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***Review:***

# Space–time processing for inflight broadband connectivity: critical analysis, challenges, and future directions[#]

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**Abstract:** Inflight broadband connectivity (commonly termed as inflight connectivity) can be considered one of the remaining milestones for ubiquitous Internet provision; therefore, several enabling technologies are being investigated to provide high-capacity, reliable, and affordable Internet access. Multiple-input multiple-output (MIMO), based on the space–time processing (STP) concept, is one of the dominant technologies that consistently appear on the list of inflight connectivity (IFC) enablers. STP shows the potential to significantly increase user throughput, improve spectral/energy efficiencies, and increase the capacity as well as reliability of airborne networks through spatial multiplexing/diversity techniques. This article presents the preliminary outcomes of substantial research on STP techniques for enabling IFC, as the exploratory study on this topic is still in its early stages. We explore the theoretical principles behind different STP techniques and their implementation in airborne networks in direct air-to-ground (A2G) scenarios for the provision of a reliable and high-speed IFC. We also analyze the current technologies and techniques used for IFC and highlight their benefits and limitations. We present a comprehensive review that compares different STP techniques using metrics such as bit error rate (BER), spectral efficiency (SE), and capacity. Last, but not least, we discuss the substantial research challenges encountered and the prospective future research avenues that require special attention for enhancing the deployment of STP systems in forthcoming airborne networks, particularly for enabling IFC. Overall, this research study contributes to the body of knowledge by providing insights into the use of STP techniques in airborne networks for enabling IFC. It emphasizes the theoretical foundations, presents a literature review, discusses challenges and limitations, identifies potential areas for future research, and provides a performance analysis.

**Key words:** Airborne Internet access; Inflight broadband connectivity; Multiple-input multiple-output (MIMO); Precoding; Beamforming; Direct air-to-ground communication (DA2GC); Space–time processing
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## 1 Introduction

The emergence of modern terrestrial-based radio communication systems during the last four decades has made possible the availability of low-cost and high-speed Internet around the globe for ground users. The provision of Internet services to airborne users just like it is being provided on the ground seems to be a remaining milestone and is a critical challenge for both industry and academia. Internet access is becoming increasingly important for being connected even while moving around. Furthermore, the rate at which information is being exchanged is of utmost importance, regardless of location and time.

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### 1.1 Significance of inflight broadband connectivity (IFC)

Air travel will increase considerably in the upcoming years. For instance, the International Air Transport Association (IATA) projects that 8.2 billion people are likely to use airplanes as a mode of transportation by 2037 (International Air Transport Association, 2018). If we look at the pre-COVID scenario, in 2020, about 4.7 billion passengers used aircraft as a mode of transportation (Statista, 2022). Apart from the passengers' desire for high-speed Internet connectivity, the growing interest in providing Internet access to passengers by commercial airlines has led to the emergence of inflight connectivity (IFC) as an essential requirement, as >80% of the airlines are investing in personalized passenger experiences. Airlines are continuously upgrading their fleets to enable IFC. As per the market report published by Euroconsult in 2022, 9000 commercial aircraft were equipped with inflight broadband connectivity systems in 2020, and this figure increased to 9900 in 2021. By 2031, Euroconsult estimated that 21 000 commercial airplanes will provide connectivity, which is more than double the current number (Euroconsult, 2022).

Similarly, airlines providing IFC facilities are getting an overwhelming response from passengers. According to a report released in 2021, IFC showed significant signs of popularity as total bandwidth consumption by 120 commercial airlines offering IFC services increased to over 192 Gbit/s. This capacity is dramatically increased as half of the airlines' passengers are ready to pay the extra fee for inflight broadband connectivity services.

More specifically, a survey conducted by Deloitte in 2018 revealed that IFC is an important selection factor for about 55% of the passengers, while another 67% are willing to switch airlines to get consistent and fast internet connectivity and 20% have already done so (Deloitte, 2018). According to the Inmarsat *Passenger Experience Survey 2022*, the majority of passengers are willing to fly with airlines that consistently offer high-quality wireless fidelity (Wi-Fi). In a study of 11 000 passengers, 79% of the respondents claimed to have used inflight broadband in the previous year when it was available (Inmarsat, 2022).

The increasing interest shown by the airline industry in the provision of high-speed broadband connectivity to passengers has made IFC a significant source of revenue as well as a world of increasingly attractive commercial opportunities. According to a recent study by the Verified Market Research, the IFC market size was assessed to be $6.70 billion in 2023 and is anticipated to reach $11.79 billion by 2030, growing at a compound annual growth rate (CAGR) of 8.4% (Nalepka et al., 2023). Similar to this, a study conducted by the London School of Economics and Political Science in collaboration with Inmarsat predicts that by 2035, broadband-enabled ancillary revenue will amount to approximately $30 billion for airlines. The resulting revenues will generate a market with a total value of around $130 billion (Grous, 2017).

The broadband-enabled ancillary revenue can be divided into four primary areas, which include broadband access (54% contribution to the overall revenue), e-commerce (35%), advertising (8%), and streaming and premium content (3%). The connected cabin is changing dramatically as a result of technological advancements in wireless communication systems. More opportunities than ever before exist for airlines to generate broadband-enabled supplementary revenue to enhance the current auxiliary revenue. At a cost of $17 per passenger, "traditional" ancillary revenue sources like seat upgrades, onboard duty payments, and luggage fees currently generate around $60 billion for airlines. When it comes to high-quality broadband, passengers choose to pay more, placing this trait above cost at a significantly lower cost of $4 per passenger (Grous, 2017). These figures indicate that the growth and deployment of IFC technologies and systems will become one of the major economic drivers; therefore, there is a dire need for both industry and academia to continue exploring this enormous opportunity.

### 1.2 Limitations and challenges

Leading aeronautical approaches for enabling IFC are based on satellite connectivity, direct air-to-ground communication (DA2GC) networks, and aeronautical ad-hoc networks (AANETs). The traditional and most popular technique for enabling IFC, especially for long-haul flights over the ocean, is satellite connectivity. The DA2GC networks use the specialized ground stations (4G or 5G) deployed in terrestrial areas to address the satellite connectivity issues. AANETs are designed to solve the primary defects of the dominating solutions (both satellite connectivity and AANETs).

Despite the availability of the aforementioned technologies for enabling IFC, there are still challenges such as the provision of high-speed, low-cost, reliable, and efficient connectivity. The following is a list of some of these challenges and limitations that need to be addressed:

1. Limited data rate and availability. The biggest issues with inflight Wi-Fi are speed, limited availability, gaps in coverage, and dropouts. Even the current infrastructure can provide around 100 Mbit/s per aircraft, but it is still far from that of terrestrial Wi-Fi.

2. Coverage limitations. Airborne networks relying on ground-based infrastructure have coverage issues, especially for long-haul flights over the ocean. Although satellites solve some of the restrictions, expanding the satellite network to keep up with the increasing demand is not always straightforward.

3. Bandwidth limitations. Airborne networks have limited bandwidth available for providing Internet connectivity to passengers. The available bandwidth is shared among all the connected devices on the aircraft, which can result in slow speed and congestion during the peak usage time.

