electronics

MDPI

Review

ISAC towards 6G Satellite–Terrestrial Communications: Principles, Status, and Prospects

Yang Gu [1,2], Tianheng Xu [1,3,*], Kai Feng [1,2], Yuling Ouyang [1,3], Wen Du [4], Xin Tian [1] and Ting Lei [4]

1 Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai 201210, China; guyang@sari.ac.cn (Y.G.); ouyangyuling@sari.ac.cn (Y.O.); tianx@sari.ac.cn (X.T.)
2 School of Electronic, Electrical and Communication Engineering, University of Chinese Academy of Sciences, Beijing 100049, China
3 Shanghai Frontier Innovation Research Institute, Shanghai 201100, China
4 DS Information Technology Co., Ltd., Shanghai 200032, China; duwen@dscomm.com.cn (W.D.); leit@dscomm.com.cn (T.L.)
* Correspondence: xuth@sari.ac.cn

Abstract: With the evolution of fifth-generation (5G) to sixth-generation (6G) communication systems, the utilization of spectrum resources faces incremental challenges. Integrated sensing and communication (ISAC) technology, as a crucial element in 6G technology, is expected to enhance energy efficiency and spectrum utilization efficiency by integrating radar and communication signals, achieving environmental awareness, and enabling scene interconnection. Simultaneously, to realize the vision of seamless coverage in 6G, research on integrated satellite-terrestrial communication has been prioritized. To integrate the advantages, ISAC for integrated satellite–terrestrial networks (ISTNs) in 6G has emerged as a potential research direction. This paper offers an extensive overview of the present state of key technologies for ISAC and the development of ISTNs. Meanwhile, with a focus on the ISTN-oriented 6G ISAC system, several hotspot topics, including future application scenarios and key technological developments, are outlined and demonstrated.

Keywords: integrated sensing and communication (ISAC); integrated satellite–terrestrial networks (ISTNs); waveform design; beamforming

Citation: Gu, Y.; Xu, T.; Feng, K.; Ouyang, Y.; Du, W.; Tian, X.; Lei, T. ISAC towards 6G Satellite–Terrestrial Communications: Principles, Status, and Prospects. *Electronics* **2024**, *13*, 1369. https://doi.org/10.3390/electronics13071369

Academic Editors: Dimitris Kanellopoulos and Giovanni Crupi

Received: 8 February 2024
Revised: 27 March 2024
Accepted: 3 April 2024
Published: 4 April 2024

1. Introduction

In recent years, with the large-scale commercialization of fifth-generation (5G) wireless networks, sixth-generation (6G) wireless networks have become the focus of a new round of technological competition [1]. It is expected that society will step into a new era of intelligent 6G in 2030 [2]. The visions of 6G include further enhanced mobile broadband, massive machine-type communication, ultra-massive machine-type communication, long-distance and high-mobility communications, and extremely low-power communications [3,4]. It is anticipated that 6G will achieve deep integration between intelligent applications and networks to enable appealing use cases such as virtual reality and environment sensing based on artificial intelligence and the Internet of Things (IoT) [5]. Therefore, 6G is considered an essential driver for many emerging applications, which require high-quality wireless connectivity as well as high-precision and robust sensing capability [6].

Existing terrestrial communication mainly focuses on terminals in urban areas, but the coverage performance is poor in remote mountainous areas, deserts, and oceans due to the lack of base stations (BSs), while satellites can be used to extend the coverage of terrestrial communication networks [7,8]. The integrated satellite–terrestrial networks (ISTNs) will combine satellite communication and terrestrial communication to pave the way for wide-area coverage and seamless connectivity [9]. Meanwhile, with the rapid growth of the wireless communication industry and the ever-increasing demand for connection services, spectrum resources are becoming increasingly scarce [10]. Conventional sensing and communication systems are typically designed separately and operate within distinct frequency bands. However, due to the evolution of technologies such as millimeter wave, terahertz, and massive multiple-input multiple-output (MIMO), communication signals in high-frequency bands typically exhibit high resolution in both the time and angular domains, allowing for high-precision sensing based on communication signals. Integrated sensing and communication (ISAC) enables communication systems and radar systems to utilize the same frequency band and hardware for enhancing energy efficiency, boosting spectrum efficiency, and lowering hardware expenses. In recent years, extensive research has been conducted on terrestrial communication and sensing. However, considering the ubiquitous connectivity of 6G, the research on satellite–terrestrial ISAC is meaningful. In the future, ISAC technology will be further integrated into the ISTNs to realize a more efficient and intelligent integrated architecture and achieve global cooperative sensing.

At the current stage, ISAC technology research towards ISTNs faces the following challenges. (1) The application scenarios of satellite–terrestrial ISAC have not been clearly defined, and it is necessary to explore potential scenarios ISAC towards ISTNs. (2) For the new type of integrated system, the original technology may no longer be applicable. Therefore, new key technologies derived from the integrated system need to be explored to provide key support for the integrated system.

The primary goal of this paper is to provide an overview and outlook on the development of ISAC towards ISTNs. These mainly include potential scenarios, key technologies, and future research directions. Through this paper, we hope it can be an opportunity to outline a way forward to realize ISAC towards ISTNs in the future.

The main contributions of this paper are summarized as follows:

- We studied the development of existing ISAC in various frequency bands and analyzed the characteristics of existing technologies.
- We summarize the development status of ISTNs, key technologies, and networking architectures.
- We propose three use cases for the future ISAC towards 6G ISTNs. Using the characteristics of ISTNs, we discuss the road for the existing ISAC technology towards ISTNs.

The remainder of this paper is organized as follows. In Section 2, we introduce the historical development history, evaluation metrics, prototypes, and key technologies of ISAC. In Section 3, we present the development status, key technologies, and network architecture of ISTNs. In Section 4, we introduce the possible application scenarios and key technologies in the future ISAC towards 6G ISTN system and present our perspectives on the evolution direction of ISAC technology towards ISTNs. In Section 5, we present potential research directions for the future development of ISAC towards ISTNs. Finally, in Section 6, we present our concluding remarks.

2. The Development Status and Key Technology Of ISAC

With the development of 6G technologies, ISAC has emerged as a focal point of 6G research, drawing significant interest and active participation from standardization organizations and research institutes, such as the International Telecommunication Union (ITU), Hexa-X, the Institute of Electrical and Electronics Engineers (IEEE), and the 3rd Generation Partner Project (3GPP). In Table 1, we list some institutes that are actively participating in ISAC research.

Table 1. The work of institutes participating in ISAC research.

Institutions	Related Work
ITU	ITU considers ISAC as an emerging technology trend for the future [11].
Hexa-X	Hexa-X considers ISAC as one of the main architectures of 6G and emphasizes its role in sensing services [12].
IEEE	In IEEE 802.11bf, it focuses on enhancing wireless local area network sensing [13].
3GPP	3GPP summarized and proposed the future use cases and service requirements of ISAC [14].

2.1. History of Development

The development of ISAC originated in the last century. At first, radar and communication systems were two separate systems that developed independently and gradually moved towards integration with the evolution of 5G technology. In the 1860s, Mealey et al. [15] combined communication and radar sensing technology for the first time and used radar to transmit pulse code groups, in which part of the pulses in each group were used for information transmission. The authors of [16] proposed the first ISAC scheme using chirp signals. Braun et al. [17–19] explored how to use orthogonal frequency division multiplexing (OFDM) for waveform parameter design in ISAC. Liu et al. [6,20–22] reviewed the overall development of ISAC in recent years. They introduced the process of ISAC from the stage of radar and communication evolving separately to the gradual integration between two systems, ultimately realizing ISAC. At present, universities, enterprises, and standardization organizations have actively participated in the research of ISAC technology, which greatly promotes the development of ISAC.

2.2. Evaluation Indicators

With the development of existing ISAC technologies, several evaluation metrics have been commonly used as a basis for measuring the performance of ISAC, and in this subsection, we present the commonly used existing metrics.

(1) MSE

Mean squared error (MSE) is a statistical measure that quantifies the average squared difference between predicted and actual values. It is often used as an evaluation metric to measure the consistency between the optimized radar beam and the desired beam in ISAC. In [23], MSE is used as the radar beam objective function at time 0, to accurately align the target direction with the known position.

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(\theta_i - \hat{\theta}_i)^2, \tag{1}$$

where θ_i and $\hat{\theta}_i$ denote the ideal and estimated value in direction i, and n denotes the number of directions.

(2) CRB

The Cramér–Rao bound (CRB) stands for the lowest possible variance attainable for any unbiased estimator of the parameter θ that is unbiased and calculated by inverting the Fisher information.

The accuracy of ISAC parameter estimation is usually measured by the CRB. The authors of [24] use the CRB as the target estimation, and the CRB is denoted as

$$\mathrm{CRB}(\theta) = \frac{\sigma_R^2 \mathrm{tr}(A^H(\theta)A(\theta)R_x)}{2|\alpha|^2 L(\mathrm{tr}(\dot{A}^H(\theta)\dot{A}(\theta)R_x)\mathrm{tr}(A^H(\theta)A(\theta)R_x) - |\mathrm{tr}(\dot{A}^H(\theta)A(\theta)R_x)|^2}, \tag{2}$$

where L represents the length of frame, σ_R^2 is the variance of Gaussian noise, θ is the azimuth angle of the target relative to the BS, α is the reflection coefficient, R_X denotes the sample covariance matrix of X, and $\dot{A}(\theta) = \frac{\partial A(\theta)}{\partial \theta}$.

(3) SCNR

Signal-to-clutter-noise ratio (SCNR) represents the ratio of radar sensing signal to clutter plus noise signal, which can effectively measure the quality of radar signal in an ISAC system. In [25], the problem of maximizing the sensing SCNR was formulated to optimize the performance of the system. SCNR can be expressed as

$$\omega^* = arg \max \frac{|\omega^H A(\theta_0) x|^2}{\omega^H (R_c + I)\omega}, \tag{3}$$

where ω denotes the received beamforming vector, R_c is a corresponding covariance matrix, θ_0 is the location of radar target, $x \in \mathcal{C}^{1\times N_t}$ is composed of the data signal for all users, and A is a matrix representing the product of the transmit and receive array steering vectors.

(4) SINR

Signal-to-interference-plus-noise ratio (SINR) is a crucial performance metric that measures the quality of the received signal. It can effectively measure the quality of communication signal in an ISAC system. In [26], it is used as a condition to constrain the optimal solution of the target function. SINR can be mathematically expressed as

$$\mathrm{SINR} = \frac{P_s}{P_i + P_n}, \tag{4}$$

where P_s, P_i, and P_n denote the power of signals, interference, and noise.

(5) Achievable rate

The achievable rate refers to the transmission throughput that can be realized under the given communication channel conditions and is an important indicator for communication performance evaluation. In [27], in the communication performance-centric ISAC, the achievable rate is optimized as a constraint objective to realize optimal communication performance.

$$\mathrm{R} = \log_2 (1 + \frac{S}{N}), \tag{5}$$

where S is the power of signal, and N is the power of noise.

(6) Energy efficiency (EE)

With the rapid growth of energy-saving demand, EE has attracted increasing attention as an important performance metric. The authors of [28] defined the objective function of EE as

$$\eta = \frac{E_1(W)}{E_2(W)}, \tag{6}$$

where W is the coefficient of beamforming, $E_1(W)$ is the weighted sum rate, and $E_2(W)$ is total power consumption. In [29], the authors studied the EE optimization problem of rate splitting multiple access in ISTNs. By using the constrained soft actor–critic algorithm, EE is optimized to achieve the goal of energy saving.

2.3. Prototypes Studies

With the development of ISAC, multiple universities and companies have conducted hardware experiments on ISAC prototypes and gradually applied ISAC in practical scenarios; for example, China Telecom and ZTE have utilized ISAC to ensure low-altitude safety during the Asian Games [30]. These experiments involve the construction of practical systems to further test and optimize the performance of ISAC systems. They are conducted on the 6G ISAC prototype across various frequency bands and scenarios to validate the system performance with different metrics. To meet the performance requirements of ISAC, multiple research teams have initially built experimental ISAC systems.

2.3.1. Prototype Based on the Sub-6 GHzFrequency Band

In [31], an ISAC system based on OFDM was developed. The system operates at a central frequency of 4 GHz with a bandwidth of 400 MHz. This system enables indoor target localization and tracking. The sensing signal processing includes basic processing, interference suppression, and system calibration. Considering the prototype's signal bandwidth and constrained by the coherent processing interval, algorithm optimization is proposed to enhance the resolution performance of the system.

2.3.2. Prototype Based on the Millimeter-Wave Frequency Band

As millimeter-wave is regarded as a key technology in the context of 6G, the photonic-based ISAC systems have received widespread attention due to their ability to generate high-frequency broadband signals of millimeter wavelengths using the optical devices [32,33].

In [34], the system consists of an ISAC BS and sensing targets. By using the universal OFDM waveform in the millimeter-wave frequency band, with a center frequency of 28 GHz and a bandwidth of 400 MHz, the BS can sense the environment in real-time with high resolution. The study focuses on the impact of uneven cyclic prefixes on various sensing algorithms for Doppler estimation, and three methods are investigated to resolve this issue.

In [35], the baseband signal is generated through the digital-to-analog converter module and intermediate frequency module from the millimeter-wave platform. It is upconverted by the 28 GHz RF head to reach the phased array antenna, where the receiving antenna at the target can receive the communication data of the integrated signal. At the same time, the receiving end of the integrated system demodulates the reflected echo of the sensing-integrated signal, enabling synchronous updating of target position information. The test results confirm that the proposed algorithm can achieve acceptable target detection performance within a 10 m range with an average position error of 0.189 m, as well as a stable data rate of 2.86 Gbps, in the 28 GHz millimeter-wave frequency band.

2.3.3. Prototype Based on the Terahertz Frequency Band

Terahertz (THz) refers to the electromagnetic waves with frequency ranging from 300 GHz to 3 THz, which is one of the key enabling technologies for 6G mobile communication [36]. The communication system in the THz frequency band has received widespread attention in the research of ISAC due to its ultra-large communication bandwidth. Based on the ultra-large bandwidth, it can achieve extremely high precision in positioning and tracking technology solutions.

In [37], the prototype adopts THz compound semiconductor devices, digital-to-analog and analog-to-digital converter boards, and low-complexity signal processing technology. The experimental bandwidth is 13.6 GHz, and the radio frequency range is 220 GHz, which can simultaneously provide long-distance coverage of up to 3.5 km, a high data rate of up to 240 Gbps, and a high spectral efficiency of 17 bit/s/Hz for ISAC services.

In [38], a THz sensing prototype with millimeter-level imaging resolution is built to demonstrate the feasibility of THz-ISAC, considering the physical aperture constraints of typical mobile devices. A solution of virtual aperture with a MIMO structure and sparse scanning approach is proposed. The prototype operates at a carrier frequency of 140 GHz with an 8 GHz bandwidth. The feasibility of achieving millimeter-level sensing resolution using THz communication signals is verified.

