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A review of direct-to-device satellite technology in bridging connectivity gaps in Malaysia

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ABSTRACT

The connectivity gap in rural and remote regions of Malaysia remains a significant challenge due to the high costs and technical challenges of deploying fixed-line infrastructure like fiber optics and copper cables. Similarly, expanding cellular networks such as 4G and 5G to these areas is often economically unfeasible for mobile network operators (MNOs) due to low returns on investment. Direct-to-device (D2D) satellite technology has recently emerged as a promising solution, gaining interest from both industry and academia. D2D enables direct communication with standard mobile phones and internet of things (IoT) devices, extending coverage to underserved regions without requiring extensive ground infrastructure. This paper provides a comprehensive overview of D2D technology, its technical aspects, and its suitability as a complementary solution to terrestrial networks. This paper also discusses how D2D technology can bridge the connectivity gap in Malaysia, offering a possible solution to enhance digital inclusion in rural and remote communities.

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1. INTRODUCTION

The internet has become a vital component of modern life, deeply embedded in daily activities as the digital age advances. People across generations rely on the internet not only for communication but also for diverse applications, including education, work, and leisure. It serves as a gateway to social media, online shopping platforms, and countless other applications that enhance both productivity and entertainment.

According to a study by the GSM Association (GSMA), 57% of the world's population uses mobile internet [1]. However, a coverage gap persists, with 4% of the global population still lacking mobile broadband access. In Malaysia, 97% of populated areas currently have internet connectivity, leaving 3% without coverage [2]. The mobile broadband coverage by state as of June 2024, presented in [3], reveals that Sarawak has the largest coverage gap, followed by Sabah and Pahang. These states are known for their vast forested areas, which pose challenges to terrestrial network deployment. Existing terrestrial networks are unable to address these connectivity gaps in rural and remote areas due to a lack of commercial viability. GSMA reports that deploying new base stations in rural regions can cost twice as much as in urban areas, with revenue expectations up to ten times lower [4].

Previously, a study on broadband over power lines (BPL) was conducted to provide internet connectivity to longhouse communities in Bawang Assan, Sarawak [5]. In this pilot project, basic internet connectivity was provided through an electric grid, with recorded download speeds ranging between 6 and

9 Mbps. Similarly, fixed wireless access (FWA) has been explored as a solution for rural and remote connectivity in Malaysia. In [6], FWA technology was deployed at proof of concept (POC) sites in Melaka to provide broadband access. Its fast deployment and cost-efficiency make it a viable alternative to traditional base stations. Another approach to extending rural coverage involves the use of repeaters. In [7], repeaters were deployed to enhance LTE coverage in two rural areas of Malaysia characterized by palm plantations, hilly terrain, and forested regions. These repeaters successfully extended LTE coverage beyond the targeted areas while improving throughput performance, with recorded download and upload speeds of 7.49 and 9.38 Mbps, respectively. For internet of things (IoT) applications, long-range (LoRa) technology has been studied for mangrove forest monitoring in Malaysia [8]. In this study, LoRa was used for wireless remote sensing in Sabak Bernam, Selangor. The study demonstrated that LoRa enables point-to-point data transfer, including image transmission, despite its limited bandwidth.

While these technologies have demonstrated effectiveness in extending connectivity, they are often constrained by factors such as limited signal range, reliance on stable power sources, and dependence on existing terrestrial infrastructure. An unresolved challenge found from previous works is the need for a seamless, cost-effective solution that eliminates the need for additional hardware, making it suitable for individual users in remote areas. As a result, alternative solutions are required to overcome these challenges. This paper explores direct-to-device (D2D) satellite technology as a promising alternative for bridging connectivity gaps, offering a solution that overcomes the limitations of both terrestrial and traditional satellite networks.

This paper is structured as follows: Section 2 provides an overview of D2D technology, highlighting its differences from current satellite systems and key industry players, along with notable D2D milestones. Section 3 discusses the technical challenges in D2D implementation, including doppler shift, latency, and path loss. Section 4 explores current D2D initiatives in Malaysia, regulatory considerations, and potential use cases for D2D technology in the country. Finally, section 5 concludes the research, summarizing key findings and implications.

