International Journal of Innovative Research in Computer Science and Technology (IJIRCST)
ISSN (Online): 2347-5552, Volume-13, Issue-4, July 2025
DOI: https:/doi.org/10.55524/ijircst.2025.13.4.12
Article ID IRP-1665, Pages 109-115
www.ijircst.org

The Role of Antennas in Ensuring D2D Scenario in Satellite Mobile Communications

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Received 1 July 2025; Revised 15 July 2025; Accepted 29 July 2025

ABSTRACT- The article considers the role of antennas in providing direct communication between user devices via satellite networks (D2D scenarios), which is becoming especially relevant in light of the introduction of 5G/6G NTN standards and the development of LEO satellites. The analysis of technical and design requirements for antennas that provide stable communication in conditions of terminal and satellite mobility is performed. Key antenna parameters such as gain, radiation pattern, polarization, efficiency, as well as their impact on the channel quality are described. Attention is paid to the issues of EIRP, SAR balance, polarization matching and automatic pointing. The analysis of issues related to antenna miniaturization, SAR limitations and energy efficiency, as well as the prospects for D2D integration into mass mobile devices is performed. In conclusion, it is shown that further development of D2D communication requires innovative antenna solutions capable of operating in the Ku/Ka bands and providing high throughput with miniaturization and energy efficiency.

KEYWORDS- 5G NTN, D2D, Frequency Range, Satellite, Antenna, Phased Array.

I. INTRODUCTION

In recent years, there has been a rapid growth in interest in direct communication between user devices via satellites - the so-called Direct - *to* - *Device* (D2D) communication. This technology allows ordinary smartphones and terminals to communicate directly with satellite networks without the participation of ground infrastructure, providing coverage in hard-to-reach areas and in emergency situations. Development of low-orbit satellite systems (LEO) and standardization of 5G *Non-Terrestrial Networks* (NTN) in 3 GPP releases 17-18 stimulate the integration of satellite communications with mobile devices (Figure 1) [1], [2]. The companies SpaceX (Starlink), AST SpaceMobile, Iridium, Globalstar and others have already demonstrated the functionality of such systems – from sending SMS messages to video calls directly via satellite.

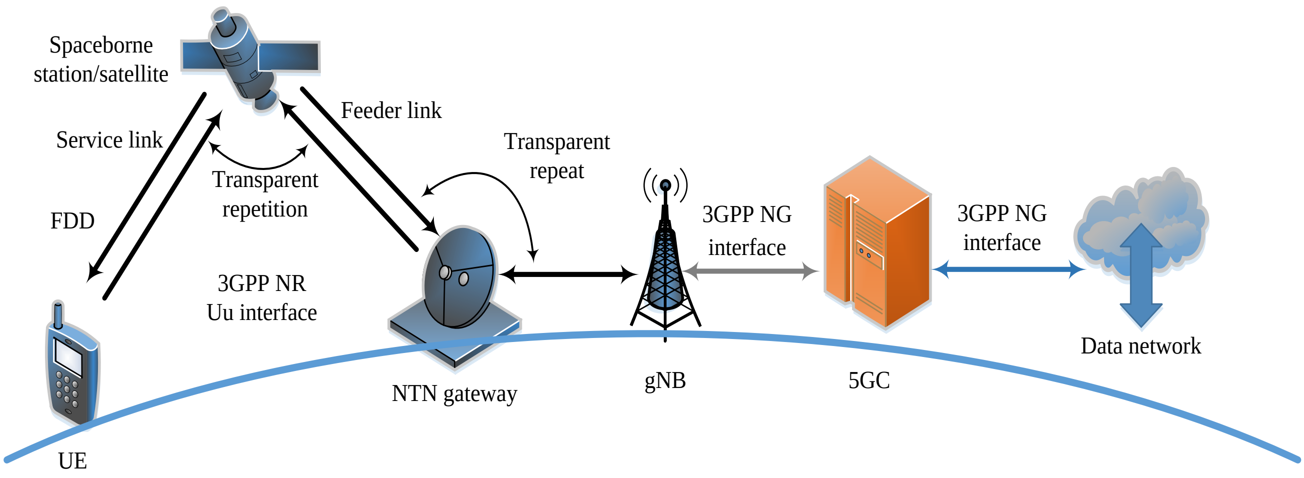

Figure 1: Integration of satellite communications with mobile devices [2]

Antennas are a key link in D2D communication via satellite. Their characteristics (gain, radiation pattern, polarization, efficiency, etc.) determine the ability of a mobile device to establish a reliable communication channel with a satellite in orbit. The task is complicated by the mobility of both satellites (especially in low orbits moving relative to the observer) and user terminals themselves (for example, a smartphone in the user's hand or a sensor on a moving object). The antenna must either have a wide field of view to cover the satellite at different angles, or dynamically redirect the beam when the position changes, preferably without the user's participation in pointing the antenna. At the same time, the dimensions, weight, and power consumption of the antenna are strictly limited by the capabilities of portable devices [3].