4. Network cost and complexity. Implementing and maintaining an airborne network infrastructure can be expensive and complex. It requires specialized equipment, regular upgrades, and ongoing maintenance to ensure reliable connectivity. These factors can make it challenging for airlines to adopt and deploy such networks on a large scale.

5. High aircraft mobility. The aircraft needs uninterrupted backhaul connectivity to provide a high-quality communication experience. High mobility and traveling over an extensive geographic range make it challenging to deliver the same degree of connectivity in mid-air as provided by ground-based systems.

6. Optimization. There are fundamental optimization problems in existing airborne network designs and applications that need to be addressed for effective information transfer.

7. Regulatory considerations. IFC involves compliance with various regulatory and safety requirements. The networks must not interfere with aviation systems or compromise flight operations. Meeting these regulations while providing seamless connectivity can be a complex task for airborne network providers.

8. Standardization. Concerning the freedom to select service providers and equipment, there is a standardization gap in IFC. Airlines would have the essential flexibility to swap service providers and avoid the possible drawback of vendor lock-in if open technologies for inflight connectivity were adopted and deployed. Vendor dependency results from the common practice of purchasing the embedded systems, connectivity hardware, and software as a package from a single supplier. Service providers are frequently lacking the freedom to use parts from different vendors that better fit their business needs.

9. Security concerns. Airborne networks need robust security measures to protect the data transmitted between the aircraft and the ground infrastructure. Securing the network against potential cyber threats, ensuring passenger privacy, and preventing unauthorized access are critical challenges in providing IFC.

10. Cost to passengers. While IFC is desirable by the passengers, it often comes at an additional cost. The fees imposed by most airlines for network access act as a deterrent, discouraging many passengers from using the service. As mentioned, one of the biggest issues with the current IFC is the limited data rate. The data rate of wireless communication systems can be enhanced in several ways, of which space–time processing (STP) is at the top. STP improves wireless channel performance and reliability by employing spatial multiplexing and diversity techniques. In a nutshell, STP is a set of signal-processing techniques that can improve the network performance and capacity. Also, researchers and network designers are now paying close attention to communication systems that operate at millimeter bands due to the low-frequency spectrum's inability to handle the large bandwidth requirement. The utilization of millimeter wave (mmWave) bands along with STP techniques can be considered a potential candidate to handle the challenges being faced by airborne networks.

The improvements in existing technologies, the adoption of emerging techniques/technologies, and the development of innovative solutions are anticipated to overcome these challenges and improve the quality, reliability, and availability of inflight broadband connectivity. An appropriate technology complemented by the right business model would serve as a roadmap for the transition to the new era of IFC.

### 1.3 Scope of the survey

IFC has become a vital part of the aviation industry, a result of technological advancements. The key figures mentioned in the preceding subsection highlight the significance and growing acceptance of IFC in aviation. This growing fascination stimulates further investigation of IFC by drawing the attention of both academia and industry. Numerous studies have been conducted with respect to the exploitation of different STP techniques for enabling IFC (a detailed discussion of the current notable research works is presented in Section 8); however, these research findings are not consolidated into a single study, and investigating them requires significant time and effort.

This prospect motivates us to bridge the gap by performing an in-depth review of STP techniques tailored to airborne platforms (for IFC), notably for DA2GC scenarios. Similarly, the integration of STP with other emerging technologies for enabling IFC has received minimal attention. For instance, combining STP with mmWave and optical wireless communication (OWC) may synergistically improve airborne networks' overall efficiency and reliability.

We believe that there is a need for a comprehensive research study that provides a holistic overview of STP techniques, investigates various integration possibilities, analyzes the system performance, thoroughly discusses the potential challenges, and outlines future research prospects to be able to provide robust, reliable, and efficient inflight broadband connectivity.

### 1.4 Contributions

The primary contributions of this study, aimed at employing STP techniques to enable IFC, are summarized below:

1. Theoretical principles. We present a comprehensive review and understanding of the theoretical principles behind STP techniques. This includes the concepts of spatial multiplexing and diversity techniques like precoding, beamforming (BF), and multiple-input multiple-output (MIMO) processing as well as their applications in DA2GC scenarios.

2. Literature review. We conduct a thorough literature review of recent research studies related to STP techniques in airborne networks. This review covers the leading approaches for enabling inflight broadband connectivity along with their limitations.

3. Challenges and limitations. We discuss the challenges and limitations of STP in airborne networks. This includes the effects of the environment, aircraft mobility, Doppler shifts, fading, and interference on the performance of these techniques.

4. Performance analysis. We thoroughly analyze the application of STP techniques in airborne networks to demonstrate their effectiveness. The investigation compares several STP techniques as well as the capacity performance of the entire network.

5. Potential areas for future research. We outline potential directions for future study, including examining the integration of STP techniques with both traditional and cutting-edge communication technologies. We also highlight the key aspects that must be considered while conducting cost-benefit analysis of DA2GC networks.

Overall, this research study contributes to the understanding of STP techniques in the context of airborne networks for enabling IFC. Together, the theoretical foundations, literature review, discussion of challenges and limitations, identification of relevant areas for investigation, and performance analysis add to the existing body of literature in this field of study.

## 2 Airborne Internet connectivity vs. inflight broadband connectivity

The earliest communication with aircraft was achieved using visual signaling such as with colored paddles and hand signs. At the beginning of the 20th century, the first air–ground communication (aeronautical radio link) was proposed with the invention of the first radio transmitter by AT&T in 1917 (Mahmoud et al., 2014). This invention allowed voice communications to take place between pilots and ground personnel. The system known as communication, navigation, and surveillance/air traffic management (CNS/ATM) combines numerous techniques and technologies to enable air-to-ground (A2G) communications and their applications to ATM (supplementary materials, Section 1). Inflight broadband connectivity forms a part of aeronautical passenger communications (APCs).

Airborne Internet connectivity and inflight broadband connectivity are interrelated concepts, often used interchangeably, but they refer to slightly different aspects of providing Internet services in airborne networks.

Airborne Internet connectivity encompasses the broader concept of providing Internet access or communication capabilities to any aerial platform, including airplanes, drones, or other airborne vehicles, and is not limited to commercial passenger aircraft. It integrates various systems and technologies to enable data transmission and communication for diverse purposes in advancing communication, surveillance, research, and operational capabilities in the airspace. Airborne Internet connectivity aims to create a connected environment in the skies, allowing seamless communication and data transfer between various airborne platforms.

IFC is the term that specifically refers to the provision of Internet or data services through a secure, private, and reliable peer-to-peer communication link between aircraft and the Internet infrastructure or gateway. It focuses on providing broadband Internet access to passengers who are traveling from one location to another. Inflight broadband connectivity typically involves satellite or A2G communication systems for establishing a link between the aircraft and the ground-based Internet service-providing networks.

In essence, inflight broadband connectivity is a subset of the large scope of airborne Internet connectivity. Airborne Internet connectivity not just involves passenger connectivity but also encompasses a broader scope, including connectivity for various aerial platforms and purposes beyond commercial flights. Whereas, inflight broadband connectivity refers more specifically to the Internet services provided to passengers on commercial airplanes during their journey. Table 1 summarizes the key differences between airborne Internet connectivity and inflight broadband connectivity. The rest of the paper focuses on inflight broadband connectivity.

