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Survey on Land Mobile Satellite System: Challenges and Future Research Trends

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ABSTRACT Mobile satellite systems can be characterized as a major solution since they offer mobile communication services to users in different environments and for several significant purposes. In numerous conditions, satellite systems have exclusive competences in terms of broad coverage, robustness, broadcast, and multicast capabilities. However, the implementation of Land Mobile Satellite (LMS) systems still faces some limitations regarding connectivity and stability, leading to unreliable communication. Therefore, the target of this paper is to offer a comprehensive overview of land mobile satellite systems and services from various perspectives. This includes the classification of LMS systems, the operating frequency bands, and the representative Mobile Satellite Services (MSS) systems. The research challenges and future research are further described. Such information will contribute to the understanding of satellite systems and the currently faced issues that must be addressed.

INDEX TERMS Land mobile satellite systems, survey study on satellites, satellite, and satellite challenges.

I. INTRODUCTION

To date, modern satellite technology has facilitated our daily communications thanks to the idea of space-based communication, proposed by Arthur C. Clarke in 1945, which included radio communication between three equidistant satellites and the ground. The scientific discovery of geostationary satellites served as the key in the subsequent development of modern satellite technologies [1]–[3]. Both transistor and rocket technologies for military purposes have resulted in the development of communication satellites. Upon the launch of the National Aeronautics and Space Administration (NASA) in July 1958, most technological programs in the United States were classified into two distinct groups, i.e., military and civil/scientific. Upon the emergence of commercial satellites, military satellites were categorized into communication, reconnaissance (or spying), and navigation (or commonly known as GPS) [1], [4].

Since the early 1950s, NASA worked with many organizations such as the Radio Corporation of America (RCA) and Hughes Aircraft Company to determine the essential technologies that would result in making communication satellites feasible. However, all primary studies and analyses of communication satellites were unable to establish an operational communications satellite, yet their engineering data were of importance for later experiments. The first artificial satellite that was successfully positioned in orbit around the Earth was launched on the fourth of October 1957 by the former Soviet Union [5]. That satellite was introduced as Sputnik 1, which is also known as the first successful worldwide weather satellite. This journey for orbiting superiority led to the founding of the nation's early space programs and the launch of Explorer-1 in 1958, the first operational U.S. satellite [6]. The United States' earliest attempts to comprehend Earth's weather from space began in the 1950s. Numerous experimental programs were conducted and by 1959, the Explorer VII satellite was produced. Subsequently, another meteorological satellite was launched by NASA on the first of April in 1960. The satellite was introduced as the Television Infra-Red Observation Satellite (TIROS-1). It was also known as the first successful weather satellite globally. The early geostationary satellites for communication were established and validated in 1963. For example, in 1963 and 1964, Syncom II and III were successfully launched and had transmitted the 1964 Tokyo Olympics via TV. The developments for more efficient systems then continued in the following decades. In 1984, the first mobile satellite research program was conducted by the NASA, named MSAT-X, and was governed by the Jet Propulsion Laboratory (JPL). Since then, significant advances have been

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achieved in LMS systems which made them up-to-date and operational. Satellite networks could support communication services even in remote areas that are not well served by existing terrestrial infrastructures. Their applications include mobile communication in sectors such as land mobile, aeronautics, maritime, transport, rescue & disaster relief, military, etc. Hence, there is renewed interest in MSSs [7].

The LMS system can be defined as a satellite-based communication system that assists terrestrial mobile clients. It provides major advantages to remote lands, sea, and aerial services. Furthermore, it brings efficient service to mobile devices and terrestrial communications. LMS systems are vitally crucial for the third generations (3G), fourth generations (4G) and more broadly for the fifth generations (5G) of wireless systems. With the implementation of the first phase of 5G system, the high throughput Satellites is expected to providing between 50 - 200 Gbps up to 1 Tbps by early 2020s. Moreover, LMS satellites be able to roll-out their provided services in widespread range of spectrum bands, such as: L-Band {1 GHz – 2 GHz}, S-Band {2 GHz – 4 GHz}, C-Band {3.4 GHz - 6.725 GHz}, Ku-Band {10.7 GHz - 14.8 GHz}, Ka-Band {17.3-21.2 GHz, 27.0-31.0 GHz} and Q/V-Bands {37.5 GHz - 43.5 GHz, 47.2 GHz - 50.2 GHz and 50.4 GHz - 51.4 GHz} and other more bands [8], [9]. The 5G network, also, introduces a corporate network architecture to which all other wireless technologies can stick to. Therefore, 5G network will radically change how satellite is integrated into the mainstream of the future wireless networks, achieving full interoperability within the end-to-end 5G network. Previously, satellite manufacturing has played catch-up, where there was a limited integration between satellites systems and the terrestrial mobile communications systems. Although there were attempts to enable integration further, it does not reaching up noticeably to the full integration. But in the future mobile communications networks, there will be more efficient integration between the satellite systems and future mobile networks. With the coming 5G network, there will be a noticeable development in the satellite network from the early stage to interoperate within the future 5G core architecture. Thus, the Satellite can support the targeted key usage scenarios for the 5G system, such as higher data rate, ultra-reliable communications, broadcast and massive Machine to Machine (M2M), connections and IoT applications. Moreover, the satellite will be part of the future 5G ecosystem. The most four satellite ''Sweet Spots'' that will be available in the next 5G Ecosystem are: (i) Trunking and Head-End-Feed, (ii) Backhauling and Tower Feed, (iii) Communications on the Move, and (iv) Hybrid Multiplay. The importance of these systems is significantly rising for several applications such as massive Internet of Things (IoT), Machine to Machine (M2M), Device-to-Device (D2D), mobile broadband (MBB) communications, broadcasting, etc. To compare with Land Mobile Terrestrial (LMT) systems, LMS systems provide services that are unattainable in LMT systems. LMS systems offer an efficient and more economical service to LMT system clients.

Satellite mega-constellations is another significant axis in the coming satellite systems that need deep studies and strategic planning. As it will contribute to the integration between the space and terrestrial systems, it is also considered as a threat to the future of space. In the near future, there will be several hundred to thousands of slightly small sized Satellites, which will be deployed to provide various services. The key driver of these mega-constellations is to deliver global internet coverage, to everywhere at any time even to the remote and isolated areas. SpaceX and OneWeb are the most successful Satellite mega-constellations that will be widely implemented in the near future [10]. In 2017, the U.S. Federal Communications Commission (FCC) imposed rules demanding constellation operators to launch half their permitted number of satellites within the first six years of getting U.S. approval, and the complete constellation within nine years of getting the approval [11]. Failure to meet those milestones caps the authorization at the number of spacecraft launched before the clock ran out. OneWeb, which was granted U.S. market access in 2017, has until 2023 to launch 360 of its permitted 720-satellite constellation. SpaceX, which received approval in 2018 for 4,425 satellites, has until 2024 to orbit at least half that total [11].

The emergence of satellite-based mobile communications has led to a growing number of studies related to land mobile satellite channel in multiple frequency bands. LMS systems can be used to actualize global personal communication networks [12], [13] by providing services such as finding location, radio paging, interconnection to the public switched telephone & private networks, voice communication, and data transmission to various terminals such as land vehicles, marine vessels, aircrafts, remote data collection with control sites, and moveable terminals.