II. RELEVANCE OF D2D COMMUNICATION IN SATELLITE SYSTEMS (LEO/NTN)

Global coverage and elimination of communication "white spots" is one of the important tasks of modern telecommunications systems. The presence of a direct connection between a device and a satellite allows providing communication services where there is no terrestrial infrastructure (for example, oceans, deserts, mountainous areas, etc.), or it is damaged (areas of natural disasters). D2D communication via satellite is considered an addition to terrestrial cellular networks 5G/6G to ensure communication at any point at any time (*ubiquitous connectivity*). Standardization 3 GPP NTN in Rel.17 recognized the need to support satellites in 5G [4]. Specific frequency bands for point-to-point communications were identified: the L-band ~1.6 GHz (bands n253 – n255) and S-band ~2.0 GHz (n256) are reserved for NTN, and the Ku/Ka-bands (n510–n512) are also being considered for advanced applications. LEO constellations in low orbit (300–1500 km) are receiving particular attention due to their low latency and more favorable power balance compared to geostationary (GEO) satellites. For example, low-orbit systems such as Starlink and OneWeb can provide an acceptable link budget even for small antennas of user devices, while communication with GEO (~36 thousand km) is possible mainly for narrowband services (SOS messages, IoT) due to high propagation losses [5][6][7][8][9].

Traditional mobile satellite operators such as Iridium, Globalstar, Inmarsat have historically provided services through special terminals (satellite phones, portable terminals) in the L- and S-bands. The system is currently being adapted to 5G standards. NTN to interact with mass-market devices. Companies like SpaceX, AST SpaceMobile proposes to use existing terrestrial cellular spectrum on satellites to directly serve regular smartphones without modification. The ability to provide broadband services such as 4G/5G data directly to smartphones via satellites is a major development in the industry [4].

A special category of D2D applications is the Internet of Things (IoT) and communications M2M *(machine-to-machine)*. Satellite IoT constellations (groups of artificial satellites working together as a single system, specifically designed to provide communication between IoT devices, such as Orbcomm, Lacuna, Myriota) are already using compact narrowband terminals to collect data from sensors around the world. Integrating these services into standard protocols (NB-IoT NTN) allows regular IoT modules to connect via GEO and LEO satellites. D2D provides a backup communication channel for critical applications, for example, eCall/bCall- enabled vehicles can send emergency messages via satellite when there is no cellular coverage. Emergency services are also showing great interest in direct satellite communications, given its resilience to terrestrial infrastructure disruption and global coverage. Scenarios *public safety* (coordination of actions in emergency situations, communication between emergency rescue teams) increasingly include satellites as a backup or the basis of the network. In general, D2D communication via satellites is turning from a highly specialized niche (satellite phones for expeditions, etc.) into a mass technology designed to complement terrestrial 5G/6G networks and eliminate the problem of digital inequality based on geographic features [7] [8].

III. THE ROLE OF ANTENNAS IN ENSURING THE EFFICIENCY OF D2D SCENARIOS IN MOBILE ENVIRONMENTS

The antenna path largely determines the possibility and quality of direct communication between the device and the satellite. A portable device (phone, tablet, sensor) is limited in size and power, which makes it difficult to achieve high antenna gain and an energy-efficient channel to the spacecraft in orbit. Therefore, to ensure an acceptable signal level, approaches such as ensuring high sensitivity of satellite receivers and enhanced transmission from the satellite are used; optimization of the antenna diagram for satellite geometry; automatic direction and phase control (beam steering); polarization and orientation of the device; balance of Effective Isotropic Radiated Power (EIRP) and Specific Absorption Rate (SAR) [10].