2. OVERVIEW OF DIRECT-TO-DEVICE TECHNOLOGY

2.1. Understanding D2D technology

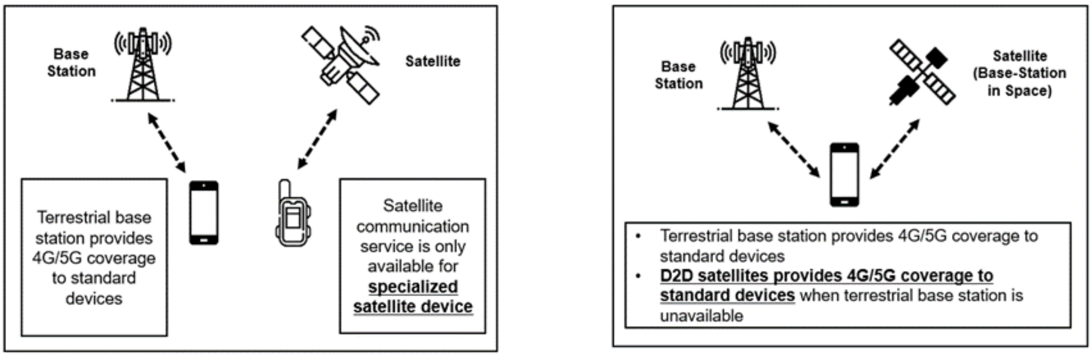
D2D is a technology that enables direct connectivity from satellite to unmodified mobile phones. Also known as direct-to-cell or sat-to-phone, this technology provides coverage extension to areas unreachable by the terrestrial or ground-based station, by providing “space-based” coverage from the satellite. This technology aims to supplement the current terrestrial network to reduce the coverage gap by providing connectivity to remote or challenging geographical areas.

The concept of delivering satellite connectivity directly to user equipment (UE) has been around for some time. Currently, satellite services provide connectivity in areas without terrestrial networks via specialized satellite phones, often used by professionals in remote locations such as forest rangers and emergency responders. Additionally, services like Starlink offer satellite broadband for users in regions lacking fixed-line or mobile network infrastructure. Starlink's solution involves user terminals that can be deployed for stationary or mobile use, requiring an unobstructed view of the sky to function [9]. However, the high costs associated with the hardware and data plans make these services less appealing for rural communities.

In contrast, D2D technology eliminates the need for specialized equipment or additional hardware, enabling standard mobile phones to connect directly to satellite networks. This seamless integration allows users to maintain connectivity in areas where terrestrial networks are unavailable or unreliable [10]. Figure 1 highlights the key differences between traditional satellite communication and the emerging D2D satellite communication. Figure 1(a) illustrates the conventional satellite communication model, whereas Figure 1(b) presents the concept of D2D communication. Traditionally, satellite connectivity has been restricted to specialized devices, whereas standard mobile phones have relied solely on terrestrial cellular networks such as 4G or 5G. With D2D technology, these same phones can now connect directly to satellites, enabling mobile coverage even in the absence of terrestrial infrastructure.

2.2. D2D technology players and key milestones

The market segment for D2D technology can be divided into two categories: standard mobile devices and IoT devices. Currently, three main companies are leading the race in D2D for standard mobile devices: Lynk Global, AST SpaceMobile, and Starlink (SpaceX). Lynk was an early player in the D2D market, achieving the first two-way connection with its cell-tower-in-space in 2021. Lynk brands its D2D service as “Sat-to-phone”. AST SpaceMobile has also maintained a strong presence, achieving several industry-first milestones in 2023. SpaceX, meanwhile, has made significant strides in 2024, leveraging its satellite launch expertise as an industry advantage and branding its D2D service as DTC. Table 1 provides a summary of the constellation details for the three companies, respectively [10]-[19].