On the other hand, there are some limitations that are faced by the implementation of LMS systems [13]–[15]. The communication channel between a satellite and a land-based mobile client is still one of the critical challenges that degrade communication reliability. Multipath interference and shadowing represent the main challenges that can cause serious changes in the received power, resulting in restricted system performance in terms of outage probability [16] and [17] and other key performance indicators [18]–[20]. Satellite orbits can be classified into four major types: geostationary orbit (a significant geosynchronous orbit), highly elliptic orbit (HEO), medium Earth orbit (MEO), and low Earth orbit (LEO); each of these orbits offers various advantages and disadvantages.

Consequently, this paper provides a comprehensive overview of Land Mobile Satellite systems. The classification of LMS systems is described, including Geostationary Earth Orbit Systems, Medium Earth Orbit Satellite Systems, Low Earth Orbit Satellite Systems, and Highly Elliptic Orbit Satellite Systems. The operating frequency bands used in these satellite systems are also highlighted. Moreover, the representative MSS systems are discussed, including the INMARSAT, IRIDIUM, GLOBALSTAR and

FIGURE 1. Sputnik 1, the first artificial satellite successfully positioned in orbit around earth lunched on the fourth of October 1957 [5].

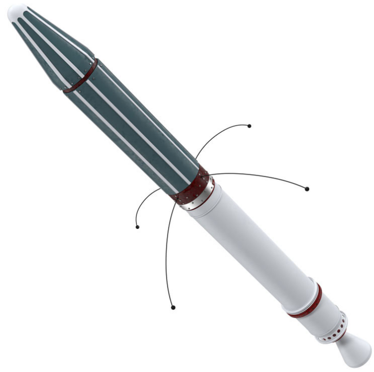

FIGURE 2. Explorer-1, the first operational U.S. satellite [6], lunched in 1958.

THURAYA services. Research challenges and future studies are briefly described. Such information will contribute to the understanding of satellite systems and the currently faced issues that must be addressed.

II. OVERVIEW ON SATELLITES

Satellites revolve around the Earth in a circular or elliptical path. Nowadays, satellite communication systems serve as relays and amplifiers for enabling radio communication between a transmitter and a receiver at two different places on Earth. They are also introduced as objects that revolve around a planet in a circular or elliptical path. The idea of using satellites stems from Arthur C. Clarke where each satellite is connected to other satellites as well as to the receiver on the ground for worldwide communication. The invention of geostationary satellites is the key for subsequent development of modern satellite technologies [1].

As previously mentioned, both transistor and rocket science technologies have formed the foundation of modern satellite technology. Upon launching the civil space program in 1958 by NASA, satellite programs have been tailored for military and civil/scientific purposes. Commercial satellites came next, mainly designed for communication and navigation purposes such as the GPS [1], [4].

Since the early 1950s, NASA worked with many organizations such as the RCA and Hughes Aircraft Company to determine the essential technologies that would result in making communication satellites feasible. However, all initial research and analyses of communication satellites failed to lead to an operational communications satellite, yet their engineering data were of importance for later experiments. The first artificial satellite successfully positioned in orbit around the Earth was launched on October 4, 1957 by the former Soviet Union [5]. That satellite, as illustrated in Figure 1, was introduced as Sputnik 1, which is globally known as the first successful weather satellite. This journey for orbiting superiority led to the founding of the nation's early space programs and the launch of Explorer-1 in 1958; the first operational U.S. satellite [6], as presented in Figure 2. As previously mentioned, the United States' earliest attempts to assess Earth's weather from space began in the 1950s. Numerous experimental programs were conducted and by 1959, the Explorer VII satellite was produced, as displayed in Figure 3. Subsequently, NASA launched another meteorological satellite on April 1, 1960. The Satellite was introduced as TIROS-1, as illustrated in Figure 4. It was also known as the first successful worldwide weather satellite. The early geostationary satellites for communication were established and validated in 1963. In 1963 and 1964, Syncom II and III were successfully launched by transmitting the 1964 Tokyo Olympics via TV. The developments for more efficient systems then continued in the following decades.

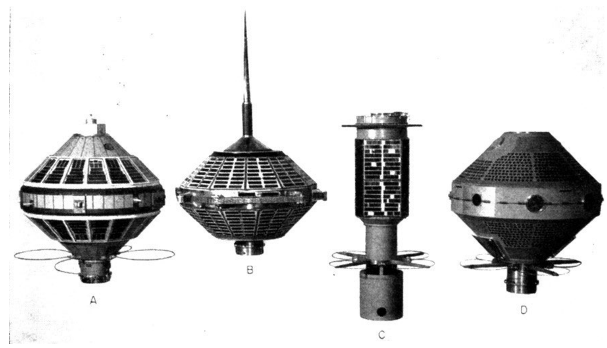

FIGURE 3. Explorer VII, lunched in 1959.

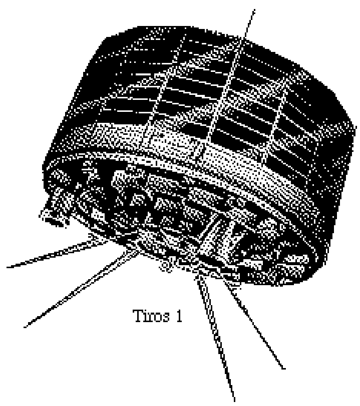

FIGURE 4. TIROS-1, the first meteorological satellite lunched by NASA on the first of April 1960.

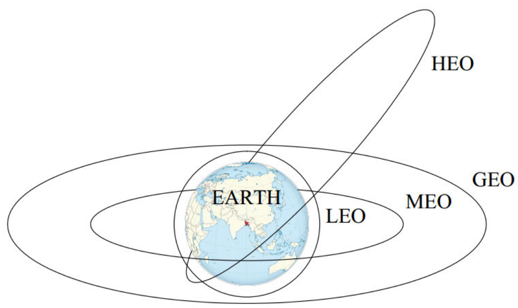

FIGURE 5. Types of satellite Orbits [22].

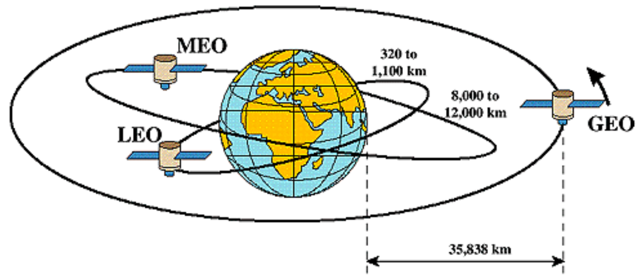

FIGURE 6. Geostationary earth orbit [22].

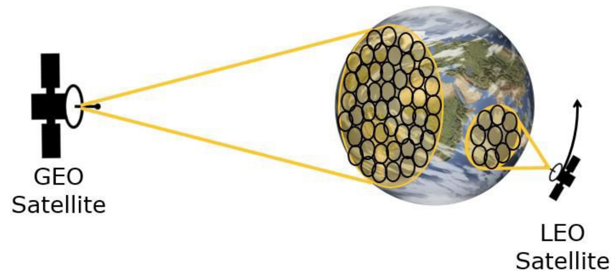

FIGURE 7. Coverage of geostationary earth orbit [24].