A. Ensuring high sensitivity of satellite receivers and enhanced transmission from the satellite-

In this approach, satellites are equipped with high-gain antennas and powerful transmitters to compensate for the small size and low gain of the antenna on the device. For example, some satellites have huge deployable antenna arrays to form a strong beam to the ground. At the same time, the phone transmits with the minimum required power, and the satellite receives the signal using a highly sensitive receiver. However, increasing the transmitting power of the satellite and the size of its antenna is limited by the on-board energy and design capabilities, so they also try to improve the antenna solutions on the terminal [11][12][13].

B. Optimization of the antenna diagram for satellite geometry-

To communicate with a moving LEO satellite, the omnidirectional antenna of the device is forced to radiate in all directions, wasting most of the energy. Therefore, an antenna with a hemispherical radiation pattern, covering half the sky (above the horizon), but with a minimum of radiation downwards into the ground, is preferable. The ideal diagram is close to a cardioid: the maximum is directed towards the zenith, and the minimums are under the device (Figure 2) [14].

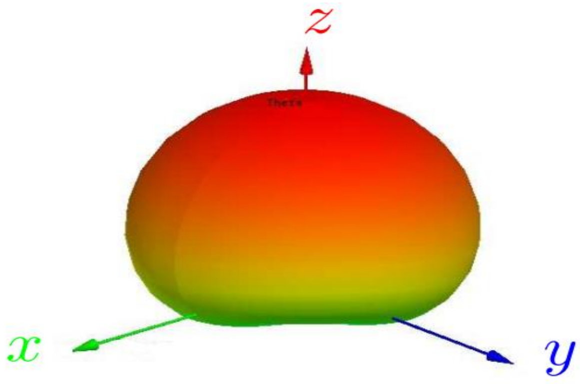

Figure 2: Hemispherical radiation pattern

This shape provides gain to satellites at low elevation angles without significant “dropouts”. Example: compact helical and quadrifilar antennas of satellite phones have a nearly hemispherical pattern and circular polarization, which reduces dependence on the orientation of the device.

C. Automatic control of direction and phase (beam steering)-

In mobile conditions (for example, a user walks with a smartphone, a car with a receiver drives) and with moving LEO satellites, it is very important that the main beam of the device's antenna is pointed at the satellite. For this case, the most effective and modern solution is phased antenna arrays with electronic beam scanning. Such antennas can instantly change the direction of radiation without mechanical rotation, “tracking” the satellite along the calculated trajectory. This is especially important for vehicles: airplanes and ships traditionally had mechanical stabilized antennas following the GEO satellite, but with the advent of LEO constellations, a much higher speed of pointing and switching between satellites is required, achievable only electronically. In addition, electronic arrays allow several beams to be formed simultaneously and quickly switch between satellites (which is important for “seamless” x andover between devices). For example, a flat active array for aviation has two independent receive beams and one transmit beam, which allows it to simultaneously operate with LEO and GEO (or two LEO) satellites, maintaining communication during switching [15].

D. Polarization and orientation of the device-

Due to the fact that user devices can be oriented arbitrarily, circular polarization of the signal is often used. The satellite channel traditionally uses RHCP/LHCP polarization (Right-Hand Circular Polarization/Left-Hand Circular Polarization) precisely to eliminate losses when rotating or tilting the receiver antenna. Iridium, Globalstar, GPS, etc. satellites use right-hand circular polarization, and portable antennas comply with it. In the 3 GPP standard NTN also provides for the use of circular polarization in some modes, or dual linear (vertical/horizontal) with combining to achieve orientation independence. Thus, even if the phone is at an angle or the user holds it horizontally, sufficient signal is effectively received [16][17][18][19].

E. Balance of EIRP and SAR-

For the uplink (transmission from the device to the satellite), it is critical to achieve the required EIRP at minimum power. High antenna gain helps to achieve this, but a large antenna is impractical. Therefore, the transmitter itself is often amplified, but the power is limited by electromagnetic safety standards (SAR). A conflict arises: for the signal to reach the satellite, the phone needs a high EIRP, but regulatory standards do not allow an uncontrolled increase in radiated power near a person. This problem is solved in a comprehensive manner: by optimizing the gain of the antenna system with acceptable dimensions, effectively using the transmitter power (e.g., pulse modes, narrow band), and adding beamforming at the level of several elements. In addition, options for remote or foldable antennas during transmission are considered, for example, plug-in modules or accessories that the user points at the satellite during an outgoing communication session.