## 3 Leading approaches for the provision of inflight broadband connectivity

In this section, the primary approaches for the provision of Internet access to aircraft passengers, including satellite connectivity, DA2GC networks, and AANETs, are described.

### 3.1 Satellite connectivity

Geostationary/Medium/Low Earth orbit (GEO/MEO/LEO) satellites are the three primary types of satellites that provide Internet access through satellite connectivity. Furthermore, the first and most-often employed method of enabling IFC is satellite connectivity. The overall communication

**Table 1 Key differences between the airborne Internet connectivity and inflight broadband connectivity**

| Aspect | Airborne Internet connectivity | Inflight broadband connectivity |
|---|---|---|
| Scope | Aiming to provide communication and data transmission capabilities for any aerial platform like the passenger aircraft, drones, military aircraft, and scientific research aircraft | Aiming to provide a seamless and enjoyable Internet experience to commercial passenger airplanes during the flight |
| Typical application | Applications range from real-time data exchange to surveillance, reconnaissance, remote monitoring, emergency response, military and defense operations, and scientific research | Allowing passengers to browse the Internet, access emails, stream videos, and perform other online activities while in transit |
| Technology and infrastructure | Using a variety of technologies such as satellite communication, high-altitude platforms (like balloons or drones), ground stations, and other specialized equipment depending on the application | Typically involving specialized systems for connection with the Internet gateway through satellite or A2G-based infrastructure, communication system installed on commercial aircraft, onboard servers, and Wi-Fi network |

Sources: Grous (2017); Deloitte (2018); Euroconsult (2022); Inmarsat (2022); Nalepka et al. (2023)

between the aircraft and the Internet server is accomplished in three steps as shown in Fig. 1. First, the signals are sent to the satellite via the external antenna mounted at the top of the aircraft. In the second step, the satellite amplifies the incoming signals and transmits them to the gateway (ground station). In the last step, the ground station exchanges the information with the Internet server.

Table 2 provides a brief comparison of LEO, MEO, and GEO satellites, and Table 3 lists some of the major satellite operators along with the supported data rate (Abo-Zeed et al., 2019).

Some of the major IFC providers using the satellite connectivity platforms mentioned in Table 3 are Gogo (through INTELSAT), Global Eagle, Panasonic Avionics, StarLink, OneWeb, Swift Broadband, Broadband Global Area Network, and OnAir (supplementary materials, Section 2.1).

Although satellite-based systems are efficient in terms of coverage for long-haul flights over the ocean, their main drawbacks include long transmission paths, high latency, and low data rates. Additionally, a satellite-based solution for short- and medium-distance flights is pricey, requires bulky/heavy equipment, and has high latency in areas with significant air traffic. Furthermore, the system's overall efficiency is reduced by the expensive equipment and high operational and maintenance costs.

### 3.2 DA2GC networks

The DA2GC networks are based on the existing cellular communication model for providing IFC as shown in Fig. 2.

Although these networks provide two-way communication from A2G and ground-to-air (G2A), they are mostly termed DA2GC by the research community. The provision of inflight broadband connectivity using STP techniques in the DA2GC scenario is the main focus area of this research study. Before the IFC requirement, the DA2GC networks were (and are being) used for operational purposes to share flight-related operational and administrative data in real time. The existing long-term evolution (LTE) technology is used for designing the specialized ground stations for enabling IFC (supplementary materials, Section 2.2).

Although A2G communication has undergone significant test and research, it is still awaiting widespread deployment. The DA2GC network, which uses a variety of contemporary technologies, has been suggested as a potential contender to address the challenges faced by satellite-based networks, such as excessive latency and high

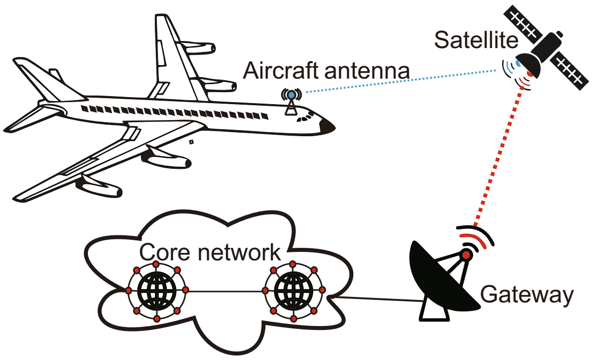

**Fig. 1 Inflight broadband connectivity through a satellite**

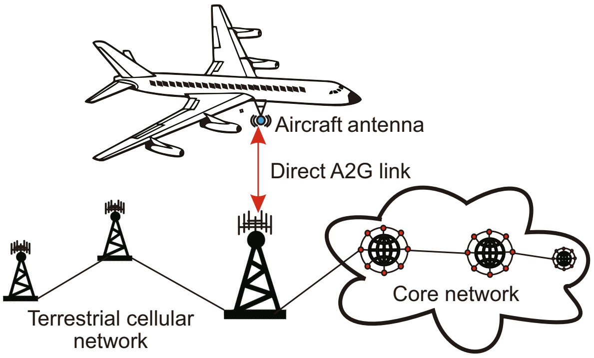

**Fig. 2 Inflight broadband connectivity through the A2G network**

**Table 2 Comparison of different satellite platforms (LEO, MEO, and GEO)**

| Platform | Typical height (km) | Round-trip time (ms) | Orbital period (h) | Typical number of satellites | Most common type |
|---|---|---|---|---|---|
| LEO | 500–2000 | 30 | 1.5 | 40–70 | Iridium system (66 satellites) |
| MEO | 5000–20 000 | 100 | 2–12 | 10–12 | ICO system (12 active satellites) |
| GEO | 36 000 | 250 | 24 | 3 | Inmarsat system |

Sources: Abo-Zeed et al. (2019); Bilen et al. (2022)

**Table 3 Notable satellite-based IFC operators**

| Operator | Operating frequency | Data rate | Remark |
|---|---|---|---|
| Inmarsat | L, Ka, and S bands | Up to 10 Mbit/s per aircraft | Inmarsat owns and operates 14 GEO satellites |
| Iridium | L band | 352–704 kbit/s with a maximum speed of 1.4 Mbit/s | Iridium constellation consists of a meshed network of 66 LEO cross-linked satellites and 9 in-orbit spares |
| INTELSAT | C and Ku bands | 15 Mbit/s downlink and 3 Mbit/s uplink per aircraft | Over 50 satellites in GEO (Gogo Internet) |
| ViaSat | Ka band for downlink and K band for uplink | >20 Mbit/s downlink and 2 Mbit/s uplink per aircraft | Currently, 4 satellites in GEO |
| Telesat | C, K, and Ka bands | Claims download speed 50 Mbit/s and upload at 10 Mbit/s | Telesat has 298 LEO and 13 GEO satellites |
| StarLink | X, Ku, K, and Ka bands will be used | Claims providing download speed between 100 Mbit/s and 200 Mbit/s with a latency as low as 20 ms | SpaceX is working toward a constellation of >30 000 satellites in LEO to provide high-speed Internet coverage around the world |
| OneWeb | X band for downlink and Ku band for uplink | Will provide >100 Mbit/s per aircraft with latency <70 ms | Currently, OneWeb operates 110 satellites and has planned for 650 satellite constellations in LEO |

Sources: Abo-Zeed et al. (2019); Bilen et al. (2022)

installation/equipment and maintenance costs. Due to its affordable price, ease of use, and speedy installation, DA2GC might be the most widely used technology to enable IFC over the mainland in the upcoming years. However, the high-throughput requirements and the coverage limitations for long-haul flights over the ocean are not addressed by the present DA2GC technologies. The capacity is shared when numerous aircraft are connected to the same ground station, which reduces the overall efficiency. This is among the primary drawbacks of A2G communication. Additionally, channel impairments, interference, handover number, and high aircraft mobility can hinder the current cellular-based DA2DC networks from supporting the anticipated increase in IFC demand.

