Satellite Communication

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Abstract

Satellite communications is a fast-growing technology, in recent years, it has attracted significant attention and investment due to its potential to transform global connectivity. This paper discusses its background and recent advancements, we focus on how 5G technologies can help address current shortcomings in satellite communication standards. We explore the two main phases of system integration, key enabling technologies, and the role of Artificial Intelligence (AI) in improving satellite communication. Specific areas include beam hopping, anti-jamming measures, and predicting network traffic.
The paper also investigates Dense Small Satellite Networks (DSSNs) in detail, covering their essential components, emerging technologies, and challenges. Key topics include smart steerable antennas, access techniques for multiple users, strategies for energy harvesting and optimization, and methods to enhance routing and networking in DSSNs. The results emphasize the significant potential of combining 5G and AI technologies to solve challenges and open new opportunities in satellite communication systems.

Keywords:

Satellite Communications, 5G Technologies, Artificial Intelligence (AI), Beam Hopping, Anti-Jamming, Network Traffic Prediction, Dense Small Satellite Networks (DSSNs), Smart Steerable Antennas

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1. Introduction

Since their inception, satellite communications have been used in a wide range of applications, including media broadcasting, backhaul transportation, and news gathering. With the continuous development of Internet applications, satellite communications are entering a period of transition in which the focus of system design is gradually shifting towards data services, in particular broadband satellite communications. The main factors driving this change include a) the rapid rise of media streaming, which is gradually replacing traditional linear media broadcasting. b) the increasingly urgent need to expand broadband coverage, especially in underserved areas, such as developing countries, the aeronautical and maritime domains, and rural areas.[Koldheli2021] Because of its high throughput requirements, satellite communication is now commonly combined with 5G technology, while there is also a portion of new technology integrating AI to optimize communication performance, in addition, this paper also contains satellite deployment technology and satellite system technology breakthroughs.

To realize high-speed Internet, both terrestrial mobile systems and satellite mobile systems are trying to make the best use of their strengths, while at the same time trying to compensate for their weaknesses. Terrestrial mobile systems can provide high data rates and low latency, but current systems can only cover about 20% of the land area, which is only 6% of the entire earth's surface. [Chen2020] In contrast, satellite mobile communication systems can achieve truly global coverage and have higher survivability in the event of disasters, especially earthquakes and tsunamis, but every satellite mobile communication system inevitably faces the challenge of long-distance transmission. Therefore, in the fifth-generation mobile communications (5G) phase, both industry and academia are promoting the convergence of terrestrial mobile communications with satellite communications in pursuit of global coverage.

2. System Integration for 5G in satellite communications

In recent years, mobile communication standards have evolved into a new era of B5G and 6G. Low-Earth orbit (LEO) satellites and the Internet in space have become hot topics. This section analyses the deficiencies in existing satellite communication standards and identifies trends in two phases of integration of terrestrial mobile and satellite communication systems: compatibility with 5G and integration within 6G. Based on an analysis of the challenges faced in both phases, the key technologies are explained.

2.1 Deficiencies in current satellite communication standards

Current broadband satellite communication standards have some significant drawbacks, including the following:
aEc High latency: Since satellite communications usually rely on geosynchronous orbit (GEO) satellites, signals need to traverse long distances with high round-trip latency. This high latency poses a greater challenge for real-time applications (e.g., video conferencing, online gaming), and the user experience can be significantly affected.
aEc Limited bandwidth: The total bandwidth capacity of broadband satellites is relatively limited, especially when spectrum resources are restricted. In user-intensive areas or high-demand hours, bandwidth sharing may cause network speeds to drop, failing to meet modern broadband demands for high speeds and low latency.
aEc High equipment and operating costs: The high costs of satellite launch, ground station construction and user terminal equipment result in satellite communication systems being much more expensive to deploy and maintain than terrestrial networks. This limits its large-scale application to a certain extent, especially in economically underdeveloped regions.
aEc Weak anti-interference ability: Satellite signals are easily affected by weather conditions (e.g., rain failure), especially when transmitted in high frequency bands (e.g., Ka-band), and the problem of signal attenuation becomes more obvious. In addition, the adaptive ability of satellite communication in case of interference or blockage is weak, which will affect the stability and reliability of communication.
aEc Intense competition for spectrum resources: Satellite communication and terrestrial wireless communication systems need to share limited spectrum resources, and spectrum allocation is becoming increasingly tight. As the demand for broadband increases, how to reasonably allocate and efficiently utilize spectrum resources has become an important challenge.