2.3.4. Prototype Based on the Optical Wireless Frequency Band

As the next generation of wireless communication technology, 6G will integrate communication and sensing capabilities. It is gradually extending into the optical spectrum in some home and industrial applications. Due to the significant gap between the optical spectrum and the traditional electromagnetic spectrum, it does not cause electromagnetic interference to traditional radio frequency bands. It is particularly suitable for sensitive environments such as smart healthcare and industrial manufacturing.

In [39], to meet the high communication rate and high-precision sensing requirements in scenarios such as healthcare and industry automation, the Huawei 6G research team has proposed ISAC with optical wireless. Through optical wireless links such as visible light and infrared spectra, precise sensing and localization of robots can be achieved, and remote commands can be given to the robots. The optical link in the prototype also enables high-speed wireless transmission of real-time video between the robot and the controller. By detecting subtle changes in facial color or abdominal movement, the prototype can monitor a person's heartbeat and respiratory status in a real-time and non-contact manner.

2.4. Key Technology

2.4.1. Waveform Design for ISAC

The integrated waveform of ISAC is capable of simultaneously accomplishing the functions of radar detection and communication signal transmission. Among the existing integrated signals, they can be mainly divided into three types, which are the waveform centered on communication, the waveform centered on radar, and the new integrated waveform [40].

The communication waveform is mainly based on OFDM. In [22], the authors summarized a series of integrated waveforms centered on OFDM, including the integration of OFDM and linear frequency modulation (LFM), the combination of OFDM and phase coding, and the union of OFDM and spread spectrum. They also compared the advantages and disadvantages of different waveform combinations. A dual-functional radar-communication (DFRC) system [41] utilized the proposed OFDM radar waveform design technique to maximize the communication capacity. It can achieve a performance trade-off between two subsystems. ISAC based on orthogonal multiple access (OMA) has achieved remarkable results. In recent years, academic researchers have also conducted certain research on ISAC with non-orthogonal multiple access (NOMA). NOMA superimposes the signals of multiple users in the same frequency band, improving the spectrum utilization efficiency and enhancing the system transmission rate. It can mitigate inter-user interference when the channels are highly correlated or the system is overloaded. In [42], the authors revealed the trend of ISAC access technology, transitioning from orthogonal to non-orthogonal; introduced the basic models of the downlink and uplink ISAC; and effectively eliminated interference between users through rational design and new sensing-to-communication interference.

Within the radar waveform-based ISAC waveforms, the frequency-modulated continuous wave (FMCW) can measure the distance and velocity of objects. This is achieved by transmitting a continuous waveform with a continuously changing frequency and observing the frequency shift of the reflected signal. In [43], the authors embedded the communication signal into the radar pulse signal by using different beams and index modulation to achieve communication and detection. In [44], the authors conducted a waveform design based on FMCW and indexed modulation. It is demonstrated that the bit error ratio (BER) performance is superior to methods utilizing only phase modulation.

Among the new waveforms, orthogonal time frequency space (OTFS) [45] has the advantage of adapting to the high Doppler frequency shift environment. An ISAC scheme based on OTFS [46] is proposed to mitigate the impact of communication signals on radar sensing in the time-frequency domain through the method of echo preprocessing. In [47], the authors proposed an efficient approximate maximum likelihood algorithm based on OTFS, which is superior for distance and velocity estimation. The authors of [48] used OTFS for ISAC-assisted receiver design and utilized the novel deep residual denoising network framework to achieve effective channel estimation, which has higher performance and system robustness. An ISAC framework based on OTFS modulation was proposed in [49], which adopts a matched filter radar sensing scheme based on fractional parameter estimation to achieve better BER and estimation performance. In addition, in [50], the authors proposed the novel universal frequency multi-carrier waveform and compared it with the conventional OFDM. They experimentally proved that it has performance improvement with respect to spectral efficiency and system complexity.

In Table 2, the performance differences between two types of communication waveforms OFDM and OTFS are comparatively analyzed.

Table 2. A brief comparison between OFDM and OTFS signals in ISAC system.

Indicator	OFDM	OTFS
BER	It maintains a low BER in conditions of a low SNR scenario.	It maintains a low BER in conditions of a low SNR scenario.
Peak-to-average power ratio (PAPR)	High	Lower than OFDM
Symbol size	Larger	Smaller
Stability	Susceptible to delay and Doppler effects	Utilizing modulation information in the delay-doppler domain exhibits stability

2.4.2. ISAC Beamforming

Beamforming has many advantages for communication and target sensing. On the one hand, it can improve the effectiveness of power utilization, so that the sensor can better capture the position, speed, shape, and other information of the target, which improves the reliability of environmental sensing. On the other hand, beamforming can be used to suppress interference and enhance the anti-interference capacity, which is very important for some applications in special environments.

Over the past few years, there has been a notable surge in research efforts aimed at optimizing ISAC beamforming, resulting in improved quality of ISAC functions. In [51], the authors designed an algorithm to reduce the complexity of beamforming where the two subsystems of communication and radar are co-located on the same BS. The authors of [52] introduced a new symbol-level precoding (SLP) technique into ISAC and studied the related waveform design technology. The principle of SLP based on quadrature phase shift keying is shown in Figure 1. It mainly uses interference signals to make the received signal more conducive to decision-making. The radar beam diagram without modulus length constraints is shown in Figure 2. Simulation results show that both block-level precoding and SLP can achieve better beam gain. In [53], the authors enhanced the beam shape through the optimization of the waveform based on OFDM. The authors of [25] studied DFRC beamforming for MIMO radar sensing and multi-user MIMO (MU-MIMO) communication to propose a generalized beamforming method. In [54], the authors combined space–time adaptive processing (STAP) and SLP to propose a STAP-SLP-based ISAC system. An interrupt-based DFRC beamforming design is proposed [55], which can sense imperfect channel state information to achieve high communication rates and detect passive targets. In [56], a design for block-level beamforming in ISAC systems is proposed, which introduces a finite alphabet input. This approach is more realistic compared to the original infinite-length Gaussian signal. In [57], the authors introduced a new packet SLP strategy and optimal algorithms to address the max–min fair problem and power constraint problem. The authors of [58] studied the problem of maximizing the EE of ISAC systems under the premise that user communication and radar sensing are simultaneously ensured at the BS. A multivariate alternating minimization framework [59] is proposed to address the non-convex issue of optimizing the performance of communication and radar. In [60], an alternating minimization framework is developed to address the problem of minimizing the MSE of the designed beamforming and the target beampattern under the constraints of communication quality of service (QoS).

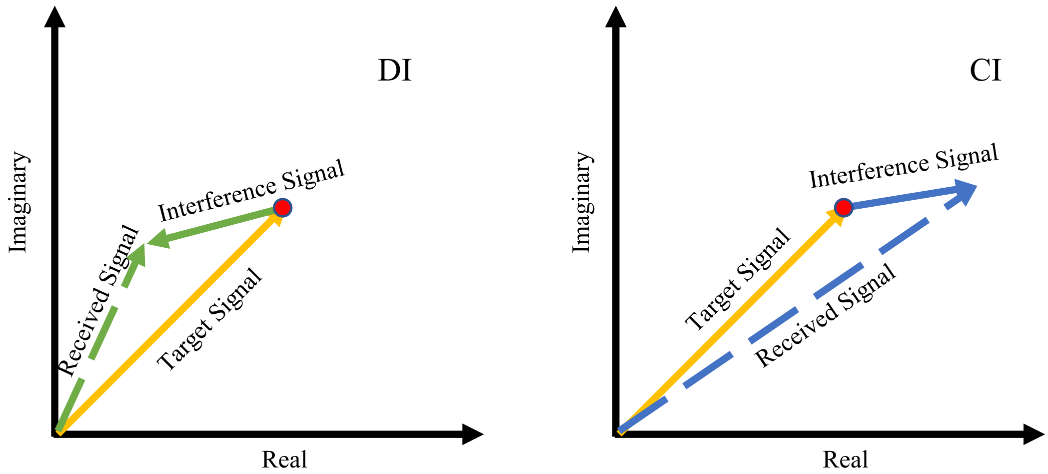


Figure 1. Symbol-level precoding principle: schematic diagram.

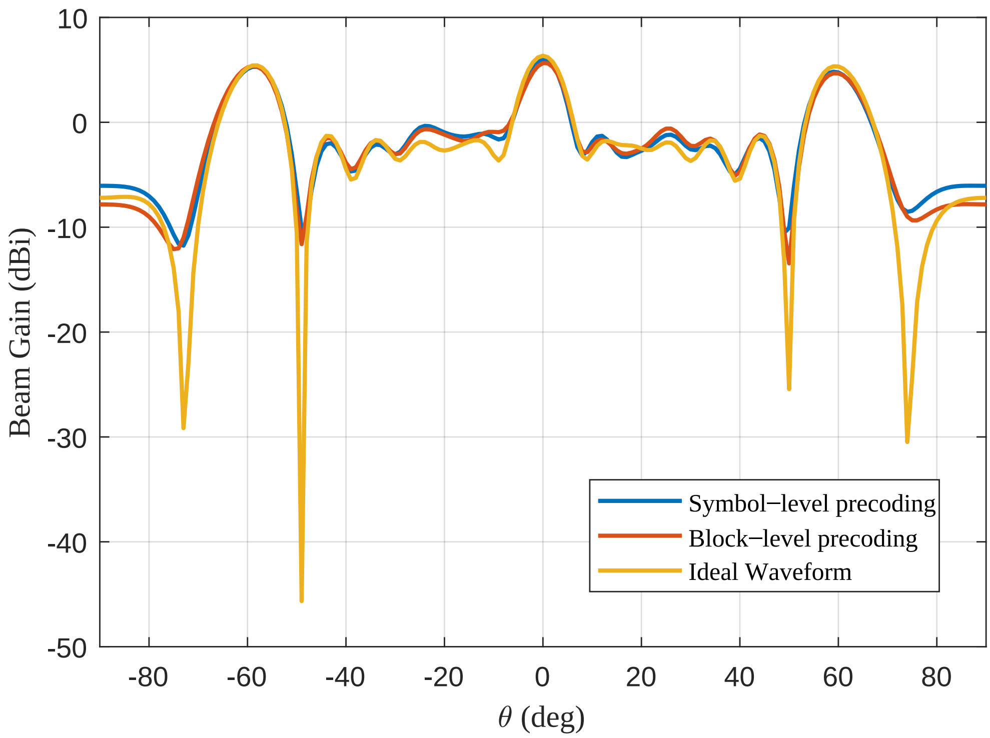


Figure 2. Antenna beamforming without modulus constraint (four users).

In summary, this section investigates the communication and sensing metrics, optimization objectives, and the proposed methods in related studies, which illustrates the research progress of ISAC beamforming at the current stage. The related works are summarized in Table 3. In the optimization for the ISAC waveform, the proposed algorithms simplify the computational complexity of beamforming and optimize the energy distribution to different degrees compared with the previous algorithms. At the same time, the use of new waveforms, such as the introduction of SLP technology, can further reduce the limitations of constraints and lead to more degrees of freedom. Given that the beamforming technique can implement a novel approach to energy allocation, we can improve the system performance, including power loss, accuracy, anti-interference, etc., which is conducive to the development and application of ISAC in future communication systems.

Table 3. Summary of beamforming in ISAC systems.

Ref.	Optimization Objective	Communication Metrics	Sensing Constraints	Pros	Cons
[51]	Minimization of the weighted difference between the beam pattern error and the SINR	Maximize downlink communication SINR	Minimize MSE between ideal and designed beam patterns	Significantly reduced computational complexity	Not considering power allocation
[52]	Minimize MSE between the designed and the ideal beam while concurrently satisfying QoS requirements and constant modulus power constraints	Guarantee the quality of multi-user communications	Minimize MSE between ideal and designed beam patterns	Use symbolic-level precoding to provide additional degrees of freedom	Not considering Doppler scenarios
[53]	Minimize the Cramér-Rao lower bound for distance and velocity, root MSE, and PAPR of the transmitted waveform	Guarantee the quality of communication	Optimize the frequency domain sample to fill the radar subcarrier to improve the performance of the system	OFDM waveform optimization	Low computational efficiency
[25]	Communication-centric and radar-centric optimization to achieve system performance domain boundaries	Guarantee the quality of communication	Maximize SCNR	Low-complexity beamforming design and optimal power distribution	Only single-target radar sensing
[54]	Maximize radar output SINR and meet communication QoS requirements, total power constraints, and waveform constraints	Guarantee communication quality (constant mode and PAPR)	Maximize the SINR	Combine STAP and SLP	No research on low complexity algorithms in practical scenarios
[55]	Maximize signal power in the beam direction	Outage SINR constraint	Maximize transmit direction gain towards sensing direction	For imperfect channel state information scenarios	Only single-target radar sensing
[56]	Maximize minimum Euclidean distance between noise-free received signals	Guarantee the quality of communication	Maximize transmit direction gain towards sensing direction	Beamforming design for finite letter signal ISAC systems	No consideration of duplex system
[58]	Maximize the energy efficiency of multi-user communications	Guarantee the SINR of the communication user	Maximize transmit direction gain towards sensing direction	Reduce computational complexity and maximize energy efficiency	No consideration of duplex system
[59]	Minimize average error power and ensure radar waveform similarity to ideal waveforms	Minimization of the average error power at the receiver	Minimize MSE between ideal and designed beam patterns	Provide lower complexity	No consideration of frequency fading channels
[60]	Under QoS and constant-mode power constraints, minimize the MSE between the designed and ideal beam patterns	Minimization of the average error power at the receiver	Minimize MSE between ideal and designed beam patterns	Lower complexity is provided at the cost of a smaller loss of radar MSE performance	No consideration of dynamic scenarios

3. Development Status and Key Technologies of ISTNs

In light of the accelerated growth in communication technologies, terrestrial wireless networks have achieved tremendous success in terms of communication rate and quality of service [61]. However, there are still some remote areas that remain unconnected due to economic and technical reasons [62]. Therefore, satellite–terrestrial integration will be the key research direction of future wireless networks to empower seamless coverage worldwide [63].

3.1. Development Status

There are many countries that aspire to achieve the construction of ISTNs as a significant objective. As early as the beginning of the twentieth century, the United States Department of Defense proposed the idea of building an integrated information network between the sky and the earth. It utilizes coordinated LEO satellites for efficient multicast communications, aiming to maximize user communication and provide a secure network environment for a comprehensive battlefield [64]. Europe and other related countries have also launched multiple ISTN projects, including CoRaSat, SANSA, SaT5G, etc. [65]. In addition, China has launched a comprehensive project of an integrated information network of space and ground in Science and Technology Innovation 2030 to carry out technological research and development of ISTNs.

In recent years, international organizations, such as 3GPP, have established some special working groups to promote the standardization of ISTNs [66]. The development of relevant standards starts from satellite support for basic connectivity capabilities to satellite expansion and performance enhancement until the final large-scale constellation construction, which can realize inter-satellite collaboration and satellite–terrestrial integration. In 3GPP technical report (TR) 38.811 [66], the deployment scenarios, and channel models of satellite networks are defined. The access to satellite networks as well as the modification and updating of terminals and original terrestrial networks are studied in 3GPP TR 22.822 [67]. In the R17 standard [68], a complete non-terrestrial network deployment architecture is provided, stipulating the methods of time synchronization, mobility management, link switching, and so on.

