Timeliness of Information in 5G Nonterrestrial Networks: A Survey

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***Abstract*—This article explores the significance of the timeliness of information in the context of fifth generation (5G) nonterrestrial networks (NTNs). As 5G technology continues to evolve, its integration with nonterrestrial components, such as satellites, high-altitude platforms, and unmanned aerial vehicles brings about new possibilities and challenges for ensuring the timely delivery of information. In this article, we delve into the network structure of NTNs and emphasize the significance of timeliness in various applications, including 5G massive Internet of Things and enhanced mobile broadband. We conduct an in-depth review of the design technologies and methodologies that enhance the timeliness of information in these applications. These include network architecture design, resource allocation, protocol design, modulation design, trajectory planning, reconfigurable intelligent surfaces design, energy harvesting scheduling design, offloading strategy design, and caching strategy design. By exploring these technical aspects and solutions, we aim to provide valuable insights into ensuring timely information delivery in 5G NTN. Furthermore, we propose potential future research directions to further improve the timeliness of information in NTNs. Recognizing the importance of timeliness and addressing the related challenges will unlock the full potential of 5G NTN, enabling the successful deployment and operation of a wide range of applications and services that depend on real-time data exchange.**

***Index Terms*—Age of Information (AoI), fifth generation (5G), Internet of Things (IoT), nonterrestrial network (NTN), timeliness of information,**

I. INTRODUCTION

THE FIFTH generation (5G) and envisioned sixth generation (6G) wireless communication will lead to a revolutionary leap forward in terms of data rates, network reliability, latency, massive connectivity, and energy efficiency [1]. The key features of 5G wireless communication include enhanced network capacity, extended coverage, reduced latency, and improved resilience. Moreover, 5G communication unlocks opportunities for advanced use cases, such as autonomous vehicles, remote sensing, Internet of Things (IoT) applications, and immersive experiences. With its ultralow latency and high bandwidth capabilities, 5G can enable real-time communication, seamless handovers [2], [3], and ubiquitous connectivity, powering innovative solutions and transformative experiences [4].

However, even though 5G offers these remarkable capabilities, deploying the network in rural areas presents unique challenges. These challenges arise from the varying degree of terrain that may be encountered when installing cables or fibers between the cellular stations. The network in rural areas is further complicated by these geographical and infrastructural difficulties. To address this issue, nonterrestrial network (NTN) has been proposed in 5G. Recently, NTN has gained significant attention and interest due to its potential to extend connectivity to underserved areas, support global communications, and enable innovative applications. Enabling 5G systems to support NTNs has been a focal point of exploration within the third generation partnership project (3GPP) since Release 15 [5]. Release 15 primarily involves defining deployment scenarios and channel models for satellite networks [6]. In Release 16, there is a proposal for new radio (NR) to support NTN solutions, including evaluations of performance and adaptability across various deployment scenarios [7]. The enhancement scheme for NR NTNs and the Narrowband-IoT project are ongoing efforts within 3GPP for Release 17 standards [8], [9]. These endeavors aim to evolve the capabilities of 5G and beyond to support expanded NTN functionalities. Within the context of the 5G NTN, it offers a range of advantages, including comprehensive service coverage and global connectivity, seamless service continuity and resilience for various use cases, heightened availability and reliability, and adaptable service scalability, as visually depicted in Fig. 1. Through the fusion of 5G's substantial capacity with the adaptability and worldwide reach of nonterrestrial elements, NTN has the potential to provide dependable connectivity and top-tier services to users situated in remote or underserved locales, even in challenging environmental conditions. Particularly noteworthy is NTN's capacity to extend coverage and connectivity, facilitating communication between the geographically dispersed areas and bridging the digital divide. By capitalizing on an interconnected satellite network,

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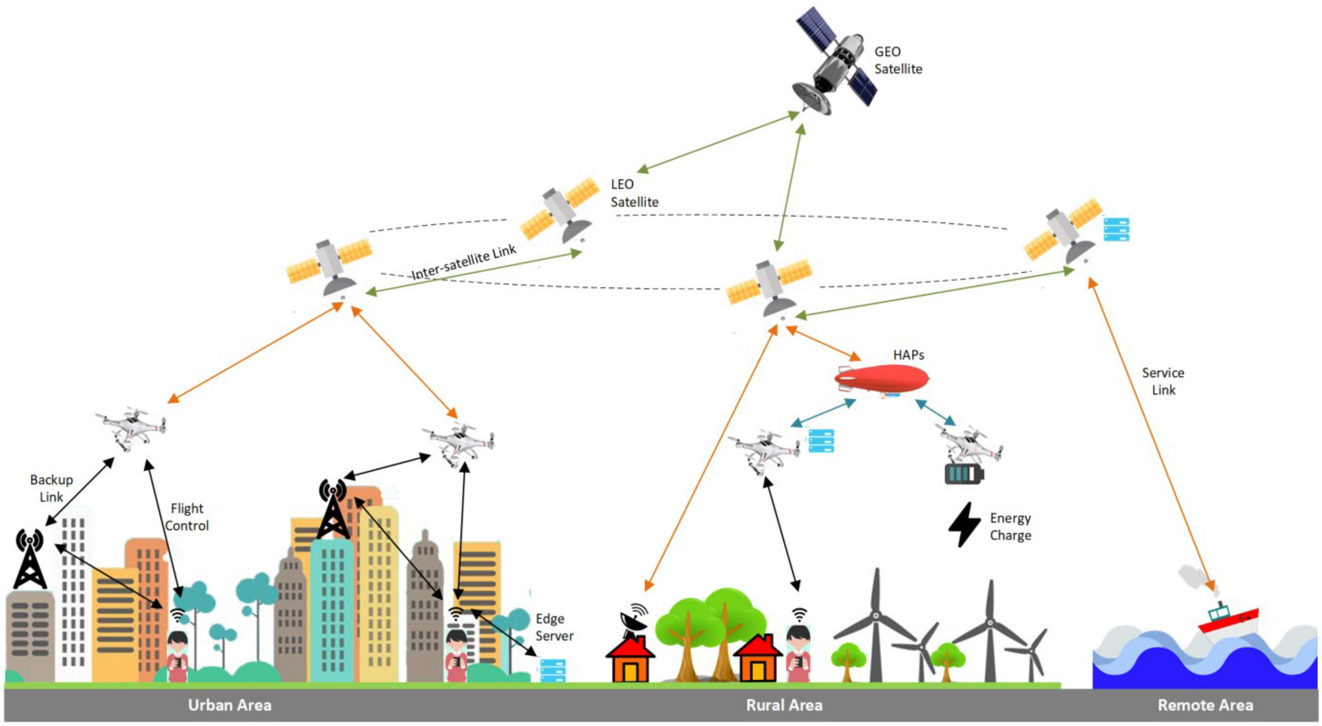

Fig. 1. Example network structure for 5G NTNs.

TABLE I
COMPARISON OF SURVEY CONTENT WITH EXISTING SURVEYS AND TUTORIALS (PARTIALLY COVERED: ∂ AND COVERED: ✓)

Reference	Satellite	UAV	Network Structure	Application	Timeliness of Information
[10]		✓	✓	✓	
[11]		✓	✓	✓	
[12]		✓	✓	✓	
[13]		✓		✓	∂
[14]		✓		✓	∂
[15]	✓				
[16]	✓			✓	
[17]	✓		✓	✓	∂
[18]	✓		✓	✓	
[19]	✓	✓	✓	✓	∂
[20]	✓	✓	✓	✓	
[21]	✓	✓	✓	✓	
Our Paper	✓	✓	✓	✓	✓

we can overcome the limitations posed by Line of Sight (LoS) constraints. This capability empowers NTN to deliver connectivity to remote communities, maritime zones, disaster-affected regions, and other demanding locations.

In the realm of 5G NTN, the timeliness of information emerges as a crucial aspect that significantly enhances the efficacy and usability of the network, standing as a fundamental pillar for ensuring its effectiveness and reliability in communication and service delivery. At its core, 5G NTN aims to extend connectivity to underserved areas, support global communications, and enable innovative applications, making timeliness paramount in achieving these objectives, especially where rapid and reliable data transmission is essential. This importance extends across various domains, from emergency response and environmental monitoring to autonomous systems and immersive applications. In emergency scenarios, 5G NTN plays a crucial role by enabling swift communication and coordination among first responders, ultimately saving lives through real-time updates and efficient rescue operations. Additionally, in industries reliant on remote sensing and monitoring, timely data collection and analysis facilitated by 5G NTN are essential for informed decision making and risk mitigation. Moreover, in autonomous systems and immersive experiences like virtual reality (VR) gaming, timely data transmission is vital for safe operation and user satisfaction, respectively. As the deployment of 5G NTN advances, prioritizing and optimizing timeliness will be essential for realizing its full potential in driving innovation, resilience, and connectivity on a global scale. Thus, this work aims to provide a comprehensive survey on the timeliness of information in 5G NTN.

A. Prior Related Surveys

The previous related survey papers are listed in Table I. In particular, the study by [10] provides an overview of essential background information and space–air–ground integrated networks, along with discussing related research challenges in the emerging integrated network architecture. Furthermore, it conducts an exhaustive review of various 5G techniques from both the physical and network layers, while also exploring potential use cases of unmanned aerial vehicle (UAV) systems. The survey by [11], discussions encompass the network architecture, transmission mechanisms, resource allocation, as well as trajectory planning and positioning problems for high-altitude platforms (HAPs), low-altitude platforms (LAPs), and UAV systems, aiming at achieving high reliability and low latency data transmission. In [12], attention is directed toward the network structure and potential use cases of UAV systems, alongside discussions on recent technologies adoptable in UAV systems and their performance impacts. The review by [13] delves into the study of UAV-aided reconfigurable intelligent surfaces (RISs) systems, considering aspects, such as energy consumption, secrecy performance, and efficiency enhancement. The work by [14] offers a comprehensive overview of integrating UAVs into cellular networks, emphasizing the integration of advanced techniques into UAV systems.

While the aforementioned works primarily focus on UAV systems, subsequent studies shift their focus to satellite systems. In [15] and [16], the physical layer security issues and potential solutions to enhance security in satellite-enabled networks are discussed. Furthermore, works on employing edge caching in satellite IoT networks to reduce transmission time and effectively utilize limited satellite resources are reviewed in [17]. The work by [18] provides a brief discussion on the satellite system architecture, features, challenges, and multiple-layer protocols. Both the UAV and satellite systems are covered in [19], investigating potential integration technologies for NTNs. Additionally, the 3GPP NTN features and their potential for satisfying user expectations in 5G and beyond networks are reviewed in [20]. Moreover, a comprehensive survey of the current research in the integrated space-air-ground architecture and the enabling technologies for NTNs is presented in [21].

Despite the extensive research on 5G satellite and UAV networks, few studies have significantly contributed to the discussion of the timeliness of information in 5G NTN. This lack of emphasis on timeliness has motivated the current work.

B. Contributions

This article aims to deliver a comprehensive and concise review of the research dedicated to enhancing the timeliness of information in NTNs. Drawing upon a thorough examination of existing literature, our objective is to summarize key findings, methodologies, and proposed solutions aimed at bolstering the prompt delivery of data within NTNs. Through this review, our endeavor is to furnish readers with a lucid comprehension of the present research landscape concerning the timeliness of information in NTNs, while also delineating prospective research directions for further investigation. This article's key contributions encompass the following aspects.