2.2 Two Stages of System Integration

In order to complete existing communication systems, a new trend has emerged that combines terrestrial mobile communications with satellite communications. Its main purpose is to build a high-throughput satellite network in low-Earth orbit to solve the problem of insufficient coverage of terrestrial communications. In this way, the integration of satellite and terrestrial systems will result in lower construction costs, while at the same time meeting the requirements of different services and different applications. Due to the different requirements, challenges and technologies, it is expected that the system integration of terrestrial mobile and satellite communications can be basically divided into two phases in the current 5G and beyond:
(1) Compatible with 5G: current satellite communication systems can be developed mainly based

on 5G technologies and compatibility, reusing key 5G technologies to the maximum extent.
(2) Integrated in 6G: Terrestrial mobile communications and high, medium and low orbit satellite communications will be harmoniously integrated in the future 6G. [Sun2020]

2.3 Key Technologies of 5G-based Satellite Communication

(a) Waveforms The main factor affecting waveform selection is the Peak to Average Power Ratio (PAPR). Since the satellite's on-board power amplifier (PA) is very sensitive to the efficiency of the PA, waveforms with high peak-to-average power ratios must use more power for setback. For terrestrial 5G systems, both OFDM and DFT-s-OFDM waveforms can be supported, while DFT-s-OFDM has a lower PAPR than OFDM. in general, OFDM waveforms have better peak cancellation than DFT-s-OFDM waveforms, which are close to sinusoidal single-carrier waveforms, and the improvement may be relatively limited.
(b) Advanced coding and modulation For terrestrial systems, QAM is usually selected for higher spectral efficiency. For satellite systems, PSK is usually recommended to reduce the PAPR. pi/2-BPSK can be used for channels with a very low signal-to-noise ratio (SNR), and for higher SNRs, QPSK, 8PSK, 16APSK, and higher-order APSK can be used. in terms of channel coding, the data channel of the 5G New Radio (NR) uses LDPC coding, while the control channel mainly uses Polar coding. In terms of channel coding, the 5G new radio (NR) uses LDPC coding for data channels and Polar coding for control channels. From a practical coding performance point of view, 5G coding is currently the best compromise between complexity and performance, and it is therefore recommended that the channel coding of satellite systems be fully compatible with 5G NR systems.
(c) Doppler frequency shift Compensation In satellite communication systems, especially in the LEO case, the relatively large Doppler shift affects frequency synchronization and thus system performance. There are usually two approaches to Doppler frequency shift estimation and compensation. One is a closed-loop approach, where the UE does not have ephemeris and GNSS position information, and therefore requires a base station to indicate the frequency deviation. The other is an open-loop approach, where the UE has ephemeris and GNSS position information, so the UE can estimate the actual value of the Doppler shift and compensate accordingly. To simplify the Doppler estimation, the center of the beam is usually assumed to be the reference point, so the base station only needs to compensate for the Doppler shift of the reference point, while the UE only needs to compensate for the residual Doppler, i.e., the difference in Doppler between the UE position and the reference point. The residual Doppler value is much smaller than the absolute value of the Doppler shift. It depends on the radius of the beam. Typically, the residual Doppler value is 1 to 2 KHz in the L-band and not more than 20 to 30 KHz in the Ka-band.
(d) Synchronization The main problem of the synchronization channel is how to synchronize the UE and the gNB in time and frequency and obtain the cell ID information and system broadcast information, so as to prepare for the UE to access the network. The downlink synchronization of the UE can be divided into three steps: the satellite signal search, the cell ID search and synchronization, and the cell broadcast information acquisition. For satellite signal search, ephemeris-assisted search and blind search should be considered. For GEO signals, blind search is feasible, but the search time is longer. For LEO signals, accurate ephemeris information is usually available, so the search time is much shorter. After tracking the satellite, the UE will first detect the Primary Synchronization Signal (PSS) for coarse time and frequency synchronization,

and then the UE will use the Secondary Synchronization Signal (SSS) for fine time and frequency synchronization. Cell ID information can be obtained from the PSS and SSS. In addition, the UE demodulates the PBCH to obtain the Master Information Block (MIB), information related to the transmission time of the Synchronization Signal Block (SSB), the RMSI, and other system parameters for use in the subsequent random-access process.
(e) Paging For GEO satellites, the mobility management scheme is similar to that of terrestrial systems because the satellite is relatively stationary, and the coverage area of each beam is relatively fixed. When a UE is connected to a base station on the satellite and/or a base station is connected to the core network, the connection does not change over time unless the UE moves from one beam to another. Therefore, traditional mobility management schemes based on RRM measurements can be directly applied. For LEO satellites, special mobility management schemes should be considered since the satellites are always moving around the earth and the coverage of each beam is also moving. In idle mode, mobility management is mainly realized through the selection/re-selection process controlled by UE. While in the connected mode, mobility management is mainly realized through the switching process of network control.