(a) (b)

Figure 1. Comparison between (a) traditional satellite communication and (b) D2D satellite communication

Table 1. Constellation details for Lynk global, AST Spacemobile, and SpaceX

Company	Number of satellites	Altitude (km)	Frequency (MHz)
Lynk Global	Planned: 5000 satellites Current: 2 test satellites launched (Lynk 04 ULTP, Lynk 05 Shahnon) 3 commercial satellites launched (Lynk Tower)	500-550	Space-to-earth: 617-960 Earth-to-space: 663-915
AST SpaceMobile	Planned: 243 satellites Current: 2 test satellites launched (BlueWalker) 5 commercial satellites launched (BlueBird)	725-740	Space-to-earth: 617-960, 1805-2360 Earth-to-space: 663-915, 1710-2320
SpaceX	Planned: 2016 satellites (Gen2 Starlink) Current: 320 commercial satellites launched	340-360 525-535	Space-to-earth: 1429-2690 Earth-to-space: 1429-2690

The most recent development in D2D technology comes from SpaceX, which announced that it has reached a significant milestone by deploying enough satellites to enable commercial service for its DTC technology. As of 25 November 2024, the company has launched a total of 320 satellites, marking the completion of the first stage of its satellite network [19]. This milestone enables SpaceX to provide reliable text messaging services to customers. Earlier, on October 6, 2024, the Federal Communications Commission (FCC) authorized SpaceX to use Starlink DTC satellites in areas of North Carolina severely impacted by Hurricane Helene [20]. T-Mobile customers in the affected areas were able to send SMS texts over Starlink DTC satellites. On 26 November 2024, SpaceX received approval from the FCC to begin commercial operations of its DTC service [21]. The FCC also granted permission for a subset of SpaceX's second-generation satellites to orbit approximately 200 kilometers closer to Earth, a move aimed at reducing latency and enhancing service quality. With these approvals, SpaceX is ready to serve United States customers through its partnership with T-Mobile, providing connectivity in cellular dead zones. A beta service is expected to launch soon in the United States, initially available to SpaceX employees.

Another significant achievement to date is AST SpaceMobile's successful launch of the commercial BlueBird satellite on 12 September 2024 [16]. These five commercial satellites are expected to offer broadband services across the United States, initially supporting beta testing for AT&T and Verizon users [22], [23]. Following this, AST SpaceMobile has secured an initial contract with the space development agency (SDA) as a prime contractor to the United States Government [24]. The selection by SDA is for another transaction (OT) agreement to compete for upcoming prototype demonstration projects under the hybrid acquisition for proliferated low earth orbit (HALO) program.

Figure 2 summarizes the timeline of D2D technology testing by Lynk Global, AST SpaceMobile, and SpaceX [25]-[32]. The tests include text messaging, voice calls, video calls, and broadband data services. This timeline spans from 2021 to 2024.

While these companies have focused on cellular-based spectrum deployment, notable advancements have also been made by companies adopting the mobile satellite service (MSS) approaches [33]. Globalstar’s partnership with Apple represents a significant milestone in D2D technology. In November 2022, they launched the “Emergency SOS via satellite” feature, starting with the iPhone 14, enabling users to send emergency messages when terrestrial cellular coverage is unavailable [34], [35]. Such an example can be seen in the Hurricane Milton incident [36]. Similarly, Google has introduced a feature called “Satellite SOS” in its Google Pixel 9 series. Google has partnered with Skylo and Garmin to enable users to send SOS messages via satellite when cellular networks are unreachable [37]. Figure 3 shows the emergency SOS services. Figure 3(a) presents a snapshot of Apple’s emergency SOS via satellite, while Figure 3(b) shows Google’s satellite SOS interface.