1) Delving into the examination of NTN structure and exploring design elements that contribute to enhancing timeliness within NTNs. Specifically, scrutinizing essential design facets, including network architecture, resource allocation, protocol design, modulation design, trajectory planning, UAV-enabled RIS, energy harvesting scheduling, offloading strategy, and caching strategy.
2) Outlining future research directions to improve the timeliness of information within NTNs. Notably, dynamic adaptation of modulation and coding strategies, combined with next-generation multiple access technologies, offers significant potential to reduce transmission latency. Implementing innovative routing and resource allocation solutions optimizes network architectures and traffic flow, thereby expediting information delivery in NTNs. Additionally, integrating terahertz (THz) communication into NTNs significantly enhances inter-satellite communication throughput. Exploring the use of quantum communications and blockchain technologies addresses security challenges across the multilayered networks of satellites and UAVs within NTNs.

C. Survey Outline

This article's structure is depicted in Fig. 2. Section II introduces the performance metric used to gauge the timeliness of information. Section III addresses associated features and challenges, underscores the significance of timeliness within the NTN framework, and presents various architecture options for NTNs. In Section IV, we delve into the technologies and methodologies to enhance the timeliness of information in NTNs. Section V outlines the potential future research directions and opportunities. Finally, this article concludes in Section VI.

II. Introduction to Timeliness

In 5G and envisioned 6G communications, numerous applications and services hinge on real-time communication, where prompt information delivery is indispensable. Real-time communication embodies the capacity of 6G networks to facilitate instant and ultraresponsive data exchange among the interconnected devices and systems. With the escalating demand for these real-time applications, timely wireless communications stand as pivotal prerequisites for achieving precise monitoring and control in such contexts [4], [22]. In the realm of real-time applications, upholding the freshness of information emerges as a critical factor, as outdated data could lead to the system failures and pose safety hazards. Industries like aviation, maritime, emergency response, and financial services particularly demand immediate data transmission to ensure efficient operations, safety, and informed decision making. Various applications, including financial transactions, stock trading, online gaming, video conferencing, and live broadcasting, rely on the minimal latency and prompt data exchange. In critical scenarios like disaster response or military operations, timely information could literally be a matter of life and death. Furthermore, timely information proves indispensable for effective remote collaboration and connectivity. In distributed work environments, real-time communication tools and access to shared information foster seamless collaboration, irrespective of geographical distances.

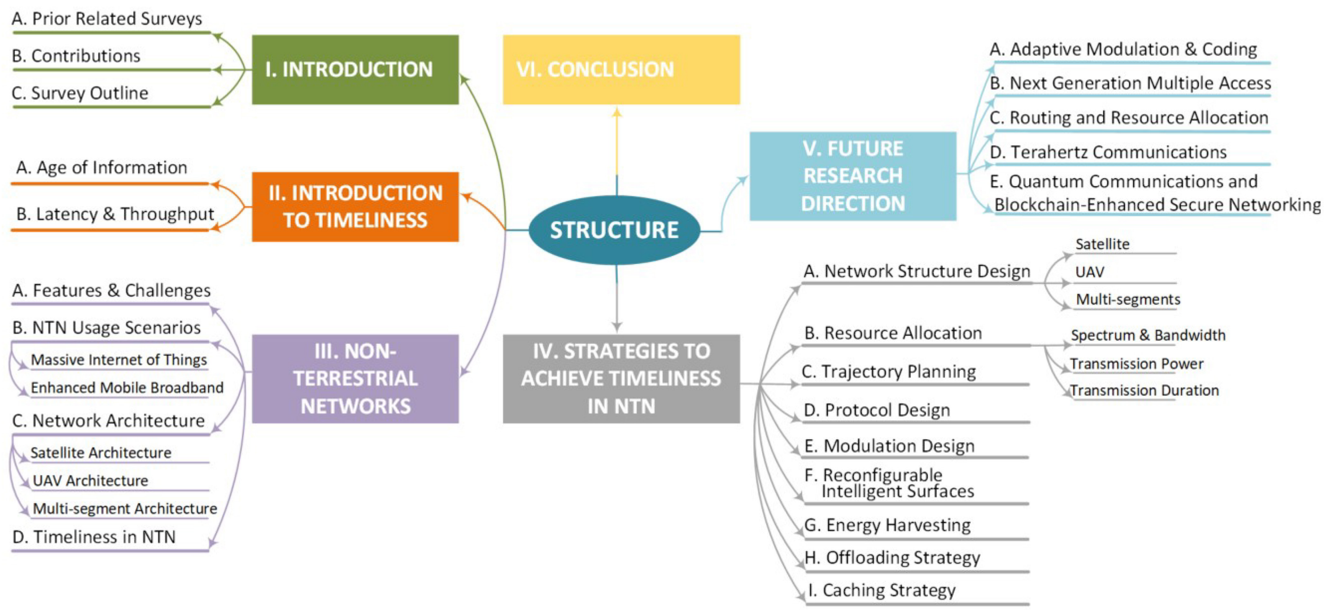

Fig. 2. Visualization of the survey structure.

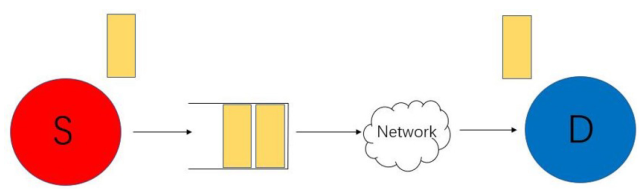

Fig. 3. Source (S) transmitting state update packets to destination (D) through the wireless communication network.

Timely updates and notifications guarantee that the team members remain connected and collaborate efficiently.

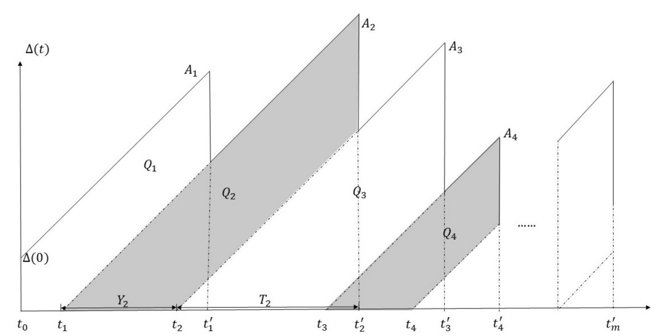

Fig. 4. Example of AoI evolution over time.

A. Age of Information

In order to fully characterize the freshness of delivered information, the concept of Age of Information (AoI) was introduced as a new performance metric [23]. AoI is utilized to quantify the freshness of a communication system from the perspective of the receiver. Specifically, AoI is defined as the elapsed time since the final successfully received packet was generated by the transmitter. This time metric captures both the latency of a transmitted packet and the throughput of the system.

A simple update model is shown in Fig. 3, where a source S generates state update packets and transmits them to the destination D via a wireless communication network. In this system, we denote $V(t)$ as the generation time of the final successfully detected packet at D, introducing the AoI process $\Delta(t)$ shown in Fig. 4 and given as

$$\Delta(t) = t - V(t). \tag{1}$$

In Fig. 4, the transmitted packets are generated at times $t_1, t_2, \ldots$, and received at the time $t'_1, t'_2, \ldots$. When the jth packet is successfully delivered to D, $V(t)$ is updated to t_j, resetting the AoI to the delay that the packet experienced in the network, i.e., $\Delta(t'_j) = t'_j - t_j$. In the absence of a newer update, the age process $\Delta(t)$ grows at an unit rate, resulting in the characteristic sawtooth pattern of the AoI process.

Given an AoI process $\Delta(t)$, the average AoI can be calculated using a sample average. In particular, the time average AoI is given as

$$\Delta_\tau = \frac{1}{\tau}\int_0^\tau \Delta(t)\mathrm{d}t \tag{2}$$

where $(0, \tau)$ is the interval of observation and the ensemble average AoI can be obtained by adopting $\tau \to \infty$. Considering that D receives the mth packet at the end of this time interval, i.e., $\tau = t'_m$, the integral part in (2), i.e., $\int_0^\tau \Delta(t)\mathrm{d}t$, is the sum of disjoint areas Q_j, $j = \{1, 2, \ldots, m\}$, given by

$$\int_0^\tau \Delta(t)\mathrm{d}t = \sum_{j=1}^{m} Q_j + \frac{T_m^2}{2} = Q_1 + \frac{T_m^2}{2} + \sum_{j=2}^{m} Q_j. \tag{3}$$

From Fig. 4, the area Q_1 is a polygon and Q_j is an isosceles trapezoid for $j \geq 2$. Let us denote $Y_j = t_j - t_{j-1}$ as the interarrival time, which is the time interval from the generation time of $(j-1)$th packet to the generation time of the jth packet, and $T_j = t'_j - t_j$ as the latency, which is the time interval from

TABLE II
LIST OF ABBREVIATIONS

3GPP	3rd Generation Partnership Project
5G	Fifth Generation
6G	Sixth Generation
AI	Artificial Intelligence
AoI	Age of Information
AR	Augmented Reality
BS	Base Station
CDI	Content Delay Index
CSI	Channel State Information
DRL	Deep Reinforcement Learning
eMBB	Enhanced Mobile Broadband
HAP	High-Altitude Platform
HARQ	Hybrid Automatic Repeat Request
IoT	Internet of Things
GEO	Geostationary Earth Orbit
GNSS	Global Navigation Satellite System
LAP	Low-Altitude Platform
LEO	Low Earth Orbit
LoS	Line-of-Sight
LTE-M	Long Term Evolution Machine type communications
MAC	Medium Access Control
MEC	Mobile Edge Computing
MEO	Medium Earth Orbit
ML	Machine Learning
NB-IoT	Narrow-Band Internet of Things
NOMA	Non-Orthogonal Multiple Access
NGMA	Next Generation Multiple Access
NTN	Non-Terrestrial Network
NR	New Radio
PAoI	Peak Age of Information
PPP	Poisson Point Process
QKD	Quantum Key Distribution
RIS	Reconfigurable Intelligent Surface
SDMA	Space Division Multiple Access
SHS	Stochastic Hybrid System
THz	Terahertz
UAV	Unmanned Aerial Vehicle
UE	User Equipment
VR	Virtual Reality

the generation time of the jth packet to the time that the jth packet is successfully delivered to D. Hence, Q_j can be derived from two isosceles triangles, i.e.,

$$Q_j = \frac{1}{2}\left(Y_j + T_j\right)^2 - \frac{1}{2}T_j^2 = \frac{Y_j^2}{2} + Y_j T_j. \tag{4}$$

From (3), when $\tau \to \infty$, the impact of Q_1 and T_m^2 on the average AoI is negligible, i.e., $\lim_{\tau\to\infty}[(2Q_1 + T_m^2)/2\tau] = 0$, because Q_1 and T_m^2 are finite. When Y_j and T_j are the stationary ergodic processes, the average AoI is given as

$$\Delta = \frac{\lim_{m\to\infty}\frac{1}{m-1}\sum_{j=2}^{m} Q_j}{\mathbb{E}\left[Y_j\right]} = \frac{\mathbb{E}\left[Q_j\right]}{\mathbb{E}\left[Y_j\right]} = \frac{\mathbb{E}\left[Y_j^2\right] + 2\mathbb{E}\left[Y_j T_j\right]}{2\mathbb{E}\left[Y_j\right]}. \tag{5}$$

The average AoI analysis in (5) can be applied to a wide range of service systems without making specific assumptions about the traffic pattern and the queue discipline. It is worth noting that a substantial interarrival time Y_j may lead to a small queue size, resulting in a low waiting time and, consequently, a low latency T_j. Due to the correlation between Y_j and T_j, evaluating $\mathbb{E}[Y_j T_j]$ may pose challenges, making the average AoI analysis difficult.