3. Artificial Intelligence in Satellite Communication

The wireless communications industry has grown much faster than expected in recent years, while at the same time there are new requirements for coverage of communications networks in various industries, making satellite communications urgently needed. As a supplement to traditional terrestrial networks, satellite communication systems can provide access to uncovered and under-covered cities, rural areas, mountainous regions and oceans. In general, there are three main types of satellites, including geosynchronous equatorial orbit (GEO), medium Earth orbit (MEO) and low Earth orbit (LEO).[Fourati2021]
GEO satellites have an orbital period equal to the Earth's cycle. It appears fixed to a ground observer. LEO and MEO satellites have shorter periods. Many LEO and MEO satellites are needed to provide continuous global coverage. Iridium NEXT, for example, has 66 LEO satellites and 6 spares. SpaceX's Starlink program has 4,425 LEO satellites and a number of spares.[Maral2020]

3.1 Beam Hopping

Since satellite resources are expensive, there is a need for efficient systems that are optimized and have time-sharing characteristics. In conventional satellite systems, resources are fixed and uniformly distributed between beams [Vazquez2016]. Consequently, conventional large multibeam satellite systems show a mismatch between the resources provided and the resources requested; the demand for some spot beams is higher than the capacity provided, resulting in unmet demand, while the demand for other spot beams is lower than the installed capacity, resulting in the provided capacity being unused. Therefore, in order to improve multibeam satellite communications, there was a need for flexibility in the allocation of satellite resources within the service area.

3.1.1 AI Solutions for Beam Hopping

Some researchers have found some AI-based approaches and can break through these limitations to some extent. In order to optimize the transmission delay and system throughput of a multibeam satellite system, Hu et al [Hu2020] proposed an optimization problem and modeled it as a Markov decision process (MDP). Then, they used Deep Reinforcement Learning (DRL) to solve the beam illumination design problem and optimally modeled the long-term cumulative reward of the MDP. As shown in Fig 1. An agent takes action and receives feedback from the environment. Ultimately, their proposed DRL-based BH algorithm reduces the transmission delay by 52.2% and improves the system throughput by 11.4% compared to previous algorithms.

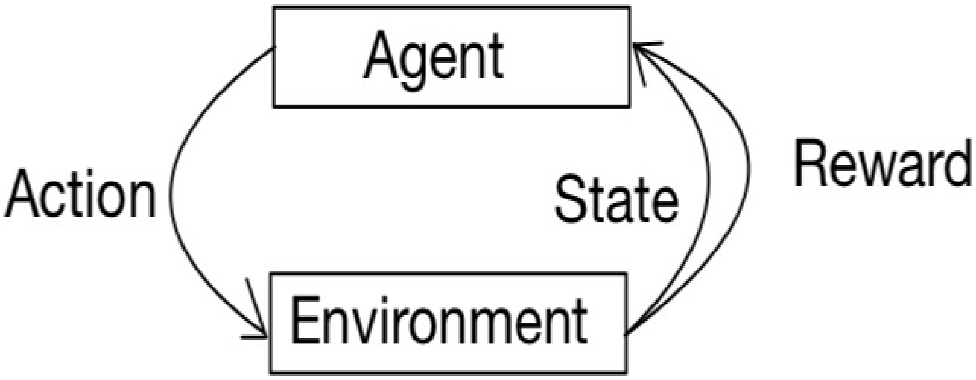

Figure 1: Reinforcement learning scenario

3.2 Anti-Jamming

Satellite communication systems are designed to cover large areas, however, in the case of tactical communication systems using satellites, this characteristic makes them susceptible to jamming or attack. Therefore, reliability and security are primary considerations when designing a satellite communications system, and its anti-jamming (AJ) capability is critical. Launching jamming attacks on key positions and critical equipment in the satellite network can increase the delay or even paralyze the whole satellite system. Therefore, various AJ methods have been designed to mitigate possible attacks and ensure the reliability of satellite communications.