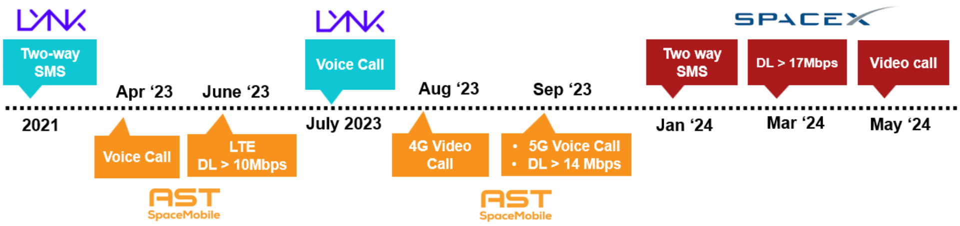
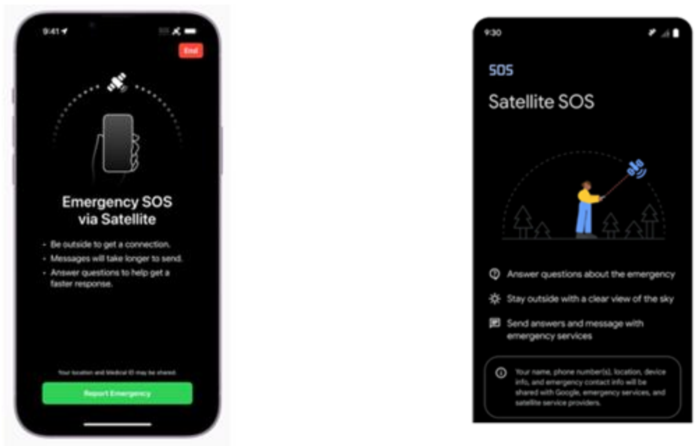


Figure 2. Milestones of D2D testing by Lynk Global, AST Spacemobile, and SpaceX



(a) (b)

Figure 3. Emergency SOS services of (a) emergency SOS via satellite by Apple and (b) satellite SOS by Google

Other players of D2D focusing on the MSS spectrum are China Telecom and Viasat. In May 2024, China Telecom introduced D2D services in Hong Kong, powered by the Tiantong-1 satellite system. This service ensures comprehensive coverage for residents and travelers commuting between Shenzhen, Hong Kong, Zhuhai, and Macao [38], [39]. On 15 October 2024, Viasat reported that it demonstrated D2D connectivity in India, partnering with an Indian telecommunication provider BSNL. They have successfully demonstrated two-way messaging and SOS messaging through one of Viasat’s geostationary L-band satellites [40], [41].

3. TECHNICAL CHALLENGES IN D2D IMPLEMENTATION

Understanding the technical challenges in D2D implementation requires examining non-terrestrial networks (NTNs). NTNs are wireless communication systems that operate above the Earth's surface, utilizing satellites in low earth orbit (LEO), medium earth orbit (MEO), and geostationary earth orbit (GEO), as well as high-altitude platforms (HAPS), air-to-ground networks, and unmanned aerial vehicles (UAVs) [42], [43]. These systems are essential in addressing connectivity gaps, particularly in remote and underserved regions. Figure 4 illustrates the NTN ecosystem, showcasing satellites across GEO, MEO, and LEO, along with emerging platforms like HAPS and UAVs [43].