Since, its introduction in [23], the concept of AoI has garnered significant attention and interest. Early research focused on employing AoI as a performance metric for the state update delivery systems through the simple queuing models. To analyse AoI performance, queuing theory emerged as an efficient and widely used mathematical methodology, leading to the application of AoI analysis in various queue theoretic frameworks [24], [25], [26], [27], [28], [29], [30], [31], [32], [33]. Subsequently, research interests shifted toward the age-aware scheduling policy design in multiuser systems, where the scheduling policy plays a crucial role in optimizing the order of packet transmissions to improve AoI performance [34], [35], [36], [37], [38], [39], [40], [41], [42], [43]. Moreover, AoI performance was analysed in more specific systems, including NTNs [44]. This continued exploration of AoI and its application in diverse scenarios highlights its significance in understanding and optimizing information freshness in various communication systems.

Short packet communication has been widely considered a promising solution for reducing transmission latency in real-time applications due to its unique benefits in delay reduction. The transmission error in such systems highly depends on the transmitted packet length [45], [46], [47]. Compared to traditional long packet communication, in short packet communication systems, there is a tradeoff between the transmission error and transmission time, impacting the timeliness of information in a two-fold manner. As the transmitted packet length increases, it simultaneously extends the transmission time while reducing the transmission error. Consequently, to enhance AoI performance, encoding methods have been devised [48], [49], [50], [51], [52], [53] to effectively balance these two performance metrics. This enables a cooperative approach that optimizes both the transmission error and transmission time considerations.

B. Latency and Throughput

When assessing the time-relevant performance of a communication system, two widely used metrics are latency and throughput. Latency refers to the time delay between the generation of information at the source and its reception at the destination. Minimizing latency is essential for ensuring prompt information delivery, as elevated latency can detrimentally impact applications, such as video streaming, voice communication, online gaming, and real-time monitoring. On the other hand, throughput signifies the rate at which data needs to be transmitted through the system, quantifying the quantity of information that needs to be conveyed within a specified time span. Maintaining high throughput is critical for timely information delivery, as it equips the system to efficiently handle a substantial volume of data.

Real-time applications necessitate both the low latency and high throughput transmission. Low latency minimizes the delay in transmitting information, while high throughput empowers the system to effectively handle significant data volumes. However, a potential tradeoff can exist between these two performance metrics [54]. Fig. 5 illustrates the effect of latency and throughput on timeliness of information. In

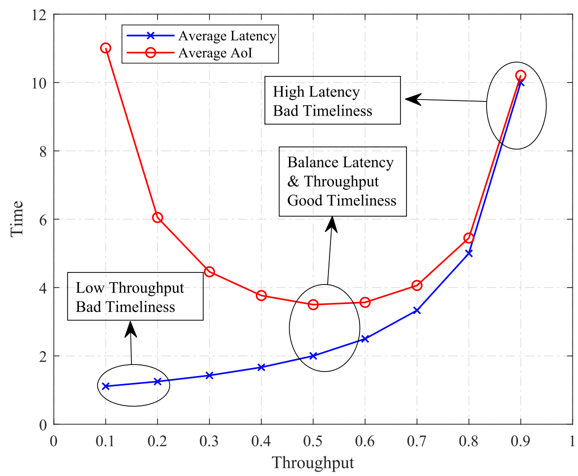

Fig. 5. Effect of throughput and latency on timeliness of information.

this context, high throughput might result in considerable queuing delays, consequently increasing latency, and vice versa. Therefore, achieving a balance between both the metrics becomes paramount to attain optimal performance concerning both timely and efficient information dissemination. In essence, to accurately gauge and quantify the timeliness of information in real-time applications, it is essential to employ a suitable performance metric that takes into account both the latency and throughput considerations.

III. Nonterrestrial Networks

As defined by the 3GPP, an NTN refers to a network that operates, either partially or fully, for communication purposes through a spaceborne vehicle, i.e., geostationary earth orbit (GEO), medium earth orbit (MEO), and low earth orbit (LEO) satellites, or an airborne vehicle i.e., HAPs and UAVs. NTN integration refers to the process of integrating NTN with the existing terrestrial networks and communication infrastructure. This integration allows for seamless communication and connectivity between the NTNs and terrestrial networks, enabling the users to access services and resources across both the domains. NTN integration plays a significant role in extending connectivity, expanding the network coverage, and enabling seamless communication across both the nonterrestrial and terrestrial domains. It facilitates the realization of the full potential of NTNs, allowing user equipments (UEs) to leverage the benefits of both network types for enhanced communication and connectivity experiences.

A. Features and Challenges

In the expansive domain of NTNs, a dynamic interplay of distinctive features and intricate challenges shapes the landscape of communication technology. These networks, operating beyond the confines of terrestrial infrastructure, offer unprecedented opportunities alongside formidable obstacles.

At the forefront of NTN features lies the expansive coverage they provide, extending communication capabilities to regions traditionally underserved by the terrestrial networks. By leveraging satellite or UAV-based connectivity, NTNs transcend geographical barriers, ensuring communication continuity even in remote, inaccessible areas, such as rural locales, oceans, and airspace. This expansive coverage fosters connectivity across diverse mobile platforms, including vehicles in motion, airborne aircraft, sea-faring vessels, and individuals on the move, revolutionizing domains, such as transportation, aviation, maritime activities, and disaster response scenarios.

However, NTNs also confront the challenges inherent to their nonterrestrial nature. One such challenge stems from the dynamic and complex environments in which NTNs operate. Atmospheric variations, ionospheric disturbances, and space weather events pose formidable obstacles, necessitating innovative adaptive techniques and predictive models to ensure reliable communication links. Furthermore, the proliferation of satellites, UAVs, and other nonterrestrial platforms introduces complexities in interference management. With an increasing number of communication nodes orbiting Earth or traversing the skies, the potential for signal interference and spectral congestion amplifies significantly. To address this challenge, NTNs must employ cutting-edge techniques, such as advanced beamforming, dynamic spectrum access, and cognitive radio.

Sustainable power management emerges as yet another critical facet, necessitating innovative solutions to address the energy demands inherent in satellite operations and ground-based infrastructure. From solar power generation and energy-efficient propulsion systems to intelligent grid integration and energy harvesting technologies, NTNs must continuously explore and implement novel approaches to ensure the long-term sustainability and autonomy of their energy systems.

Security and resilience stand as pillars of utmost importance in the realm of NTNs, as these networks play increasingly integral roles in critical infrastructure and essential services. To safeguard against an array of potential threats, including cyberattacks, jamming attempts, and natural disasters, NTNs must employ innovative cryptographic techniques, robust key management protocols, and resilient network architectures.

Moreover, the seamless integration of NTNs with the existing terrestrial networks presents a multifaceted challenge, encompassing interoperability, compatibility, and seamless handover between the disparate network domains. Innovative protocols, standards, and architectures are essential in facilitating smooth integration, enabling seamless communication and resource optimization across heterogeneous network environments.

In navigating these features and challenges, NTNs stand poised to revolutionize the landscape of global communication, offering unparalleled connectivity and resilience across diverse environments and applications. Through continuous innovation and collaboration, NTNs can realize their full potential in shaping the future of communication technology.

B. NTN Usage Scenarios

As NTNs are envisioned to play a crucial role in expanding 5G services to remote areas, providing coverage in challenging terrains, and enabling seamless connectivity for various applications, the next section explores the primary usage scenarios and applications of NTN in the context of 5G.

1) Massive Internet of Things: In recent years, the global connectivity of the IoT devices has witnessed a remarkable surge [55], [56], a trend projected to persist with an anticipated 75 billion connected devices estimated by 2025 [57]. Ensuring such extensive connectivity is a critical performance metric for the IoT technologies. Although UAVs have showcased swift and adaptable IoT connectivity in regions lacking ground infrastructure, their operational duration and coverage remain restricted. To achieve worldwide connectivity, GEO satellites emerge as valuable assets, particularly in scenarios where terrestrial infrastructure faces either temporary or permanent impairment. Nevertheless, satellite communication channels pose a significant challenge due to the substantial round-trip delays within the transmission link.

To address the issues arising from increased delays over nonterrestrial links, 3GPP studies propose leveraging global navigation satellite system (GNSS) capabilities and satellite ephemeris data. This approach aims to mitigate the impact of these factors on the nonterrestrial link performance. By integrating GNSS capabilities with satellite ephemeris data, precompensation technology can effectively mitigate a significant portion of the delay inherent in channel modeling, aligning the characteristics of nonterrestrial links with those typically observed in terrestrial links.

In response to the challenges posed by satellite communication channels, researchers have put forth various novel communication technologies, alongside adaptations to the existing narrow-band IoT (NB-IoT) protocol. For instance, the work by [58] introduces the turbo-frequency-shift keying modulation, a novel air interface tailored for NB-IoT usage. This innovative interface adeptly handles the delays and Doppler effects encountered in satellite channels. Furthermore, the work by [59] delves into an NB-IoT receiver architecture specially designed to address impairments within satellite communication channels. By exploring and validating these solutions within Rel-17, 3GPP aims to establish the requisite baseline standards for leveraging NB-IoT and long term evolution machine type communications (LTE-M) technologies to support NTNs, thereby ensuring enhanced connectivity for the growing IoT ecosystem.

2) Enhanced Mobile Broadband: Enhanced mobile broadband (eMBB) aims to bring the advantages of 5G technology to the general public. As outlined in Release 15 [6], eMBB satellite services cover four distinct use cases: 1) diverse connectivity; 2) global service continuity; 3) multimedia service connectivity; and 4) public safety. One of the primary applications of eMBB is to facilitate innovative mobile experiences, such as high-definition video streaming, augmented reality (AR), and VR on the move. Consequently, ensuring the timeliness of information becomes crucial to support these functionalities effectively. In such scenarios, data processing often requires significant time and computing resources, surpassing the local server capacities of UEs and straining the traditional centralized computing systems, which struggle to manage the increasing workload from numerous users. This challenge can result in prolonged response times, heightened latency, and an overall deterioration in the system performance.

To address these challenges, modern systems employ mobile edge computing (MEC) and edge caching techniques. MEC leverages the deployment of edge servers at the network periphery, alleviating a portion of data processing tasks from local servers. Compared to centralized computing, MEC reduces latency and enhances the overall system responsiveness [60]. Yet, MEC alone might still encounter latency issues when accessing frequently requested data from remote servers. To further enhance the system performance, caching plays a crucial role. Caching involves storing frequently accessed data closer to the users, reducing the need for repeated retrieval from remote servers. By incorporating caching mechanisms into the network architecture, the system can optimize data delivery and further reduce latency. Popular content or frequently requested data can be cached on the edge devices, enabling faster access and reduced transmission delays. Notably, in NTN enabled MEC and caching systems, the timeliness of information becomes a critical performance metric.

In MEC systems, due to the limited computation resource and the power consumption of UEs, it is necessary to offload computing tasks to the edge server. In the ground terrestrial-based MEC system, the main challenge is to determine whether or not to offload and how much should be offloaded [61], [62]. This decision is influenced by several parameters, including the computing capacity of the edge server, the number of users, and the status transmission rate [63]. When compared to the local computing scenario, offloading computing tasks to the edge computing has a twofold effect on the end-to-end latency. While the computation time decreases, the transmission latency, propagation delay, and transmission errors can increase the overall end-to-end latency, especially in the satellite-enabled MEC systems.