Thus, the quality of the antenna determines whether a link will be established, how long it will last, and at what data rate in D2D scenarios. In mobile conditions, solutions with wide angular coverage (±70° from the zenith and more), electronic adjustment of the diagram, and minimization of the influence of the device orientation are of particular value. Combining these requirements with miniaturization is a complex engineering task solved by new types of antennas [16][17][18][19].

IV. ANTENNA REQUIREMENTS FOR D2D SATELLITE COMMUNICATIONS

Some of the main requirements that are imposed on antennas for organizing D2D communications via satellite are operating frequency ranges, terminal mobility, and the antenna parameters themselves.

A. The operating frequency range determines the physical dimensions of the antenna and the nature of propagation-

L -ban-. Frequencies ~1–2 GHz. Wavelength ~18–30 cm. Antennas in this range are relatively large for pocket devices (at frequencies of 1.6 GHz, a quarter of the wavelength is ~5 cm), but are still possible in the form of retractable pins or internal planar elements. The advantage of the L -band is low attenuation in the atmosphere; the ability to pass through foliage; less criticality of pointing accuracy. Historically, most satellite phones (Iridium - 1616 MHz, Thuraya - ~1545 MHz, Globalstar - 1610 MHz) operate in the L-band. Requirements for antennas in the L-and: circular polarization, bandwidth ~±5% for Doppler coverage, gain of the order of 0–3 dBi (sufficient for communication, considering the powerful satellites). The problem is the placement of the L-antenna in a thin smartphone. A compromise could be to use existing LTE antennas at harmonics of the 700–900 MHz range or to re-tune them to 1.6 GHz, but this reduces efficiency [18], [20].
S -band. Frequencies 2–4 GHz. Wavelength ~7.5–15 cm. Some new systems operate in this range, for example, the planned satellite service in the 1980–2010 MHz band for communication with telephones (n256 band). Increasing the frequency allows a slightly smaller antenna, but the sensitivity to blockages by the user's body increases, and the required phasing accuracy is higher. The S-band is still relatively gentle on the environment, i.e. rain and trees provide a slight attenuation [26]. Antennas can be made in the form of printed patches ~5–8 cm in size. The requirements are narrowband (usually 5–20 MHz channels), gain comparable to L-band, but the efficiency of the antenna in a compact case is lower (since the antenna is electrically shorter relative to λ). High-dielectric substrates or emitters with complex geometries are required to accommodate long electrical lengths in a small volume [18], [20], [28].
Ku/Ka-ranges (frequencies 10–18 GHz/26–40 GHz). Here the wavelength is centimeter (Ku ~ 2 cm, Ka ~ 1 cm). Such frequencies are used for broadband access, for example, Starlink uses ~10-12 GHz down and 14 GHz up for the user terminal. At these frequencies, the slightest obstacles block the signal, and the required antenna gain is very high. However, for portable handheld terminals (not smartphones), Ku/Ka is the main range. Antennas here are phased active arrays with tens and hundreds of elements.

The size is determined by the required gain, so to provide a gain of ~30–35 dBi in Ku (necessary for an acceptable SNR), the panel must be about 30–50 cm in diameter. This is significantly larger than a phone, so such terminals are separate devices (for example, Starlink equipment, Figure 3) [21]. In the Ka-band, the shorter wavelength allows for a smaller panel, but the atmospheric losses are higher, requiring more elements for the same efficiency. In the context of the D2D scenario, Ku/Ka can be used for high-speed links, such as between drones or for special modems where the user is willing to point the device at the satellite.

Figure 3: Starlink satellite internet antenna

B. Terminal mobility and its impact on antenna design-

A mobile terminal can move at different speeds, from the speed of a pedestrian to that of an airplane. The faster the movement, the faster the angular position of the satellite in the sky changes, and the more important is the dynamic reconfiguration of the antenna. For example, for a car at a latitude of ~50° LEO, the satellite will be visible for 5–10 minutes, with the maximum signal when the satellite is at an altitude of ~30–40° above the horizon. An antenna with a fixed orientation (for example, a flat panel built horizontally into the roof) will provide the most effective signal reception at the zenith, but with a loss of angle, the efficiency will drop sharply. The solution is either to use a mechanical mount (as in old INMARSAT terminals for cars), or electronic scanning. Currently, almost all new *SatCom - on - the - move developments* rely on phased antenna arrays. For example, Intellian OW10/11 OneWeb ground vehicle terminals are flat panels capable of scanning the beam ±50–70° in height, maintaining communication down to the lowest angles until the satellite disappears (Figure 4) [22].