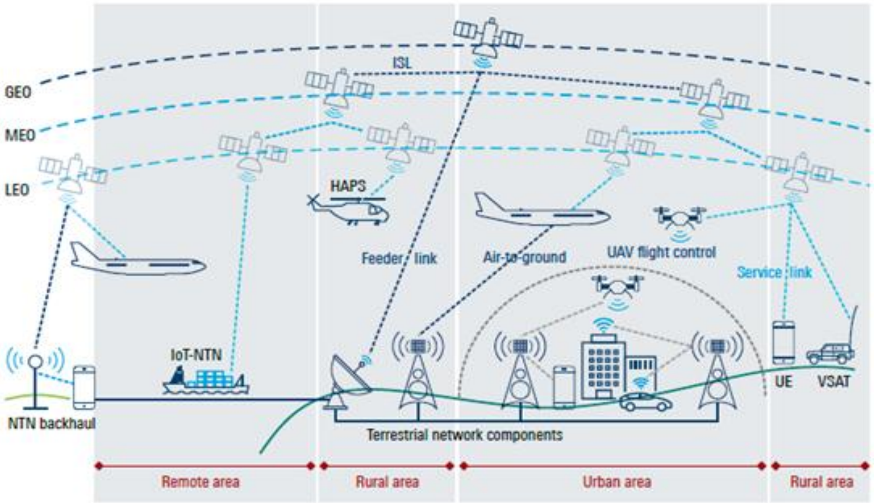


Figure 4. General connectivity overview of NTN [43]

Recently, much research in NTN has focused on D2D technology. The integration of NTNs into the 3rd generation partnership project (3GPP) standards is expected to revolutionize modern communication by merging cellular networks with satellite communications [44], [45]. Cellular technologies, such as 4G and 5G, were originally designed for terrestrial networks. Therefore, adapting these technologies to the NTN ecosystem demands extensive research, particularly in RF propagation. Key technical challenges in this integration include addressing Doppler shift, latency, and path loss.

The motion of the space base-station (satellite) combined with the movement of the UE introduces a time-varying Doppler shift throughout the connection [43], [46]. The high relative speed of the satellite significantly affects the transmitted signal's frequency, with the shift transitioning from positive to negative as the satellite approaches and then moves away from the UE. This frequency shift poses challenges for maintaining synchronization between the satellite and the UE. Additionally, the satellite's rapid movement causes its antenna beam to shift quickly, resulting in constantly changing coverage spots on the ground. The use of steerable beams that can dynamically adjust to account for both the satellite's relative speed and beam footprint on the ground is therefore essential for D2D communication. This phenomenon is illustrated in Figure 5 [46].

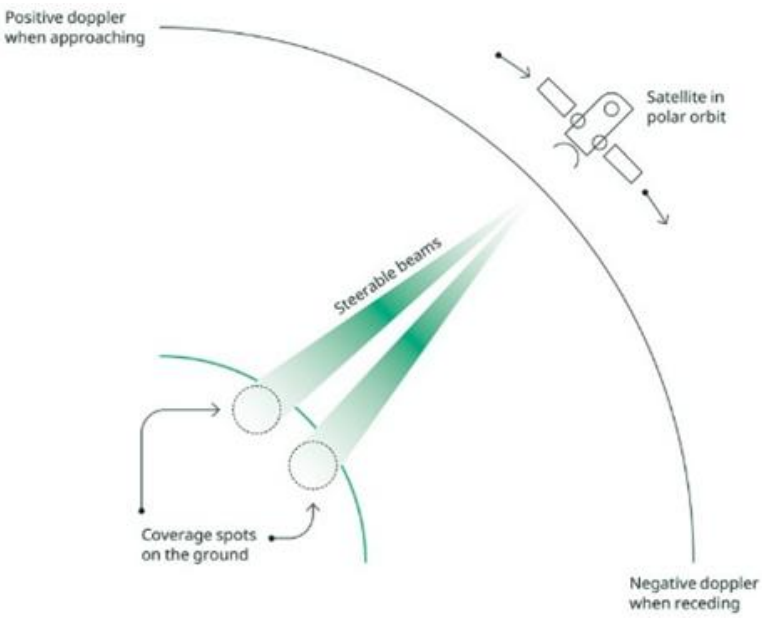


Figure 5. Doppler shift in the NTN network [46]

Another challenge for D2D is on the round-trip time, or latency [43], [46], [47]. The significant distance between the terrestrial UE and the space base station results in inherently high latency. In contrast, terrestrial networks benefit from the relatively short distance between the UE and the base station, enabling low-latency communication through infrastructure optimization, duplexing techniques, and UE capabilities [46]. However, the high latency in D2D poses limitations for certain technologies that have become standard in cellular networks, such as 5G. Therefore, D2D must address these challenges, particularly in delivering reasonable throughput to users. Figure 6 illustrates the latency associated with different orbital satellites.