In cache-enabled nonterrestrial systems, the implementation of edge caching becomes crucial to further mitigate transmission latency and enhance system throughput, especially in cache-enabled satellite networks. Effective edge caching requires careful consideration of factors, such as cache placement location, cache size, content popularity, and user mobility patterns. An intelligent caching strategy is essential to maximize the benefits of edge caching while minimizing the risk of cache misses and stale content. Employing edge caching in nonterrestrial systems decreases transmission delay while potentially increasing computation time. However, for satellite networks, the increase in computation time is not significant compared to the decrease in transmission delay, resulting in an overall decrease in end-to-end latency. Furthermore, edge caching enhances throughput by enabling efficient and rapid content delivery. With cached content readily available at the edge servers, there is less congestion on the network and reduced reliance on the backhaul links to the central data centers. This optimized data distribution results in higher throughput and a smoother user experience, even during peak usage periods.

C. Network Architecture

A typical terrestrial cellular radio access network comprises various system elements, including the UE, the base station

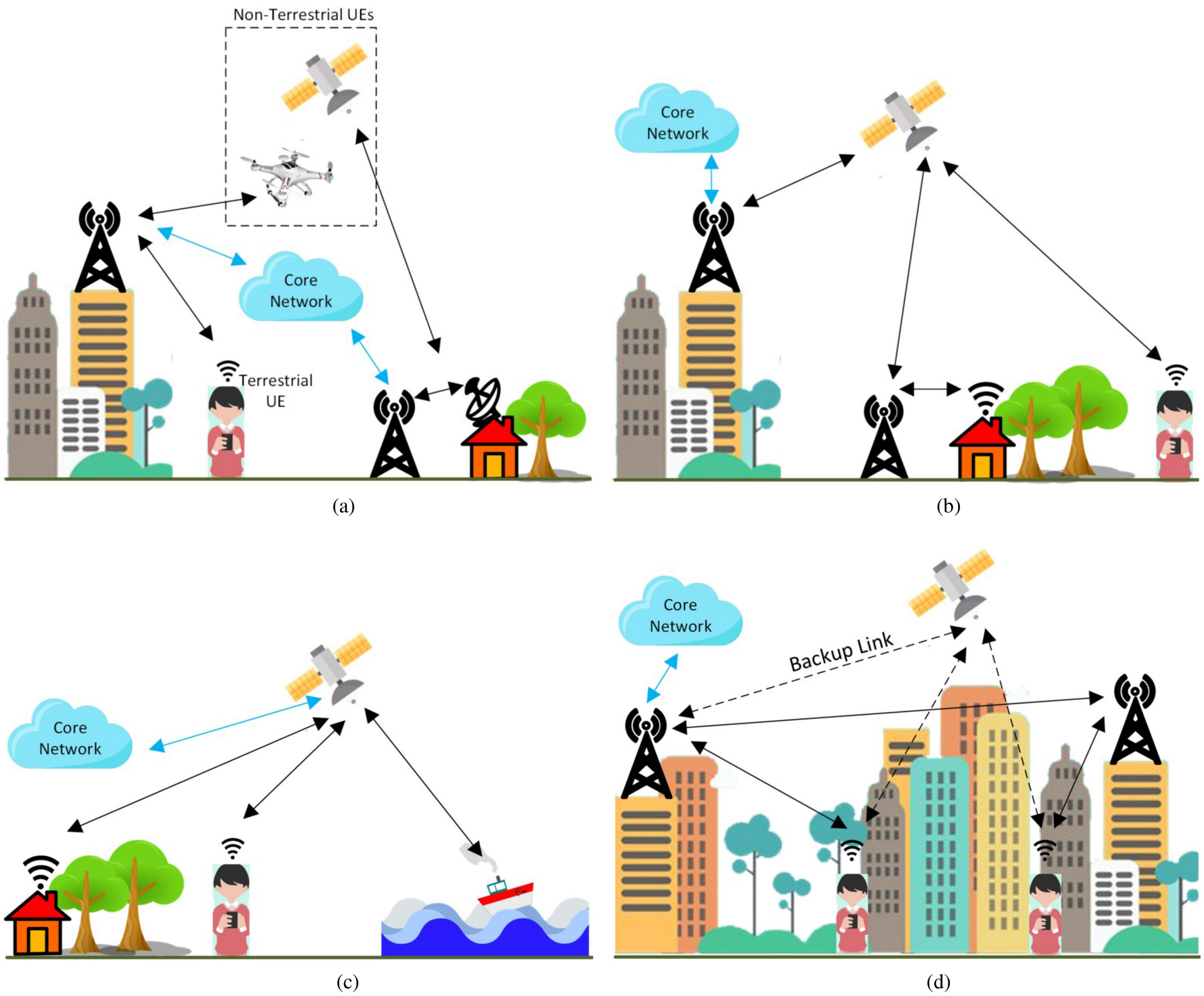

Fig. 6. Architecture options of nonterrestrial platforms. (a) Nonterrestrial platform as an user. (b) Nonterrestrial platform as a relay. (c) Nonterrestrial platform as a BS. (d) Nonterrestrial platform as a backup.

(BS), the core network, and the data network. The architecture of NTNs is designed to facilitate seamless connectivity, global coverage, and reliable communication services through the integration of UEs, satellite networks, ground BSs, control systems, terrestrial networks, and security mechanisms. This architecture aims to meet the specific requirements of nonterrestrial communication, enabling connectivity in areas where the traditional terrestrial networks are inaccessible or impractical. The integration of NTN components into the existing terrestrial architecture can significantly impact the typical communication chain. Depending on the placement of the nonterrestrial platform, the following architecture options may exist as follows.

1) *Nonterrestrial Platform is an User:* In this scenario, the NTN platform is referred to as an UE, as shown in Fig. 6(a), where the NTN platform is accommodated and supported by the terrestrial network infrastructure.
2) *Nonterrestrial Platform is a Relay Node:* In this scenario, the NTN platform serves as a relay node, supporting the communication link between the UEs and the BS, as depicted in Fig. 6(b). The NTN platform is employed in the communication link between the UEs and the BS to provide direct access connectivity. The backhaul is established from the spaceborne platform to ground gateway, which connects to a 5G core. Additional relays may exist between the spaceborne platform and the ground gateway, facilitated by other spaceborne platforms.
3) *Nonterrestrial Platform is a BS:* In this scenario, the NTN platform functions as a BS, as shown in Fig. 6(c). The functionalities of the BS are integrated into the NTN platform, enabling it to function as a BS when the NTN platform possesses sufficient processing capabilities with a regenerative payload.
4) *Nonterrestrial Platform is a Backup:* In this case, the NTN platform operates as a backup, as depicted in Fig. 6(d), when the original communication link between the UEs to the core network is interfered. This backup connection enhances the network resilience, ensuring continuous connectivity and minimizing service disruptions.

In the realm of real-time applications, nonterrestrial platforms primarily serve as relay nodes and backup solutions, attracting significant attention in research.

The details of the architecture for NTNs are discussed below.

1) Satellite Architecture: A satellite-enabled network is a communication infrastructure that facilitates long-distance data transmission between the satellites in a chain or hop-by-hop manner, offering global coverage [64]. These networks play a vital role in connecting remote or poorly served areas where terrestrial infrastructure is limited. By employing a multihop approach, satellite-enabled networks extend their coverage to even the most inaccessible locations, ensuring reliable communication and connectivity in areas with inadequate traditional networks. Data travels through a chain of communication links from the source to intermediate satellites and finally to the destination [65]. Each satellite acts as a relay, forwarding data packets to the next satellite in the chain until reaching the intended destination, ensuring efficient and scalable data transmission over extended distances.

Satellite-enabled IoT systems offer various architecture options tailored to specific application scenarios and traffic requirements [66]. The primary architecture involves utilizing a constellation of satellites orbiting the Earth to act as communication relays between the IoT devices and the BS in the core network. Satellites offer ubiquitous coverage, eliminating the limitations of terrestrial networks and enabling IoT connectivity in areas lacking traditional infrastructure. Integrating satellite technology with IoT opens up numerous possibilities across industries. However, the long distances between the satellites and IoT devices can present challenges to the optimal performance of the satellite-enabled IoT systems [67]. Latency is a primary concern, and the distance may also result in increased power consumption and reduced signal strength. Energy efficiency becomes crucial, given that the IoT devices often rely on limited power sources like batteries. Additionally, signals traveling over extended distances may experience degradation or interference, affecting reliability and transmission speed, thus impacting the timeliness of information.

The architecture of a satellite-enabled MEC system combines satellite communication with edge computing to offer efficient and low-latency services in remote and underserved areas [68]. Edge servers are equipped on satellites to facilitate data processing for UEs. This setup enables users to access computing power and resources at the network edge, closer to the end users, while utilizing satellite links for connectivity. In the satellite-enabled MEC system, UEs like smartphones, tablets, or IoT devices communicate with the satellites for data offloading, processing, and accessing satellite connectivity. Satellites act as the edge servers with compute resources, storage, and networking capabilities, supporting compute-intensive tasks and offloading processing from UEs to reduce latency and enhance the overall user experience [69].

The benefits of satellite enabled networks are numerous [5], [6]. In particular, satellite enabled networks offer increased reliability and resilience. By employing multiple communication links, these networks can mitigate the impact of link failures or signal degradation, which improves the reliability, further enhancing the timeliness of the system. If one link in the chain experiences interference or disruption, the data can be rerouted through alternative paths, ensuring continuity and minimizing service interruptions. This resilience is particularly crucial for critical applications, such as emergency communications, remote sensing, or disaster response. Furthermore, satellite enabled networks support enhanced scalability and capacity. As the demand for connectivity grows, additional satellites can be incorporated into the network, expanding its capacity and accommodating a larger number of connected devices. This scalability makes satellite enabled networks well-suited for supporting the demands of high capacity in ultradense regions, where a vast number of UEs require reliable and widespread connectivity.

2) UAV Architecture: An UAV-enabled network leverages UAVs as flying relays to extend the reach of wireless connectivity and enhance communication capabilities, especially in areas with limited or no terrestrial infrastructure [70]. UAVs act as mobile nodes, establishing communication links between the distant locations, effectively creating a communication path [71], [72]. This architecture enables data transmission over long distances, bypassing obstacles and geographical constraints.

In UAV-enabled IoT systems, UAVs and IoT technologies work together to offer enhanced data collection, improved coverage, mobility, and real-time data availability [73]. UAVs fly over specific areas to collect data from the IoT devices, accessing hard-to-reach or hazardous locations and providing connectivity and data collection capabilities. The enhanced data collection improves situational awareness and enables more accurate monitoring and analysis. Compared to the satellite-enabled IoT systems, UAV-enabled systems offer flexibility in deployment and reconfiguration, reducing operational costs and time. UAVs can be easily deployed and redirected to different areas or specific targets, allowing for dynamic data collection and responsive adjustments to changing requirements.

In UAV-enabled MEC systems, UAVs are equipped with computing resources to facilitate data processing for UEs. The deployment of computing resources closer to users significantly reduces latency in data processing and service delivery [74]. However, the limited payload capacity and battery life of UAVs need to be considered. This constraint affects the complexity and scale of applications that can be hosted on UAVs and the duration and availability of UAVs for MEC services. To address these issues, careful offloading strategies need to be designed.