NASA launched the first mobile satellite research program called MSAT-X in 1984. Thereafter, LMS systems became fully operational, leading to the growth of worldwide communication services. Players in sectors such as automotive, aeronautical, maritime, rescue & disaster relief, military, etc., heavily rely on mobile communication services. Therefore, market opportunities are present for MSS [7].

The LMS system can be defined as a satellite-based communication system that assists terrestrial mobile clients. It provides major advantages to remote lands, sea, and aerial services. It also brings efficient service to mobile devices and terrestrial communications. LMS systems are extremely crucial for the third and fourth generations of wireless systems. The importance of these systems is significantly rising for numerous applications such as communications, broadcasting, etc. Compared to LMT systems, LMS systems bring services that are not attainable in LMT. LMS systems offer an efficient and more economical service to clients of LMT systems.

The benefits offered by satellite-based mobile communications have triggered the interests of many researchers in studying the land mobile satellite channel in multiple frequency bands. Seemingly, LMS can be adopted to realize global personal communication networks [12] since they provide global positioning service and facilitate communication between a wide range of users.

III. CLASSIFICATION OF LMS SYSTEMS

The land mobile satellite systems can be classified in terms of satellite orbits, either static or non-static orbit systems, which are also known as synchronous or asynchronous orbit systems, respectively. The most known static orbit system is identified as the Geostationary Earth Orbit (GEO) system. Non-static orbit satellites have two main classes: circular and oval orbits. The circular orbit mobile satellite communication system has two different types: the MEO and the LEO. The oval type is the satellite with an elliptical orbit shape. Most of Earth's satellites are placed in the oval orbit. HEO is one of the oval orbits. These four different types (GEO, MEO, LEO, and HEO) are further explained in the following subsections. Figure 5 presents a brief illustration of the different types of satellite orbits [21].

A. GEOSTATIONARY EARTH ORBIT SYSTEMS

The approximate GEO satellite altitude and substitute is located $\sim$ 36000 km above the ground [22] and rotates on its orbit at the same angular speed as that of the Earth around its axis. Hence, GEO remains at the same spot on the Earth's equator as the Earth rotates [21]. This means the GEO system coordinates with the Earth's rotation. The Earth needs 23 hours, 56 minutes, and 4.09 seconds to rotate on its axis, and that is the same time needed for the GEO system to rotate on its axis. The coverage provided by GEO will be only for the area located directly in front of the satellite, but it is wider than what can be provided by the LEO satellite, as illustrated in Figure 7. According to [23], three satellites can generally provide global coverage. They can cover utmost of the earth's area, but, the polar locations cannot be covered by GEO satellites, since there is a maximum latitude (approximately 81° degrees if we consider the horizon, but for communications maybe it is even 75° degrees) that can be covered from this type of orbit. Of course, visibility worsens at higher latitude and is poor in built-up areas. In this case, terrestrial and low-orbit satellite systems are more effective as no handover is needed during connection.

Due to the high operating frequency of the GEO satellite, it is recommended to employ GEO satellites for fixed communication while having large antennas on the Earth stations. Numerous GEO systems have been used to offer services to mobile clients. According to King (2007), mobile terminal antennas can nowadays provide a link with much wider beam footprints in order to enhance user mobility. Land mobile satellite services powered from GEO satellite systems are now available in regions such as Europe, North America,

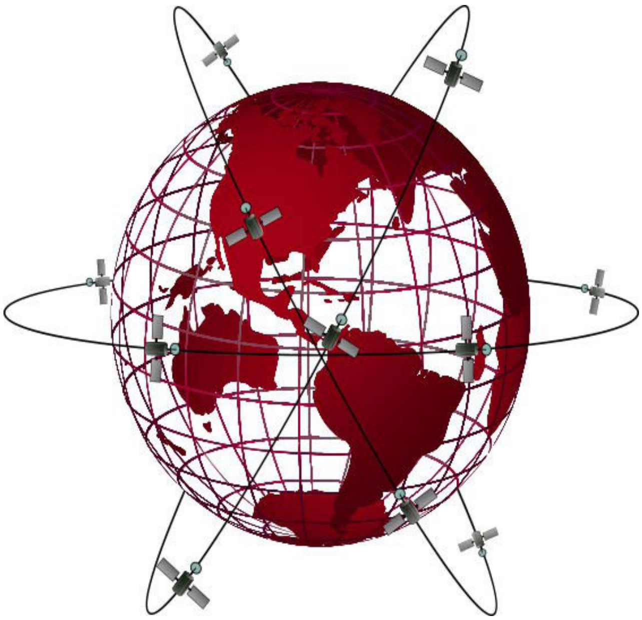

FIGURE 8. Medium earth orbit [22].

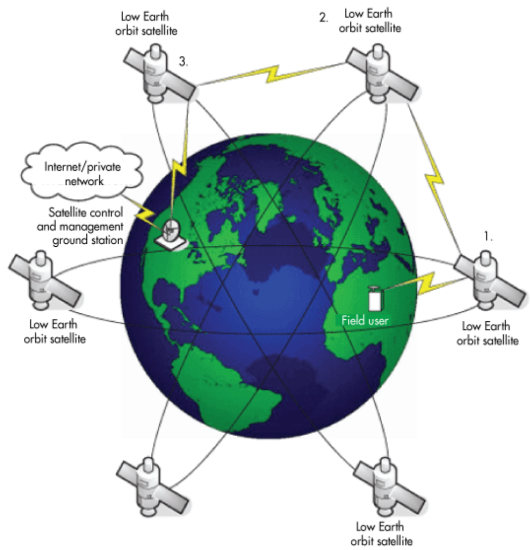

FIGURE 9. Low earth orbit (LEO).

Australia, Middle East, and South East Asia. The service providers are Inmarsat, Euteltracs, Emsat, Optus, N-Star, Msat, Aces, and Thuraya. Currently, GEO satellites are used as TV satellites, radio broadcasting satellites, weather satellites, etc. This serves as the backbone for telephone networks as well. Since it is troublesome to directly communicate with personal terminals on the ground, non-static orbits are adopted for most mobile satellite communication systems.

B. MEDIUM EARTH ORBIT SATELLITE SYSTEMS

The height of the MEO satellite ranges from 8000 km to 12000 km above the ground. Since it is closer to the Earth (relative to GEO), the end-to-end latency in data transfer is much lower and the link budget condition is better [25]. However, the number of MEO satellites needed to cover the entire Earth is higher ($\sim$30). In other words, the handover operation is more frequent [7]. A single MEO satellite can only be used in store-and-forward mode for localized coverage. In order to optimize the link, more satellites should be employed to ensure higher guaranteed minimum elevation angle to the user [26]. A MEO satellite system is currently employed in GPS (owned by the US military), Glonass (Russia), and Galileo (Europe) navigation systems. However, there are only a few MEO satellite systems (e.g. ICO) used for mobile satellite communication services [23].

C. LOW EARTH ORBIT SATELLITE SYSTEMS

LEO satellites are located within 300 km to 1500 km above the ground and experience shorter period between 95-120 minutes (see Figure 9). In fact, the elevation of LEO satellites determines the quality of the communication link. The visibility of a LEO satellite is deeply affected by the exact altitude and the minimum elevation angle that is required by the considered system. Typically, it is visible for about 10 to 20 minutes at a time [27], [28]. In practice, multiple orbital planes should be used. An handoff procedure is necessary to enable communication between two Earth stations [21]. Orbcomm, Iridium, Globalstar, and Constellation Communications have provided mobile satellite voice/data services from LEO systems during the nineties. However, this business was unsuccessful as terrestrial mobile communications could provide cheaper service at higher quality [23]. Currently, LEO systems are mainly employed for military operations and communications in barren regions.