3.2. Key Technologies of ISTNs

3.2.1. FSO of ISTNs

Free-space optical (FSO) communication has attracted widespread attention in both academia and industry [69]. FSO communication has numerous advantages, including strong anti-interference capabilities, much higher communication rates than traditional radio frequency methods, large information capacity, compact and lightweight equipment, and low power consumption [70]. It has been proven that FSO communication is a promising technology. As early as 1995, the Japan Aerospace Exploration Agency successfully achieved 1 megabit per second data download speeds from its engineering test satellite KIKU-6 to a ground station in Tokyo [71]. In 2016, Europe proposed the European Data Relay System, aiming to use innovative laser communication technology to transmit data between LEO satellites and geostationary earth orbit satellites [72]. The National Aeronautics and Space Administration recently conducted a milestone experiment on the international space station, successfully establishing a bidirectional laser communication link between the laser communications relay demonstration equipment and the LEO user terminal at a speed of 1.2 gigabits per second [73].

In recent years, academic research has also focused on optimizing FSO communication in inter-satellite and satellite-to-ground links. Studies on FSO communication have primarily involved modeling and analyzing atmospheric channels, satellite-to-ground and inter-satellite network architectures, energy-efficient collaboration [74], and satellite network routing strategies. In [75], dual-hop mixed radio frequency/free-space optical networks, where backhaul-to-relay and relay-to-user communications employ FSO and RF links, are investigated. For the backhaul-to-relay link, FSO communication is considered to meet the high throughput requirements of high-altitude platform satellites. By optimizing system performance through solving non-convex problems, simulations demonstrate achievable rates for FSO links under atmospheric conditions while proving that the proposed joint optimization algorithm enhances system throughput. In [76], the authors integrate high-altitude platforms into an integrated air-ground communication system and propose a novel FSO transmission network. Ground stations impose restrictions on the selection of high-altitude platforms to mitigate the effects of atmospheric turbulence. Experimental results demonstrate that the proposed architecture exhibits superior transmission rates and reliability. Additionally, in [77], the authors propose a multi-objective reinforcement learning-based routing strategy in a multi-layer network architecture. The satellite network considers large-scale, ultra-high-density, and highly dynamic LEO satellite networks and avoids conflicts by introducing cooperative mechanisms. Simulations demonstrate that the proposed algorithm outperforms existing routing algorithms in terms of packet loss rate and other performance metrics.

Despite existing progress, there are still limitations, including a lack of research on inter-satellite routing protocols, insufficient consideration of the impact of spatial obstacles, and the absence of adaptive topological control mechanisms for existing satellite architectures.

3.2.2. THz of ISTNs

The short wavelength of THz is negatively affected by the reflectance, transmittance, and absorption of materials, especially in the atmosphere, resulting in high propagation losses. However, the concentration of water vapor molecules near the earth's surface decreases with the increase in altitude, making the THz frequency range highly promising for communication in an environment approximating vacuum, such as space. It is estimated that satellite-to-aircraft communication links have sufficient budget for THz communication [78]. Terahertz/radio frequency hybrid communication is of great significance for space–air–ground integrated networks to improve transmission efficiency and achieve 6G smart connectivity. Therefore, satellite THz communication has attracted widespread attention. In [79], the authors proposed an analytical framework to study the coverage probability and average achievable rate of a downlink THz LEO satellite-aircraft network with directional antennas. In [80], a comprehensive analysis and optimization of integrated space–air–ground communication with multi-band terahertz/radio frequency communication was presented. Based on this model, expressions for SINR and rate coverage probability were derived, and the system coverage and transmission rate performance were evaluated. A simulated annealing-based algorithm was proposed to maximize node performance. In [81], the authors developed a complex mathematical framework to simulate directional interference between crosslinks in millimeter-wave/THz satellite communication networks. It focused on crosslink interference, analyzed sources of interference, and proposed interference mitigation solutions. In practical applications, the high power of the THz signal generator introduces higher noise figures. In the future, research on satellite THz technology will focus on the aspects of antenna layout, beam design, transmitter design, and so on.

3.2.3. Network Architecture of the ISTNs

The ISTN architecture shows great promise for future wireless networks, attracting the attention of numerous researchers. In this section, we will summarize the ISTN architectures in existing studies and analyze their reliabilities.

(1) Hybrid satellite–terrestrial relay network

The signals between satellites and terrestrial terminals suffer from severe attenuation caused by clouds, fog, beam tilt during transmission, and obstacle shielding, which will result in a significant decline in communication quality. To enhance the quality of satellite–terrestrial communication, ground relay nodes are utilized to improve the reliability and stability of communication. Bhatnagar et al. [82] proposed the concept of a hybrid satellite–

terrestrial relay network (HSTRN), where multiple antenna relay nodes forward the satellite signals to the target users based on beamforming techniques. There are two types of relay networks: basic relay structure [83] and cooperative relay structure [84,85].

The basic relay structure is shown in Figure 3a. In HSTRN, the masking effect hinders the user from establishing a stable communication link with the satellite. However, through the implementation of terrestrial relays, satellite users can maintain communication when the direct link experiences masking. This contributes significantly to enhancing the stability of the overall system. The cooperative relay structure shown in Figure 3b does not incorporate the masking effect in the direct link between the satellite and the user. Therefore, signals from the direct link can be merged into the signals obtained by the transmission of relay nodes.

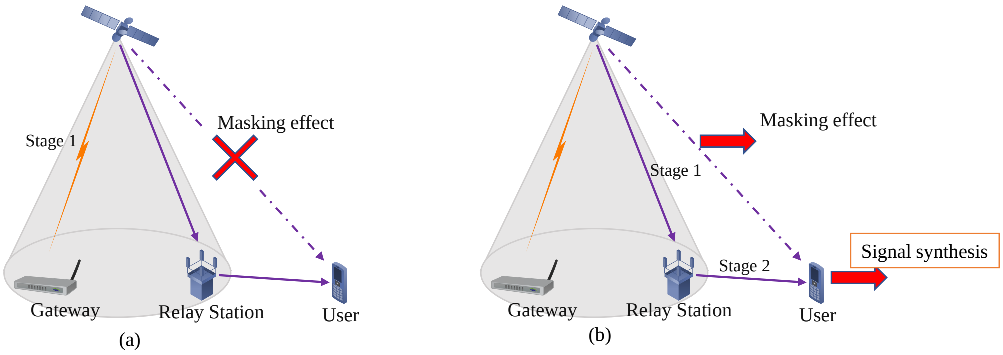


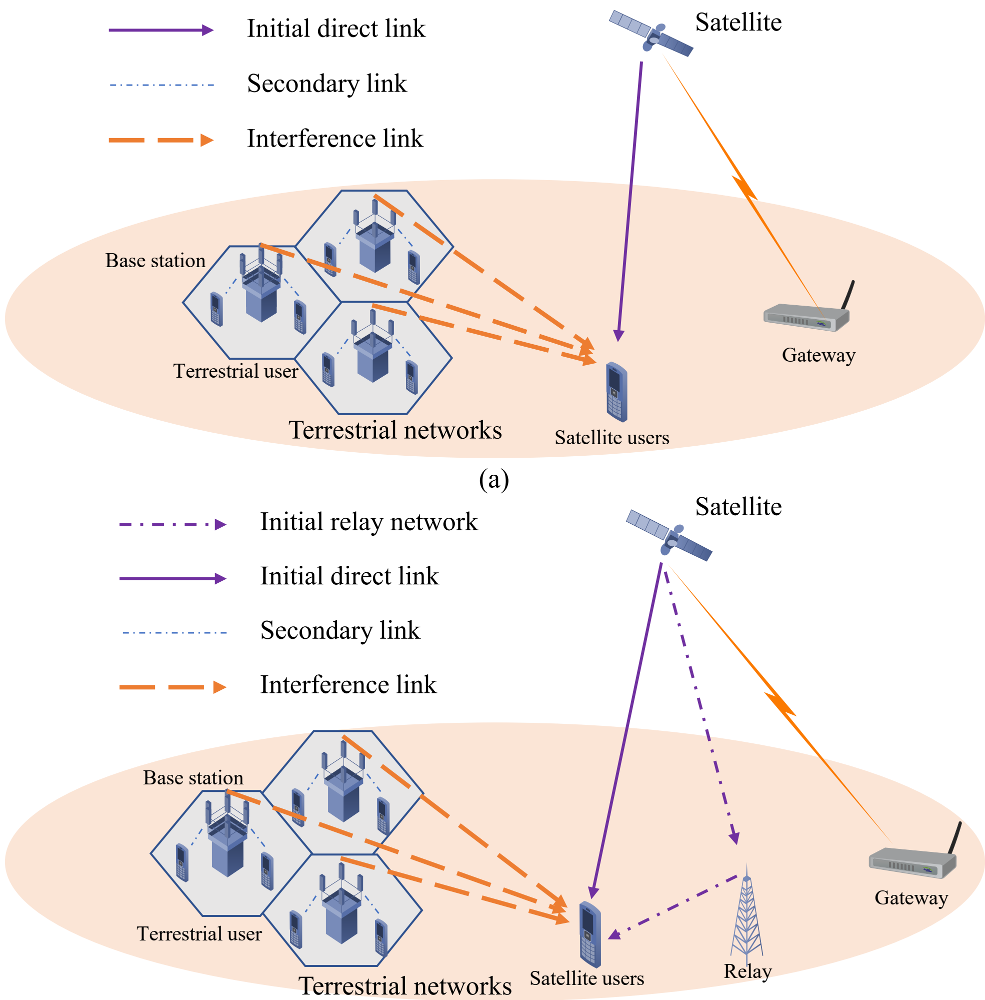
Figure 3. Architecture of HSTRNs. (**a**) Basic relay architecture. (**b**) Cooperative relay architecture.

(2) Cognitive satellite–terrestrial network

With the growing demand for wide-band communications and a large number of connectivity devices, the spectrum scarcity of satellite communications becomes an imminent issue. It is a feasible method for rational sharing of spectrum resources to optimize the efficiency of spectrum resource utilization [86]. Cognitive radio (CR) is considered as a spectrum management approach in conventional wireless communication systems It allocates the same spectrum resources to both major and minor networks, which enhances spectrum utilization rate [87]. In this way, we can classify them into cognitive relay networks and cognitive satellite–terrestrial networks.

The fundamental structure of the cognitive satellite–terrestrial network, as shown in Figure 4a, comprises satellite networks and terrestrial networks. The satellite networks possess licensed spectrum resources, thereby enabling the transmission of signals on demand. The terrestrial networks reuse the same spectrum with the satellite networks, the mechanism of which operates on the premise of ensuring no interference with satellite networks. Through the reuse of spectrum resources between satellites and terrestrial systems, enhanced spectrum efficiency can be attained, thereby mitigating the strain on spectrum resources. In [87], the authors studied the performance of cognitive satellite–terrestrial networks and compared the outage performance of three secondary transmission schemes, which verified the superiority of the directional beamforming technique.

The cognitive relay architecture is shown in Figure 4b, where relay nodes are introduced into the cognitive satellite–terrestrial network to construct the novel relay network architecture [88]. The satellite network, which is the main network in the architecture, transmits signals to the satellite users within the licensed frequency bands with the aid of the terrestrial relay. When the terrestrial BS serves as a relay to facilitate satellite network transmission, the terrestrial network is granted permission to reuse the licensed frequency bands of the primary satellite network.



(a)

(b)

Figure 4. (**a**) Architecture of cognitive satellite–terrestrial network. (**b**) Architecture of cognitive satellite–terrestrial relay networks.

4. Development Trend and Key Technology of ISAC towards 6G ISTNs

4.1. Future Application Scenario

In ISAC, signals are used to realize the sensing functions such as detection, localization, identification, and imaging. It obtains information about the surrounding environment, allocates communication resources intelligently and precisely, and enhances the user experience [89]. The satellite–terrestrial integration network will involve the deep integration of space-based, air-based, and ground-based networks to realize the access and application of unified terminal equipment to satisfy different users. satellite–terrestrial ISAC can further sense the ground conditions, thus better elucidating the city operation, environmental changes, and other information. It provides intelligent decision-making for overall satellite–terrestrial deployment, realizes dynamic deployment of resources, and optimizes the efficiency and performance of the system. This section considers three potential application scenarios of satellite–terrestrial ISAC and proposes a satellite–terrestrial network architecture for ISAC.

4.1.1. Environmental Sensing and Dynamic Resource Allocation

In a real-world application, users served by the same BS, satellite, or vehicle are dynamically changing. This situation leads to a reality where traditional static wireless resource allocation can not always be optimal [90]. Through ISAC, the system detects active users within the coverage area and provides relevant information to the edge nodes and control center. Subsequently, the effective resource allocation of different frequency bands is optimized according to the actual situation.

The BS will utilize the ISAC system to detect the environment within the range [91] and upload the surrounding data to the superior terminal in real time. As for the high-speed moving satellites in ISTNs and various types of vehicles, the radar image information obtained from remote sensing can be used to allocate resources [92]. In [93], the authors proposed an ISAC-assisted random-access dynamic resource allocation scheme for ISTNs. Relay nodes can obtain the situation of users within the scope through signal sensing and use the sensing data to assist in random access. The dynamic users are organized into orthogonal clusters in the frequency domain. The active users are intelligently grouped into distinct orthogonal clusters in the spectral domain. The dynamic bandwidth allocation factor is optimized to improve the overall data transmission rate, surpassing previous schemes in packet loss rate. For spectrum sharing, CR technology can be employed. In a multi-user environment where multiple users share the bandwidth resources, the users can be divided into different levels. When high-priority users have lower traffic demands, the idle bandwidth can be dynamically allocated to lower-level users. Additionally, in dynamic scenarios, it is necessary to design algorithms to meet the optimal energy allocation and improve the efficiency of resource utilization. In [94], a joint design method is proposed to optimize the allocation of subcarriers and transmit power for both sensing and communication tasks. By optimizing the allocation of subcarriers and transmit power, the minimum total power required by the system can be obtained.

4.1.2. Relay Node Positioning and Beam Alignment

The ISTNs are based on terrestrial networks and integrate non-terrestrial networks to jointly build a multi-access converged network architecture across space–air–ground areas. In the envisioned future architecture of ISTNs, the space base is mainly composed of satellites, the air base consists of various types of aircraft, the ground base is made up of land-based cellular mobile communication networks, and the sea base includes various types of oceanic underwater wireless communications, offshore coastal wireless networks, ocean-going vessels, etc. [95]. The relative positions between the nodes are not often stationary, which brings certain challenges to the communication signal transmission process. As a hub between satellites and the ocean, UAVs play a crucial role in the space–air–ground–sea network [96]. In [97], a new integration of UAVs and DFRC systems is explored to assist data collection in ocean monitoring scenarios. In the future, by introducing ISAC in the ISTNs, the position of the receiver will be sensed using integrated signals, and a directional beam will be used for sending signals. Hence, we can improve the quality of communication while reducing the power loss at the transmitter.