3.2.1 AI Solutions for Anti-Jamming

In mobile communications, mobile devices can utilize RL to achieve optimal communication policies within a dynamic game framework without the need to know the interference and radio channel model [Xiao2018]. As shown in Fig 2, The red line represents the found jammed path, and the green one represents the suggested path.

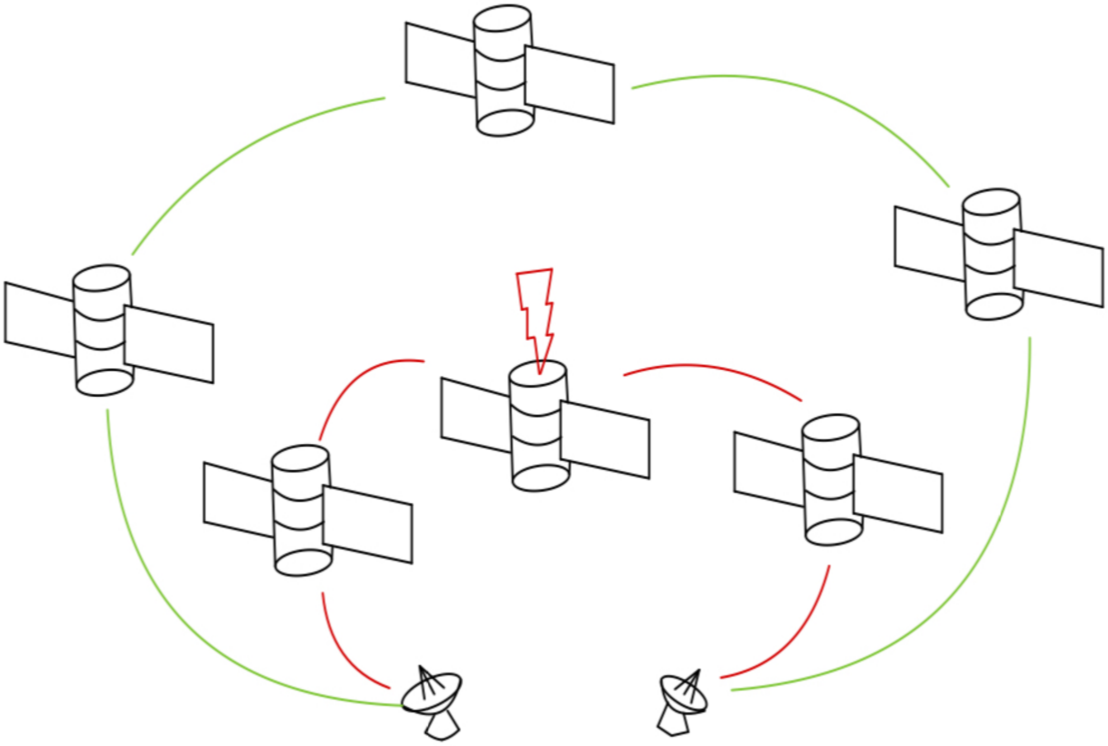

Figure 2: Space-based anti-jamming(AJ) routing.

Han et al [Han2020] proposed to utilize a pacing-based AJ approach - AJ Routing - that employs AJ learning methods to block intelligent jamming in Internet of Satellites (IoS). Han et al [Han2020] showed how DL can be used to deal with the large decision space arising from the high dynamics of IoS by combining game-theoretic modeling with RL to model the interaction between smart jammers and satellite users as a Stackelberg AJ Routing game. DRL, and in particular behavioral criticism algorithms, where the source node is the state and the expected rewards for selected behaviors are valued by the criticism network, can solve the routing problem for heterogeneous IoS while preserving a subset of available routes, simplifying the decision space of the Stackelberg AJ routing game. Based on this routing subset, a popular RL algorithm, Q-Learning, is used to quickly respond to intelligent interference and adjust AJ strategies. *Subsequently, Han et al* [Han2020] *combined game-theoretic modeling and RL to obtain AJ policies based on dynamic and unknown interference environments in satellite-enabled Army Internet of Things (SatIoT).* [Fourati2021] *In this paper, we investigate distributed dynamic AJ coalition formation games to reduce energy consumption in jamming environments and propose a hierarchical AJ Stackelberg game to express adversarial interactions between jammers and satellite IoT. Adversarial interactions between jammers and satellite IoT devices.*

3.3 Network Traffic Forecasting

Due to the nature of satellite communication systems, differences in traffic predictability can lead to very different effects in many satellite applications such as congestion control, dynamic routing, dynamic channel assignment, network planning, and network security, so we need to predict network traffic. *Satellite network traffic is self-similar and exhibits long range dependence (LRD)* [Bie2019]. However, the computational complexity of terrestrial network models based on self-similarity is high; satellite computers have limited computational resources due to limited space and power supply, and the design model of terrestrial satellite networks is not applicable to satellite networks. Therefore, an efficient design for satellite network traffic prediction is needed.