LEOs can be further classified into little LEOs ($<$ 1 GHz, up to 10 kbps) and big LEOs ($>$ 1 GHz). Both Code-division multiple access (CDMA) and the S-Band (about 2 GHz) can be applied [21]. Little LEOs are mainly used for paging, burst communication, tracking, equipment monitoring [25], and low-rate messaging. Orbcomm was the first operational little LEO launched in April 1995. Its operating frequency is between 138.00 MHz to 150.05 MHz. There are about 30 little LEO satellites used to support subscriber data rates of 2.4 kbps (upload) and 4.8 kbps (download) [25]. The services offered by big LEOs are almost similar to those of small LEOs, with the addition of voice and positioning services. For example, big LEO (such as Globalstar) requires no onboard processing between satellites since most processing is performed by the Earth's stations. Globalstar is linked with traditional voice carriers [25].

D. HIGHLY ELLIPTIC ORBIT SATELLITE SYSTEMS

A highly elliptic orbit satellite is located further away from LEO and MEO satellites, i.e. an apogee ranges from 40000 km to 50000 km and a perigee ranges from 1000 km to 20000 km (see Figure 10). Typically, the speed of HEO satellite is lower than that of LEO and MEO satellites, as shown in Figure 11. Examples include Telstar and many Russian communication satellites. During the perigee phase,

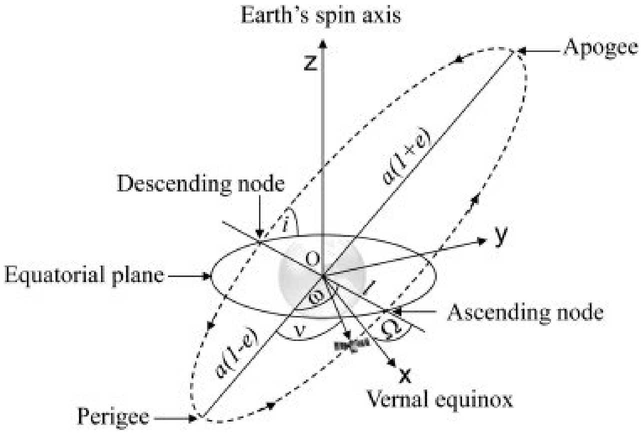

FIGURE 10. Highly elliptic orbit [30].

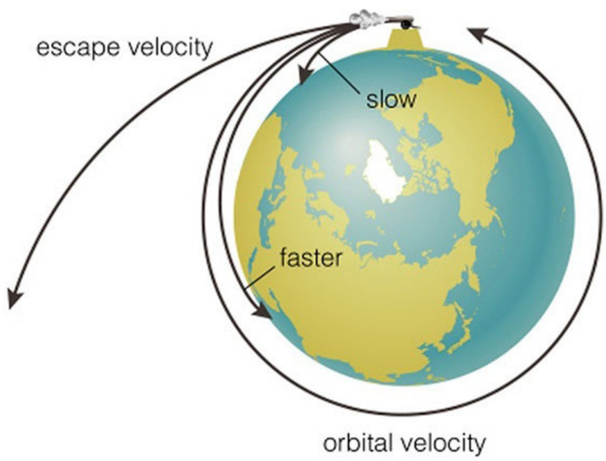

FIGURE 11. Impact of orbit velocity of the object on the orbiting earth [31].

the HEO satellite is closer to Earth and appears to travel at a higher speed (opposite to that during the apogee phase) [1]. Therefore, most communications satellites operate in the apogee phase for easier tracking. To ensure continuous communication, multiple HEO satellites and ground stations are required. HEO satellite is good for regional coverage, but the angle of inclination must be 63.14° [29]. This is a serious drawback for satellite coverage of locations with lower latitudes. Increased flexibility can be achieved by manipulating the inclination angle of circular orbit planes between 0° and 90°.

IV. OPERATING FREQUENCY BANDS

A major part of communication satellites technology is the operational frequency of transmitters and receivers. The method for information transmitted to/from the satellite is accomplished by electromagnetic waves or radiation such as radio waves, visible light, X-rays, etc. Electromagnetic waves represent the basic approach to exploit satellites or platforms of high elevation. In communication, the efficiency of manipulating and detecting electromagnetic (EM) waves is

TABLE 1. ITU frequency range designations relevant" to satellite applications.

Acronym	Designation	Frequency Range
VHF	Very High Frequency	30–300MHz
UHF	Ultra-High Frequency	300MHz–3 GHz
SHF	Super High Frequency	3–30 GHz
EHF	Extremely High Frequency	30–300 GHz

TABLE 2. IEEE (radar) band designations.

Band	Frequency Range
L	1–2 GHz
S	2–4 GHz
C	4–8 GHz
X	8–12 GHz
Ku	12–18 GHz
K	18–27 GHz
Ka	27–40 GHz
V	40–75 GHz
W	75–110 GHz

of great importance. The International Telecommunications Union (ITU) has designated several broad radio-frequency and generic bands, as shown in Table 1 [32].

Since the ITU designations are rather broad, it is now more common to adopt the band designations set by the Institute of Electrical and Electronic Engineers (IEEE) [33], as shown in Table 2.

Although most current mobile satellite services operate in the L and S bands, greater demand for bandwidth means that some services are now operating from VHF up to Ka bands. The MSS, with allocated frequencies in the L and S-bands, have a greater degree of refraction and better penetration of physical obstacles such as foliage and non-metallic structures. However, low frequency bands such as L and S-bands were not enough to satiate the growing desire for high data rate and broadband services; therefore, real steps have been taken in order to use higher frequency bands such as Ka (20-30 GHz), Q/V (40-50 GHz), or EHF (20-45 GHz) bands in Land Mobile Satellite systems. As a result, the first commercial satellites with Ka-band transponders are now in operation [34].

During the World Administrative Radio Conference (WARC) held in 1987, ITU had allocated specific spectrums to mobile-satellite services in the L/S-bands (details can be found in [35]). Since the European regulatory framework for the use of L/S-bands by MSS has become obsolete, the European Commission consulted the MSS manufacturers and operators for the use of 2x30MHz bandwidth in L/S-bands (i.e. the band (1980–2010) MHz in uplink and (2170–2200) MHz in downlink). The decision was welcomed by many MSS operators [7].