4.1.3. Space Environment Sensing

In the complex space environment, there is a multitude of space debris. Based on the recent data available, 7800 of the 10,550 satellites in space are presently operational. The number of identified space debris objects ranging from 1 mm to 10 cm is about 131 million. More than 630 incidents of collisions with these objects resulting in equipment damage have been reported [98]. To prevent financial losses caused by space debris, terrestrial-based radar system detection techniques have been the common solution. However, small objects are difficult to detect. Therefore, integrating communication satellites with sensing techniques to detect the specific position and velocity information of space debris can ensure the safety of space equipment. Based on the multi-debris environment in space, the authors proposed a modulation scheme with triangular LFM and V-shaped LFM pulses [99]. Simulations have demonstrated a significant performance improvement in radar velocity and range estimation capabilities compared to the conventional linear frequency modulation system. For radar and communication systems deployed in space, radar and communication share spectrum resources but suffer from mutual interference.

In [100], the author proposes an overlapping subarray configuration to reduce the impact of spectrum sharing on radar detection performance. By mapping communication signals to the null space, mutual interference is minimized. Experimental results validate the effectiveness of this method. Furthermore, proper power allocation is crucial for satellites. In [101], the author focuses on the coordinated optimization of power and bandwidth allocation in the system. By employing an alternative optimization algorithm, the optimal solution is obtained to improve energy efficiency.

4.1.4. ISAC towards ISTNs

In the future, ISTNs will mainly consist of three layers, which are the satellite network, air network, and terrestrial and oceanic networks. Some terrestrial users fail to establish a connection with the satellite network due to signal fading in the satellite–terrestrial link and differences in communication protocols. In that case, the air network can extend connectivity outside the BS coverage area.

To implement ISAC towards ISTNs, ISAC technology will be integrated into the three-layer space–air–ground communication network. Firstly, ISAC technology will be integrated into the satellite terminal to facilitate satellite networking and management, while also enhancing space environment sensing. Additionally, it will enable sensing and imaging of the ground environment using LEO satellites [21]. At the same time, the air network integrates ISAC technology to effectively sense ground user targets and acquire the motion information of vehicles. By leveraging the cooperative capabilities of UAVs, these aerial platforms can effectively operate as mobile antenna arrays. This collaborative arrangement enables the achievement of high-resolution imaging capabilities through synchronized movements and coordinated signal processing techniques in all types of weather, day or night [20]. Moreover, their flexibility makes them instrumental in controlling smart cities [102]. Ultimately, the general ISAC technology is deployed at the ground terminal to facilitate user target localization and management of resources.

The overall network structure is shown in Figure 5. In this network, each device senses and communicates with each other, establishing an integrated space–air–ground–sea network for the future.

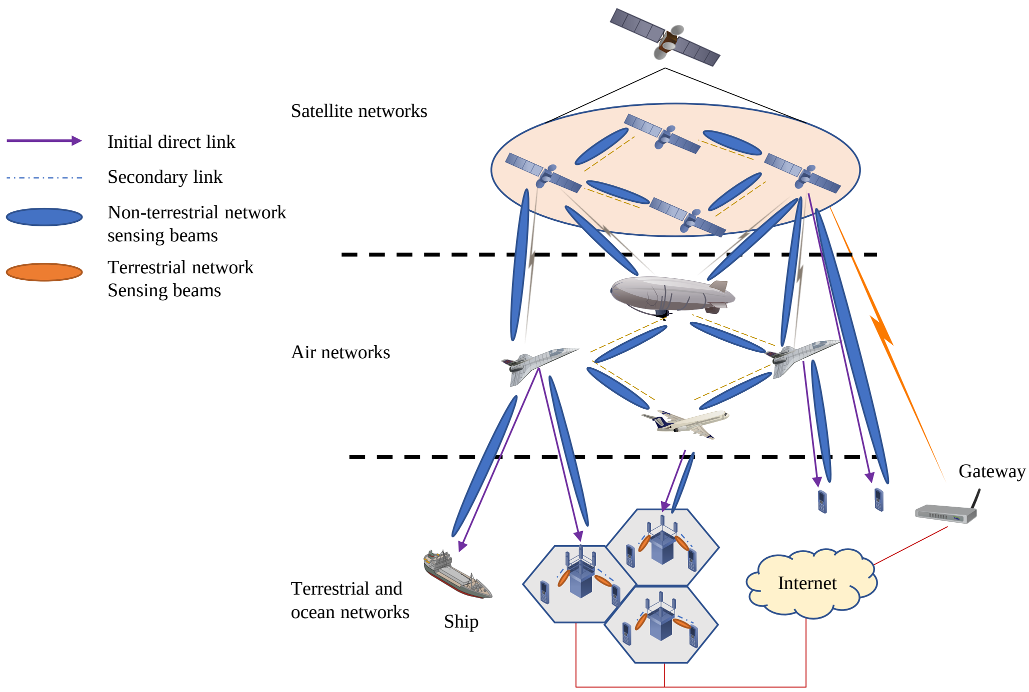


Figure 5. 6G ISAC towards space–air–ground–sea networks.

4.2. Critical Techniques in Integrated Design

The construction of an integrated satellite–terrestrial system with ISAC will face multiple challenges. We need to explore critical technologies including interference cancellation, distributed cooperative sensing, frame structure design, waveform design, and beam enhancement.

4.2.1. Interference Cancellation Technique

In the ISTN system, communication will utilize spatial isolation, time isolation, space-division multiplexing, and spectrum management to achieve satellite–terrestrial spectrum sharing and frequency multiplexing [9]. Similarly, in the ISAC system, it is inevitable to experience interference from both internal signals and external clutter signals. Therefore, implementing appropriate interference cancellation strategies can improve both communication quality and the accuracy of object detection. In the ISAC system, the multiplexing of the spectrum by radar and communication signals can help to further improve spectrum efficiency and minimize costs. However, the transmission with same-frequency signals will lead to self-interference and interference from external sources, which requires specific anti-interference techniques during network deployment [40]. Feng et al. [103] introduced the mutual interference problem from the coexistence and co-designed systems. In co-located systems, radar and communication transceivers regard each other as coexisting sources of interference, so it is necessary to analyze the signal interference existing among them. In the radar-communication co-designed system, the radar and the communication system will constitute a complete joint unit integrating signals, waveforms, and other relevant parameter structures.

For the radar-communication coexistence system, radar and communication systems are deployed together, spectrum sharing technology can be used for better cooperation of them [104]. Their signal can be mapped into the zero domains of each other to minimize the interference. Dong et al. [51] established optimization equations based on maximizing SINR and radar covariance matrix matching. It eliminates the mutual interference between radar and communication waveforms by setting up zero-domain mapping of mutual interference. Shan et al. [105] proposed an ISAC solution based on a time-modulated antenna array. The technique is used to realize radar range target detection and directional communication and to avoid mutual interference in the DFRC system. In [106], the authors proposed that for cooperative scenarios, the time-sharing approach is a straightforward and practical implementation solution to avoid mutual interference and simplify the system. In this scheme, the system of MIMO radar and communication employs time division multiplexing for coexistence, and the solution to suppress the clutter interference is acquired by optimizing convex functions.

For the radar-communication co-design system, Keskin et al. [107] utilized OTFS waveforms along with a low-complexity generalized likelihood ratio test detection algorithm. This algorithm increases the maximum detectable range and speed by embracing the inter-symbol interference (ISI) and the inter-carrier interference (ICI) effects. In [108], the authors eliminated signal interference by using OFDM with zero padding (ZP) and single carrier frequency division multiple access (SC-FDMA). In [109], the authors maximized the minimum SINR under the total energy constraints and communication QoS guarantee using the technique of forcing zeros. In [110], the authors used the remote interference management signal for target detection, which is placed on the third OFDM symbol of the second slot. Through a unified frame structure, it can avoid mutual interference between systems.

The pros and cons of the above research are listed in Table 4. Among the interference cancellation techniques in ISAC systems, for the systems of radar-communication coexistence, the primary issue is the elimination of mutual interference. Based on the implementation of effective interference cancellation, it is desired to further optimize the time and space complexity of the algorithm and realize better communication and radar detection performance.

Table 4. Summary of key technologies for interference cancellation technique in ISAC towards ISTN systems.

Type	Ref.	Pros	Cons
Radar communication coexistence system	[51]	• Low storage occupancy • Low time complexity • Higher radar and communication transmission rates	Not considering power allocation
	[105]	• Lower BER • Low communication side lobes	Only considering one radar beam and one communication beam
	[106]	• Higher SINR	Not considering robust design of communication system mismatches
Radar communication co-design system	[107]	• ISI and ICI are used to extend the maximum non-blurring range of sensing. • Higher probability of detection	Not considering power allocation
	[108]	• Higher probability of detection • Better range performance in the middle and long distances	Not setting variable guard intervals
	[109]	• Better SINR Item: lower average power limit • Lower algorithm complexity	Only considering one communication pair of the transmitter and receiver

With the development of communication technology, the existing interference cancellation technology based on terrestrial ISAC is still applicable in the future 6G ISTN scenario, but some technical optimization needs to be carried out in satellite and airspace. The interference signal of the ground mainly comes from the internal interference of the system and the clutter signal in the surrounding environment, while the interference of the satellite signal includes interference within the system, radio interference scattered by the cosmic environment, and interference between satellites. For high-throughput satellites, which have multiple directional beams pointing to the ground, inter-beam anti-interference is a key issue, and it is necessary to ensure that different frequency bands are used in adjacent areas as much as possible. In addition, as the number of satellites in earth orbit increases, the distance between satellites will decrease, and the difference in elevation angle between adjacent satellites will gradually decrease. As a result, if the beam of the ground uplink signal is shifted and pointed to the wrong neighboring satellite, the target satellite will have a low SNR, and the spectrum sensing technology will be used to identify the spectrum of the interfering signal. In addition, considering the attenuation of the signal by the atmosphere and environment between satellites and ground, reasonable power allocation combined with the sensing environment is an effective way to make up for the interference of the natural environment.

4.2.2. Distributed Cooperative Sensing Technology

More integration of satellite–terrestrial application scenarios will emerge in the 6G era, and ubiquitous terminals will further complicate the heterogeneous network [65]. By ISAC technology, the information parameters acquired by the ISAC system are processed in the cloud, and the cross-convergence of communication, sensing, and computing can be realized [111]. Meanwhile, 6G is expected to be highly integrated for networks of all frequency bands. It can promote intelligent human–machine–thing interconnection and multi-system collaboration, thus optimizing the service quality of the full-frequency band. Satellites, aircraft, ground relays, and terminal devices are utilized to form a multi-level ISAC architecture for the ISTNs. In this network, the deployed ISAC intelligent nodes will work together with intelligent terminals, the ISAC access network, and the core network to construct an innovative distributed cooperative sensing system. Each node in the system collaborates to support the integration and interconnection of intelligent information.

In the integrated space–air–ground network, UAVs can collect information and data from ground IoT devices while simultaneously communicating with multiple LEO satellites [112]. Within a swarm of UAVs, ISAC will realize the positioning and dynamic sensing of UAVs, stabilize the formation of the UAV swarm, and sense the surrounding environment with high accuracy, enhancing the communication effectiveness of the swarm. In [113], the authors introduced cooperative wireless positioning technologies in which UAVs, BS, and cars are viewed as sensing nodes from the perspectives of spatial cooperation and spatiotemporal cooperation. In [114], the authors discussed the potential challenges and development directions of ISAC systems where UAVs act as nodes. From the perspective of BS, UAV nodes will achieve environmental sensing, optimize the communication process, and further realize beam management. It is proposed that there are three types of cooperative sensing technologies, namely, multi-static cooperation, multi-band cooperation, and multi-source cooperation in [115]. These cooperative sensing technologies are mainly achieved through dense networks of remote radio units and multiple sensors to gather sensing parameters comprehensively and multidimensionally, thereby enhancing comprehensive detection performance. In [116], the authors utilized the mobility of UAVs, beamforming, and power control technologies to reduce mutual interference. Through communication between UAVs, they share sensing results to extend the sensing range. In [117], the authors introduced satellite ISAC technology into terrestrial ISAC systems and proposed better beam tilting algorithms and pre-coder optimization algorithms.

In the future, numerous ISAC nodes will be deployed in the space–ground integration scenario. If other ISAC terminals are also transmitting the same channel signal for environmental sensing, the system performance will be degraded. Therefore, we recommend that the air be divided into regions, and the adjacent sensing areas should be allocated different frequency bands. In addition, CR technology is introduced to optimize spectrum utilization. Specifically, for two ISAC terminals that share the same band resources, we divide one into a primary terminal and one as a secondary terminal. While the primary terminal communicates and senses, the secondary terminal does not work. When the primary terminal is not working, the secondary terminal performs ISAC functions. This further optimizes the performance of collaborative sensing and scheduling of multiple systems.

Table 5 summarizes the cooperative sensing technology in the ISAC system. It can be found that future cooperative sensing technology will present the trend of combining centralized and distributed information, spatial and spatiotemporal cooperation, data diversification, and cutting-edge technology. It aims to enhance inter-network connectivity, making it easier for upper management to coordinate. At the same time, it achieves greater communication reliability and sensing precision through internal network collaboration.

Table 5. Summary of distributed cooperative sensing technology in satellite–terrestrial ISAC systems.

Ref	Networking Elements	Cooperative Approach
[113]	UAV, BS, and UE	• Space cooperation and space–time cooperation
[114]	UAV and BS	• Centralized and distributed collaboration
[115]	Satellite, UAV, BS, and UE	• Centralized control unit unified management • Adopt multi-source data symbols
[116]	UAV and BS	• Beamforming, power control technology • UAVs communicate with each other to share detection results
[117]	Satellite, BS, and UE	• Introduce satellite communication sensing technology

4.2.3. Unified Frame Structure Design

The ISTNs will include a variety of scenarios. To support the requirements of these diverse scenarios, a unified frame structure design will be adopted. The adaptive wireless frames and subframes will meet communication needs in different domains and scenarios. At the same time, for ISAC signals, a unified and flexible frame structure is beneficial for scenario adaptability and signal processing. By designing flexible frame structures and employing various scheduling techniques, it can adapt to different communication scenarios, thus improving the efficiency and reliability of communication and enhancing detection accuracy. Aiming at the characteristics of high latency and high Doppler shift in satellite–terrestrial transmission, compensation techniques for frames will be designed to achieve reliable access and efficient transmission, improving the transmission quality and reliability.

In [115], the authors utilized the 5G New Radio (NR) standard to propose four optional mapping patterns for the physical downlink shared channel (PDSCH) based on demodulation reference signal (DMRS). Simulations unveiled the relationship between sensing and communication performance. In [116], the authors proposed three principles for the design of ISAC frame structures, thus coordinating with UAVs to achieve cooperative gain. In [35], the authors introduced an algorithm in their research, which is based on the 5G NR communication protocol. This algorithm not only integrates the advanced waveform capabilities but also empowers the efficient utilization of time and frequency resources, which has high localization accuracy and data transmission rate. In [118], the author introduced frequency hopping MIMO radar as the foundational system for implementing dual-function radar communications. They developed a downlink communication scheme for frequency hopping DFRC systems based on multi-antenna receivers, addressing estimation and synchronization challenges in MIMO scenarios. An integrated frame structure for radar communication based on the 3GPP standard is designed in [119], which can be used to transmit training symbols and conduct channel estimation. In [120], the authors combined frequency division multiplexing (FDM), time division multiple access (TDMA), and communications carrier sense multiple access (CSMA) to form the RadChat scheduling scheme, thus greatly reducing the level of radar interference. In [121], the authors designed waveforms by optimizing cost functions based on the constrained combination of the peak side lobe ratio (PSLR) and integrated side lobe ratio (ISLR) of velocity ambiguity functions. By solving this optimization equation, the system can have high detection and estimation performance in a high SCNR scenario, thereby reducing the cost of the system.