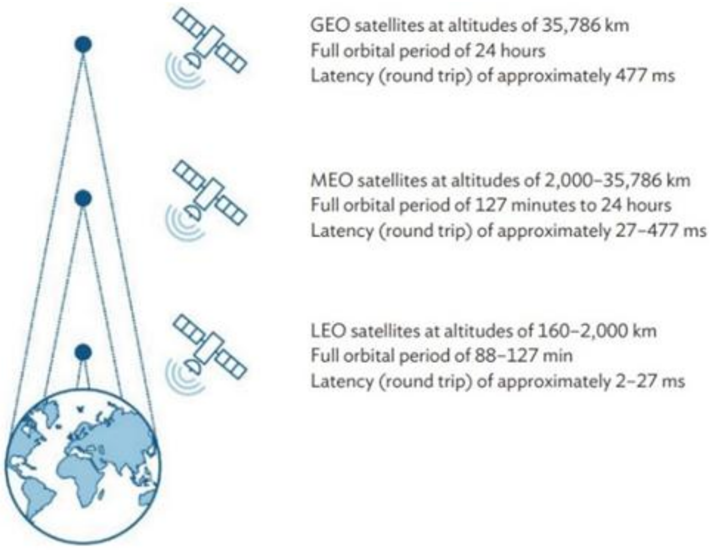


Figure 6. Latency comparison between different orbital satellites [48]

The large distance between the terrestrial UE and the space base station also results in significant path loss. The overall path loss consists of several components: basic path loss (primarily free-space path loss), attenuation caused by atmospheric gases, attenuation due to atmospheric scintillation, and building-entry loss [49]. For LEO satellites, the typical free-space path loss is around -160 dB, while for GEO satellites, it is approximately -190 dB [49]. Given the limited transmission power and sensitivity of the UE, D2D must address this issue to support cellular services such as voice and video calls. One potential solution lies in enhancing the transmission and reception capabilities of satellite payloads [50]. To support standard UEs, which typically have 23 dBm of transmit power, large phased-array satellites with higher gain and power are necessary [46].

4. BRIDGING MALAYSIA'S CONNECTIVITY GAP WITH D2D

4.1. D2D Initiatives in Malaysia

In 2020, the government launched JENDELA with the goal of improving the quality of digital infrastructure and services across the country [51]. Phase 1 of JENDELA, which ran from 2020 to 2022, focused on expanding 4G mobile coverage, targeting 96.9% coverage in populated areas. Phase 2 of JENDELA aims to address the remaining 3% of internet coverage in populated areas, ensuring that all Malaysians have access to internet connectivity by 2025. To achieve this, the government has identified satellite broadband as a key solution for providing basic voice and internet services in geographically challenging regions [2]. In [52], it was reported that more than 2,000 sites have been installed with satellite broadband service, particularly in Sabah and Sarawak.

Recently, the Communications Minister announced that Malaysia is exploring emerging technologies, including D2D satellite technology, to enhance the nation's telecommunications coverage. In May 2024, the Minister projected that D2D services could become available in Malaysia by 2026 or 2027 [53]. A strategic move in this effort is the establishment of a satellite telecommunications research center, in partnership with the Chinese company GeeSpace and the Malaysian Telecommunications Company Altel [54]. GeeSpace, a subsidiary of Geely Technology Group, is affiliated with Proton, Malaysia's national car brand, as Geely holds a 49.9% stake in the company [55]. According to the communications minister, D2D is important because it is able to solve connectivity problems in remote places, including those at national borders or for fishermen at sea. This collaboration is working towards a POC by the second quarter of 2025 for LEO satellite IoT, high precision positioning, and D2D technology [56]. As of October 2024, GeeSpace operates 30 satellites in orbit and plans to expand its constellation to 72 satellites by the end of 2025 [57].