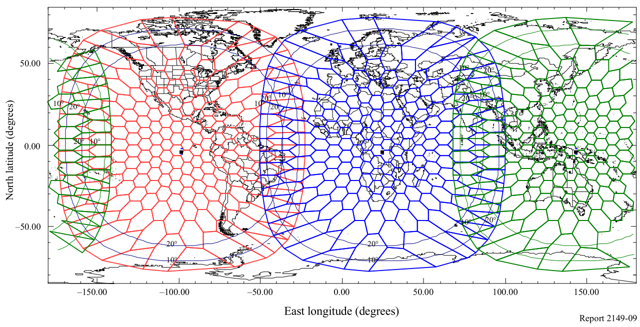

FIGURE 12. **Inmarsat spot-beam coverage [38].**

L/S-band technology has been used for decades as it accommodates small onboard antennas and experiences minimal signal attenuation and atmospheric interference. However, due to limited L/S-band resources and the increasing popularity of broadband services, Ku and Ka bands have been given more priority of late for MSSs. To date, Ku-based MSSs are used to provide broadband services in transportation. ITU-R assigned Ka band frequency portions to MSSs and Fixed Satellite Systems (FSSs) on a primary basis, while Ku band frequency portions to MSS are on a secondary basis. However, the coverage of Ku-band satellites is poor overseas because these satellites focus on landmasses [36].

V. REPRESENTATIVE MOBILE SATELLITE SERVICES (MSS) SYSTEMS

The era of MSS began in 1979 upon the launching of the Marisat satellite by COMSAT (USA). On the other hand, the era of public mobile satellite service began upon the establishment of the International Maritime Satellite Organization (Inmarsat) initialized by the International Mobile Organization (IMO) [32]. In this section, some MSS systems, such as Inmarsat (ICO), Iridium, Globalstar, and Thuraya, are discussed.

A. INMARSAT

Inmarsat was founded in 1979 to serve the maritime industry. To date, Inmarsat provides broadband communication services to aeronautical players (e.g. Boeing and Airbus airplanes [7], [37]) and enterprises via GEO satellites [7]. The Broadband Global Area Network (BGAN) system is one of the most innovative systems developed by Inmarsat to provide services such as telephony, Internet, messaging, etc., via the three Inmarsat-4 satellites. Various parameters can be manipulated to enhance transmission efficiency.

According to ITU (ITU-R M.2149-1), during emergencies (e.g. damage of local infrastructure) and natural disasters, Inmarsat terminals can be deployed to establish an early warning network where the data from monitoring sensors can be transmitted to a central command center. The Inmarsat spot beam coverage and system components are shown in Figures 12 and 13, respectively [7].

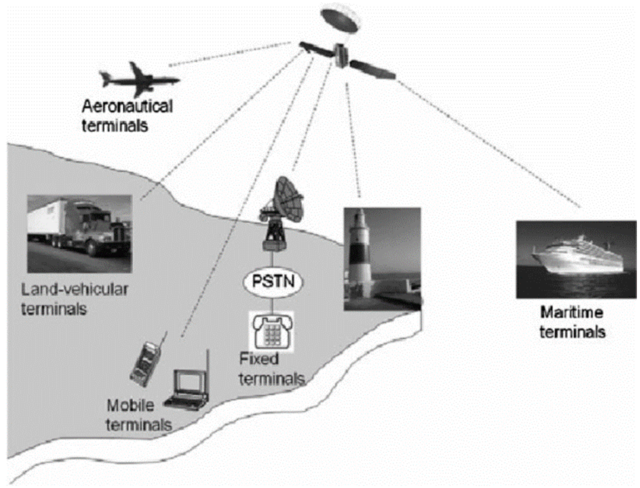

FIGURE 13. **Inmarsat system components.**

1) LAND EARTH STATIONS IN INMARSAT:

IMO does not own any Earth stations connected to the Inmarsat satellites. These Earth stations (better known as Land Earth Stations (LES), Coast Earth Stations (CESs) for maritime, and Ground Earth Stations (GESs) for aeronautical services), are used to bridge the satellite network of IMO and terrestrial telephone, data, and telex networks. Normally, LES operators purchase LES devices from satellite telecommunications equipment vendors specializing in INMARSAT LESs [1].

There are four INMARSAT satellite regions: the Atlantic Ocean Region-East (AOR-E), the Atlantic Ocean Region-West (AOR-W), the Indian Ocean Region (IOR), and the Pacific Ocean Region (POR) [1]. Therefore, four LESs are required to provide global coverage. In practice, the LES operator would seek assistance from other LES operators to access the global network.

2) INMARSAT SYSTEM SERVICES

a: INMARSAT MARITIME SAFETY SERVICES

The INMARSAT system offers maritime safety services via the INMARSAT-A, -B, and -C platforms. There is a feature called "distress call" whereby a simple action (e.g. pressing a button of the satellite terminal in the ship) would trigger the sending of an emergency message to CESs and Ship Earth Stations (SESs). The distress call would then be channeled to a rescue coordination center (e.g. coast guard station [1]) at the frequency of 1645.5–1646.5 MHz. The distress call is prioritized over other calls. Some government-owned INMARSAT satellites support internationally recognized emergency reporting service known as Emergency Position-Indicating Radio Beacons (EPIRBs) [1]. In fact, many of these INMARSAT services are tailored to meet the requirements of special users. In this paper, INMARSAT-A, INMARSAT-C, and INMARSAT-M services are reviewed.

INMARSAT-A (initially known as ''Standard A'') is inherited from the MARISAT service offered in 1976. There were ~20,000 INMARSAT-A terminals with unique identification numbers (Mobile Earth Stations (MESs)) in the 1990s (peak era), whereby most of them (~80%) consisted of Ship Earth Stations (SESs). The others have been used in smaller suitcases, motor vehicles, and remote fixed configurations.

INMARSAT-C services were launched in 1991 to serve small MESs that employ miniature and omnidirectional antennas. They work based on the simple store-and-forward concept, thus avoiding real-time or duplex end-to-end communications. For data transmission, the MES operator provides the required input data (e.g. identification number, number of MESs, and INMARSAT ocean regions) to the selected LES.

INMARSAT-M was launched in 1992 for fax and data transmission. The supported data transfer rate is up to 4.8 kb/s by using small directional antennas. It can be installed on a ship deck and a briefcase terminal. INMARSAT-M is well-known for its real voice regeneration.

B. IRIDIUM

Iridium is a global digital cellular system designed for commercial mobile communication with low traffic density and high terminal population. It is attractive since its terminal is small and exhibits insignificant communication delay. Nevertheless, its implementation cost is relatively high [35]. The name Iridium stems from the fact that 77 low flying communications satellites are used for communication purposes, mimicking the iridium atom that contains 77 electrons around its nucleus [1], [26], [32].

In February 2007, Iridium launched the Iridium Next Initiative by heavily investing on network enhancement. It became fully operational in 2016 [1]. There are 66 satellites in the Iridium system located at the altitude of 780 km on six polar orbit planes. These orbital planes are near-polar with an inclination of 86.4°. The satellites of this system support complete information exchange via inter-satellite links. The general constellation topology used in the Iridium system and its schematic diagram are shown in Figures 14 and 15, respectively [7], [26].