### 3.3 AANETs

The purpose of AANETs is to combine the beneficial features of both the satellite and the DA2GC networks into a single framework. AANETs are created by establishing air-to-air links between the aircraft rather than depending on a centralized node or entity. One aircraft in the network acts as a destination aircraft that is connected to the Internet server as shown in Fig. 3. Air-to-air links are used to transport data packets from a source aircraft to a destination aircraft. Greater aircraft density could make it easier to establish AANETs since the link distances get shorter with the increasing number of aircraft, and resultantly stronger links between aircraft can be established.

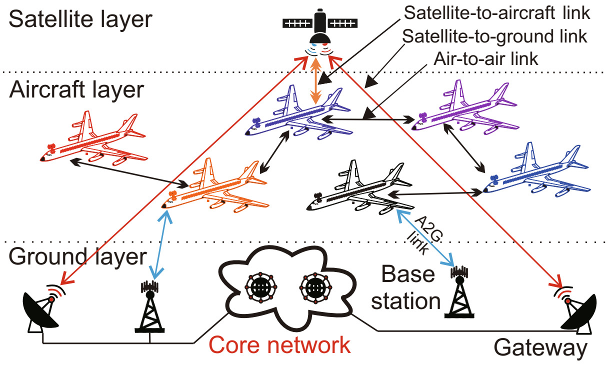

**Fig. 3 Inflight broadband connectivity through AANETs**

Due to the atmospheric effects, the air-to-air links in AANETs are extremely susceptible and could rapidly vanish. Additionally, the transmitted signals are attenuated by water or ice particles in clouds, and this impact is found to be more significant for higher frequencies. For frequencies >5 GHz, both atmospheric gases and rainfall cause absorption and scattering, leading to high channel error rates (Kesavan et al., 2014; ITU, 2015). The transport, network, and data link layers of AANETs present research problems as a result of these environmental factors along with the mobility of aircraft.

Offering Internet connectivity through AANETs faces significant challenges. The difficulties posed by the extremely dynamic and unstructured environment cannot be overcome by the current terrestrial-based algorithms. Apart from being highly vulnerable to atmospheric conditions, the movement of aircraft by itself creates complexities and design difficulties. Also, a significant number of aircraft must be present in the airspace to create an AANET. Additionally, a link can only be established between two aircraft once they are within the communication range of each other.

# 4 STP

STP is used in wireless communication systems to improve channel performance and reliability. It involves processing the signals transmitted and received by multiple antennas to take advantage of the spatial and temporal diversity of the wireless channel. STP takes advantage of the capability of a multi-antenna system to simultaneously transmit and receive multiple (independent) data streams.

Two major categories of STP techniques, namely, spatial multiplexing and diversity techniques, are shown in Fig. 4. Faster data transfer still requires the utilization of these techniques, even in the presence of a high-capacity wireless channel. Spatial multiplexing techniques can be used to simultaneously transmit multiple independent data streams to achieve high data rates. Diversity techniques, on the other hand, aim to improve transmission reliability by receiving or transmitting the same information-carrying signals via multiple antennas (Alamouti, 1998). The diversity techniques' primary objective is to convert wireless channels susceptible to Rayleigh fading into robust additive white Gaussian noise (AWGN)-like channels to avoid catastrophic signal fading (Cho et al., 2010). The maximum attainable transmission rate when using spatial multiplexing techniques may be equal to the MIMO channel capacity. However, the achievable capacity (or transmission rate) may be significantly reduced when using diversity techniques.

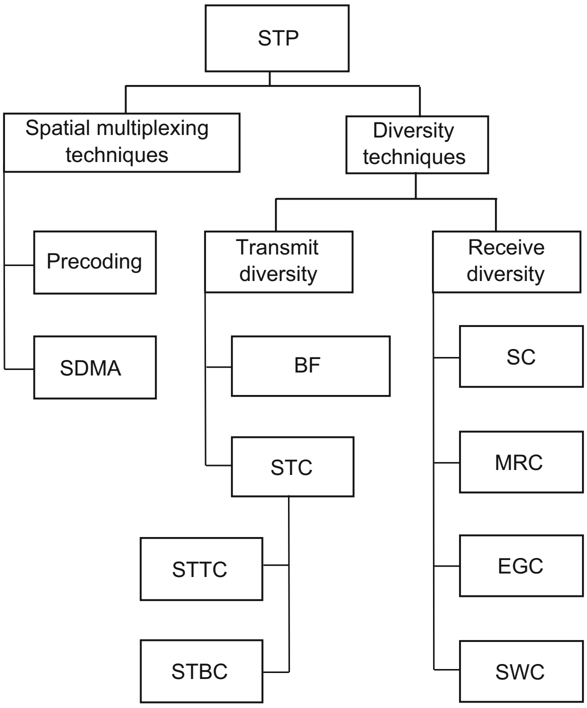

**Fig. 4 Categories of STP techniques**

## 4.1 Spatial multiplexing techniques

Spatial multiplexing increases the data rate by exploiting the spatial properties of the wireless channel without requiring more bandwidth or power. Using multiple antennas at the transmitter and receiver enables the simultaneous transmission of multiple data streams over the same frequency channel. Each antenna transmits the data simultaneously, and the receiver then combines the signals coming from several antennas to recover the original data streams. Spatial multiplexing techniques can be further classified as precoding and space division multiple access (SDMA). In MIMO communication systems, these techniques can be employed individually or in combination to improve data throughput.

### 4.1.1 Precoding techniques

Precoding is one of the key concepts in spatial multiplexing (STP), which transfers complexity from the receiver side to the base station (BS) by applying powerful signal-processing techniques at the transmitter side. To minimize the interference and increase the spectral efficiency (SE), a BS employs precoding techniques (Albreem et al., 2021). Precoding has significant beneficial effects in STP, which is described in detail in Section 6.

### 4.1.2 SDMA

In SDMA, a distinct space is made available for each user, and all the connected users can use the same time–frequency (TF) resource simultaneously (Ilcev, 2020). Several beneficial characteristics of the SDMA technology render it ideal for usage in mobile radio systems as all required changes solely affect the BSs and do not affect mobile units. Additionally, the SDMA technology can be adapted to any mobile radio system presently in use or soon to be launched because it is compatible with time division multiple access (TDMA), frequency division multiple access (FDMA), and code division multiple access (CDMA) multiple-access techniques. In essence, SDMA uses many smart antennas at the BS, which has a far higher capacity than the single-antenna systems.