4.2. Regulatory matters

A comprehensive regulatory framework is essential to ensure the successful deployment of D2D services in Malaysia. Among the areas that need to be considered under this framework are licensing and spectrum management. Clear and well-defined regulations will provide industry stakeholders with the necessary guidelines to understand compliance requirements and facilitate seamless implementation of D2D services.

In general, regulations related to the space policy cover two main resources: orbital slots and spectrums [58]. The International Telecommunication Union (ITU) manages and coordinates orbital slots. For a telco to deploy a satellite service in Malaysia, it must first submit a satellite filing to obtain international recognition of the mentioned resources. In Malaysia, the Malaysian Communications and Multimedia Commission (MCMC) is responsible for the registration of Malaysia's allotments, assignments, and satellite network filings at the ITU [58]. The Malaysian Space Board Bill 2020 was presented for its first reading in Dewan Rakyat on 3 November 2020 [59]. The aim of the Bill is to set up a Space Board to regulate the space industry in Malaysia. Some of the important guidelines covered in the Bill include licenses to build or manufacture a space object, a launch permit to launch a space object into space, and to register a space object that has been launched into the earth's orbit or beyond with the space regulator [58]. Regarding D2D services, the Communications Minister has tasked the MCMC with evaluating applications related to this emerging technology [56].

As D2D integrates cellular and satellite networks, spectrum management poses a significant challenge. Currently, global industry players utilize two spectrum options for D2D: cellular and MSS spectrum. Cellular spectrum encompasses frequency bands used by mobile network operators (MNOs) for terrestrial communication, including those for 4G and 5G services. MSS spectrum, in contrast, is allocated for satellite communication and utilizes frequency bands such as L-band and S-band [33], [60]. In Malaysia, MCMC governs spectrum management under the Communications and Multimedia Act 1998 (CMA) and the Communications and Multimedia (Spectrum) regulations 2020 [61].

Both cellular spectrum and MSS spectrum have their own advantages and disadvantages [33], [62], [63]. Cellular spectrum requires coordination with regulatory bodies at the country level, which can lead to delays in service rollout. In contrast, the MSS spectrum offers a more straightforward approval process, with some satellite operators already holding landing rights in specific countries. From a consumer perspective, cellular spectrum is more attractive because D2D services can be accessed using standard mobile phones without hardware modifications. MSS spectrum, however, is limited to phones with integrated chipsets that support satellite connectivity, such as the iPhone 14 and Google Pixel 9. In Malaysia, the remaining 3% of populated areas are primarily rural communities, where affordability for high-spec mobile phones may be a significant barrier. Table 2 provides a summary of the advantages and challenges of the two spectrum approaches [33], [62], [63].

Table 2. Advantages and challenges between cellular spectrum and MSS spectrum

	Cellular Spectrum	MSS Spectrum
Regulatory approval	Requires coordination with regulatory bodies at country level, which may result in delays in service rollout.	Approval is typically more straightforward. Some satellite operators already have landing rights in certain countries.
Hardware modifications	Services can be accessed using standard mobile phone without hardware modifications.	Require hardware modifications (chipset) in mobile phone to meet specific satellite requirements.
Scability	Easier to scale with existing mobile phone and MNO infrastructure.	Scaling involves both satellite infrastructure and mobile phone manufacturer
Industry players	Lynk Global, AST Space Mobile, SpaceX	Globalstar, China Telekom, Mobile Satellite Services Association (Viasat, Terrestar Solution, Ligado Networks, Omnispace, Yahsat),

Considering the current achievements in D2D milestones, the global trend of partnerships between satellite operators and MNOs is progressing rapidly. For instance, beyond the United States, SpaceX has established collaborations with MNOs such as KDDI (Japan), Rogers (Canada), Optus (Australia), One NZ (New Zealand), and Salt (Switzerland) [17]. In the Southeast Asia region, Lynk Global has partnered with Globe Telecom, a major MNO in the Philippines [64]. Malaysia could similarly benefit from such partnerships to enhance connectivity in its rural and remote areas. However, careful policymaking is essential to facilitate spectrum sharing while ensuring coexistence between cellular and satellite networks without causing interference to existing services.