The Iridium system is proposed to be in complete cooperation with the existing terrestrial system. The dual-mode hand-held transceivers of Iridium would first try to access local cellular telephones before using the satellite system. If it is not possible to use the terrestrial systems, because of long distance or overload traffic on those systems, the terminal would automatically switch to its satellite mode. Motorola has proposed bidirectional operation in the L-band (1616–1626.5 MHz); that is, the same frequencies would be used for uplinks and downlinks on a timeshared basis. Messages from one telephone to another would be transmitted from the hand-held unit to the satellite and then transmitted from the satellite to the satellite using Ka-band

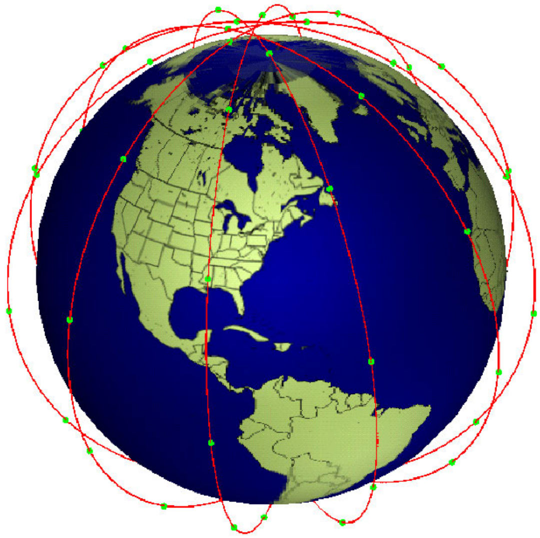

FIGURE 14. Iridium constellation topology in LEO System [39].

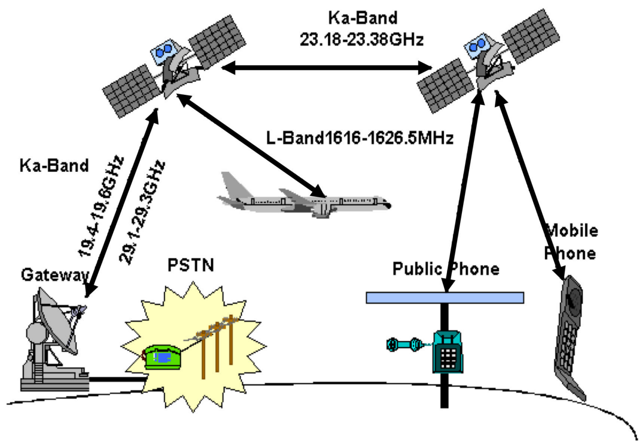

FIGURE 15. Iridium system overview [40].

(23.18–23.38 GHz) intersatellite links until the satellite viewing the destination telephone is reached [26].

C. GLOBALSTAR

Globalstar, a company based in the US, provides personal mobile satellite telecommunication services since 1999 such as the Internet, private data network connectivity, positioning, short messaging service, and call forwarding to more than 120 countries; mainly from the mid-latitude region [32]. Several LEO satellites at the altitude of ~1500 km are deployed in the Globalstar system to provide global coverage, as shown in Figure 16 [1], [32].

The system combines the strengths of the LEO satellite and spread spectrum CDMA technologies. The latter can provide more efficient power control and vocoder with voice activation and satellite diversity using the soft handover technique. In fact, this system relies on frequency division/spread spectrum/CDMA for accessing satellite via

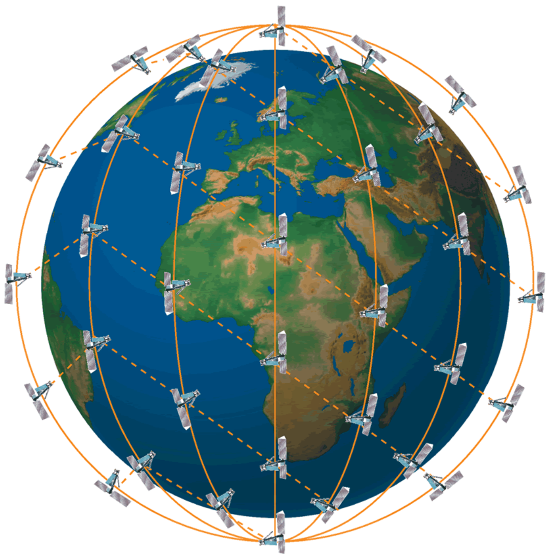

FIGURE 16. Globalstar constellation topology in LEO System [41].

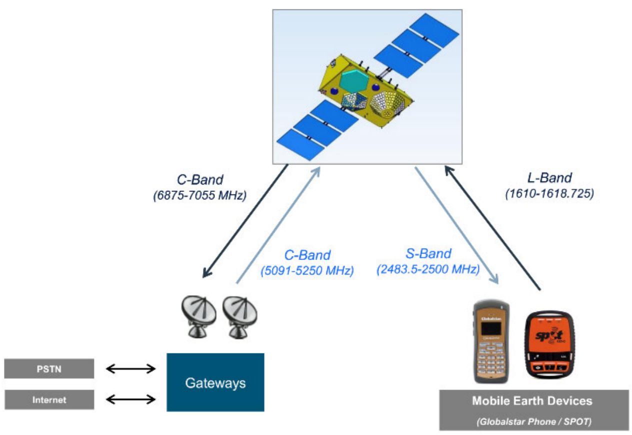

FIGURE 17. Globalstar bent-pipe network architecture.

the forward (S-band) and return service links (L-band). The details can be found in [25], [32]. In contrast to the little LEO systems, the Globalstar system requires no onboard processing between satellites. It is integrated with traditional voice carriers, and calls are processed via Earth stations. In order to route long-distance calls, the bent-pipe approach is adopted; its architecture is shown in Figure 17 [25], [37].

D. THURAYA

Thuraya was founded in the United Arab Emirates (UAE) in 1997 by several prominent national telecommunications operators and international investment houses. The Thuraya system was initiated in year 2001 with an anticipated life-span of 12 years [26]. It owns and runs two L-band geostationary mobile satellite systems in order to provide telecommunication services to small hand-held and portable terminals in several nations, as shown

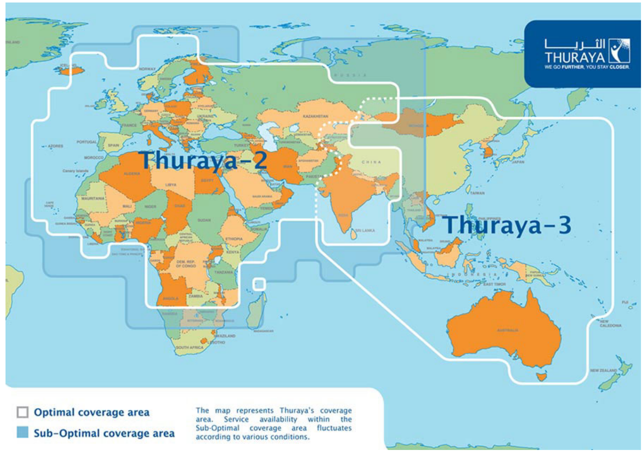

FIGURE 18. Thuraya coverage map for Thuraya-2 and Thuraya-3.

in Figure 18. Its customers are mainly from sectors such as energy, government, broadcast media, maritime, military, aerospace, and humanitarian Non-Govemmental Organizations (NGOs).

The system allows one to switch between satellites and terrestrial networks. Also, the voice quality of the Thuraya telephone service is on par with that of Global System for Mobile Communications (GSM). The details of the operating frequency bands of the mobile link can be found in [26], [32]. The services offered are telephony, fax, data, short messaging, positioning (via GPS), emergency services, and high-power alerting. The userbase of Thuraya's service has been extended to rural and maritime environments [32]. For maritime communication, the packet data rate is up to 60 kb/s. A distress button can be triggered to initiate emergency communication.

VI. RESEARCH CHALLENGES

Satellite communication systems suffer from several challenges and limitations. In this study, the significant challenges related to signal propagation are highlighted in the following subsections.

