** to support D2D activities via delegation alignment and co-funding mechanisms.

FOR INDUSTRY

- **Invest in D2D-capable space, ground, and user terminal technologies,** leveraging 3GPP standards to ensure interoperability and scalability.
- **Build partnerships with mobile operators, satellite network operators**, satellite primes, and application developers for end-to-end solution delivery.
- **Engage in cross-sector pilots** (e.g., logistics, public safety, utilities) to validate real-world demand.
- **Contribute to 3GPP Release 20+** and CAMARA API design to ensure NTN integration is feature-complete.

FOR MEMBER STATES AND POLICYMAKERS

- **Support strategic investment** in D2D through national R&D and deployment funds.
- **Encourage spectrum flexibility and regulatory innovation**, particularly for shared bands and cross-border D2D use cases.
- **Coordinate with EU agencies** (e.g., DG CONNECT, EUSPA) to align D2D efforts across European programmes.
- **Promote inclusion of D2D in national broadband and emergency communication strategies.**

FOR RESEARCH AND ACADEMIA

- **Advance core research** in satellite waveform design, Doppler mitigation, and multi-orbit handover.
- **Leverage federated testbeds** for experimentation and protocol validation.
- **Develop open-source tools and emulators** to lower entry barriers for startups and SMEs.

9.3 CALL TO ACTION

Direct-to-Device satellite communication is no longer a distant concept—it is a tangible, rapidly evolving domain that will define the next decade of mobile and satellite convergence. Europe has the skills, assets, and vision to lead this transformation, but only through **coordinated, timely, and bold action**.

ESA invites all stakeholders—governments, operators, manufacturers, researchers, and innovators—to join forces in building a European D2D ecosystem that delivers **ubiquitous, resilient, and sovereign connectivity for all**.

10. ANNEX

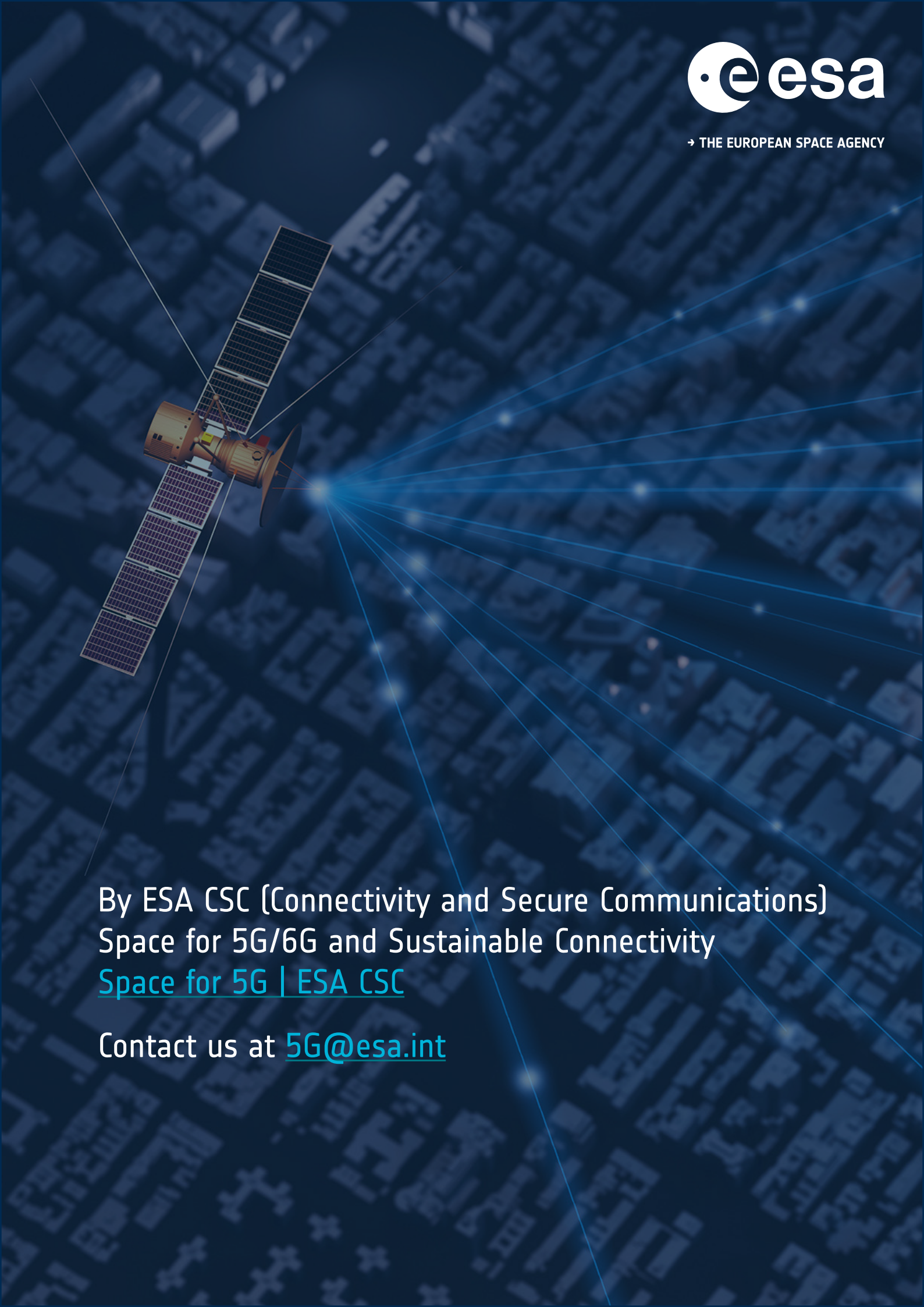
This annex provides supporting material to enrich the understanding of the Direct-to-Device (D2D) ecosystem, key terminology, timelines, and reference initiatives relevant to the European and global context. It is intended as a practical reference for technical readers, policymakers, and collaborators.

10.1 TIMELINE OF KEY MILESTONES IN D2D DEVELOPMENT

Year	Milestone/Event
2023	3GPP Release 17 finalised with support for NTN (NB-IoT and NR)
2024	ESA-led D2D chipset and terminal development underway via ARTES
2024	ESA D2D Workshop
2025	D2D demonstrations planned at ESA 5G/6G Hub and GSMA Mobile World Congress (MWC)
2026	Expected in-orbit validation of European D2D terminals and protocols
2027	3GPP Release 20 expected to begin defining native 6G D2D capabilities
2027	MSS S-Band 2027, WRC 2027
2029–30	Targeted commercial availability of integrated TN/NTN services including D2D

10.2 SELECTED REFERENCES AND RESOURCES

- 3GPP Work Items: www.3gpp.org/DynaReport/WI-List.htm
- GSMA CAMARA APIs: www.camaraproject.org
- ESA 5G/6G Hub: https://www.esa.int/5G_6G_Hub
- ESA ARTES Programme: https://artes.esa.int
- JOINER Testbed (UKRI/DSIT) https://www.ukjoiner.org
- ITU-R Reports and WRC Documents: https://www.itu.int
- ESA D2D Workshop 2024: https://connectivity.esa.int/sites/default/files/2025-01/Direct_to_Device_An_Opportunity_For_Europe.pdf



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