3.3.1 AI Solutions for Network Traffic Forecasting

Liu and Li [Liu2018] achieved higher prediction accuracy with less training time by applying principal component analysis (PCA) to reduce the input dimensions and then using generalized regression neural networks. Extreme Learning Machines (ELMs) have also been used for satellite node traffic load prediction prior to routing. Bie et al [Bie2019] used EMD to decompose satellite traffic with LRDs into a series of single-frequency traffic with SRDs in order to reduce the prediction complexity and increase the prediction speed. They combined EMD, Drosophila optimization and ELM methods to achieve more accurate predictions at a higher speed compared to previous methods

4. Dense Small Satellite Networks (DSSNs)

Multiple mobile terrestrial communication systems (MTCS) can benefit from a dense small satellite network (DSSN) in low Earth orbit (LEO). However, the potential benefits can only be realized if the DSSN infrastructure is carefully considered and the appropriate DSSN technology is identified. In this section, we discuss several components of the DSSN infrastructure, including satellite formations, orbital paths, inter-satellite communication (ISC) links, and the communication architecture for data transfer from source to destination. We also review important technologies for DSSN and the challenges of using them in DSSN.

4.1 Main Components in DSSN

4.1.1 Satellite Formations

aEc Constellation: A formation in which all satellites are identical in design and function.

- Advantages: This configuration is cost-effective and has high redundancy because identical satellites are easy to manage and replace.
- Disadvantages: Requires precise orbital planning to maintain proper alignment and coverage.

aEc Cluster: Consists of non-identical satellites that can operate cooperatively.

- Advantages: Allows replacement of individual modules rather than entire satellites, potentially reducing maintenance and replacement costs.
- Disadvantages: More complex and costly to design due to the need for compatibility between different components.

4.1.2 Satellite Orbits

aEc Polar Orbits: All orbital planes in this configuration pass over Earth's poles.

- Advantages: This orbit type offers predictable satellite paths and enhanced coverage over polar regions, which are often underserved by traditional satellite systems.
- Disadvantages: Coverage is limited at lower latitudes, making it less effective in regions farther from the poles.

aEc Rosette Orbits: A highly inclined orbital configuration designed to maximize coverage over a wide area from the poles.

- Advantages: This orbit arrangement allows for nearly global coverage with a minimal number of satellites (typically five), achieving broad spatial reach with fewer resources.
- Disadvantages: Provides less effective coverage around equatorial areas, necessitating complementary orbits for global reach.

aEc Hybrid Orbits: A combination of polar and rosette orbits designed to leverage the strengths of each.

- Advantages: This approach provides greater flexibility in coverage options, enabling customized coverage solutions.
- Disadvantages: The increased flexibility comes at the cost of added complexity in system design and management.

4.1.3 Inter-Satellite Communication (ISC) Links

aEc Radio Frequency (RF): Communication links utilizing the radio spectrum.

- Advantages: Supports a variety of bands (UHF, S, K, Ka, Ku), allowing for adaptable design trade-offs to optimize for specific requirements.
- Disadvantages: RF links are susceptible to interference, and establishing communication over long distances often necessitates large antennas, which can be impractical or costly.

aEc Optical Wireless Communication (OWC): Free-space optical communication where modulated data is transmitted via unguided optical channels, typically using wavelengths between 500nm and 2000nm.

- Advantages: Offers high directivity, bandwidth, and security, along with low power consumption, making it suitable for high-performance data transmission.
- Disadvantages: Implementation is challenging due to high costs and the need for precise beam alignment to maintain stable connections.

aEc Visible Light Communication (VLC): Uses LED lights as transmitters to convey data through visible light.

- Advantages: Cost-effective with very low power requirements, which makes it suitable for power-constrained applications.