Compared to the satellite-enabled networks, UAV-enabled networks offer more flexibility and lower propagation delay, enhancing the timeliness of information. Research interests are focused on resource allocation design and trajectory planning to improve the system performance, including transmission reliability, latency, throughput, and AoI performance. Additionally, technologies like nonorthogonal multiple access (NOMA) and RIS are utilized in the UAV systems to further enhance the system performance [75], [76].

3) Multisegment Architecture: In a multisegment network, multiple nonterrestrial platforms may be used as the relay nodes to facilitate information transmission between the UEs and the BS [77]. In this integrated network, satellites play the role of the network backbone, offering wide-area coverage and long-distance communication capabilities. Positioned in space, they are equipped with communication payloads for data transmission and reception. Satellites establish communication links not only with ground stations but also with each other, enabling data exchange and network connectivity. They effectively serve as intermediaries, relaying data between the HAPs, UAVs, and ground stations. HAPs are positioned at high altitudes in the stratosphere, above commercial air traffic but below satellites. They function as intermediate relay nodes between the satellites and UAVs or ground stations. UAVs operate at lower altitudes and can be mobile nodes within the network. They can be deployed for specific tasks or missions, such as surveillance, data collection, or communication relaying. UAVs are equipped with communication equipment that enables them to establish connections with the satellites, HAPs, and other UAVs. They can serve as dynamic relays in the network, extending the coverage and connectivity to remote or inaccessible areas.

D. Timeliness in NTN

The NTN stands as a foundation in delivering reliable and efficient communication services, highlighting the critical importance of timely information dissemination across diverse applications. Real-time data serves as the key element for swift decision making and effective response strategies, particularly in dynamic scenarios, such as disaster response efforts [78]. Access to up-to-the-minute information directly influences the coordination and execution of rescue operations, enabling emergency personnel to make informed decisions promptly, thus saving lives and minimizing damage. In addition to disaster response, NTNs are instrumental in various critical communication services, including emergency response systems, public safety networks, and military operations. In these contexts, the timely dissemination of information is paramount for ensuring that actionable intelligence reaches decision makers without delay. This entails issuing emergency alerts to the public, providing situational updates to first responders, or transmitting command directives to military units, highlighting the indispensability of NTN communication channels in terms of speed and reliability. Moreover, NTN's significance extends to applications like remote sensing and monitoring, encompassing environmental surveillance, agricultural monitoring, and infrastructure inspections. The ability to deliver data in real-time is crucial here; promptly relaying the sensor data and monitoring information enables swift anomaly detection, proactive response to changing conditions, and effective risk mitigation. For instance, in environmental monitoring, rapid detection of pollution incidents or natural disasters allows for immediate intervention and mitigation efforts.

In IoT systems, where the sensors and devices generate a continuous stream of data across vast networks, the timeliness of information is paramount [79]. Any delay or latency in data transmission could lead to erroneous decisions. For instance, consider remote monitoring systems for critical infrastructure like oil pipelines; timely detection of leaks or anomalies is vital for preventing environmental disasters and ensuring operational integrity. Prioritizing the timeliness of information transmission within the NTN-enabled IoT systems ensures optimal performance, empowering stakeholders to act decisively based on the most current and accurate data available.

Beyond these critical domains, 5G-enabled NTNs play a pivotal role in a diverse array of applications where real-time information is imperative. In autonomous vehicles, for example, split-second decisions are necessary to ensure passenger safety and efficient navigation. NTN's ability to provide uninterrupted, high-speed connectivity ensures seamless communication among the vehicles and infrastructure elements, enabling rapid responses to changing road conditions and potential hazards, thereby enhancing the overall safety and efficiency on the roads.

Furthermore, smart city applications heavily rely on timely data availability to manage various urban systems effectively. Real-time information about traffic flow, congestion levels, and accidents enables dynamic adjustments to traffic signals and routing algorithms, reducing gridlock and optimizing energy usage. Additionally, real-time monitoring of surveillance cameras, sensors, and emergency response systems enhances public safety and resilience within urban environments.

In manufacturing and industry 4.0 settings, 5G-enabled NTNs facilitate real-time monitoring and control of equipment and production processes. High-speed connectivity and low-latency communication enable manufacturers to gather the real-time data on equipment status, operational performance, and product quality. This information enables predictive maintenance strategies, minimizing downtime, optimizing workflows, and responding promptly to market demands, thereby enhancing the overall productivity and competitiveness.

In essence, 5G-enabled NTNs extend far beyond traditional communication services, encompassing a wide range of applications where real-time information is essential for making informed decisions and driving positive outcomes. By providing reliable, high-speed connectivity and low-latency communication capabilities, NTNs enable innovation and efficiency across various sectors.

IV. Strategies to Achieve Timeliness in NTN

Given the importance of timely information in NTNs, we delve into various design approaches aimed at enhancing timeliness within NTNs in this section, as outlined in Table III.

A. Network Structure Design

In order to ensure timely information within the NTN networks, the design of network structures is tailored for the satellites, UAVs, and multisegment networks.

1) Satellite: The massive LEO satellite network architecture proposed in [80] underscores a profound shift toward network architecture design aimed at minimizing AoI or latency, representing a significant advancement in performance enhancement. Employing a nearest neighbor search algorithm, this architecture meticulously determines multihop links and relay satellite positioning, thereby prioritizing latency

TABLE III
DESIGN METHODS IN NTNS TO ENHANCE THE TIMELINESS OF INFORMATION

Design Method		Reference
Network Architecture Design	Satellite	[80]–[89]
	UAV	[90]–[94]
	Multi-segments	[95], [96]
Resource Allocation	Spectrum and Bandwidth	[83], [84], [97]–[115]
	Transmission Power	[96], [116]–[126]
	Transmission Duration	[127]–[139]
Trajectory Planning		[91], [95], [140]–[146]
Protocol Design		[147]–[150]
Modulation Design		[151]–[156]
Reconfigurable Intelligent Surfaces		[121], [123], [157], [158]
Energy Harvesting		[117], [120], [126], [129], [133]–[138], [145], [146], [159]–[162]
Offloading Strategy		[85]–[89], [109]–[114], [163]–[167]
Caching Strategy		[90]–[94], [139]–[141], [143]–[146], [168]–[172]

TABLE IV
COMPARISON OF AOI OPTIMIZATION SOLUTIONS: PERFORMANCE METRICS, APPLICABLE SCENARIOS, AND IMPACT ON TIMELINESS

Related Works	Performance Metric	Applicable Scenario	Impact on Timeliness	Description of Impact on Timeliness
[80]	Transmission latency	Single user, single satellite as relay node	Partial positive	Limited to single-user systems and cannot be extended to multi-user systems.
[91]–[93], [111], [164]–[167]	End-to-end latency	Multi-user, multi-satellites and UAVs network	Positive	The end-to-end latency decreases, which improves AoI performance.
[109], [110], [112]–[114]	End-to-end latency	Multi-user, single satellite as edge server	Positive	The end-to-end latency decreases with a fixed throughput, which improves AoI performance.
[85]–[87]	Transmission latency	Multi-user, multi-satellites, two-tier cache system	Partial positive	The transmission latency decreases, but the computation time is not evaluated.
[88], [89]	Transmission latency	Multi-user, multi-satellites as single-tier cache	Positive	The transmission latency decreases with a high throughput and acceptable cost, which improves AoI performance.
[115]	End-to-end latency	Multi-user, single satellite, ground cache	Positive	The end-to-end latency decreases with a high throughput, which improves AoI performance.
[95], [96], [125], [173]	Throughput	Multi-user, multi-satellite-and-UAV network	Positive	The capacity of the network increases, which improves AoI performance.
[97]	Reliability, throughput	Multi-user, multi-satellite as BSs	Positive	The network capacity increases, which improves AoI performance.
[118], [174]	Throughput	Multi-user, single UAV as BS	Two-fold	The increase of throughput may increase the transmission latency, which may have two-fold effect on AoI performance.
[142], [170], [172], [175]	Transmission latency	Multi-user, multi-UAVs, flying cache	Partial positive	The transmission latency decreases, but the computation time is not evaluated.
[147]	End-to-end Latency	MAC and physical layer protocol	Positive	The transmission latency decreases, which improves AoI performance.
[154]	Transmission error rate	Channel coding protocol	Two-fold	Both the transmission reliability and latency increase, which may have two-fold effect on AoI performance.
[157]	Reliability	Single user, single UAV as relay node	Partial positive	Limited to single-user systems and cannot be extended to multi-user systems.
[161]	Transmission latency	Multi-user, multi-UAV as BSs	Positive	The transmission latency decreases with fixed throughput, which improves AoI performance.
[163], [169]	Transmission latency	Multi-user, single satellite as edge server	Partial positive	The transmission latency decreases, but the computation time is not evaluated.
[144]	End-to-end latency	Multi-user, single UAV as edge server	Positive	The end-to-end latency decreases with a fixed throughput, which improves AoI performance.
[145], [146]	Throughput	Multi-user, single UAV as edge server	Two-fold	The throughput increases, which may increase the transmission latency. Hence, it may have two-fold effect on AoI performance.
[171]	End-to-end latency	Multi-user, multi-UAVs, flying cache	Positive	The end-to-end latency decreases with a fixed throughput, which improves AoI performance.

reduction—an essential element for the system enhancement. While the focus on minimizing latency proves advantageous in single-user scenarios, it can inadvertently lead to network congestion and reduced throughput in multiuser environments, as highlighted in [81]. Addressing these challenges, a cooperative transmission control mechanism is proposed, mitigating buffer usage and latency while ensuring high throughput and flow fairness in multiple satellite communication systems [81]. Additionally, a transmission path selection algorithm aimed at minimizing the average AoI is proposed in [82], highlighting the crucial role of tailored network architecture in meeting diverse communication needs.

Dual connectivity emerges as a pivotal strategy for optimizing throughput and latency [83]. In consideration of a multiorbital satellite dual connectivity networks, a hybrid resource allocation algorithm tailored for this network structure is introduced in [84]. This algorithm outperforms existing solutions by achieving lower average latency and higher peak data rates, emphasizing the significance of innovative network architecture in modern communication systems.

Emphasizing the significance of network architecture with caching capability enabled, caching mechanisms play a crucial role in reducing content retrieval delays and enhancing the overall system performance. In [85], a multitier cache system encompassing ground stations, MEO/LEO satellites, and satellite gateways is proposed, aimed at minimizing content retrieval delays from the satellite backhaul. Similarly, in [86], a two-tier cache-enabled GEO-LEO satellite network architecture, complemented by a regional user interest-aware caching scheme, is introduced for enhanced performance. Expanding on the cache-enabled network paradigm, the work by [87] proposes a two-tier cache network architecture, combining caching capabilities on LEO satellite constellations with terrestrial cloud cache, thus forming a "cache in space" system. This approach demonstrates its ability to meet diverse latency requirements from applications at an acceptable cost compared to conventional cloud-based approaches. Furthermore, innovative cache in space systems utilizing LEO satellite constellations are explored in [88] and [89]. In [88], the focus is placed on cache node selection and content updating schemes, successfully reducing transmission delay and enhancing throughput. Meanwhile, in [89], a content distribution strategy employing lightweight construction algorithms is introduced, significantly reducing transmission time and further optimizing the system performance.