### 4.2 Diversity techniques

Diversity approaches are used to reduce the loss in error performance (the aim is to steepen the bit error rate (BER) vs. the signal-to-noise ratio (SNR) curve) caused by unstable wireless fading channels, such as those vulnerable to multipath fading (Ventura-Traveset et al., 1997). The idea behind diversity in data transmission is that severe fading is relatively unlikely to occur simultaneously across multiple statistically independent fading channels. There are several strategies to achieve diversity gain; some of them are as follows (Cho et al., 2010):

1. Space diversity. To construct independent wireless channels, multiple antennas that are sufficiently apart (typically more than $10\lambda$, where $\lambda$ represents the wavelength corresponding to the carrier frequency) are used.

2. Polarization diversity. The independence of vertically and horizontally polarized paths is used to implement independent channels.

3. Frequency diversity. At sufficiently distant frequency bands (greater than the coherence bandwidth), the same information is repeatedly transmitted.

4. Time diversity. The same data are repeatedly transmitted at significant time intervals (usually greater than the coherence time).

5. Angle diversity. Multiple receiving antennas with varying directivities are used to receive the same information-carrying signal from diverse directions.

Receive diversity and transmit diversity are the two primary categories of diversity techniques.

#### 4.2.1 Receive diversity

Receive diversity is based on the fact that a wireless channel is susceptible to change over time due to fading, interference, and noise, and these time-varying features can be used to improve the received signal quality. To improve the overall signal quality, these techniques aggregate numerous copies of the same signal that have experienced various degrees of fading, accomplished by using multiple antennas at the receiver.

A variety of approaches can be used to combine the received signals in the various antennas, including selection combining (SC), maximal ratio combining (MRC), equal gain combining (EGC), and switched combining (SWC). Since the transmitter side is the primary area of focus in this study, receive diversity techniques have not been discussed.

#### 4.2.2 Transmit diversity

The primary disadvantage of receive diversity is that it imposes most of the computational load on the receiver side, which can lead to excessive power consumption and complex signal processing requirements. As an alternative, diversity gain can be achieved at the transmitter side using techniques such as BF and space–time coding (STC). These methods shift the processing burden away from the receiver and require only minimal linear operations for signal recovery. STC, a transmit diversity technique, is briefly discussed in this subsection, while BF is described in detail in Section 7. The key advantage of STC is that it enables the receiver to exploit transmit diversity and maximize diversity gain using a simple linear processor. Moreover, since STC does not require channel state information (CSI) estimation at the receiver side, it further reduces computational cost and energy consumption (Tarokh et al., 1998; Hughes, 2000).

Space–time block codes (STBCs) and space–time trellis codes (STTCs) are two different categories of ST codes. STBCs were developed for using a simple linear decoding algorithm at the receiver for a specific number of transmit and receive antennas. By doing this, STBC makes it possible to improve link quality while minimizing channel fading and offers reliable communication (higher BER performance) (Santumon and Sujatha, 2012; Djemamar et al., 2022). As a result, the STBC application has substantially expanded and is adopted in the MIMO-based WiMAX (IEEE 802.16e) wireless communication standard. This standard uses a minimum mean square error (MMSE) receiver ($2 \times 2$ MIMO system) to implement the Alamouti ST block coding algorithm (Pathak and Pandey, 2014).

The Alamouti code, designed specifically for the scenario of two transmit antennas, is the first and most well-known STBC (Alamouti, 1998). The current STBCs employ a generalized form of the basic Alamouti code to communicate with any number of antennas. By using STTC, an alternate type of STC, the coding gain can be increased even more. Typically, STTCs outperform STBCs at the expense of the maximum likelihood (ML) decoder's increased complexity. For an in-depth study on STBC and STTC, interested readers can refer to Hanzo et al. (2002) and Larsson and Stoica (2003).

## 5 ST wireless communication systems

As shown in Fig. 5, a typical ST wireless communication system is made up of $N_{\mathrm{T}}$ transmit and $N_{\mathrm{R}}$ receive antennas.

STP system (commonly referred to as MIMO) can increase the throughput by a factor of min ($N_{\mathrm{T}}$, $N_{\mathrm{R}}$) in comparison to a traditional single antenna (single-input single-output (SISO)) system without using more spectral bandwidth or transmit power. Due to the steadily increasing demand for reliable and high-capacity communication networks, multi-antenna systems have been actively investigated and successfully implemented in several contemporary wireless standards like WLAN, WiMAX, LTE, and LTE-Advanced (Cho et al., 2010). We still need to find effective methods for achieving high reliability or transmission rates, even when a high-capacity wireless channel is available.

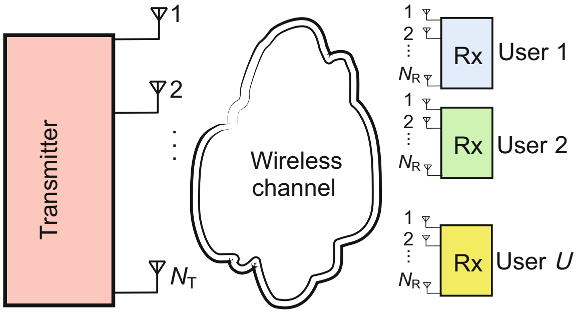

**Fig. 5 Space–time wireless communication system**

Single-user-MIMO (SU-MIMO) and multiuser-MIMO (MU-MIMO) are the two fundamental configurations for STP systems. In the SU-MIMO system, a BS/transmitter (equipped with $N_{\mathrm{T}}$ antennas) communicates with a single user (having $N_{\mathrm{R}}$ antennas). The system gain can be maximized by using spatial modulation and BF techniques.

A single BS (equipped with $N_{\mathrm{T}}$ antennas) serves several users (each one having $N_{\mathrm{R}}$ antennas) using the same radio resources in the MU-MIMO system. Thus, multiple users can share the wireless channel spatially. The fundamental issue with the MU-MIMO system is interference among co-channel users. A complex receiver architecture/design is used to minimize this co-channel interference.

It was established about three decades ago that the SU-MIMO systems' channel capacity is proportional to $N_{\min}$ ($N_{\min} = \min(N_{\mathrm{R}}, N_{\mathrm{T}})$) (supplementary materials, Section 3). In reality, MIMO offers at most $N_{\min}$ spatial degrees of freedom, which resultantly increases the overall system capacity.

Numerous studies have been conducted to compare the performance of SISO, single-input multiple-output (SIMO), multiple-input single-output (MISO), and MIMO systems/channels (Lyu, 2016; Wang X et al., 2016; Sarangi and Datta, 2018; Alrubei et al., 2020). Since MIMO channels are random, so is the capacity, which is a function of the channel.

Ergodic capacity and outage probability (or outage channel capacity) are the two commonly used performance parameters for the random channels. Ergodic capacity is used to describe the capacity of ergodic channels (an ergodic channel is a frequency-nonselective random channel, in which all states of the channel can be experienced over the entire data frame). On the other hand, outage capacity is used to measure the performance of non-ergodic channels (in non-ergodic channels, only a limited number of channel realizations may be experienced).