- Disadvantages: Susceptible to background illumination noise, necessitating advanced optical filters at the receiver end, which complicates the system design.

4.1.4 Space-Ground Communication (SGC) and Ground-Space Communication (GSC) Architecture

aEc Direct Communication with Destination: This architecture enables direct data transfer from the source to the destination node without intermediate relays.

- Advantages: Simple architecture with no requirement for inter-satellite communication (ISC) links, which reduces overall system complexity.
- Disadvantages: Can experience extremely high worst-case latency, especially for distant destinations.

aEc Communication with Ground Infrastructure Support: Data is transmitted from the source to the nearest ground station, which then relays it to the destination.

- Advantages: Achieves moderate latency without requiring ISC links, leveraging existing ground infrastructure to reduce complexity.
- Disadvantages: Dependent on a reliable terrestrial network and specialized gateways to manage data transfer across different protocols and communication technologies.

aEc Communication with Space Infrastructure Support: Data is initially routed through space to a satellite closest to the destination node.

- Advantages: Capable of achieving very low latency when supported by fast ISC links, ideal for applications where time-sensitive data transmission is critical.
- Disadvantages: Requires a fully connected space network, which adds to the complexity and cost of deployment.

aEc Hybrid Communication Using Both Space and Ground Infrastructure: Data can be routed either through space or ground infrastructure nodes as needed.

- Advantages: Provides exceptional flexibility and can achieve very low latency, adapting to varying network conditions and requirements.
- Disadvantages: Complex system design, necessitating both ISC links and a robust terrestrial network, which increases both the technical and financial demands of implementation.

4.2 DSSN Technologies and Challenges

The realization of a seamless and efficient DSSN depends on addressing several key technological challenges. This section delves into critical aspects such as smart steerable antennas, energy harvesting and optimization, and routing and networking protocols. By overcoming these challenges, we can pave the way for the successful deployment and operation of DSSNs.

4.2.1 Smart Steerable Satellite Antenna

The constantly changing distances and angles between satellites require instantly steerable DSSN antennas to ensure signal strength. These antennas also need to have high gain and ultra-wide bandwidth due to the relatively large propagation distances. Researchers at the University of Hawaii have developed an extremely lightweight (186 grams), low-power, air-scanning reverse directional antenna array for ISL links. *Low-power, low-cost, multi-loop, multi-beam bullseye antennas for nanosatellites are also being developed. Some low-loss tunable materials, such as liquid crystals, ferroelectric films, and piezoelectric materials, can be used to fabricate multibeam steerable satellite antennas* [Gao2018]. Another promising research direction is the installation of reconfigurable intelligent surfaces (RIS) on satellites. RIS can be used to passively steer radio signals and provide additional control over difficult space environments.

4.2.2 Energy Harvesting and Optimization

In general, DSSN satellites are powered by solar panels. Fluctuations in access to solar energy occur as the position and angle of the orbit change. When the orbital path of DSSN satellites is predictable, the fluctuations in solar energy can be easily predicted. In DSSN, a joint energy optimization problem for the whole network or a subset of satellites can be formulated. Literature [Fraire2018] designed a battery-aware liaison scheme for DSSNs, and the authors considered a detailed battery model as well as ISC and SGC link budgets in their analysis. Frequent charging and discharging cycles affect the battery life, which in turn affects the overall performance and operational life of the DSSN. Literature [yamng2016] presents an energy efficient DSSN routing problem with the objective of maximizing battery life. The study developed an algorithm that integrates energy efficiency and quality of service requirements for path length and maximum link utilization.

4.2.3 Routing and Networking in DSSNs

Depending on the routing metrics, we can design routing algorithms for DSSNs in a targeted manner. Switching-optimized routing algorithms use a connectivity matrix to identify the presence of ISC links; bandwidth-delay routing algorithms use delay and bandwidth as routing matrices; destruction-resistant routing algorithms enhance the survivability of the network by using the state of the links as a routing metric; Stiener-free routing can support a large number of satellites; distributed multipath routing provides better delay and can track the ever-changing topology of the DSSN, and dynamic routing algorithms based on mobile ad-hoc network based dynamic routing algorithms provide high autonomy and limited overhead.

5. Conclusion

This paper provides an overview of three representative satellite communication technologies: integrated 5G satellite communication, AI and its different sub-domains including ML, DL and RL, and DSSN.