Figure 4: Intellian panel OW 10HL

For a smartphone, the situation is more complicated. This is due to the fact that the user can change the orientation of the phone, can put it in a pocket. All this affects the signal level. It is necessary to either warn the user to keep the phone open and pointing to the sky (as is implemented in the iPhone when sending an SOS, the phone tells you where to turn), or have a multi-element antenna system covering different sides of the device. Potentially MIMO technology (Multiple Input Multiple Output), which uses multiple antennas on both the transmitting and receiving sides, may be one solution. Several small antennas around the perimeter of the phone can be used in turns and the antenna with the best satellite reception (i.e. spatial diversity) can be selected for transmission/reception. Even now, modern smartphones have 4–8 built-in antennas for different ranges. Adding a satellite function may involve using, say, a GNSS antenna (which is tuned to ~1.57 GHz GPS, close to 1.6 GHz satellite services) to transmit/receive messages. Thus, the device does not need a separate large antenna, it reuses the existing one, but in a different mode. However, the efficiency of this approach is still low, so additional accessories appear: satellite shimods, or cases with an antenna. For example, Thuraya Telecommunications Company introduced the Thuraya adapter SatSleeve+, which connects to a smartphone via wireless Wi-Fi. The adapter allows you to communicate, exchange information, and use the Internet (Figure 5) [23].

Figure 5: Thuraya adapter SatSleeve +

C. Antenna parameters-

The main characteristics of an antenna include: gain (or directivity, dBi), radiation pattern, polarization, efficiency (radiation efficiency), bandwidth, and load characteristics (matching, permissible power). Let 's consider these characteristics in relation to the D2D scenario.

The antenna gain determines how much energy the antenna focuses in the desired direction. High gain (>20 dBi) is desirable to compensate for long ranges, but this is difficult to achieve in portable devices due to the small aperture size. Thus, an isotropic antenna of 0 dBi radiates in all directions; a small spiral can have a peak of 3–5 dBi; while a phased array of 30 cm × 30 cm gives ~ 30 dBi or more. Since satellites used to have large antennas, ~ 0–3 dBi was enough for satellite telephony. But for broadband services, a minimum of 15–20 dBi from the user side is required, which is achieved either by folding reflectors (as in Inmarsat BGAN terminals) (Figure 6) or electronic arrays (as flat Starlink/OneWeb terminals) [24].

Figure 6: Inmarsat satellite terminal BGAN Explorer 710

The radiation pattern should be either omnidirectional (for continuous coverage, but with low gain) or directional with steering. For D2D scenarios, a common compromise is a wide radiation pattern covering the entire upper hemisphere (Figure 2). This allows not to lose the satellite while moving, but reduces the peak gain. For example, the radiation pattern of a helical antenna can cover up to 100–120° from the zenith (then rolls off) (Figure 7) [25]. In the context of mobility, the viewing angle is also assessed: a good mobile terminal has a viewing angle of 180° (from horizon to horizon) with no dips deeper than –10 dB. "Blind zones", for example, directly above the horizon or behind the user (if the body is shielding), are undesirable, but practically inevitable. Multipath reflections (from buildings, etc.) can be used to mitigate losses when the antenna pattern is blocked by parts of the human body. Circular polarization helps to partially receive reflected signals without strong depolarization loss.

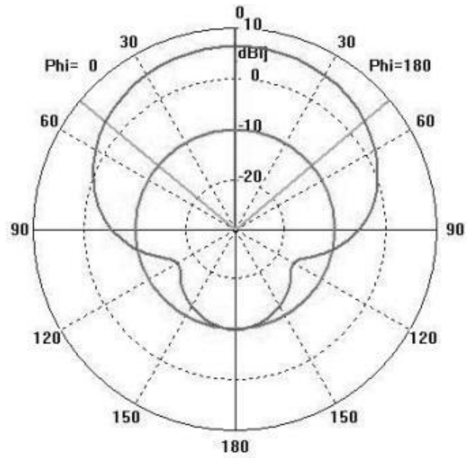

Figure 7: Directional diagram of a flat helical antenna

Polarization. In satellite communications, circular polarization is predominant, since it reduces fading due to receiver rotation and reflections. If linear polarizations are used, they are usually dual - so that the receiver can accept any angle. In 5G standards NTN specifies that devices must support RHCP/LHCP for NB-IoT and NR or have a polarization matching program. Implementation of circular polarization in a compact antenna is usually more difficult (it is necessary to excite orthogonal modes with a phase shift of 90°), but solutions are available: quadrifilar antennas, obliquely fed patches, helices. In portable terminals, the polarization is usually fixed by RHCP (Iridium, GPS, etc.) [27]. This requires that the satellite uses the corresponding one (e.g. Iridium satellites transmit and receive RHCP). Mismatch will result in a loss of about -20 dB in cross-polarization losses, which is unacceptable. Therefore, polarization matching is an important point in the integration of the terrestrial and satellite segments.