A. HIGH PROPAGATION PATH LOSS

The effective use of high-altitude platforms is dependent on the efficiency of EM wave propagation through the Earth's atmosphere [32]. Generally, the quality of service (QoS) of land, aeronautical, and maritime types of mobile terminals is heavily dependent on the environmental factor. However, the location of fixed Earth stations or gateways can be optimized to ensure maximum visibility with the satellite at all times. For frequency of more than 10 GHz, the propagation impairment is mainly due to natural phenomena such as rain [26]. In general, propagation environments that obstruct the propagation of satellite signals can be classified into ionospheric, tropospheric, and local; as shown in Figure 19 [26], [34].

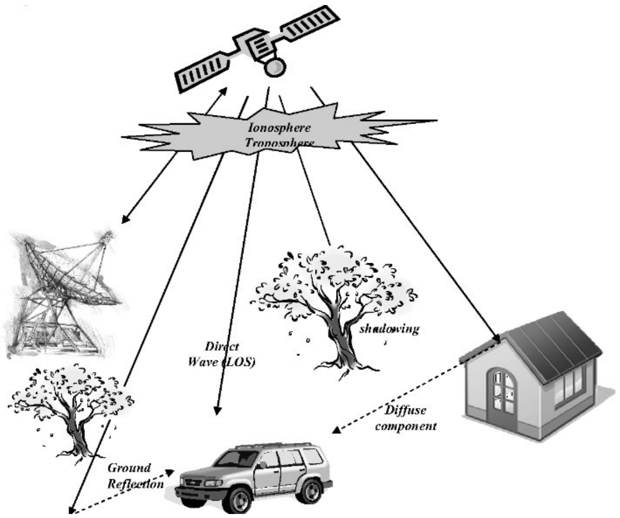

FIGURE 19. Mobile network propagation components.

The **ionosphere** is the top layer of the Earth's atmosphere with 50 km–1000 km of elevation. In this region, absorption, scintillation, and polarization rotation are some of the common propagation impairments. Absorption occurs due to the combination of ions and electrons. Non-uniform refractive index of the ionosphere region leads to scintillation. Lastly, polarization is dependent on the orientation of the EM field [1], [26], [42]. Generally, the strengths of these impairments decrease with respect to frequency [42]. Therefore, ionospheric effects are more pronounced for operating frequencies below 3 GHz.

The **troposphere** is the bottom layer of the Earth's atmosphere that extends above the ground to the height of 7 km - 20 km. Tropospheric effects are more evident in waves of above 3 GHz. These effects mostly stem from air and rain.

As shown in Figure 20, there are three basic propagation mechanisms that influence the propagation of EM waves in a mobile communication system: reflection, diffraction, and scattering. Reflection occurs when the EM wave impinges on a very large object. Diffraction arises when the radio path between the transmitter and receiver is retarded by a surface with sharp edges. The sharp edge acts as a new source, causing the wave to travel in a different direction. Scattering takes place when the propagation medium consists of many small objects (smaller than the EM wavelength); e.g. rough surfaces in the channel.

B. BUILDING PENETRATION LOSS

Serving indoor users remains as a very challenging issue. The associated challenges are entry loss and information delay. In fact, the entry loss is the most critical one. Delay, however, is in the order of several tens of nanoseconds. These issues arise due to the blocking of direct EM signals as the wave hits the external wall of a building [43]–[45]. The operation of satellite systems is severely degraded in

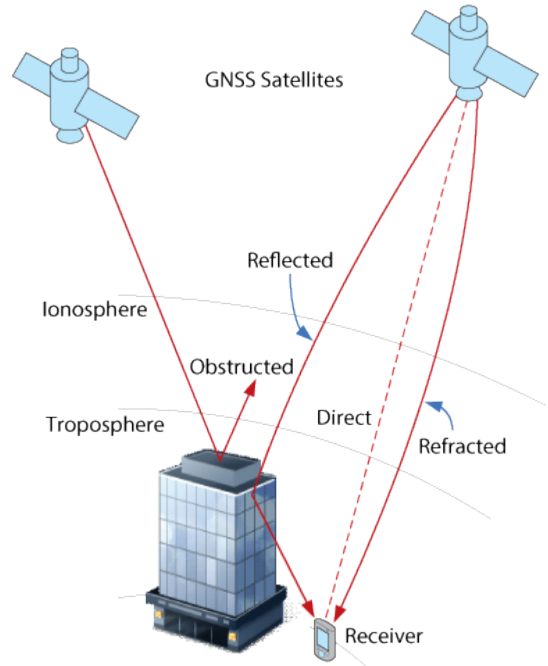

FIGURE 20. The basic propagation mechanisms.

the presence of heavy shadowing, especially when the direct link between the satellite and the terrestrial destination is blocked by obstacles [46]. There is a solution has been proposed to solve this issue, in which is introduced as a hybrid satellite-terrestrial relay network [47]–[51]. This solution aims to offer low-cost coverage for populated/urban areas by maintaining non-line-of-sight (NLOS) connections. Although it has the capability for contributing further coverage, an issue related to the blocking signal is still a challenge.

C. SATELLITE PROPAGATION DELAY

The time taken for a signal to travel between locations on a transmission path is known as the propagation time. Coupled with the radio signal propagation speed, the distance from the GPS satellite can be accurately computed (known as pseudo-ranging). In order to calculate the propagation time (see Figure 22), the clocks in the GPS satellite and the GPS receiver are first synchronized. From Figure 22, a GPS satellite transmits a specific coded message at a particular time. The GPS receiver would then search for the respective code. If a match is found, the difference between current time and sending time is taken as the propagation time.

D. RAIN ATTENUATION

In tropical and equatorial countries, rain attenuation is the main impairment; particularly for signals of frequency > 10 GHz (see Figure 23). At the high frequencies bands, additional rain attenuation causes severe signal losses and resulting in a major threat for the system accessibility,

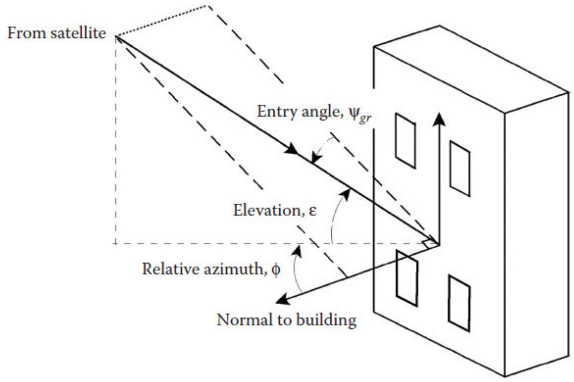

FIGURE 21. Outdoor-to-indoor Propagation Geometry.