Table 6 summarizes the design and contribution of the frame structure. In general, for the integrated frame structure of ISTNs in the future, the terrestrial-based ISAC frame structure optimization scheme can still be used, and the frame multiplexing technology can be used to improve efficiency. However, it still needs to be optimized according to the characteristics of ISTNs. In the ISTNs, we recommend that the 5G NR frame structure can still be used in order to reduce changes to the existing frame structure. However, it is necessary to consider the new impact of the future ISTN architecture on ISAC signal transmission. In the network, there are a large number of ISAC devices, and sensing frames must be included to realize the sensing function. Considering that the addition of sensing will introduce more information parameters, including the target's position, motion state, surrounding environment, etc., the transmission of sensing parameters will greatly increase the load in a single frame and reduce the space for communication information. Consideration can be given to adding sensing-related information into the existing frame structure in the form of multiplexing to alleviate the reduction in communication resources. In addition, for long-distance communication transmission and sensing from air to ground, there will be a large loss of signals due to atmospheric attenuation and long-term transmission, so it is necessary to consider adding a self-verification scheme to achieve a low number of retransmissions for long-distance transmission.

Table 6. Summary of frame structure design in satellite–terrestrial ISAC systems.

Ref	Frame Structure Design	Contribution	Standard
[115]	Based on the 5G NR frame structure, four optional DMRS-PDSCH modes are proposed.	• PDSCH is used for communication and sensing functions. • Quantizes communication and sensing capabilities with DMRS symbols,	5G NR standard [122]
[116]	• Covers all targets. • Covers only one target. • A combination of the above ideas.	Optimizes the coordination gain effect of combining UAV ISAC.	—
[35]	The system bandwidth is 800 MHz. Eight component carriers, each containing 1200 subcarriers. Each wireless frame contains 50 subframes in 10 ms.	The algorithm for flexible time-frequency resource allocation is proposed to achieve a performance compromise between the DFRC.	5G NR standard
[118]	For every signal, the initial radar frame is utilized to estimate timing deviation and channel states, while the subsequent hops are dedicated to data transmission.	Enables radar data communication and reduce overhead.	—
[119]	The radar pulse repetition period is 1 ms, and there are 14 packets every 0.5 ms. Each packet is composed of a cyclic prefix and a data part, the cyclic prefix contains 288 symbol periods, the data part contains 4096 symbol periods, and the duration of a single symbol period is 8.146 ns.	Channel estimation is performed by transmitting known training symbols.	5G NR standard
[120]	RadChat is a combination of FDM, Radar TDMA, and Communications CSMA.	The probability of interference in automotive radars is significantly reduced, reducing the frame time of each radar by about an order of magnitude.	—
[121]	The optimization strategy is designed as a combined optimization problem of PSLR and ISLR constraints.	• 40% reduction in sensing costs. • High detection performance can be achieved at high SCNR.	5G NR standard

4.2.4. Waveform Design of Satellite–Terrestrial ISAC

ISAC waveforms have been extensively proven in terrestrial environments, but work in ISTN environments has not yet begun. For the future ISAC waveform within ISTNs, we put forward relevant development suggestions based on the sensing characteristics of satellite and ground communication. According to the propagation characteristics of satellite-to-ground channels, the signal transmission process will experience atmospheric absorption attenuation, attenuation caused by rainfall and clouds, Doppler frequency offset, and multipath fading near the ground. Therefore, the new waveform requires good performance in high Doppler and low signal-to-noise ratio environments, and the existing OFDM waveform is considered to be modified to alleviate its instability in high-mobility environments. The applicability of waveforms in satellite scenarios has been studied based on the cyclic prefix OFDM and discrete Fourier transform-spread OFDM waveforms [9,123]. Principle-based simulation validation studies on OFDM and other communication waveforms have been conducted within ISAC waveforms.

In the future scenario of satellite–terrestrial ISAC, NOMA can also be taken into consideration [124]. Considering the high latency of satellite–terrestrial transmission in the ISTNs, NOMA can effectively decrease the connection latency and communication latency of satellite–terrestrial transmission. In [125], the authors treated NOMA as an ISAC waveform. By solving the optimization equation, this method achieved radar waveform matching and the assurance of communication performance. In [42], the authors combined orthogonal multiple access with NOMA techniques to provide flexible sensing and communication between resource management schemes. In [126], the authors came up with a NOMA strategy based on multitype service coexistence handover to ensure the key requirements for the coexistence of user equipment (UE) in a dual-layer LEO high-throughput satellite constellation.

The design of the novel satellite–terrestrial ISAC waveform will greatly facilitate the multi-level transmission of information. Using the same waveform and access can reduce computational complexity, simplify signal processing, and achieve wide-area coverage of system signals and high-precision detection capabilities.

4.2.5. Beam Enhancement Technology

The beams formed by antennas in terrestrial mobile communications typically have low power. However, due to the need for long-distance propagation and large coverage areas in satellite communications, the enhancement of these beams is a necessity. Usually based on the target position, the optimal beam direction and shape parameters are obtained, and the optimal channel environment is switched to enhance the beam strength of the antenna in this direction. For 6G ISTNs, a satellite will form single or multiple beams to cover the ground area. In [127], the authors studied the robust beamforming problem for phase errors of channel state information in multi-beam satellite communications, achieving multi-regional beam coverage through the multiple beams of the satellite. In ISTNs, for multi-target sensing, the sensing terminal also requires multi-beam technology to locate multiple targets. For the detection and tracking of long-range targets, the transmitter antenna is required to form a narrower and more energy-concentrated beam. Therefore, for the signal transmission unit in the satellite and air, a large-scale antenna array with a more accurate beam direction will be adopted, and the antenna array parameters and beamforming algorithm will be optimized. As long-range beams inevitably consume a large amount of power, energy efficiency needs to be taken into account as an optimization metric in order to save energy. ISTNs from 5G to 6G will further achieve integration, and the connection between devices in the large architecture will be closer. In order to further promote the integration trend, we need to rationally allocate the resources of the overall equipment and minimize the negative interference between the internal architecture of the system. Optimized beam enhancement technology is an important part of this. In [128], the authors introduced an integrated space–air–ground system, using UAVs as relays to assist in the effective transmission of satellite signals and applying beamforming technology to optimize the beams of satellites and UAVs for optimal power distribution. In [129], the authors proposed a multi-beam ground multicast control scheme, designing an algorithm for determining cluster centers by leveraging the user distribution. This algorithm ensures that each beam can cover all users in each group, achieving multi-user access and eliminating inter-cluster interference. Additionally, ISAC beams of satellites can also sense environmental factors such as weather and remotely sensed information on the ground and enhance the quality of life. In addition, beamforming technology involves beamforming, beam tracking, and other algorithms, which improves the computational complexity of the system. Therefore, some low-cost algorithms also need to be optimized on the basis of the existing terrestrial ISAC beamforming technology.

Overall, applying beam enhancement techniques in ISTNs will improve the detection range of radars, enhance target detection capability, and optimize communication quality.

Table 7 summarizes the key technologies in the aforementioned satellite–terrestrial ISAC systems and their pros and cons.

Table 7. Summary of key technologies in satellite–terrestrial ISAC systems and their pros and cons.

Key Technologies	Pros	Cons
Interference cancellation technology	• Improves system reliability	• Increases system complexity • Raises the cost
Distributed cooperative sensing technology	• Improves sensing and coverage capability • Increases the adaptability and scalability of the system	• More complex co-scheduling algorithms are required • Leads to new information security issues
Unified frame structure design	• Simplifies system design • Reduces system overhead	• Increases the complexity of design and implementation
Waveform design of satellite–terrestrial ISAC	• Multi-level information fusion • Multi-scenario adaptation	• Complex system design and implementation • High costs and resource requirements
Beam enhancement technology for ISTN	• Efficient energy utilization • Increases the detection range of the system	• High algorithm complexity • Requires target location information in advance

5. Potential Research for ISAC towards 6G ISTNs

In this section, we speculate on the potential research directions and connections between ISAC in the ISTNs and other emerging communication technologies.

5.1. Cognitive Radio

Using CR technology is a good solution for efficiently utilizing spectrum resources. However, in the existing research on ISAC, it has not been given much attention. On the one hand, ISAC as an emerging technology is still immature, and at this stage, more experiments are needed on basic waveforms instead of the scenario with many ISAC terminals. On the other hand, ISAC achieves efficient spectrum utilization by sharing frequency bands between communication and radar sensing. In early radar and communication coexistence systems, the two subsystems operated separately, sharing a frequency band, thus requiring the use of CR technology [6]. However, with the development of 6G ISAC technology, communication and radar signals will be integrated into a single waveform. Although the new waveform will have certain impacts on the performance of existing communication and radar systems, the issue of mutual interference between radar and communication waveforms is no longer considered for the shared waveform.

In summary, in the existing research on ISAC, the application of CR technology is rarely considered. However, in the future, as ISAC technology gradually matures and is deployed for ISTNs, each ISAC terminal will become an independent entity. Furthermore, multiple ISAC terminals will enable cooperative networking, thereby achieving high-precision environmental sensing and localization. In this environment, the spectrum utilization between multiple ISAC terminals will become an important research topic. Therefore, in the future architecture of ISAC networking within ISTNs, CR technology can be adopted to maximize spectrum resource utilization.

Additionally, CR-based ISAC technology can be effectively combined with MIMO-NOMA technology. On the one hand, MIMO-NOMA allows multiple users to share a frequency band, which optimizes spectrum utilization efficiency and increases information transmission rates. On the other hand, MIMO-NOMA employs multiple antenna technology, which enhances spatial reuse, enabling spatial resource allocation. There have been many studies on CR-NOMA technology, which have achieved good results [130,131]. It is believed that the reasonable combination of this technology with ISAC can further improve spectrum efficiency and optimize energy consumption. However, the combination of these technologies also poses challenges, including complex system design, trade-offs in various technical performances, intelligent scheduling in CR environments, and the need for algorithm design for global optimization. Furthermore, hardware feasibility must be considered to mitigate hardware complexity in system implementation.

5.2. Standardization

The deployment of the ISAC system towards 6G ISTNs will face multiple demands, requiring corresponding policies and regulations. Internationally, standardization organizations typically establish standards to provide overall regulations. There are already several standards for existing ISTN and ISAC systems [14,66,67]. However, no specific standards have been proposed for ISAC towards 6G ISTNs. We suggest that standardization can be approached from the following directions.

Firstly, the division of spectrum resources needs to be addressed. The World Radiocommunication Conference of the ITU regularly conducts functional allocation of frequency bands based on the existing network layout [132]. Since the ISAC system combines communication and radar sensing in the same frequency band, using the same spectrum for a dual-functional system will inevitably impact the original spectrum planning.

The ISAC system has open links and environmental sensing capabilities, which allows it to fully sense the surrounding environment, especially in confidential areas. Therefore, the usage of the ISAC system needs to be properly registered to prevent unauthorized information gathering.

Furthermore, future ISAC system devices within the ISTN architecture require standardized parameters to ensure their production follows standards, enabling lawful usage and reasonable planning. This will also support multi-party technical management and prevent monopolies.

5.3. Security

Security is a key issue in communication network architectures. For the physical layer, the ISAC signal contains both important communication information and radar perception information, involving real-world environmental conditions and user privacy. Moreover, relying on wireless channels, ISAC signals are highly vulnerable to eavesdropping and unauthorized access. Beamforming, which focuses signals in spatial areas, inevitably increases the possibility of information leakage, necessitating robust security waveform design. In [89], the authors propose integrating security attributes into ISAC from hardware security and waveform design perspectives, actively maintaining information security.

For the future ISTNs, network layer security is also a worthwhile topic for exploration. For inter-satellite networking and information access, data encryption authentication, route selection, and secure protocols can be employed to prevent routers from being exploited by attackers for malicious operations. Encryption technology and identity authentication can also be used to protect data confidentiality and ensure reliable transmission. Additionally, ISAC towards ISTNs can enhance the system's security in real-world environments. ISAC, with its ability to perceive the surrounding environment, can greatly minimize the occurrence of physical collision accidents. Therefore, discussing the application of security in ISAC towards ISTNs is of great significance.

5.4. Artificial Intelligence

With the rapid development of artificial intelligence (AI) technology, its influence has expanded to various fields. AI-based communication technology has been widely studied, such as edge learning [133], and data-driven algorithms have created new opportunities for ISTNs. In the future, in the context of ISTN environments, the highly complex and data-intensive environment poses challenges for system optimization, and AI algorithms will be used to address these complex optimization problems. At the same time, advancements in hardware enable the deployment of AI algorithms in communication devices. There have been studies focusing on ISTNs, but for future scenarios, AI methods will be needed to allocate resources efficiently and optimize communication performance.

In [134], the authors used multiple UAVs as mobile aerial platforms for ISTNs. The method utilized centralized and distributed deep reinforcement learning solutions to optimize ISAC performance, UAV trajectory planning, power allocation, and spectrum efficiency. Furthermore, AI can enhance ISAC performance in interference management. In [135], an unsupervised learning-based communication–sensing–intelligence converged network architecture is proposed to coordinate interference. Each base station is equipped with a deep neural network for power allocation and beamforming. An unsupervised learning algorithm is proposed to allocate power for interference management, and a transfer learning approach is used to handle interference management in terms of beamforming. Therefore, the research on AI-assisted ISAC within the integrated satellite and terrestrial architecture is meaningful.

5.5. Reconfigurable Intelligent Surface

Reconfigurable intelligent surfaces (RISs), consisting of a series of reflective components, have become a focus of 6G wireless communication research for reconstructing incident signals and mitigating various challenges in wireless networks [136]. In [137], the authors provided a comprehensive survey on the recent development and advances of intelligent surfaces. In recent years, several contributions have extensively studied RIS-aided ISAC systems [138–142]. Through RIS-aided ISAC, the directionality and energy control of ISAC beams can be further achieved, especially in environments with high shadowing. When ISAC signals experience fading, RIS can effectively adopt beamforming technology during transmission [143], achieve rational energy allocation, and save energy. In the scenario where the target is blocked by surrounding obstructions, the authors utilize intelligent reflecting surfaces to assist with localization [144]. Several studies have also focused on RIS in relation to satellites [145,146]. It was shown that placing RIS units on satellite reflector arrays can provide significant gains in signal transmission for broadcasting and beamforming [147]. In [148], the authors investigated RIS-assisted satellite-to-ground covert communication in a satellite communication environment and proposed an iterative algorithm for optimization.