2) UAV: In various studies exploring UAV-enabled MEC systems, a strong emphasis is placed on the network architecture design aimed at minimizing the average AoI. For instance, in [90], a homogeneous two-UAV-enabled MEC system is examined, with joint trajectory planning of the UAVs and offloading strategy for ground UEs, all geared toward AoI minimization. In [91], a multiple UAVs-enabled MEC system is proposed, where communication link association and computation offloading strategies are devised to achieve the same goal. Further investigations delve into the optimizing system latency through intricate network architectures. In [92], a two-tier setup of UAV edge servers prompts a deep reinforcement learning (DRL)-based approach for joint trajectory planning and task offloading, ultimately aimed at minimizing latency. Additionally, a joint UAVs and satellites-enabled MEC system is explored in [93], focusing on offloading and computation scheduling strategies to reduce the end-to-end latency. Moreover, the work by [94] develops a two-tier uplink MEC network, integrating NOMA technology, where UAVs collect data with computing tasks from ground UEs and forward them to the HAP. This work meticulously designs a joint trajectory planning of UAVs and resource allocation strategy to minimize the average AoI, underscoring the significance of tailored network architectures in optimizing the system performance.

3) Multisegments: Due to the significant propagation pathloss in satellite communication links, a two-tier of satellites and HAPs system is proposed in [95], where HAPs are employed as the relay nodes between the UEs and satellites. By carefully allocating bandwidth for both the UE-HAP and HAP-satellite links, the proposed network improves the throughput by approximately 30% compared to the original satellite communication network. The work by [96] proposes a two-tier of satellites and UAVs, where UAVs collect the information from ground UEs and then upload it to the satellites. In [96], a joint UAV selection and resource allocation strategy to maximize the throughput of the system is designed.

B. Resource Allocation

Resource allocation in NTNs plays a crucial role in ensuring the timeliness of information. This involves the allocation of spectrum and bandwidth, transmission power, and transmission duration between the nonterrestrial platforms and UEs.

1) Spectrum and Bandwidth: In both the satellite and UAV systems, effective bandwidth allocation is crucial for overcoming resource scarcity and optimizing system performance. Spectrum sharing, similar to terrestrial networks, presents a viable solution to mitigate the scarcity of satellite spectrum resources [176], [177]. Consequently, optimizing resource allocation becomes pivotal, particularly in scenarios involving spectrum sharing.

For satellite systems, various approaches have been proposed to address this challenge [178], [179]. A dynamic capacity allocation algorithm aims to identify the optimal data transmission strategy in multi-UE multisatellites systems, enhancing the system reliability and throughput [97]. Additionally, joint frequency band selection, illuminated cell selection, and transmission power allocation schemes have been introduced to maximize throughput in joint LEO and GEO communication systems [98]. This scheme leverages GEO satellites as backups during high workload on LEO satellites, aiming to increase throughput and reduce transmission delay, potentially yielding a two-fold effect on AoI performance.

Similarly, in UAV systems, effective bandwidth allocation strategies are essential for enhancing the timeliness of information. Researchers investigate how to assign individual channels for UEs and allocate bandwidth for each channel. For example, bandwidth allocation optimization techniques aim to minimize the total required bandwidth while satisfying reliability and latency requirements [116]. Moreover, under UAV power constraints, scheduling algorithms among UEs optimize AoI performance in UAV cellular networks [117]. By focusing on effective bandwidth allocation strategies, both the satellite and UAV systems can better manage resources to ensure timely information transmission.

2) Transmission Power: In designing resource allocation strategies for NTNs, challenges arise particularly in heterogeneous systems where different UEs may have distinct requirements. This complexity underscores the reliance on channel state information (CSI) between the UEs and satellites, essential for effective resource allocation. However, the inherent drawback of CSI lies in its susceptibility to becoming outdated, particularly in satellite communication systems with high feedback latency. To address this, authors of [100] investigate transmission power allocation based on outdated CSI in multiuser hybrid satellite-terrestrial relay networks. Their findings reveal enhanced reliability, consequently improving the AoI performance.

Furthermore, to mitigate the long propagation delay in satellite-enabled IoT systems, several techniques are employed [180], [181]. Advanced transmission protocols, modulation schemes, and error correction techniques enhance the robustness and reliability of data transmission, mitigating the impact of signal degradation over long distances. Additionally, signal amplification and transmission power optimization techniques minimize power consumption while maintaining adequate signal strength. A joint scheduling and transmission power allocation strategy is designed in [103], incorporating NOMA technology to minimize the average AoI in a downlink satellite-enabled IoT system. Similarly, in [104], a NOMA-based status update framework is employed alongside a joint BS and satellite selection, scheduling, and transmission power allocation strategy to minimize the average AoI of the system. Moreover, a power allocation strategy leveraging the particle swarm optimization algorithm to minimize the average AoI is designed for the NOMA-based satellite-enabled IoT systems [105]. The work by [106] further formulates a power allocation problem in the NOMA-based satellite-enabled IoT systems as a Markov decision process and proposes a DRL-based power allocation strategy to minimize the average AoI.

Meanwhile, the adoption of NOMA technology has emerged as a promising avenue to enhance UAV system performance. Although NOMA presents challenges in satellite systems due to the need for instantaneous CSI, its benefits in improving spectral efficiency and throughput are noteworthy. The work by [118] designs a transmission power allocation scheme to maximize total throughput for a two-user system, while in [174], this approach is extended to a multiuser scenario. However, it is important to note that while NOMA enhances the system throughput, it may potentially increase transmission latency for each UE, thereby impacting AoI performance.

Recently, blockchain technology has emerged as a powerful tool to enhance the security of transmitted information. In [107], blockchain for information transmission in the IoT systems is employed and a power allocation scheme to accelerate the consensus process of blockchain is also proposed to minimize the average AoI of the system. Moreover, in [108], the study conducted by [107] is extended by proposing a forking-waiting-retransmission mechanism to further improve the average AoI performance in blockchain-based satellite-enabled IoT systems.

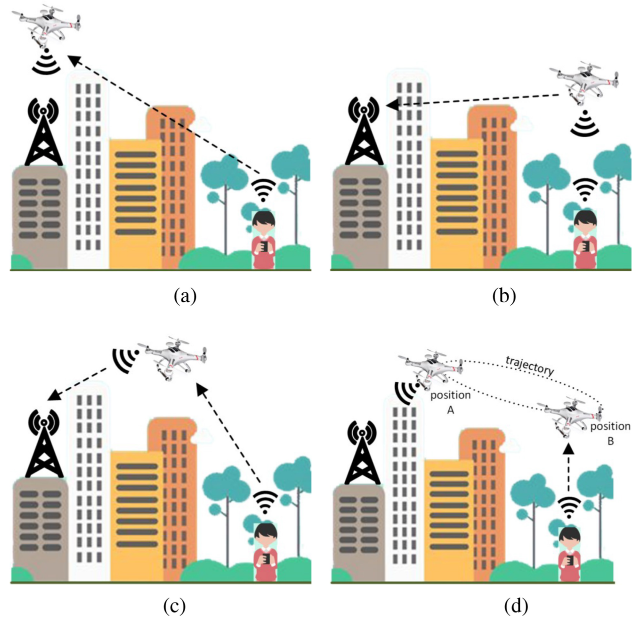

Fig. 7. Architectures of UAV-enabled networks in urban scenario. (a) Fixed UAV over BS. (b) Fixed UAV over UE. (c) Fixed UAV with optimal position. (d) Optimal trajectory planning.

3) Transmission Duration: Apart from the bandwidth and transmission power allocation, the transmission duration is also investigated in UAV systems due to short packet communication. In a short packet communication system, increasing packet length can lead to longer transmission times and decreased transmission error probability, which has a two-fold effect on the timeliness of information. Considering the impact of the packet length, the average AoI is analysed in an UAV system where the UAV acts as a mobile relay [119]. Based on the analytical results, the work by [119] provides the optimal altitude and packet block length. Furthermore, under restricted latency constraints, a joint transmission power allocation and block length optimization scheme is designed in [120] to optimize throughput and transmission error probability in a short packet communication system.

C. Trajectory Planning

Trajectory planning emerges as the most critical design aspect for enhancing information timeliness in UAV systems. It involves determining the optimal path and motion of the UAV to optimize the system performance while accounting for various constraints and factors. To demonstrate the effectiveness of trajectory planning in improving AoI performance, Fig. 8 depicts AoI as a function of the distance between the BS and UE across different architectures of UAV-enabled networks in urban scenarios (as referenced in Fig. 7). The system model considered here includes an UAV, a BS, and an UE, with both high-rise urban and urban scenarios taken into account. As depicted in Fig. 8, strategic trajectory positioning and planning can substantially enhance AoI performance, particularly in densely populated highrise urban areas. In [182], a trajectory planning approach is designed to minimize both the average AoI and peak AoI (PAoI), positioning the UAV directly above

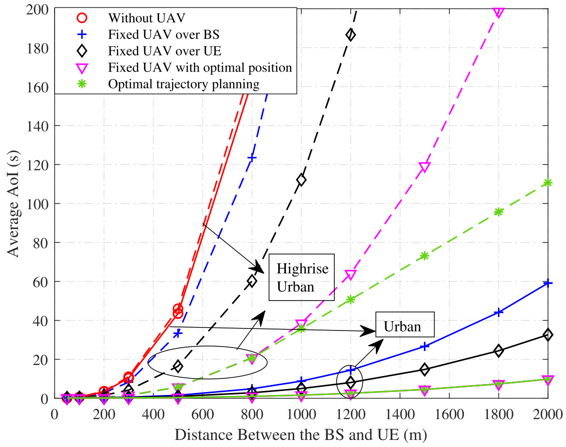

Fig. 8. Corresponding to Fig. 7, average AoI versus distance between BS and UE in urban scenario.

UEs. Recognizing that LoS conditions can amplify received power at the receiver, the work by [183] proposes a trajectory planning strategy to optimize AoI performance by considering the influence of altitude on LoS probability. Additionally, in [184], two trajectory planning strategies are introduced: one based on the Hamiltonian path algorithm and another leveraging a tree-searching algorithm. Both the strategies aim to minimize the average AoI of the system by optimizing UAV trajectory planning.

Energy constraints are crucial considerations for UAV systems as they directly impact flight endurance and operational capabilities of the aircraft. Considering these energy constraints, Ahani et al. [159] devised a trajectory plan based on the graph labeling to minimize average AoI. Similarly, kernel K-means is employed to classify underground sensor nodes into clusters in [160] and then a trajectory plan to minimize AoI is designed. By accounting for the energy constraint of each UAV, Zhao et al. [161] created a decentralized multi-UAV trajectory planning strategy in a network enabled by multiple UAVs. The aim was to reduce transmission latency for UE and thereby enhance AoI performance.

Recently, the reinforcement learning approach has emerged as an efficient and accurate tool for solving practical problems. Utilizing DRL, the work by [185] adopts a compound-action actor-critic algorithm to design trajectory planning for minimizing the average AoI in a network with multiple UAVs. Factoring in packet expiration times, a reinforcement learning approach for trajectory planning is employed in [186], aiming to minimize the average AoI and reduce the rate of expired packets. By framing the trajectory planning problem as a Markov decision problem with an infinite state space, a joint design between the trajectory and resource allocation using the DRL approach to minimize the average AoI is proposed in [122].