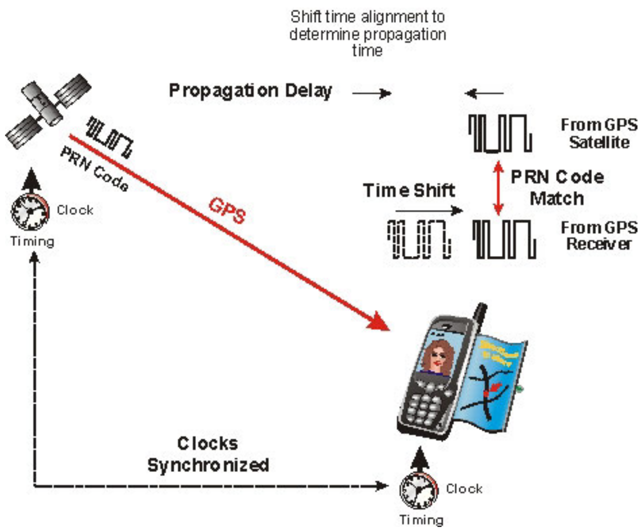

FIGURE 22. Satellite signal propagation delay.

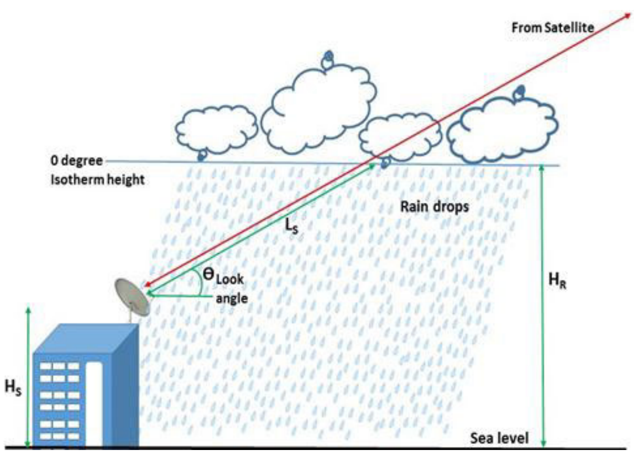

FIGURE 23. Impact of rain on satellite propagation signal.

particularly in the tropical region like Malaysia as it is characterized by heavy rain rates overall the year. Figure 24 shows the rain attenuation in dB based on different frequency bands. The results are estimated by using long-term radar

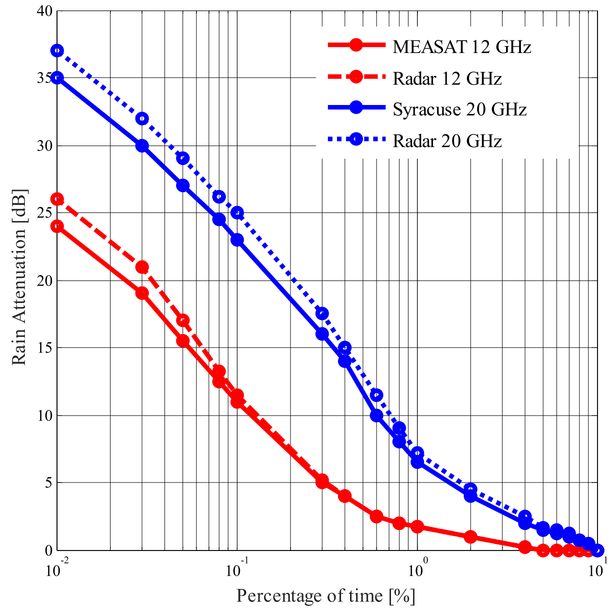

FIGURE 24. The rain attenuation (dB) is exceeded for both beacon receiver's measurement and predicted by radar simulation.

measurements in south Malaysia (Johor Bahru), by exploiting the horizontal structure of rain from the radar database and simulating inner-city and highway mobile terminals scenarios [52]. The results indicate that the resulted attenuation due to rain is a significant issue needs to be addressed in the coming satellite systems. Furthermore, the rain drops lead to scattering and absorption of EM wave energy. Consequently, Ku/Ka-band broadcasting services experience frequent link outage, especially during rainy days. Therefore, the design of satellite service is dependent on parameters such as estimated duration of rain fade, rain time, and rain frequency [43]–[45], [53], [54].

Most of the deference in LMS comes from the mobility feature of the ground terminal, whereas this movement changes the surrounding environment, elevation angles, and the climate gradually or rapidly; hence the LMS channel is strongly environment-dependent. The knowledge of rain drop size distribution (DSD) is essential to make an accurate estimation of the attenuation experienced by electromagnetic waves travelling through rain. Although there have been numerous studies to understand, parameterize, and estimate DSD from various locations, large uncertainties remain in the temporal variability of DSD and their dependence on rainfall types and climatological regimes.

In addition to the specific attenuation estimation, an improved slant path rain attenuation model, specifically for heavy rain regions, is also necessary. This is due to the typically lower prediction accuracy of the models currently available (with respect to temperate regions). Many uncertainties are critical in equatorial regions where there are only limited experimental results of DSD available. Therefore, it is worthwhile to further investigate and estimate the natural characteristics of DSD in Malaysia with respect to existing experimental database and several well-known DSD models from the established literatures.

The specialty of LMS systems require unique treatment when designing them, considering that the channel modeling should not assess the mobility and rainfall effects separately. Therefore, propagation models should be used in order to improve the Fade Mitigation Techniques (FMT). We expect that this will enhance the matching of the link budget to the propagation conditions in real time, especially the rain and mobility of the ground unit. In fact, rain fields derived by weather radars are a useful tool for the simulation of those FMTs based on the temporal and spatial variabilities of rain.

VII. FUTURE RESEARCH

Based on the previous review in this study, there are several issues that must be addressed in this area of research, as listed in the following:

- The communication channel between a satellite and a land-based mobile client is still one of the critical challenges that degrade communication reliability. Multipath interference as well as shadowing represent the main challenges that can cause serious changes in the received power, resulting in restricted system performance in terms of outage probability [12] and [13], interference [55], throughput [20] and other key performance indicators [18], [19]. Satellite orbits can be classified into four major types: geostationary orbit (GEO – a significant geosynchronous orbit), HEO, MEO, and LEO; offering various advantages and disadvantages.
- Investigating the propagation of LMS satellite signal in different environments such as indoor, outdoor, during rain, without rain, hot weather, and cold weather.
- Finding the relation between LMS and tropical rainfall effects in Ku/Ka-band land mobile satellite channels.
- Determining the margin level so as to address the high path loss, long propagation delay, and rain attenuation loss for the LMS system.
- Developing an improved path loss, delay profile, and rain attenuation model for LMS application in equatorial regions.
- The physical layer security of a Land Mobil Satellite systems is one of the hot topics that need to be deeply studied in the near future of next LMS networks [56], [2], [13], [57]. There is a need for developing techniques that can secure the communication between the satellite network and terrestrial cellular networks.
- The cognitive architecture of land mobile satellite systems and terrestrial cellular networks are of the research area that needs further deep study [55], [56], [58], [59]. Although several research centres have conducted various research in this field worldwide, issues related to security, managing shared spectrum, outage probability, interferences and mobility have not been efficiently solved.

VIII. CONCLUSION

This study provides an inclusive survey of land mobile satellite systems as well as services from various perspectives. The study excluded the grouping of LMS systems, the operating frequency bands, and the characteristics of MSS systems. From the review, it has been observed that the communication channel between a satellite and a land-based mobile client is still one of the most critical challenges that degrade communication reliability. This encompasses high path loss, long propagation delays, multipath interference, shadowing, reflection, scattering, and rain attenuation. Meanwhile, the propagation modeling for path loss, delay profile, and rain attenuation model for LMS systems are still an open area for research which must be addressed.

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