Ergodic capacity is the average of the channel's instantaneous capacity, which is determined using the channel's probability density function (PDF). The outage probability (calculated from the channels's CDF and denoted as $\varepsilon$) is the likelihood of the channel capacity $C$ falling below a specific threshold information rate $R$ (bit/(s·Hz)). Simply, the likelihood of achieving a reliable transmission rate $R$ can be determined by $1 - \varepsilon$.

Using the equation (supplementary materials, Section 3.2)

$$C = B\log_2\left\{\det\left(\boldsymbol{I}_{N_{\min}} + \frac{P\boldsymbol{Q}}{N_{\mathrm{T}}\sigma^2}\right)\right\},$$

where $B$ represents the channel bandwidth, $\boldsymbol{I}$ represents the identity matrix, $P$ represents the transmitted signal power, $\boldsymbol{Q}$ represents the Wishart matrix, and $\sigma^2$ represents the noise variance, we can compute the ergodic capacity of an $N_{\mathrm{T}} \times N_{\mathrm{R}}$ MIMO channel, which is shown in Fig. 6.

It provides a quick comparison of SISO, SIMO, MISO, and MIMO systems' capacity with different antenna configurations (4, 5, and 8) over different SNR (0–30 dB) values. The findings demonstrate a notable increase in the system capacity when multiple antennas are deployed.

Due to the limited transmission system in SISO, the capacity value increases very slowly when SNR rises, ranging from 0.83 to 9.10 bit/(s·Hz). By increasing the number of antennas and SNR in the MISO and SIMO, we can verify that there is no significant variation in capacity. Also, the capacity for MISO and SIMO systems is very similar to that for SISO (no multiplexing gain). However, in the case of MISO, NT transmit channels are available, and they provide a power gain when the power is allocated using the water-filling algorithm. Similarly, the SIMO system increases the effective SNR and provides power gain. In the case of a single antenna, if we want to increase the transmit power, we will need high-power amplifiers, which increases the overall system cost and complexity.

Finally, as the number of antennas and SNR are increased, the MIMO system capacity increases significantly. The capacity value for $4\times4$ MIMO ranges from 3.3 to 34.9 bit/(s·Hz), for $5\times5$ MIMO from 4.1 to 46.4 bit/(s·Hz), and for $8\times8$ MIMO from 6.7 to 69.1 bit/(s·Hz), which is the maximum capacity. Fig. 7 compares the MIMO channel capacity ($2\times2$ and $4\times4$ MIMO) without the CSI knowledge on the transmitter side when SNR is 10 dB (the figure is reproduced from Cho et al. (2010) using MATLAB R2017a). Here, we consider a random MIMO channel with outage channel capacity $\varepsilon$ as a statistical notion of the channel capacity. As previously established, the outage channel capacity is defined as the highest achievable transmission rate with an outage probability smaller than $\varepsilon$. It can be read from the figure that for a $2\times2$ MIMO, the 0.1 outage capacity is approximately 4 bit/(s·Hz), whereas for a $4\times4$ MIMO channel, the 0.1 outage capacity is approximately 9 bit/(s·Hz). Moreover, if we want to attain a transmission rate of 9 bit/(s·Hz) in the case of a $2\times2$ MIMO, the corresponding outage capacity approaches 1.0. It is clear from Fig. 7 that adding more antennas increases the overall system performance as well as the ST channel capacity.

Similarly, Lyu (2016) and Wang X et al. (2016) examined the performance of MU-MIMO systems. The observations made indicate the superiority of the MU-MIMO system over the SU-MIMO system. Wang X et al. (2016) described a large-scale field trial undertaken by Huawei and NTT DOCOMO to evaluate the performance of the MU-MIMO system in 5G mobile communications, with a focus on linear (Eigen zero-forcing (EZF)) precoding and

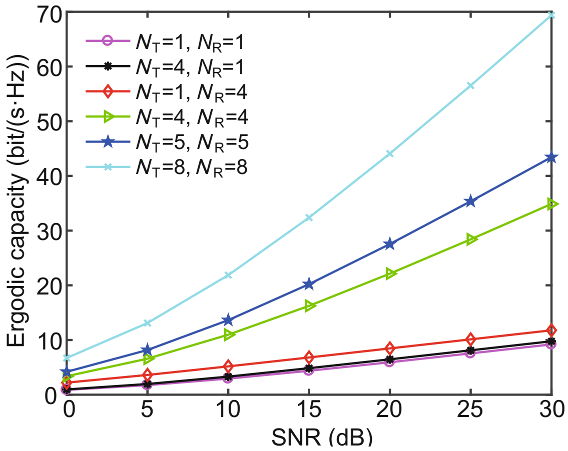

**Fig. 6 Ergodic capacity of an $N_{\mathrm{T}}\times N_{\mathrm{R}}$ MIMO system**

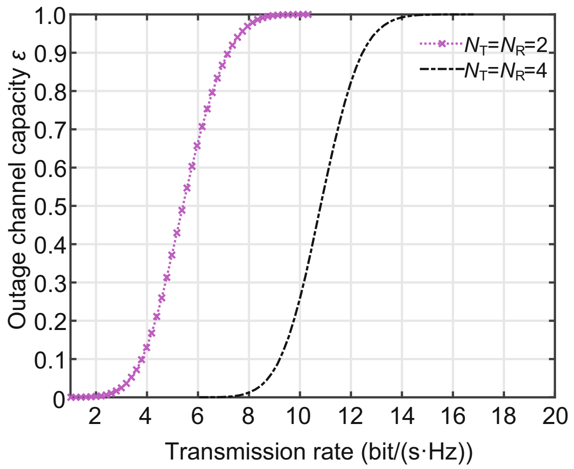

**Fig. 7 Capacity of a random MIMO channel (with unknown CSI and SNR = 10 dB)**

nonlinear precoding (Tomlinson–Harashima precoding (THP)). The trial was carried out in the 2.3-GHz band based on LTE advanced specifications, with modifications in the higher-order MU-MIMO. The field trial evaluated the MU-MIMO system considering different precoding schemes under various user equipment (UE) deployment configurations. The single-cell deployment scenario was considered to test the performance of downlink transmissions. The BS was equipped with an antenna array comprising 64 antenna elements. The antenna elements had a 3-dB main lobe width of 60 degrees.

Table 4 shows the maximum cell throughput and spectrum efficiency recorded in the trial when 24 UEs are served. Downlink MU-MIMO transmissions using linear precoding have a spectrum efficiency that is roughly 11–14 times higher than that of SU-MIMO with varying system bandwidths. Whereas THP nonlinear precoding increases the spectrum efficiency by 14 times over SU-MIMO, with a relative gain of approximately 10% over linear precoding. The maximum cell throughput with linear precoding is 1.35 Gbit/s with 100 MHz bandwidth and 311 Mbit/s with 20 MHz bandwidth. When employing nonlinear precoding (THP), the maximum cell throughput is 343 Mbit/s, with a corresponding spectrum efficiency of 43 bit/(s·Hz) using 20 MHz bandwidth.