Based on the above foundation, it is expected that in the ISTNs, RIS-aided ISAC will optimize beam intensity and power allocation, improve power efficiency, and ultimately enhance system performance.

6. Conclusions

Combining the sensing capability of radar with the original information transmission capability of communication, ISAC can enhance the high-precision positioning, imaging, and environment reconstruction capabilities of devices to enable sensory enhancement and the connection of everything. In addition, ISTNs will integrate satellites, various types of vehicles, land, and the ocean, aiming to provide seamless global network coverage and resolve the challenge of poor connectivity in remote regions.

Based on the above visions, we provided a comprehensive survey of ISAC technology towards 6G ISTNs in this paper. Firstly, we introduced the historical development process, evaluation indicators, and the key technologies of ISAC. Then, the development status of ISTNs was elaborated, especially the integrated network architectures. Finally, we proposed the potential scenarios and the key technologies for future satellite–terrestrial ISAC. ISAC technology and the construction of ISTNs are in a state of rapid development. It is believed that ISAC technology will be deeply integrated into the ISTNs and ultimately realize the interconnection of everything.

Author Contributions: Conceptualization, Y.G. and T.X.; methodology, Y.G.; software, T.X.; validation, Y.O., W.D., X.T. and T.L.; writing—original draft preparation, Y.G.; writing—review and editing, T.X. and K.F.; supervision, T.X. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded in part by the Science and Technology Commission Foundation of Shanghai (No. 22511100600), the International Partnership Program of Chinese Academy of Sciences for Future Network (No. 307GJHZ2023070FN), the Pudong Industry, Education and Research Cooperation Program (No. PKX2022-D02), and the Shanghai Special Fundation of Promoting High-Quality Industrial Development (No. 2211106).

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: Authors Wen Du and Ting Lei were employed by the company DS Information Technology Co., Ltd. The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

3GPP	The 3rd Generation Partner Project
5G	Fifth generation
6G	Sixth generation
AI	Artificial intelligence
BER	Bit error ratio
BS	Base station
CR	Cognitive radio
CRB	Cramér–Rao bound
CSMA	Carrier sense multiple access
DFRC	Dual-functional radar-communication
DMRS	Demodulation reference signal
EE	Energy efficiency
FDM	Frequency division multiplexing
FMCW	Frequency-modulated continuous wave
FSO	Free-space optical
HSTRN	Hybrid satellite–terrestrial relay network
ICI	Inter-carrier interference
IEEE	The Institute of Electrical and Electronics Engineers
IMT	International Mobile Telecommunications
IoT	Internet of Things
ISAC	Integrated sensing and communication
ISI	Inter-symbol interference
ISLR	Integrated side lobe ratio
ISTNs	Integrated satellite–terrestrial networks
ITU	International Telecommunication Union
LEO	Low earth orbit
LFM	Linear frequency modulation
MIMO	Multiple-input multiple-output
MSE	Mean squared error
MU-MIMO	Multi-user MIMO
NOMA	Non-orthogonal multiple access
NR	New radio

OFDM	Orthogonal frequency division multiplexing
OMA	Orthogonal multiple access
OTFS	Orthogonal time frequency space
PAPR	Peak-to-average power ratio
PDSCH	Physical downlink shared channel
PSLR	Peak side lobe ratio
QoS	Quality of service
RIS	Reconfigurable intelligent surface
SC-FDMA	Single carrier frequency division multiple access
SCNR	Signal-to-clutter-noise ratio
SINR	Signal-to-interference-plus-noise ratio
SLP	Symbol-level precoding
STAP	Space–time adaptive processing
TDMA	Time division multiple access
TR	Technical report
UAV	Unmanned aerial vehicle
UE	User equipment
ZP	Zero padding

References

1. Wang, C.-X.; You, X.; Gao, X.; Zhu, X.; Li, Z.; Zhang, C.; Wang, H.; Huang, Y.; Chen, Y.; Haas, H.; et al. On the Road to 6G: Visions, Requirements, Key Technologies, and Testbeds. *IEEE Commun. Surv. Tutor.* **2023**, *25*, 905–974. [CrossRef]
2. Wang, Z.; Du, Y.; Wei, K.; Han, K.; Xu, X.; Wei, G.; Tong, W.; Zhu, P.; Ma, J.; Wang, J.; et al. Vision, Application Scenarios, and Key Technology Trends for 6G Mobile Communications. *Sci. China Inf. Sci.* **2022**, *65*, 151301. [CrossRef]
3. Jain, P.; Gupta, A.; Kumar, N. A Vision towards Integrated 6G Communication Networks: Promising Technologies, Architecture, and Use-Cases. *Phys. Commun.* **2022**, *55*, 101917. [CrossRef]
4. Zhang, H.; Zhou, T.; Xu, T.; Wang, Y.; Hu, H. Statistical Modeling of Evaporation Duct Channel for Maritime Broadband Communications. *IEEE Trans. Veh. Technol.* **2022**, *71*, 10228–10240. [CrossRef]
5. Vaezi, M.; Azari, A.; Khosravirad, S.R.; Shirvanimoghaddam, M.; Azari, M.M.; Chasaki, D.; Popovski, P. Cellular, Wide-Area, and Non-Terrestrial IoT: A Survey on 5G Advances and the Road Toward 6G. *IEEE Commun. Surv. Tutor.* **2022**, *24*, 1117–1174. [CrossRef]
6. Liu, F.; Cui, Y.; Masouros, C.; Xu, J.; Han, T.X.; Eldar, Y.C.; Buzzi, S. Integrated Sensing and Communications: Toward Dual-Functional Wireless Networks for 6G and Beyond. *IEEE J. Sel. Areas Commun.* **2022**, *40*, 1728–1767. [CrossRef]
7. Fang, X.; Feng, W.; Wei, T.; Chen, Y.; Ge, N.; Wang, C.-X. 5G Embraces Satellites for 6G Ubiquitous IoT: Basic Models for Integrated Satellite Terrestrial Networks. *IEEE Internet Things J.* **2021**, *8*, 14399–14417. [CrossRef]
8. Wei, T.; Feng, W.; Ge, N.; Lu, J. Environment-Aware Coverage Optimization for Space-Ground Integrated Maritime Communications. *IEEE Access* **2020**, *8*, 89205–89214. [CrossRef]
9. Qiu, Y.; Niu, J.; Zhu, X.; Zhu, K.; Yao, Y.; Ren, B.; Ren, T. Mobile Edge Computing in Space-Air-Ground Integrated Networks: Architectures, Key Technologies and Challenges. *J. Sens. Actuator Netw.* **2022**, *11*, 57. [CrossRef]
10. Wu, J.; Xu, T.; Zhou, T.; Chen, X.; Zhang, N.; Hu, H. Feature-Based Spectrum Sensing of NOMA System for Cognitive IoT Networks. *IEEE Internet Things J.* **2023**, *10*, 801–814. [CrossRef]
11. ITU. Report ITU-R M.2516-0: Future Technology Trends of Terrestrial International Mobile Telecommunications Systems towards 2030 and beyond. 2022. Available online: https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-M.2516-2022-PDF-E.pdf (accessed on 3 February 2024).
12. Hexa-X. D1.3—Targets and Requirements for 6G–Initial E2E Architecture. 2022. Available online: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5e90431aa&appId=PPGMS (accessed on 3 February 2024).
13. *IEEE Std 802.11-2020 (Revision of IEEE Std 802.11-2016)*; IEEE Draft Standard for Information Technology–Telecommunications and Information Exchange Between Systems Local and Metropolitan Area Networks–Specific Requirements–Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 4: Enhancements for Wireless LAN Sensing. IEEE: New York, NY, USA, 2024.
14. *3GPP TR 22.837*; Feasibility Study on Integrated Sensing and Communication. 3GPP: Sophia Antipolis, France, 2023.
15. Mealey, R.M. A Method for Calculating Error Probabilities in a Radar Communication System. *IEEE Trans. Space Electron. Telem.* **1963**, *9*, 37–42. [CrossRef]
16. Roberton, M.; Brown, E.R. Integrated Radar and Communications Based on Chirped Spread-Spectrum Techniques. In Proceedings of the IEEE MTT-S International Microwave Symposium Digest, 2003, Philadelphia, PA, USA, 8–13 June 2003; pp. 611–614.

17. Braun, M.; Sturm, C.; Niethammer, A.; Jondral, F.K. Parametrization of Joint OFDM-Based Radar and Communication Systems for Vehicular Applications. In Proceedings of the 2009 IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications, Tokyo, Japan, 13–16 September 2009; pp. 3020–3024.
18. Donnet, B.; Longstaff, I. Combining MIMO Radar with OFDM Communications. In Proceedings of the 2006 European Radar Conference, Manchester, UK, 13–15 September 2006; pp. 37–40.
19. Sturm, C.; Wiesbeck, W. Waveform Design and Signal Processing Aspects for Fusion of Wireless Communications and Radar Sensing. *Proc. IEEE* **2011**, *99*, 1236–1259. [CrossRef]
20. Cui, Y.; Liu, F.; Jing, X.; Mu, J. Integrating Sensing and Communications for Ubiquitous IoT: Applications, Trends, and Challenges. *IEEE Netw.* **2021**, *35*, 158–167. [CrossRef]
21. Fang, X.; Feng, W.; Chen, Y.; Ge, N.; Zhang, Y. Joint Communication and Sensing toward 6G: Models and Potential of Using MIMO. *IEEE Internet Things J.* **2023**, *10*, 4093–4116. [CrossRef]
22. Wei, Z.; Qu, H.; Wang, Y.; Yuan, X.; Wu, H.; Du, Y.; Han, K.; Zhang, N.; Feng, Z. Integrated Sensing and Communication Signals Towards 5G-A and 6G: A Survey. *IEEE Internet Things J.* **2023**, *10*, 11068–11092. [CrossRef]
23. Attiah, K.M.; Yu, W. Active Beamforming for Integrated Sensing and Communication. In Proceedings of the 2023 IEEE International Conference on Communications Workshops (ICC Workshops), Rome, Italy, 28 May–1 June 2023; pp. 1469–1474.
24. Liu, F.; Liu, Y.-F.; Li, A.; Masouros, C.; Eldar, Y.C. Cramér-Rao Bound Optimization for Joint Radar-Communication Beamforming. *IEEE Trans. Signal Process.* **2022**, *70*, 240–253. [CrossRef]
25. Chen, L.; Wang, Z.; Du, Y.; Chen, Y.; Yu, F.R. Generalized Transceiver Beamforming for DFRC with MIMO Radar and MU-MIMO Communication. *IEEE J. Sel. Areas Commun.* **2022**, *40*, 1795–1808. [CrossRef]
26. He, Z.; Xu, W.; Shen, H.; Ng, D.W.K.; Eldar, Y.C.; You, X. Full-Duplex Communication for ISAC: Joint Beamforming and Power Optimization. *IEEE J. Sel. Areas Commun.* **2023**, *41*, 2920–2936. [CrossRef]
27. Liu, M.; Yang, M.; Li, H.; Zeng, K.; Zhang, Z.; Nallanathan, A.; Wang, G.; Hanzo, L. Performance Analysis and Power Allocation for Cooperative ISAC Networks. *IEEE Internet Things J.* **2023**, *10*, 6336–6351. [CrossRef]
28. Xu, W.; Cui, Y.; Zhang, H.; Li, G.Y.; You, X. Robust Beamforming with Partial Channel State Information for Energy Efficient Networks. *IEEE J. Sel. Areas Commun.* **2015**, *33*, 2920–2935. [CrossRef]
29. Zhang, Q.; Zhu, L.; Chen, Y.; Jiang, S. Constrained DRL for Energy Efficiency Optimization in RSMA-Based Integrated Satellite Terrestrial Network. *Sensors* **2023**, *23*, 7859. [CrossRef] [PubMed]
30. Telecomreview. Revolutionizing the 19th Asian Games through 5G Advanced Technologies-Telecom Review Asia Pacific. 2023. Available online: https://www.telecomreviewasia.com/news/technology-news/3558-revolutionizing-the-19th-asian-games-through-5g-advanced-technologies (accessed on 6 March 2024).
31. Ding, S.; Chen, B.; Li, J.; Yao, J.; Yuan, Y.; Jiang, D.; Qin, F. Integrated Sensing and Communication: Prototype and Key Processing Algorithms. In Proceedings of the 2023 IEEE International Conference on Communications Workshops (ICC Workshops), Rome, Italy, 28 May 2023; pp. 225–230.
32. Dong, B.; Jia, J.; Li, Z.; Li, G.; Shi, J.; Wang, H.; Chi, N.; Zhang, J. Photonic-Based Flexible Integrated Sensing and Communication with Multiple Targets Detection Capability for *W*-Band Fiber-Wireless Network. *IEEE Trans. Microw. Theory Techn.* **2024**, 1–14.
33. Dong, B.; Jia, J.; Tao, L.; Li, G.; Li, Z.; Huang, C.; Shi, J.; Wang, H.; Tang, Z.; Zhang, J.; et al. Photonic-Based W-Band Integrated Sensing and Communication System with Flexible Time- Frequency Division Multiplexed Waveforms for Fiber-Wireless Network. *J. Light. Technol.* **2024**, *42*, 1281–1295. [CrossRef]
34. Zhang, C.; Zhou, Z.; Wang, H.; Zeng, Y. Integrated Super-Resolution Sensing and Communication with 5G NR Waveform: Signal Processing with Uneven CPs and Experiments: (Invited Paper). In Proceedings of the 2023 21st International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt), Singapore, Singapore, 24 August 2023; pp. 681–688.
35. Zhang, Q.; Li, Z.; Gao, X.; Feng, Z. Performance Evaluation of Radar and Communication Integrated System for Autonomous Driving Vehicles. In Proceedings of the IEEE INFOCOM 2021-IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS), Vancouver, BC, Canada, 10–13 May 2021; pp. 1–2.
36. Li, Z.; Dong, B.; Li, G.; Jia, J.; Sun, A.; Shen, W.; Xing, S.; Shi, J.; Chi, N.; Zhang, J. Attention-Assisted Autoencoder Neural Network for End-to-End Optimization of Multi-Access Fiber-Terahertz Communication Systems. *J. Opt. Commun. Netw.* **2023**, *15*, 711. [CrossRef]
37. Liu, Y.; Li, O.; Du, X.; Zang, J.; Liu, Q.; Wang, G. Comprehensive Prototype Demonstration of Ultra-Broadband Terahertz Platform for 6G ISAC. In Proceedings of the 2023 IEEE 34th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Toronto, ON, Canada, 5 September 2023; pp. 1–7.
38. Li, O.; He, J.; Zeng, K.; Yu, Z.; Du, X.; Zhou, Z.; Liang, Y.; Wang, G.; Chen, Y.; Zhu, P.; et al. Integrated Sensing and Communication in 6G: A Prototype of High Resolution Multichannel THz Sensing on Portable Device. *EURASIP J. Wirel. Commun. Netw.* **2022**, *2022*, 106. [CrossRef]
39. HUAWEI. 6G ISAC-OW Extends the Frontier of Spectrum for Wireless Communication Systems. 2022. Available online: https://www.huawei.com/en/huaweitech/future-technologies/6g-isac-ow (accessed on 7 March 2024).
40. Zhang, J.A.; Rahman, M.d.L.; Wu, K.; Huang, X.; Guo, Y.J.; Chen, S.; Yuan, J. Enabling Joint Communication and Radar Sensing in Mobile Networks—A Survey. *IEEE Commun. Surv. Tutor.* **2022**, *24*, 306–345. [CrossRef]