In UAV-enabled IoT systems, the features of the IoT systems, such as the presence of a massive number of devices, limited transmission power, and sporadic information generation patterns, play a significant role in trajectory planning design and must be taken into consideration. By considering the aforementioned features of the IoT system and single UAV enabled IoT system, Jia et al. [187] designed the trajectory planning for data collection from multiple IoT devices to minimize the average AoI. Zhou et al. [188] formulated the trajectory planning problem as a Markov decision process and proposed a trajectory planning algorithm utilizing DRL technique to optimize the system AoI performance. Moreover, the work by [189] designs the trajectory planning with energy constraint, leveraging DRL to solve the finite-horizon Markov decision problem to minimize the average AoI. Considering different priority of IoT devices, a trajectory planning strategy is proposed in [190] to meet the timeliness requirements of different IoT devices. Similarly, with different importance of IoT devices, Sun et al. [127] introduced a DRL-based joint trajectory planning and bandwidth allocation strategy to minimize the weighted sum of average AoI.

In practice, multiple UAVs can be employed to facilitate data collection from the IoT devices, and investigating the joint trajectory planning of these UAVs becomes imperative for optimizing system performance. In multiple UAV-enabled IoT systems, Guo and Zhao [128] proposed a joint trajectory planning and power allocation algorithm for UAVs using a multiagent deep deterministic policy gradient, with the aim of minimizing latency. Similarly, in [130], a DRL-based approach is proposed for joint trajectory planning, considering UAV energy constraints to optimize AoI performance. Furthermore, trajectory planning for multiple UAVs is addressed to minimize the average AoI in [131], taking into account battery charging processes and UAV flight energy consumption. In the context of a joint satellite and UAV-enabled networked flying platform (nonterrestrial platform) IoT system proposed in [132], where UAVs collect data from the IoT devices and transmit it to a central satellite, authors design trajectory planning for UAVs and a scheduling policy for the two-tier uplink channel, all aimed at minimizing the average AoI of the system.

D. Protocol Design

Initial efforts have focused on investigating and designing protocols within the satellite IoT systems to enhance information timeliness. Drobczyk and Martens [147], the authors introduce a medium access control (MAC) and physical layer protocol based on the low-latency deterministic network in IEEE 802.15.4e. This protocol deployment aims to establish a low-latency and deterministic satellite-enabled IoT system. Considering the sporadic information generation characteristic of IoT systems, the work by [148] designs a random access-based uplink transmission protocol for multiple IoT devices. The goal of this protocol is to minimize the average AoI within the system. Furthermore, a grant-free random access protocol is proposed in [149]. It is demonstrated that this proposed protocol yields superior AoI performance compared to the existing protocols. In [150], a WiFresh protocol is introduced, combining polling multiple access mechanisms, the last-come-first-serve (LCFS) queuing policy, and the max-weighted scheduling policy. Prototypes of the WiFresh network architecture, alongside WiFi network architecture based on the IEEE 802.11 standard [191], are implemented using the USRP devices. Experimental outcomes demonstrate that the proposed WiFresh network architecture significantly improves AoI performance when compared to an equivalent standard WiFi network, particularly under high-load conditions.

E. Modulation Design

Due to the effects of propagation pathloss and fading between the transmitters and receivers, coding techniques are employed to mitigate channel impairments. In the context of short packet communications, the higher-order modulation schemes can achieve elevated data transmission rates. However, these schemes are more susceptible to errors induced by pathloss and fading, particularly pronounced in satellite systems. Therefore, the design of modulation and coding technologies must strike a balance between the achieving higher data rates and providing adequate error correction capabilities to counteract pathloss effects. Designing modulation and coding technologies for wireless communication systems presents a significant challenge, given the mobility of users that induces fluctuations in the wireless channel over time. To address these dynamic channel conditions, an adaptive modulation and coding strategy is proposed in [151], [152], and [153]. This strategy makes real-time decisions on modulation and coding schemes based on channel conditions, aiming to maximize spectral efficiency while maintaining a low block error rate.

Apart from the adaptive modulation and coding strategy, the study of channel coding schemes has been pivotal in enhancing NTN performance. To optimize AoI performance in satellite-enabled IoT systems, Ding et al. [154] introduced a network coding HARQ protocol, which aims to recover lost information and avoid unnecessary retransmission. Moreover, the network coding HARQ protocol is utilized in [155] for a two-hop satellite enabled IoT system, where satellites collect the data from the IoT devices and forwarded it to BS. Compared to the benchmark transmission protocols, the proposed approach enhances the timeliness of information by achieving a lower average AoI. In [156], an age-oriented channel coding scheme is designed to mitigate the impact of long propagation delay and significant propagation pathloss on the timeliness of information in satellite systems.

F. Reconfigurable Intelligent Surfaces

RIS is an emerging technology in wireless communications that utilizes a large number of passive reflecting elements to manipulate and enhance wireless signals [192], [193]. An RIS consists of a planar surface composed of small, individually controllable elements, such as antennas or metamaterial units. These elements can dynamically manipulate the phase shift, amplitude, and polarization of the incident electromagnetic waves. By intelligently adjusting the reflection properties of the surface, an RIS can shape and redirect wireless signals to improve the overall system performance. UAV-enabled RIS is a cutting-edge concept that combines the capabilities of UAVs with RIS to enhance wireless communication systems. In the context of UAVs, RIS technology is integrated into UAVs, allowing them to act as flying reflectors or scatterers. These UAVs equipped with RIS elements can be deployed strategically to optimize wireless signal propagation and overcome obstacles or unfavorable channel conditions.

Various architectures of UAV-assisted RIS are introduced in [13]. In the UAV-assisted RIS system, the trajectory planning of the UAV and the phase shift elements of the RIS are two main optimized parameters. These are accompanied by resource allocation, scheduling planning, and power control. The position of the UAV-assisted RIS is designed in [157] to minimize the transmission error rates in a single UE scenario, thus reducing the AoI growth caused by the transmission errors. In [123], the altitude of the UAV, transmission scheduling, and phase shifting of the RIS are jointly designed to minimize average AoI performance in a multiple-user system.

The scheduling policy among UEs is designed in [121] by adopting a deep learning approach, aiming to minimize average AoI among UEs while considering the phase shift elements of the RIS. Similarly, Al-Hilo et al. [158] utilized DRL and block coordinate descent to jointly design trajectory planning, UE scheduling, and phase shift elements of the RIS. The goal is to improve the AoI performance and energy efficiency of UAVs.

G. Energy Harvesting

Energy harvesting is a specialized application in the IoT systems. In energy harvesting scenarios, UAVs function not only as relay nodes in the communication network but also as power suppliers for the IoT devices. In this setup, UAVs first transmit power via the wireless power transfer technology to the IoT devices. Subsequently, the IoT devices use the received power for data transmission. Research in this area begins with performance analysis in such scenarios. The stochastic hybrid systems (SHSs) framework is adopted in [133] to analyse the AoI performance of an UAV-enabled wireless power transmission IoT system. Based on the analytical results, the authors further design a joint scheduling and packet management strategy to optimize AoI performance. Dang et al. [129] proposed a joint trajectory planning and wireless power transmission scheme for the IoT devices to minimize average AoI. Similarly, trajectory planning considering both energy transmission and service time allocation is designed in [134] for a wireless powered IoT system to minimize the average PAoI. Due to the complexity of optimizing the joint UAV trajectory planning, energy harvesting scheduling, and data transmission scheduling centrally. Hu et al. [135] decomposed the problem into two individual subproblems: 1) the trajectory planning problem and 2) the joint energy and data scheduling problem. They design separate strategies for the UAV trajectory planning, energy harvesting scheduling, and data transmission scheduling. These solutions are then combined to create a joint trajectory planning, energy harvesting scheduling, and data scheduling strategy to minimize average AoI. Taking into account the effect of UAV height on the LoS transmission probability, the work by [162] design a joint 3-D trajectory planning and energy scheduling strategy to minimize the average AoI of the system.

As solving the joint trajectory planning and energy/data transmission problem through the traditional methods is challenging, learning-based approaches are adopted in [126], [136], [137], and [138]. Specifically, Liu et al. [136] designed a DRL-based joint trajectory planning, energy scheduling, and data transition strategy to minimize average AoI. Considering UAV energy constraints, Zhang et al. [137] proposed a joint trajectory planning, energy scheduling, and data transition strategy to minimize average AoI. A multiple UAV-enabled wireless power transmission system is considered in [138], proposing a joint trajectory planning, energy scheduling, and bandwidth allocation strategy for multiple UAVs to minimize average AoI. Furthermore, considering two types of UAVs, namely UAV data collectors and UAV energy transmitters, a joint trajectory planning strategy for these UAV types is proposed in [126] to minimize the average AoI of the system.

H. Offloading Strategy

Offloading strategy in the MEC systems refers to the decision-making process of determining which computing tasks or data processing should be executed on the edge servers rather than on the mobile devices themselves. The goal of offloading is to optimize the utilization of network resources, reduce latency, enhance energy efficiency, and improve the overall user experience.

In satellite-enabled MEC systems, a central challenge is designing offloading strategies and resource allocations to optimize the timeliness of information, particularly in satellite communication due to its significant round-trip delay. The end-to-end latency of satellite-enabled MEC systems is analysed in [163] and a partial offloading scheme to reduce latency is proposed. Wang et al. [109] introduced a joint computation offloading and resource allocation strategy to minimize average latency in an LEO satellite-enabled MEC network. Furthermore, considering varying user priorities, Zhang et al. [110] suggested a joint computing and communication resource allocation strategy to minimize the weighted sum latency of users.

A joint terrestrial platform and satellite-enabled MEC system is proposed, and an offloading algorithm is devised in [164] to decrease end-to-end latency. A collaborative task computing strategy is introduced in [165], where the LEO satellite edge servers can offload computing tasks to idle adjacent LEO satellite edge servers, reducing system latency. Tailored for two types of edge servers, namely LEO satellite edge servers and central cloud edge servers, a two-tier offloading strategy is proposed to optimize the end-to-end latency [166]. Moreover, a joint hybrid GEO and LEO satellite-enabled IoT network is proposed in [111], where the LEO satellites collect computing tasks from the users and determine whether to process the tasks locally or offload them to the GEO satellites. In this context, the work by [111] proposes a joint task offloading and communication resource allocation strategy to minimize latency.

It is worth noting that the joint problem of offloading scheduling and computation resource allocation is challenging to address using the traditional methods. Learning approaches, especially DRL, have emerged as powerful tools to tackle such problems. Leveraging DRL, a joint task offloading and bandwidth allocation strategy to reduce end-to-end latency is introduced in [112]. Shinde et al. [113] proposed a satellite-enabled MEC vehicular network considering limited transmission power and vehicle mobility. In this scenario, a joint offloading scheduling and computation resource allocation strategy was devised to minimize average latency. Additionally, accounting for multiple satellite edge servers, a joint design between the edge server selection and offloading scheduling strategies is proposed in [114] to minimize the average system latency.

In UAV-enabled MEC system, the primary challenge lies in designing computation offloading strategies. Leveraging SHS technology, Han et al. [168] conducted an initial analysis of AoI performance in an UAV-enabled MEC system. Building upon the analytical findings, they further design a computation offloading strategy to optimize AoI performance, while also considering UAV energy constraints. To minimize the system latency, the work by [169] introduces a generalized benders decomposition approach-based algorithm framework to jointly design trajectory planning and computation offloading strategies in UAV-enabled MEC systems. Additionally, accounting for channel availability in computing task offloading, Yang et al. [139] employ the ordinary potential game theory to address the AoI-based channel access optimization problem. They proposes a joint channel allocation and computation offloading strategy aimed at minimizing the system's average AoI.