## 6 Precoding techniques

To increase the capacity of an MIMO channel and enable it to communicate simultaneously with several users or applications, precoding is used. Precoding is a spatial multiplexing technique employed in MIMO systems to lessen or eliminate the effects of fading and interference while boosting throughput (Albreem et al., 2021). In the context of IFC, the precoding techniques can be broadly divided into linear and nonlinear groups, as shown in Fig. 8.

If the BS is equipped with $N_{\mathrm{T}}$ antennas and $U$ represents the number of single-antenna users (aircraft), then the achievable antenna array gain and the multiplexing gain are proportional to $N_{\mathrm{T}}$ and $U$, respectively. In reality, the throughput and gains that can be achieved are determined by the associated precoding technique.

Fig. 9 demonstrates a generalized block diagram for employing precoding and decoding techniques. $\boldsymbol{W}$ and $\boldsymbol{R}^{\mathrm{H}}$ are the linear precoding and decoding matrices, whereas the feedback matrices $\boldsymbol{E}$ and $\boldsymbol{F}$ are used for nonlinear precoding and decoding, respectively. The required precoding is characterized in these matrices. For instance, when $\boldsymbol{E}$ is a null matrix, the generalized precoding becomes linear precoding (Simeone et al., 2003). The average power can be adjusted using $\beta$.

### 6.1 Linear precoding techniques

In linear precoding, each antenna transmits a data stream after combining it with precoding weights, which makes it feasible to share a single data bus for downlink transmission. Let $\boldsymbol{s}$ ($\boldsymbol{s} \in \mathbb{C}^{U\times 1}$) represent the source information vector

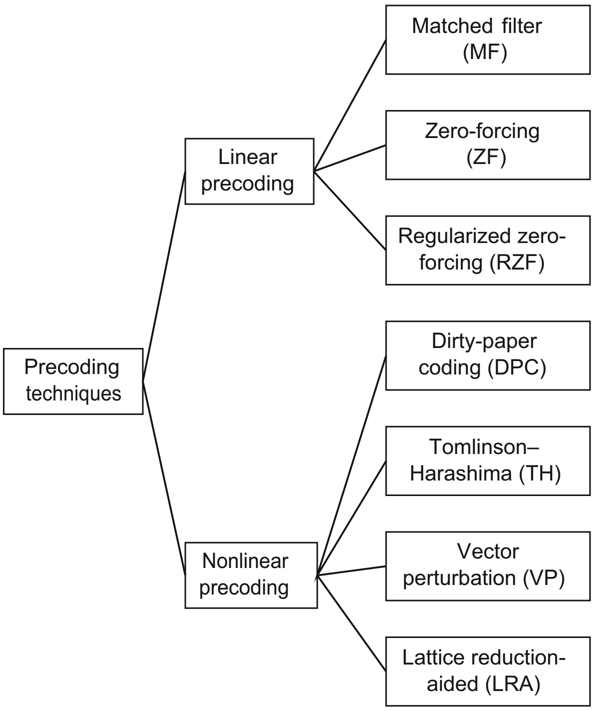

Fig. 8 Classification of precoding techniques

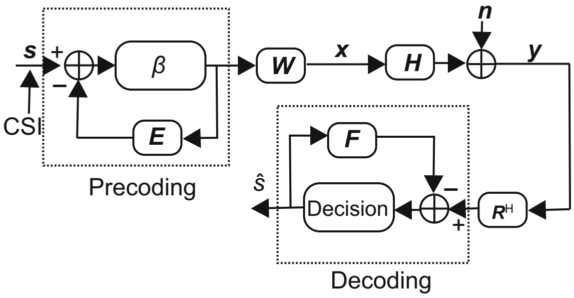

Fig. 9 Block diagram of precoding and decoding mechanisms

**Table 4 Performance comparison of the SU-MIMO and MU-MIMO systems**

| System | Bandwidth (MHz) | Cell throughput (Mbit/s) | Spectrum efficiency (bit/(s·Hz)) |
|---|---|---|---|
| SU-MIMO | 100 | 113 | 2.8 |
| SU-MIMO | 20 | 22 | 2.8 |
| MU-MIMO with EZF | 100 | 1350 | 34 |
| MU-MIMO with EZF | 20 | 311 | 39 |
| MU-MIMO with THP | 20 | 343 | 43 |

Source: Wang X et al. (2016)

(before precoding) for $U$ users (which are aircraft in the case of IFC). It is assumed that $U$ single-antenna users are served by a BS equipped with $N_{\rm T}$ antennas (where $U \leq N_{\rm T}$). As each user has a single antenna, we can write $N_{\rm R} = U$. Before transmission, the source information vector is multiplied by a linear precoding matrix $\boldsymbol{W} \in \mathbb{C}^{N_{\rm T}\times U}$ and the precoded signal vector $\boldsymbol{x}$ can be expressed as

$$\boldsymbol{x} = \alpha \boldsymbol{W}\boldsymbol{s}, \tag{1}$$

where $\alpha$ is the average transmit power at the BS. The precoding matrix $\boldsymbol{W}$ is a function of the channel matrix $\boldsymbol{H} \in \mathbb{C}^{N_{\rm T}\times U}$. To satisfy the power constraint at the transmitter side (BS), the precoding matrix $\boldsymbol{W}$ is chosen such that trace$(\boldsymbol{W}\boldsymbol{W}^{\rm H}) = 1$. Also, the power of the source signal is normalized, i.e., $\|\boldsymbol{s}\|^2 = 1$. Accordingly, the received signal vector (ignoring the multiuser interference) can be written as

$$\boldsymbol{y} = \boldsymbol{H}^{\rm T}\boldsymbol{x} + \boldsymbol{n} = \boldsymbol{H}^{\rm T}\boldsymbol{W}\boldsymbol{s} + \boldsymbol{n}, \tag{2}$$

where the noise is denoted by $\boldsymbol{n} \in \mathbb{C}^{U\times 1}$, which follows $\mathbb{C}\mathcal{N}(0, \sigma)$ with zero mean and $\sigma$ standard deviation. The downlink channel in the time division duplex (TDD) mode is simply the transpose of the channel matrix $\boldsymbol{H}$ (Fatema et al., 2018). By using the channel knowledge for designing $\boldsymbol{W}$, linear precoding aims to maximize the performance parameters for each stream. The computational complexity of the basic linear precoder is $\mathcal{O}(n^3)$, which is comparable to the complexity of an exact matrix inversion (Liu et al., 2019; Qiang et al., 2020).

Matched filter (MF), ZF, and regularized zero-forcing (RZF) are notable linear precoding techniques (supplementary materials, Sections 4.1–4.3).

Fig. 10 depicts how well MF, ZF, and RZF perform in terms of the SE attained by each scheme in conjunction with the number of BS antennas. The results are reproduced from Björnson et al. (2017) using MATLAB R2017a. In a 16-cell setup, each cell having an area of 0.0625 km$^2$ is deployed. The large-scale fading model with the median channel gain of –148.1 dB at 1 km, path loss exponent of 3.76, and standard deviation of shadowing equal to 10 is used. The UEs are spread out uniformly inside each cell, with the distance $>$35 m from the BS.