41. Temiz, M.; Alsusa, E.; Baidas, M.W. A Dual-Functional Massive MIMO OFDM Communication and Radar Transmitter Architecture. *IEEE Trans. Veh. Technol.* **2020**, *69*, 14974–14988. [CrossRef]
42. Mu, X.; Wang, Z.; Liu, Y. NOMA for Integrating Sensing and Communications towards 6G: A Multiple Access Perspective. *IEEE Wirel. Commun.* **2023**, 1–8. [CrossRef]
43. Hassanien, A.; Amin, M.G.; Aboutanios, E.; Himed, B. Dual-Function Radar Communication Systems: A Solution to the Spectrum Congestion Problem. *IEEE Signal Process. Mag.* **2019**, *36*, 115–126. [CrossRef]
44. Ma, D.; Shlezinger, N.; Huang, T.; Liu, Y.; Eldar, Y.C. FRaC: FMCW-Based Joint Radar-Communications System via Index Modulation. *IEEE J. Sel. Top. Signal Process.* **2021**, *15*, 1348–1364. [CrossRef]
45. Hadani, R.; Rakib, S.; Tsatsanis, M.; Monk, A.; Goldsmith, A.J.; Molisch, A.F.; Calderbank, R. Orthogonal time frequency space modulation. In Proceedings of the 2017 IEEE Wireless Communications and Networking Conference (WCNC), San Francisco, CA, USA, 19–22 March 2017; pp. 1–6.
46. Wu, K.; Zhang, J.A.; Huang, X.; Guo, Y.J. OTFS-Based Joint Communication and Sensing for Future Industrial IoT. *IEEE Internet Things J.* **2023**, *10*, 1973–1989. [CrossRef]
47. Gaudio, L.; Kobayashi, M.; Caire, G.; Colavolpe, G. On the Effectiveness of OTFS for Joint Radar Parameter Estimation and Communication. *IEEE Trans. Wirel. Commun.* **2020**, *19*, 5951–5965. [CrossRef]
48. Zhang, X.; Wen, H.; Yan, Z.; Yuan, W.; Wu, J.; Li, Z. A Novel Joint Channel Estimation and Symbol Detection Receiver for Orthogonal Time Frequency Space in Vehicular Networks. *Entropy* **2023**, *25*, 1358. [CrossRef] [PubMed]
49. Zhang, J.; Cai, L.; Liu, H. Integrated Sensing and Communication via Orthogonal Time Frequency Space Signaling with Hybrid Message Passing Detection and Fractional Parameter Estimation. *Sensors* **2023**, *23*, 9874. [CrossRef] [PubMed]
50. Khelouani, I.; Elbahhar, F.; Elassali, R.; Idboufker, N. Performance Evaluation of 5G Waveforms for Joint Radar Communication over 77 GHz and 24 GHz ISM Bands. *Energies* **2022**, *15*, 2049. [CrossRef]
51. Dong, F.; Wang, W.; Hu, Z.; Hui, T. Low-Complexity Beamformer Design for Joint Radar and Communications Systems. *IEEE Commun. Lett.* **2021**, *25*, 259–263. [CrossRef]
52. Liu, R.; Li, M.; Liu, Q.; Swindlehurst, A.L. Dual-Functional Radar-Communication Waveform Design: A Symbol-Level Precoding Approach. *IEEE J. Sel. Top. Signal Process.* **2021**, *15*, 1316–1331. [CrossRef]
53. Liyanaarachchi, S.D.; Riihonen, T.; Barneto, C.B.; Valkama, M. Optimized Waveforms for 5G–6G Communication with Sensing: Theory, Simulations and Experiments. *IEEE Trans. Wirel. Commun.* **2021**, *20*, 8301–8315. [CrossRef]
54. Liu, R.; Li, M.; Liu, Q.; Swindlehurst, A.L. Joint Waveform and Filter Designs for STAP-SLP-Based MIMO-DFRC Systems. *IEEE J. Sel. Areas Commun.* **2022**, *40*, 1918–1931. [CrossRef]
55. Bazzi, A.; Chafii, M. On Outage-Based Beamforming Design for Dual-Functional Radar-Communication 6G Systems. *IEEE Trans. Wirel. Commun.* **2022**, *22*, 5598–5612. [CrossRef]
56. Cong, D.; Guo, S.; Zhang, H.; Ye, J.; Alouini, M.-S. Beamforming Design for Integrated Sensing and Communication Systems with Finite Alphabet Input. *IEEE Wirel. Commun. Lett.* **2022**, *11*, 2190–2194. [CrossRef]
57. Xiao, Z.; Liu, R.; Li, M.; Liu, Y.; Liu, Q. Low-Complexity Designs of Symbol-Level Precoding for MU-MISO Systems. *IEEE Trans. Commun.* **2022**, *70*, 4624–4639. [CrossRef]
58. He, Z.; Xu, W.; Shen, H.; Huang, Y.; Xiao, H. Energy Efficient Beamforming Optimization for Integrated Sensing and Communication. *IEEE Wirel. Commun. Lett.* **2022**, *11*, 1374–1378. [CrossRef]
59. Yu, X.; Yang, Q.; Xiao, Z.; Chen, H.; Havyarimana, V.; Han, Z. A Precoding Approach for Dual-Functional Radar-Communication System with One-Bit DACs. *IEEE J. Sel. Areas Commun.* **2022**, *40*, 1965–1977. [CrossRef]
60. Yan, J.; Zheng, J. Low-Complexity Symbol-Level Precoding for Dual-Functional Radar-Communication System. In Proceedings of the 2022 IEEE Wireless Communications and Networking Conference (WCNC), Austin, TX, USA, 10–13 April 2022; pp. 234–239.
61. Wang, Q.; Zhou, T.; Zhang, H.; Hu, H.; Edison, P.; Feng, S. Deep Learning-Based Detection Algorithm for the Multi-User MIMO-NOMA System. *Electronics* **2024**, *13*, 225. [CrossRef]
62. Kuang, L.; Chen, X.; Jiang, C.; Zhang, H.; Wu, S. Radio Resource Management in Future Terrestrial-Satellite Communication Networks. *IEEE Wirel. Commun.* **2017**, *24*, 81–87. [CrossRef]
63. Dicandia, F.A.; Fonseca, N.J.G.; Bacco, M.; Mugnaini, S.; Genovesi, S. Space-Air-Ground Integrated 6G Wireless Communication Networks: A Review of Antenna Technologies and Application Scenarios. *Sensors* **2022**, *22*, 3136. [CrossRef]
64. Xu, T.; Xu, Y.; Zhou, T.; Chen, X.; Hu, H. NOMA-based spectrum sensing for satellite-terrestrial communication. *China Commun.* **2023**, *20*, 227–242. [CrossRef]
65. Tirmizi, S.B.R.; Chen, Y.; Lakshminarayana, S.; Feng, W.; Khuwaja, A.A. Hybrid Satellite–Terrestrial Networks toward 6G: Key Technologies and Open Issues. *Sensors* **2022**, *22*, 8544. [CrossRef]
66. *3GPP TR 38.811*; Study on New Radio (NR) to Support Non-Terrestrial Networks. 3GPP: Sophia Antipolis, France, 2020.
67. *3GPP TR 22.822*; Study on using Satellite Access in 5G. 3GPP: Sophia Antipolis, France, 2018.
68. 3GPP. Release 17. 2022. Available online: https://www.3gpp.org/specifications-technologies/releases/release-17 (accessed on 3 April 2024).
69. Gong, S.; Shen, H.; Zhao, K.; Wang, R.; Zhang, X.; De Cola, T.; Fraier, J.A. Network Availability Maximization for Free-Space Optical Satellite Communications. *IEEE Wireless Commun. Lett.* **2020**, *9*, 411–415. [CrossRef]
70. Liu, Y.; Tan, X.; Jia, J.; Dong, B.; Huang, C.; Luo, P.; Shi, J.; Chi, N.; Zhang, J. A Hybrid Millimeter-Wave and Free-Space-Optics Communication Architecture with Adaptive Diversity Combining and HARQ Techniques. *Photonics* **2023**, *10*, 1320. [CrossRef]

71. Via Satellie. Space Lasers Come of Age: Optical Communications for Satellites Are Ready for Prime Time. 2022. Available online: http://interactive.satellitetoday.com/via/march-2022/space-lasers-come-of-age-optical-communications-for-satellites-are-ready-for-prime-time/ (accessed on 5 March 2024).
72. ESA. European Data Relay System (EDRS). 2014. Available online: https://www.esa.int/ESA_Multimedia/Images/2014/06/European_Data_Relay_System_EDRS (accessed on 5 March 2024).
73. NASA. Laser Communication Relay Demonstration. Available online: https://esc.gsfc.nasa.gov/projects/LCRD (accessed on 5 March 2024).
74. Liu, X.; Chen, X.; Zhao, K.; Yang, L.; Zhao, Y.; Fan, C. Energy-Efficiently Collaborative Data Downloading in Optical Satellite Networks. *Wirel. Netw.* **2019**, 1–13.
75. Lee, J.-H.; Park, K.-H.; Ko, Y.-C.; Alouini, M.-S. Spectral-Efficient Network Design for High-Altitude Platform Station Networks with Mixed RF/FSO System. *IEEE Trans. Wirel. Commun.* **2022**, *21*, 7072–7087. [CrossRef]
76. Samy, R.; Yang, H.-C.; Rakia, T.; Alouini, M.-S. Space-Air-Ground FSO Networks for High-Throughput Satellite Communications. *IEEE Commun. Mag.* **2022**, *60*, 82–87. [CrossRef]
77. Mao, B.; Zhou, X.; Liu, J.; Kato, N. On an Intelligent Hierarchical Routing Strategy for Ultra-Dense Free Space Optical Low Earth Orbit Satellite Networks. *IEEE J. Select. Areas Commun.* **2024**, 1–13. [CrossRef]
78. Kokkoniemi, J.; Jornet, J.M.; Petrov, V.; Koucheryavy, Y.; Juntti, M. Channel Modeling and Performance Analysis of Airplane-Satellite Terahertz Band Communications. *IEEE Trans. Veh. Technol.* **2021**, *70*, 2047–2061. [CrossRef]
79. Wang, X.; Deng, N.; Wei, H. Coverage and Rate Analysis of LEO Satellite-to-Airplane Communication Networks in Terahertz Band. *IEEE Trans. Wireless Commun.* **2023**, *22*, 9076–9090. [CrossRef]
80. Yuan, X.; Tang, F.; Zhao, M.; Kato, N. Joint Rate and Coverage Optimization for the THz/RF Multi-Band Communications of Space-Air-Ground Integrated Network in 6G. *IEEE Trans. Wireless Commun.* **2023**, 1–16. [CrossRef]
81. Aliaga, S.; Petrov, V.; Jornet, J.M. Modeling Interference from Millimeter Wave and Terahertz Bands Cross-Links in Low Earth Orbit Satellite Networks for 6G and Beyond. *IEEE J. Select. Areas Commun.* **2024**, 1–16. [CrossRef]
82. Arti, M.K.; Bhatnagar, M.R. Beamforming and Combining in Hybrid Satellite-Terrestrial Cooperative Systems. *IEEE Commun. Lett.* **2014**, *18*, 483–486.
83. Zhao, Z.; Xu, G.; Zhang, N.; Zhang, Q. Performance Analysis of the Hybrid Satellite-Terrestrial Relay Network with Opportunistic Scheduling Over Generalized Fading Channels. *IEEE Trans. Veh. Technol.* **2022**, *71*, 2914–2924. [CrossRef]
84. Zhu, X.; Jiang, C. Integrated Satellite-Terrestrial Networks Toward 6G: Architectures, Applications, and Challenges. *IEEE Internet Things J.* **2022**, *9*, 437–461. [CrossRef]
85. Agarwal, A.; Kumar, P. Analysis of Variable Bit Rate SOFDM Transmission Scheme over Multi-Relay Hybrid Satellite-Terrestrial System in the Presence of CFO and Phase Noise. *IEEE Trans. Veh. Technol.* **2019**, *68*, 4586–4601. [CrossRef]
86. Shi, S.; Li, G.; An, K.; Gao, B.; Zheng, G. Energy-Efficient Optimal Power Allocation in Integrated Wireless Sensor and Cognitive Satellite Terrestrial Networks. *Sensors* **2017**, *17*, 2025. [CrossRef]
87. Kolawole, O.Y.; Vuppala, S.; Sellathurai, M.; Ratnarajah, T. On the Performance of Cognitive Satellite-Terrestrial Networks. *IEEE Trans. Cogn. Commun. Netw.* **2017**, *3*, 668–683. [CrossRef]
88. An, K.; Ouyang, J.; Lin, M.; Liang, T. Outage Analysis of Multi-Antenna Cognitive Hybrid Satellite-Terrestrial Relay Networks with Beamforming. *IEEE Commun. Lett.* **2015**, *19*, 1157–1160. [CrossRef]
89. Wei, Z.; Liu, F.; Masouros, C.; Su, N.; Petropulu, A.P. Toward Multi-Functional 6G Wireless Networks: Integrating Sensing, Communication, and Security. *IEEE Commun. Mag.* **2022**, *60*, 65–71. [CrossRef]
90. Xu, Y.; Xu, T.; Xu, T.; Zhou, T.; Zhang, H.; Hu, H. Elastic Spectrum Sensing for Satellite-Terrestrial Communication under Highly Dynamic Channels. In Proceedings of the GLOBECOM 2023-2023 IEEE Global Communications Conference, Kuala Lumpur, Malaysia, 4 December 2023; pp. 2434–2439.
91. Ni, Z.; Zhang, J.A.; Huang, X.; Yang, K.; Yuan, J. Uplink Sensing in Perceptive Mobile Networks with Asynchronous Transceivers. *IEEE Trans. Signal Process.* **2021**, *69*, 1287–1300. [CrossRef]
92. Moreira, A.; Prats-Iraola, P.; Younis, M.; Krieger, G.; Hajnsek, I.; Papathanassiou, K.P. A Tutorial on Synthetic Aperture Radar. *IEEE Geosci. Remote Sens. Mag.* **2013**, *1*, 6–43. [CrossRef]
93. Zhao, B.; Wang, M.; Xing, Z.; Ren, G.; Su, J. Integrated Sensing and Communication Aided Dynamic Resource Allocation for Random Access in Satellite Terrestrial Relay Networks. *IEEE Commun. Lett.* **2023**, *27*, 661–665. [CrossRef]
94. Zhu, J.; Cui, Y.; Mu, J.; Hu, L.; Jing, X. Power Minimization Strategy Based Subcarrier Allocation and Power Assignment for Integrated Sensing and Communication. In Proceedings of the 2023 IEEE Wireless Communications and Networking Conference (WCNC), Glasgow, UK, 26–29 March 2023; pp. 1–6.
95. Sun, P.Z.; You, J.; Qiu, S.; Wu, E.Q.; Xiong, P.; Song, A.; Zhang, H.; Lu, T. AGV-Based Vehicle Transportation in Automated Container Terminals: A Survey. *IEEE Trans. Intell. Transp. Syst.* **2022**, *24*, 341–356. [CrossRef]
96. Zhang, H.; Zhou, T.; Xu, T.; Cheng, M.; Hu, H. Field Measurement and Channel Modeling around Wailingding Island for Maritime Wireless Communication. *IEEE Antennas Wirel. Propag. Lett.* **2024**, 1–5. [CrossRef]
97. Liu, Y.; Zhao, S.; Han, F.; Chai, M.; Jiang, H.; Zhang, H. Data Collection for Target Localization in Ocean Monitoring Radar-Communication Networks. *Remote Sens.* **2023**, *15*, 5126. [CrossRef]
98. ESOC/ESA. Space Environment Statistics. Available online: https://sdup.esoc.esa.int/discosweb/statistics/ (accessed on 6 December 2023).