I. Caching Strategy

Caching strategy involves the process of intelligently storing and managing data at the edge devices. The primary objective of caching is to enhance the system's performance by reducing data access delays, minimizing redundant data transfers over the network, and ensuring faster retrieval of frequently requested information. By strategically caching data and computation results at the edge, cache enabled systems can improve overall efficiency, reduce network congestion, and deliver a seamless user experience with reduced latency and enhanced energy efficiency.

In satellite networks with caching capabilities, the caching capacity can be enabled either at the ground station or the satellite, forming either a single-tier cache system or a two-tier cache system with caching at both the locations. Integrating cache enabled network architecture, along with transmission techniques, leads to a significant reduction in transmission latency [194]. It is worth noting that most of the proposed cache enabled network architecture for satellite-related systems focuses on addressing transmission latency rather than the computation latency. This emphasis is primarily due to the considerable impact of propagation delay in satellite communication on overall transmission latency. However, the double-edge intelligent LEO satellite network proposed by [167], which combines MEC and caching, aims to address the end-to-end latency. It features a single-tier cache on the ground and utilizes MEC servers on both the satellites and ground stations. Additionally, the work by [167] introduces a cooperative MEC scheme with cooperation caching policies and resource allocation to further enhance the system performance.

Single-tier ground cache systems are not as effective as two-tier cache systems in terms of latency mitigation. However, in the case of nongenerative satellites or satellites with low computational capability, ground caching is the only option. A ground cache enabled GEO satellite network is proven to decrease the end-to-end delay and increase the overall throughput when combining caching with the NOMA technique [115].

Cache-enabled UAV networks are driven by the demand for rapid deployable networks in dynamic and densely populated settings like concert festivals or sports matches. The conventional fixed BSs encounter obstacles in finding the best locations and placements due to access, backhaul, and power limitations. In these situations, where attendees have similar interests, there is a high probability of multiple users downloading the same content, causing significant delays for BSs in traditional edge caching networks. UAVs emerge as an ideal solution, offering flexible alternatives to conventional BSs by acting as caching platforms to efficiently serve numerous users. By deploying UAVs as cache enabled nodes, these networks can effectively manage the escalating mobile traffic and ensure seamless data delivery to users in challenging and dynamic environments [142].

V. Future Research Direction

In the dynamic landscape of NTNs, the timely delivery of information remains of paramount importance. With the growing demand for real-time applications and services, the evolution of research should explore innovative directions to further enhance the timeliness of information in NTNs. This section outlines the prospective research avenues aimed at advancing timely information delivery within the real-time nonterrestrial platform-enabled networks and systems.

A. Adaptive Modulation and Coding Techniques

Adaptive modulation and coding techniques are vital for improving the signal quality and ensuring reliable communication in NTNs. Due to substantial propagation distances between the satellites and UEs, the coding strategies must address channel impairments like path loss and atmospheric disturbances. Higher-order modulation schemes offer higher data transmission rates but also increase susceptibility to errors from path loss [52]. Consequently, the coding methods must balance high data rates with robust error correction capabilities to counteract path loss effects. Efficient coding techniques also compress transmitted data, minimize redundancy, and maximize data throughput within limited bandwidth constraints, addressing challenges from the signal attenuation and path loss. A promising research direction in this area is the exploration of hybrid adaptive modulation and coding techniques, particularly those incorporating machine learning (ML). These techniques combine various modulation and coding schemes to optimize resource utilization and adjust dynamically to prevailing channel conditions. By continuously adapting modulation and coding strategies in response to path loss and other channel factors, these hybrid methods improve efficiency and speed up information delivery. Emerging ML-based adaptive modulation and coding techniques recognize channel conditions in real time and adjust schemes accordingly. This adaptive approach optimizes data transmission and enhances the overall network performance in NTNs.

B. Next Generation Multiple Access Technologies

Multiple access technologies are crucial for enhancing throughput and reducing latency in NTNs, which in turn improves the timeliness of information delivery for various applications. Emerging multiple access techniques, such as next generation multiple access (NGMA), go beyond traditional approaches by incorporating novel concepts like massive NOMA and advanced space division multiple access (SDMA). These schemes can support multiple users in the same resource blocks, such as time slots, frequency bands, spreading codes, and power levels. Current solutions in NGMA focus on achieving higher bandwidth efficiency and connectivity while accommodating massive user access and diverse data traffic [195]. By supporting more concurrent connections, NGMA can improve network performance in terms of massive connectivity, energy efficiency, and low latency. Additionally, the NGMA schemes must embrace intelligence to facilitate intelligent applications in 6G and beyond. Advances in artificial intelligence (AI), ML, and big data analytics offer promising approaches to tackle new challenges in intelligent NGMA. However, NGMA in NTNs faces challenges, such as managing interference and ensuring fair and efficient resource allocation among users. Addressing these challenges requires developing sophisticated algorithms for user scheduling, power allocation, and interference management. Additionally, integrating the NGMA schemes with the AI/ML techniques can lead to adaptive and intelligent resource management strategies that optimize throughput and latency. Future research should focus on enhancing the scalability and robustness of the NGMA schemes in NTNs, particularly in satellite constellations and UAV networks. This includes exploring hybrid multiple access schemes that combine different access techniques for greater flexibility and performance. Furthermore, the development of efficient and dynamic spectrum access methods can help improve spectral efficiency and reduce latency in NTNs. By tackling these challenges and advancing the research on multiple access technologies, NTNs can better support the growing demand for real-time applications and services, such as immersive VR/AR, holographic telepresence, and intelligent automation. These improvements will contribute to more efficient and timely information delivery across various emerging use cases in NTNs.

C. Routing and Resource Allocation

Routing and resource allocation play a critical role in NTNs by improving the timeliness of information delivery, particularly in the multiuser systems. One emerging solution is the development of dynamic routing algorithms that adaptively select optimal paths based on the real-time network conditions [196]. These algorithms must account for factors, such as network structure, link quality, congestion levels, and latency to determine the most efficient routes for information transmission [34]. By dynamically adjusting routing paths in response to changing conditions, NTNs can minimize delays and enhance information delivery. Multipath routing techniques present another area of potential improvement, providing fault tolerance and mitigating the impact of link failures or congestion. Leveraging multiple paths simultaneously can increase network resilience and ensure continuous data flow, even under challenging conditions. Additionally, ongoing research in ML and AI offers the potential to develop intelligent algorithms and protocols for selecting and utilizing multiple paths, optimizing network resource usage, and ensuring timely information delivery [197]. Energy efficiency is a critical consideration in NTNs, particularly in the UAV-enabled networks where limited onboard power sources, such as batteries or fuel affect flight endurance [198]. Research in energy-efficient routing and resource allocation algorithms aims to minimize energy consumption while maintaining timely information delivery. These algorithms must take into account energy-aware metrics, such as transmission power, battery levels, and energy harvesting capabilities to optimize routing decisions and resource allocation.

Future research directions should focus on refining these dynamic routing and resource allocation techniques. For instance, exploring the AI-based adaptive algorithms that can predict and respond to changing network conditions in real-time would enable more efficient use of resources and improve the overall performance. Additionally, advances in multipath routing and load balancing can contribute to fault tolerance and reliability. By addressing these areas, NTNs can significantly enhance the timeliness of information delivery for various applications.

D. Terahertz Communications

THz communications have been identified as a promising technology for supporting future 6G wireless networks due to its potential for ultrafast data rates and low latency. Current THz communication solutions offer significantly higher bandwidth than the traditional microwave and millimeter-wave frequencies, enabling rapid transmission of large volumes of data [199]. This high bandwidth results in faster information transfer, which is crucial for applications demanding real-time data exchange and high-definition streaming. However, there are notable challenges to deploying THz communication in NTNs, such as susceptibility to atmospheric attenuation and absorption, which can limit signal range and quality [200]. THz signals are affected by environmental factors like humidity and obstacles like buildings and foliage can further degrade the signal performance. These challenges need to be addressed to ensure reliable and consistent THz communication in NTNs. Future research should focus on overcoming these challenges to unlock the full potential of THz communication in NTNs. This includes developing robust adaptive modulation and coding schemes to handle varying environmental conditions and optimizing signal penetration through different materials. Additionally, advancements in THz components, such as smaller, more power-efficient transceivers, are essential for integration into NTNs. Research should also explore the efficient beam-steering technologies to improve the signal quality and extend communication range.

E. Quantum Communications and Blockchain-Enhanced Secure Networking

Quantum communications, such as quantum key distribution (QKD), offer secure, tamper-evident channels for information exchange in NTNs. These quantum methods utilize the principles of quantum mechanics to provide high-security communication by minimizing the risk of eavesdropping and ensuring data integrity and confidentiality. However, challenges, such as scalability and key management over long distances persist, especially when integrating the quantum systems into complex NTNs. Recent advances in space quantum communications have demonstrated the potential for satellite-based QKD, which can extend the range and reach of quantum-secured networks beyond the traditional terrestrial constraints [201]. Future research should focus on the development of more efficient quantum communication protocols tailored for NTN environments. This includes exploring quantum repeaters and advanced techniques like quantum teleportation to extend communication range and maintain reliability while minimizing the latency.

Additionally, the integration of the blockchain technology into NTNs can significantly enhance secure networking by providing a distributed and immutable ledger for recording transactions, agreements, and data exchanges. Blockchain's decentralized architecture ensures data integrity, transparency, and resistance to tampering, offering enhanced trust and reliability in the network. This can be particularly important for managing secure communications across multiple layers of NTNs, such as satellite constellations and UAVs [202]. Blockchain's ability to establish secure and auditable transaction records can play a key role in areas, such as user authentication, resource allocation, and billing in NTNs. It can also provide a robust framework for managing the network access control and permissions in a transparent manner. Additionally, the combination of quantum communications with the blockchain technology can create highly secure and efficient authentication methods, helping to prevent the unauthorized access and data breaches.

VI. Conclusion

NTN plays a significant role in fulfilling the requirements of 5G communication. In the context of 5G technology, the timeliness of information in NTN is of utmost importance. Timely delivery of data and information plays a crucial role in mission-critical applications, seamless mobility support, real-time collaboration, IoT applications, and enhanced user experiences. However, achieving optimal timeliness in NTNs comes with its challenges.

Throughout this survey, we have discussed the potential network structures of NTNs and investigated the technologies and methodologies utilized to improve the timeliness of information in NTNs. In NTNs, the design of the modulation protocols and transmission protocols was demonstrated, as well as the utilization of NOMA and RIS technologies to improve the timeliness of information. Apart from the protocol design and technology utilization, network architecture and resource allocation were investigated in NTNs. Moreover, considering the flexibility of UAVs, the design of trajectory planning strategies was studied using the game theory approaches and learning approaches. Due to the features of the IoT systems, the design of energy harvesting scheduling was discussed in the IoT systems. Furthermore, the design of offloading strategies and caching strategies in the MEC systems and caching systems was studied, respectively.

Moving forward, we proposed potential research directions for future studies to enhance the timeliness of information in NTNs. Leveraging advanced technologies, dynamically adapting modulation and coding strategy designs, and incorporating the NGMA and SDMA technologies effectively decrease transmission latency. Innovative routing and resource allocation solutions optimize network architectures and traffic flow in NTNs, further improving the timeliness of information. Integrating THz communication into NTN boosts intersatellite communication throughput, thereby enhancing the timeliness of information. Additionally, exploring the use of quantum communications and blockchain technologies helps address security challenges in NTNs.

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