Efficiency (radiation efficiency). Small antennas often suffer from low efficiency, since a significant part of the energy is lost in resistive losses and imperfect matching. In smartphones, the typical antenna efficiency is 20–70%. At satellite frequencies, an internal antenna may have an efficiency of no more than 30%, especially if tuned outside the optimal range. This reduces the real EIRP and the G/T (gain/noise temperature) ratio of the system. Solutions for increasing efficiency are the use of highly conductive materials, matching circuits, noise insulation (e.g. balanced antennas). The higher the operating frequency, the better the efficiency can be achieved (e.g., in Ku -panels, the efficiency of up to 50–60%). In the L-band, small antennas (on the board) can have an efficiency of up to 10–20%. Therefore, low-noise amplifiers are often added to the receiving part directly in the antenna, and powerful amplifiers are added to the transmitting part.

Table 1 provides generalized and averaged requirements and parameters for several typical D2D antenna solutions.

Table 1: Comparison of antenna characteristics for different D2D solutions

No.	Device type	Range	Antenna type	Gain (peak)	Polari-zation	Antenna size	Antenna power supply	Notes
1	Satellite phone (Iridium)	L (~1.6 GHz)	Retractable spiral / QHA	~3 dBi (zenith)	RHC	Length ~10 cm (quarter wave)	Passive (maybe LNA at the input)	Hemispherical diagram, 50% efficiency
2	IoT sensor	L (1.6 GHz)	Printed Patch / Monopol	~0 dBi	RHC	Patch 3-5 cm or ant. wire	Battery operated, low power transmitter	Low speed, optimized for energy efficiency
3	Portable Internet Terminal (BGAN)	L (~1.5 GHz uplink, 1.6 down)	Flat folding panel (reflector)	~9–12 dBi	RHC	Aperture ~20x20 cm , foldable	Active (LNA/BUC available)	GEO targeting , provides ~448 kbps
4	Broadband terminal (Starlink user terminal)	Ku (10–12 GHz down, 14 GHz up)	Phased Array 2D (Electronic Scanning)	~35 dBi	linear dual (H/V polari-zation)	Round/ rectangular panel 30-50 cm	Active (100 W consump-tion)	Auto-guidance, ±50° scanning in height, ~20–100 Mbit/s internet
5	Car Antenna (OneWeb Intelligent OW11FV)	Ku (~12 GHz)	Flat AESA, tiles	~33 dBi	RHCP/LHCP (double)	Panel ~55×55 cm	Active	Wide scanning angle, for communication on the go, IP65

Given in Table 1 are approximate. The antenna gain is specified relative to an isotropic radiator (dBi) or for CP– relative to an isotropic circularly polarized radiator (dBi). The efficiency is not specified explicitly, but for small antennas it can be 10–50%, for phased arrays 50–70%. The power consumption of active terminals is specified as total, taking into account signal processing.
Table 1 shows that there is a sharp increase in the complexity of antennas when moving to high-speed services. In practice, there is a transition from passive simple radiators to complex active phased antenna arrays.

V. CONCLUSION

Satellite communications (D2D) is a promising direction for the development of telecommunications, providing global connectivity and supporting mission-critical applications such as IoT, emergency services and broadband access. Antennas play a central role in the implementation of D2D, determining the quality and stability of communications in conditions of terminal and satellite mobility. Modern solutions such as phased array antennas, circular polarization and optimized radiation patterns help overcome limitations related to device size, power consumption and SAR. However, further development of D2D requires innovations in antenna miniaturization, increasing their efficiency and integration with existing mobile platforms. Prospects include the introduction of hybrid antennas compatible with terrestrial and satellite standards, as well as the transition to higher frequency bands (Ku/Ka) for broadband services. D2D communication has the potential to become an integral part of the 5G/6G ecosystem, eliminating digital inequality and providing connectivity anywhere in the world.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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