For integrated 5G satellite communication, with the new upsurge in the construction of LEO satellite constellations and the progress of 5G-based satellite systems in standards organizations, this paper refers to a two-phase development. On the one hand, satellite communications will be compatible with 5G, improve 5G-based technologies and maximize the reuse of 5G key technologies. On the other hand, satellite communications will be integrated with 6G and deployed in high, medium and low orbits to work with ground mobile communications. In order to solve the key challenge of system integration between terrestrial mobile communications and satellite communications, more detailed system design work will be carried out in the future for the integrated 6G terrestrial and satellite systems.

For satellite communication based on AI. This paper presents some limitations of satellite communications and discusses proposed and potential solutions based on AI. The application of AI in various satellite communication domains has yielded great results. Communication, including beam hopping, AJ, network traffic prediction, channel modelling. Future work should focus on the application of AI to achieve more efficient, safe, reliable and high-quality communication systems. While AI has made great breakthroughs in accuracy, there is still more work to be done in terms of AI interpretability and adversarial AI to achieve safer and more reliable communications.

For DSSN, the limited resources and harsh space environment of a large number of small LEO satellites make the design of DSSN very challenging. Therefore, it is important to understand the design elements of DSSN and appropriate technologies to fulfill the requirements of MTCS. We identify DSSN technologies, several research questions to be addressed, and some of the challenges to further integrating DSSNs in MTCS. With SpaceX deploying 60 Starlink satellites in 2019, DSSN will become realistic and ubiquitous in the near future. However, a significant amount of novel research work is still required in areas such as smart steerable antenna design, NOMA, energy harvesting and optimization, routing and network protocols, re-addressability, data caching and resource optimization techniques. In particular, in DSSN, the issues of space networking and the maintenance and re-addressability of satellites represent a considerable challenge.

Acronyms

- AI: Artificial Intelligence
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- LEO: Low-Earth Orbit
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- MEO: Medium Earth Orbit
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- GEO: Geosynchronous Orbit
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- B5G: Beyond 5G
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- 5G: Fifth Generation Mobile Communications
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- 6G: Sixth Generation Mobile Communications
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- PAPR: Peak to Average Power Ratio
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- PA: Power Amplifier
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- OFDM: Orthogonal Frequency Division Multiplexing
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- DFT-s-OFDM: Discrete Fourier Transform Spread Orthogonal Frequency Division Multiplexing
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- QAM: Quadrature Amplitude Modulation
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- PSK: Phase Shift Keying
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- BPSK: Binary Phase Shift Keying
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- QPSK: Quadrature Phase Shift Keying
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- APSK: Amplitude and Phase Shift Keying
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- SNR: Signal-to-Noise Ratio
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- NR: New Radio (5G Standard)
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- LDPC: Low-Density Parity-Check
-
- PBCH: Physical Broadcast Channel
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- MIB: Master Information Block
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- RMSI: Remaining Minimum System Information
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- SSB: Synchronization Signal Block
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- PSS: Primary Synchronization Signal
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- SSS: Secondary Synchronization Signal
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- UE: User Equipment
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- gNB: Next Generation Node B (5G Base Station)
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- GNSS: Global Navigation Satellite System
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- PRACH: Physical Random Access Channel
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- RRM: Radio Resource Management
-
- MDP: Markov Decision Process
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- DRL: Deep Reinforcement Learning

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- AJ: Anti-Jamming
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- FH-FDMA: Frequency Hopping Frequency Division Multiple Access
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- LSTM: Long Short-Term Memory
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- DL: Deep Learning
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- RNN: Recurrent Neural Network
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- RL: Reinforcement Learning
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- IoS: Internet of Satellites
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- SatIoT: Satellite-enabled Internet of Things
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- Q-Learning: A specific Reinforcement Learning algorithm
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- NN: Neural Network
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- SVM: Support Vector Machine
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- LRD: Long Range Dependence
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- SRD: Short Range Dependence
-
- PCA: Principal Component Analysis
-
- ELM: Extreme Learning Machine
-
- EMD: Empirical Mode Decomposition
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- DSSN: Dense Small Satellite Network
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- ISC: Inter-Satellite Communication
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- RF: Radio Frequency
-
- OWC: Optical Wireless Communication
-
- VLC: Visible Light Communication
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- SGC: Space-Ground Communication
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- ISL: Inter-Satellite Links

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- RIS: Reconfigurable Intelligent Surfaces
-
- OMA: Orthogonal Multiple Access
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- NOMA: Non-Orthogonal Multiple Access

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