99. Sümen, G.; Kurt, G.K.; Görçin, A. A Novel LFM Waveform for Terahertz-Band Joint Radar and Communications over Inter-Satellite Links. In Proceedings of the GLOBECOM 2022-2022 IEEE Global Communications Conference, Rio de Janeiro, Brazil, 4–8 December 2022; pp. 6439–6444.
100. Wu, Y.; Li, B.; Liu, S.; Wang, X. Spectrum Sharing Between Radar and Communication Systems Based on Overlapped Virtual Subarrays. *IEEE Access* **2022**, *10*, 94841–94850. [CrossRef]
101. Dong, F.; Liu, F. Localization as a Service in Perceptive Networks: An ISAC Resource Allocation Framework. In Proceedings of the 2022 IEEE International Conference on Communications Workshops (ICC Workshops), Seoul, Republic of Korea, 16–20 May 2022; pp. 848–853.
102. Han, Z.; Zhou, T.; Xu, T.; Hu, H. Joint User Association and Deployment Optimization for Delay-Minimized UAV-Aided MEC Networks. *IEEE Wirel. Commun. Lett.* **2023**, *12*, 1791–1795. [CrossRef]
103. Feng, Z.; Fang, Z.; Wei, Z.; Chen, X.; Quan, Z.; Ji, D. Joint Radar and Communication: A Survey. *China Commun.* **2020**, *17*, 1–27. [CrossRef]
104. Thakur, P.; Singh, G. *Spectrum Sharing in Cognitive Radio Networks: Towards Highly Connected Environments*; John Wiley & Sons: Johannesburg, South Africa, 2021.
105. Shan, C.; Ma, Y.; Zhao, H.; Shi, J. Joint Radar-Communications Design Based on Time Modulated Array. *Digit. Signal Process.* **2018**, *82*, 43–53. [CrossRef]
106. Qian, J.; Lops, M.; Zheng, L.; Wang, X. Joint Design for Co-Existence of MIMO Radar and MIMO Communication System. In Proceedings of the 2017 51st Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, CA, USA, 29 October–1 November 2017; pp. 568–572.
107. Keskin, M.F.; Wymeersch, H.; Alvarado, A. Radar Sensing with OTFS: Embracing ISI and ICI to Surpass the Ambiguity Barrier. In Proceedings of the 2021 IEEE International Conference on Communications Workshops (ICC Workshops), Montreal, QC, Canada, 14–23 June 2021; pp. 1–6.
108. Dokhanchi, S.H.; Barreto, A.N.; Fettweis, G.P. Performance Analysis of Zero-Padded Sequences for Joint Communications and Sensing. *IEEE Trans. Signal Process.* **2023**, *71*, 1725–1741. [CrossRef]
109. He, Y.; Cai, Y.; Yu, G.; Wong, K.-K. Joint Transceiver Design for Dual-Functional Full-Duplex Relay Aided Radar-Communication Systems. *IEEE Trans. Commun.* **2022**, *70*, 8355–8369. [CrossRef]
110. Liu, R.; Jian, M.; Chen, D.; Lin, X.; Cheng, Y.; Cheng, W.; Chen, S. Integrated Sensing and Communication Based Outdoor Multi-Target Detection, Tracking, and Localization in Practical 5G Networks. *Intell. Converged Netw.* **2023**, *4*, 261–272. [CrossRef]
111. Letaief, K.B.; Shi, Y.; Lu, J.; Lu, J. Edge Artificial Intelligence for 6G: Vision, Enabling Technologies, and Applications. *IEEE J. Sel. Areas Commun.* **2022**, *40*, 5–36. [CrossRef]
112. Zhang, H.; Xi, S.; Jiang, H.; Shen, Q.; Shang, B.; Wang, J. Resource Allocation and Offloading Strategy for UAV-Assisted LEO Satellite Edge Computing. *Drones* **2023**, *7*, 383. [CrossRef]
113. Liu, A.; Huang, Z.; Li, M.; Wan, Y.; Li, W.; Han, T.X.; Liu, C.; Du, R.; Tan, D.K.P.; Lu, J.; et al. A Survey on Fundamental Limits of Integrated Sensing and Communication. *IEEE Commun. Surv. Tutor.* **2022**, *24*, 994–1034. [CrossRef]
114. Mu, J.; Zhang, R.; Cui, Y.; Gao, N.; Jing, X. UAV Meets Integrated Sensing and Communication: Challenges and Future Directions. *IEEE Commun. Mag.* **2023**, *61*, 62–67. [CrossRef]
115. Ji, K.; Zhang, Q.; Wei, Z.; Feng, Z.; Zhang, P. Networking Based ISAC Hardware Testbed and Performance Evaluation. *IEEE Commun. Mag.* **2023**, *61*, 76–82. [CrossRef]
116. Meng, K.; Wu, Q.; Xu, J.; Chen, W.; Feng, Z.; Schober, R.; Swindlehurst, A.L. UAV-Enabled Integrated Sensing and Communication: Opportunities and Challenges. *IEEE Wirel. Commun.* **2023**, 1–9.
117. You, L.; Qiang, X.; Tsinos, C.G.; Liu, F.; Wang, W.; Gao, X.; Ottersten, B. Beam Squint-Aware Integrated Sensing and Communications for Hybrid Massive MIMO LEO Satellite Systems. *IEEE J. Sel. Areas Commun.* **2022**, *40*, 2994–3009. [CrossRef]
118. Wu, K.; Zhang, J.A.; Huang, X.; Guo, Y.J.; Yuan, J. Reliable Frequency-Hopping MIMO Radar-Based Communications with Multi-Antenna Receiver. *IEEE Trans. Commun.* **2021**, *69*, 5502–5513. [CrossRef]
119. D'Andrea, C.; Buzzi, S.; Lops, M. Communications and Radar Coexistence in the Massive MIMO Regime: Uplink Analysis. *IEEE Trans. Wirel. Commun.* **2020**, *19*, 19–33. [CrossRef]
120. Aydogdu, C.; Keskin, M.F.; Garcia, N.; Wymeersch, H.; Bliss, D.W. RadChat: Spectrum Sharing for Automotive Radar Interference Mitigation. *IEEE Trans. Intell. Transp. Syst.* **2021**, *22*, 416–429. [CrossRef]
121. Zheng, J.; Chu, P.; Wang, X.; Yang, Z. Inner-Frame Time Division Multiplexing Waveform Design of Integrated Sensing and Communication in 5G NR System. *Sensors* **2023**, *23*, 6855. [CrossRef] [PubMed]
122. *3GPP TS 38.211*; Technical Specification Group Radio Access Network; NR; Physical Channels and Modulation. 3GPP: Sophia Antipolis, France, 2021.
123. Chen, S.; Sun, S.; Kang, S. System Integration of Terrestrial Mobile Communication and Satellite Communication—The Trends, Challenges and Key Technologies in B5G and 6G. *China Commun.* **2020**, *17*, 156–171. [CrossRef]
124. Wang, K.; Zhou, T.; Xu, T.; Huang, Y.; Hu, H.; Tao, X. Fairness-Aware Energy-Efficient Power Allocation for Uplink NOMA Systems with Imperfect SIC. *IEEE Wirel. Commun. Lett.* **2023**, *12*, 2018–2022. [CrossRef]
125. Wang, Z.; Liu, Y.; Mu, X.; Ding, Z.; Dobre, O.A. NOMA Empowered Integrated Sensing and Communication. *IEEE Commun. Lett.* **2022**, *26*, 677–681. [CrossRef]

126. Hu, Q.; Jiao, J.; Wang, Y.; Wu, S.; Lu, R.; Zhang, Q. Multitype Services Coexistence in Uplink NOMA for Dual-Layer LEO Satellite Constellation. *IEEE Internet Things J.* **2023**, *10*, 2693–2707. [CrossRef]
127. Yan, Y.; Yang, W.; Zhang, B.; Guo, D.; Ding, G. Outage Constrained Robust Beamforming for Sum Rate Maximization in Multi-Beam Satellite Systems. *IEEE Commun. Lett.* **2020**, *24*, 164–168. [CrossRef]
128. Huang, Q.; Lin, M.; Wang, J.-B.; Tsiftsis, T.A.; Wang, J. Energy Efficient Beamforming Schemes for Satellite-Aerial-Terrestrial Networks. *IEEE Trans. Commun.* **2020**, *68*, 3863–3875. [CrossRef]
129. Wu, D.; Qin, C.; Cui, Y.; He, P.; Wang, R. Space-Ground Multicast Group Control for Multiuser LEO Satellite Networks. *IEEE Trans. Wirel. Commun.* **2023**, 1–12. [CrossRef]
130. Thakur, P.; Singh, G. Performance Analysis of MIMO-based CR–NOMA Communication Systems. *IET Commun.* **2020**, *14*, 2677–2686. [CrossRef]
131. Thakur, P.; Kumar, A.; Pandit, S.; Singh, G.; Satashia, S.N. Frameworks of Non-Orthogonal Multiple Access Techniques in Cognitive Radio Communication Systems. *China Commun.* **2019**, *16*, 129–149. [CrossRef]
132. ITU. World Radiocommunication Conference 2023. 2023. Available online: https://www.itu.int/wrc-23/ (accessed on 13 March 2024).
133. Xu, W.; Yang, Z.; Ng, D.W.K.; Levorato, M.; Eldar, Y.C.; Debbah, M. Edge Learning for B5G Networks with Distributed Signal Processing: Semantic Communication, Edge Computing, and Wireless Sensing. *IEEE J. Sel. Top. Signal Process.* **2023**, *17*, 9–39. [CrossRef]
134. Qin, Y.; Zhang, Z.; Li, X.; Huangfu, W.; Zhang, H. Deep Reinforcement Learning Based Resource Allocation and Trajectory Planning in Integrated Sensing and Communications UAV Network. *IEEE Trans. Wireless Commun.* **2023**, *22*, 8158–8169. [CrossRef]
135. Liu, X.; Zhang, H.; Long, K.; Nallanathan, A.; Leung, V.C.M. Distributed Unsupervised Learning for Interference Management in Integrated Sensing and Communication Systems. *IEEE Trans. Wireless Commun.* **2023**, *22*, 9301–9312. [CrossRef]
136. Liu, Y.; Liu, X.; Mu, X.; Hou, T.; Xu, J.; Di Renzo, M.; Al-Dhahir, N. Reconfigurable Intelligent Surfaces: Principles and Opportunities. *IEEE Commun. Surv. Tutor.* **2021**, *23*, 1546–1577. [CrossRef]
137. Wu, Q.; Zheng, B.; You, C.; Zhu, L.; Shen, K.; Shao, X.; Mei, W.; Di, B.; Zhang, H.; Basar, E.; et al. Intelligent Surfaces Empowered Wireless Network: Recent Advances and The Road to 6G. *arXiv* **2024**, arXiv:2312.16918.
138. Xu, J.; Yuen, C.; Huang, C.; Ul Hassan, N.; Alexandropoulos, G.C.; Di Renzo, M.; Debbah, M. Reconfiguring Wireless Environments via Intelligent Surfaces for 6G: Reflection, Modulation, and Security. *Sci. China Inf. Sci.* **2023**, *66*, 130304. [CrossRef]
139. Hua, M.; Wu, Q.; Dobre, O.A.; Swindlehurst, A.L. Secure Intelligent Reflecting Surface-Aided Integrated Sensing and Communication. *IEEE Trans. Wirel. Commun.* **2024**, *23*, 575–591. [CrossRef]
140. Chu, J.; Lu, Z.; Liu, R.; Li, M.; Liu, Q. Joint Beamforming and Reflection Design for Secure RIS-ISAC Systems. *IEEE Trans. Veh. Technol.* **2024**, *73*, 4471–4475. [CrossRef]
141. Chen, K.; Qi, C.; Dobre, O.A.; Li, G.Y. Simultaneous Beam Training and Target Sensing in ISAC Systems with RIS. *IEEE Trans. Wireless Commun.* **2024**, 1–15. [CrossRef]
142. Zhu, Q.; Li, M.; Liu, R.; Liu, Q. Joint Transceiver Beamforming and Reflecting Design for Active RIS-Aided ISAC Systems. *IEEE Trans. Veh. Technol.* **2023**, *72*, 9636–9640. [CrossRef]
143. Peng, Q.; Wu, Q.; Chen, W.; Ma, S.; Zhao, M.-M.; Dobre, O.A. Semi-Passive Intelligent Reflecting Surface Enabled Sensing Systems. *arXiv* **2024**, arXiv:2402.03042.
144. Hua, M.; Wu, Q.; Chen, W.; Fei, Z.; So, H.C.; Yuen, C. Intelligent Reflecting Surface-Assisted Localization: Performance Analysis and Algorithm Design. *IEEE Wireless Commun. Lett.* **2024**, *13*, 84–88. [CrossRef]
145. Feng, K.; Zhou, T.; Xu, T.; Chen, X.; Hu, H.; Wu, C. RIS-Aided Multi-Beam Cooperative Transmission for Satellite-Terrestrial Communication. In Proceedings of the GLOBECOM 2023-2023 IEEE Global Communications Conference, Kuala Lumpur, Malaysia, 4 December 2023; pp. 1429–1434.
146. Zheng, B.; Lin, S.; Zhang, R. Intelligent Reflecting Surface-Aided LEO Satellite Communication: Cooperative Passive Beamforming and Distributed Channel Estimation. *IEEE J. Select. Areas Commun.* **2022**, *40*, 3057–3070. [CrossRef]
147. Tekbiyik, K.; Kurt, G.K.; Yanikomeroglu, H. Energy-Efficient RIS-Assisted Satellites for IoT Networks. *IEEE Internet Things J.* **2022**, *9*, 14891–14899. [CrossRef]
148. Song, D.; Yang, Z.; Pan, G.; Wang, S.; An, J. RIS-Assisted Covert Transmission in Satellite–Terrestrial Communication Systems. *IEEE Internet Things J.* **2023**, *10*, 19415–19426. [CrossRef]