4.3. Potential use cases for D2D in Malaysia

D2D technology can be a key enabler in supporting critical use cases in Malaysia. One notable example is its application in disaster management and response. Malaysia is prone to natural disasters such as floods, landslides, droughts, and tsunamis [65]. During such events, reliable communication systems are crucial for effective search and rescue operations. Studies in [65] and [66] highlight the importance of internet connectivity, as victims often use applications like WhatsApp and social media to seek help and provide real-time updates on disaster conditions. However, terrestrial networks, including fiber optic, copper, and mobile networks, depend on ground infrastructure, which becomes unreliable or inaccessible during disasters.

When disasters like floods or landslides occur, MNOs and non-governmental organizations (NGOs) are tasked with quickly repairing damaged infrastructure and providing temporary solutions, such as WiFi access points or amateur radio communication [67], [68]. However, logistical challenges in reaching disaster-hit areas can delay the restoration of connectivity. These temporary solutions, while effective in some cases, may not provide wide coverage, especially during large-scale disasters. D2D technology offers a reliable alternative to ensure continuous communication in affected areas. By bypassing damaged ground infrastructure, D2D enables uninterrupted connectivity, facilitating faster coordination of emergency services. It ensures that first responders and affected communities can maintain access to vital communication channels, enhancing the overall disaster response process.

Another critical use case for D2D technology is border security and surveillance. Geographically, Malaysia's borders encompass two territories: West Malaysia (Peninsular Malaysia) and East Malaysia (Sabah and Sarawak), separated by the South China Sea. The country shares land boundaries with Thailand, Brunei, and Indonesia, as well as maritime borders with the Philippines, Singapore, Thailand, Brunei, and Indonesia [69]. Managing these extensive land and maritime borders requires collaboration among various agencies, including the Malaysian Armed Forces, Royal Malaysia Police, Malaysian Maritime Enforcement Agency, Immigration Department, Eastern Sabah Security Command, Malaysia Border Control Agency, and other enforcement entities [70].

The Malaysian Home Ministry is developing a national border security control master plan to enhance border security [71]. As part of this effort, a feasibility study for a National Border Control System (NBCS) is underway, focusing on incorporating artificial intelligence (AI) technology. In October 2024, RM560 million was allocated under Budget 2025 to strengthen border security, including equipping enforcement agencies with drones and AI technology [72].

In this context, D2D technology can provide critical connectivity for IoT devices in areas lacking mobile coverage. IoT sensors deployed along remote borders can detect unauthorized crossings and smuggling activities, sending real-time alerts to authorities. AI-powered smart surveillance systems can also be implemented, reducing reliance on heavily armed personnel and enhancing safety [73]. UAVs are increasingly used for border patrols [74], [75]. With D2D connectivity, UAVs can be operated remotely over challenging terrain, providing live video feeds to authorities for effective monitoring and rapid response.

5. CONCLUSION

This paper explored the potential of D2D technology as an innovative solution to bridge internet connectivity gaps in Malaysia, particularly in rural and remote regions. It highlighted the progress made by leading industry players and their key achievements in advancing D2D capabilities. The study also examined how D2D aligns with current research on NTN and addressed technical challenges such as Doppler shift, latency, and path loss. Focusing on Malaysia's context, the paper presented current D2D initiatives and emphasized the importance of a robust regulatory framework, especially concerning licensing and spectrum management. Additionally, it explored critical use cases for D2D in disaster management and border security, demonstrating its potential to support essential communication needs where traditional infrastructure is lacking. Moving forward, future research should prioritize simulations to predict coverage areas and assess performance parameters such as achievable downlink and uplink speeds and latency. These efforts, based on existing satellite constellations and Malaysia's specific geographical regions, will be vital for unlocking the full potential of D2D technology and achieving nationwide digital inclusion.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
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Azah Syafiah Mohd Marzuki	✓	✓			✓	✓	✓			✓		✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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