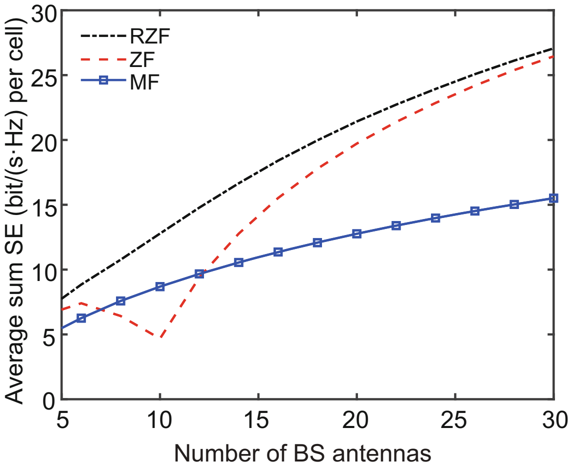

**Fig. 10 Performance comparison of linear precoding techniques**

We consider establishing communication using a bandwidth of 20 MHz and a total receiver noise power of –94 dBm. Other assumptions include an equal downlink (DL) power allocation of 20 dBm per UE and using a Gaussian local scattering channel model having an angular standard deviation of 10°. Each coherence block contains 200 samples, and the universal pilot reuse factor (of one) is applied. However, for a better channel estimate with less pilot contamination, a non-universal pilot reuse factor (two or four) may be used. We examine $U = 10$ UEs per cell and a varied number of BS antennas ($N_{\rm T}$) from 5 to 30.

For large values of $N_{\rm T}$, as shown in Fig. 10, the SE of RZF and ZF are comparable. However, SE of the ZF precoder rapidly degrades for $N_{\rm T}<10$ due to the robustness issue of canceling the interference efficiently without simultaneously destroying a significant portion of the intended signal. Hence, to obtain a robust implementation, ZF should be avoided. While MF offers only half the SE of the other schemes, it also decreases the complexity because no matrix inversions are needed.

To summarize, MF not only has the least complexity but also provides the lowest SE. RZF offers a decent compromise between SE and complexity; it can double SE compared to MF while increasing computational complexity by only a few tens of percent. RZF is always a better option than ZF because it produces comparable or better SE without ZF's robustness issues when $N_{\mathrm{T}} \approx U$. Table 5 provides a quick comparison of linear precoding techniques.

The dimension of $\boldsymbol{H}^{\mathrm{T}}\boldsymbol{H}^{*}$ grows quite enormously for large values of $N_{\mathrm{T}}$ and $N_{\mathrm{R}}$, which makes it computationally intensive. Therefore, the research community has suggested various methods (approximate/avoid matrix inversion and fixed-point iteration-based (FPIB)) to simplify these fundamental precoding techniques (supplementary materials, Section 4.4).

### 6.2 Nonlinear precoding techniques

Although linear precoding techniques are less complicated (as well as simpler), their lack of precoding precision cannot be neglected, especially when $\frac{N_{\mathrm{T}}}{U}$ is close to or equal to one (Wu et al., 2014). The most popular nonlinear precoding algorithms are dirty-paper coding (DPC), Tomlinson–Harashima (TH), vector perturbation (VP), and lattice reduction-aided (LRA) (supplementary materials, Section 5). Table 6 presents a quick comparison of various nonlinear precoding techniques.

The DPC method was first proposed in 1983, and it demonstrates that the transmitter can provide the theoretical channel's capacity while decreasing the interference once the transmitter is aware of the interference (Costa, 1983). When the precoding matrix is generated for the $k^{\mathrm{th}}$ received terminal in the MU-MIMO systems, the interference from the first up to the $(k-1)^{\mathrm{th}}$ received terminals is anticipated to be nullified. The DPC approach is impractical since it requires advanced signal processing and a wide range of codewords (Babu et al., 2015).

The DPC algorithm and the modulo arithmetic are combined to create the suboptimal

**Table 5 Comparison between linear precoding techniques**

| Precoding technique | Merit | Demerit |
|---|---|---|
| MF | If there are more BS antennas than the number of users, performance is close to optimal (Albreem et al., 2021); It has a low computational complexity since it can handle signal processing at BS (Lee, 2018); Better performance at lower SNR (Albreem et al., 2021); It performs nearly optimally in the noise-limited system (Lee, 2018) | Full diversity cannot be obtained at high SE (Qiao et al., 2018); For any positive multiplexing gains, error floors exist (Albreem et al., 2021); Lower attainable rate when there are fewer BS antennas (Fatema et al., 2018); Lacks resistance to IUI (Fatema et al., 2018; Qiao et al., 2018); Performance degradation in the case of an ill-conditioned channel (Albreem et al., 2019) |
| ZF | Low computational complexity (Albreem et al., 2021); Higher data rates compared to MF (Parfait et al., 2014; Qiao et al., 2018); Greater energy efficiency and higher performance at higher SNR (Parfait et al., 2014; Albreem et al., 2021); Being able to split a multiuser channel into several single-user channels (Albreem et al., 2021); Provides a performance vs. complexity trade-off (Qiao et al., 2018); Performs nearly at its optimal level in the interference-limited system (Qiao et al., 2018) | If the channel is highly correlated, the noise will be amplified and there will be a power cost because the noise effect is not taken into account (Peel et al., 2005); Cannot accommodate too many users (Albreem et al., 2021); Medium difficulty in the case of large $N_{\mathrm{R}}/N_{\mathrm{T}}$, as it involves a difficult matrix inversion operation (Albreem et al., 2019); Noise amplification (Fatema et al., 2018; Qiao et al., 2018) |
| RZF | Offers a trade-off between MF and ZF (Fatema et al., 2018; Bai YM et al., 2019); Better performance than ZF in the noisy environments as it considers the effect of noise (Albreem et al., 2019); Ability to eliminate IUI (Pramono et al., 2020); Optimality is assured if all users have the same ratio between the SINR required and the average channel attenuation (Albreem et al., 2021) | Requires the calculation of the matrix's inverse, which increases the complexity, especially when $N_{\mathrm{T}}$ is very large (Gao et al., 2014); $\boldsymbol{H}^{\mathrm{T}}\boldsymbol{H}^{*}$ must be symmetric positive definite (Pramono et al., 2020); For any positive multiplexing gains, error floors exist (Pramono et al., 2020; Albreem et al., 2021) |

**Table 6  Comparison between nonlinear precoding techniques**

| Precoding technique | Merit | Demerit |
|---|---|---|
| DPC | Optimal performance in the case of an interference-free environment (Babu et al., 2015; Jacobsson et al., 2017; Deka et al., 2021); Ability to eliminate the known interference at the transmitter (Babu et al., 2015); Optimum power consumption (Jacobsson et al., 2017) | High computational complexity, especially in the case of a large number of antennas (Jacobsson et al., 2017; Qiao et al., 2018); Needs large codeword and sophisticated signal processing (Jacobsson et al., 2017) |
| TH | Close to the capacity performance (Zarei et al., 2016); Efficiently avoids noise amplification (An, 2017); Ability to compensate for the interference through multiple antennas and multiple users in the system (An, 2017); Efficient ISI cancellation (An, 2017); Practical implementation (Qiao et al., 2018) | More expensive and complicated than linear precoding techniques (An, 2017); For medium or high $N_\mathrm{T}/N_\mathrm{R}$ ratio, complexity may be too high (Zarei et al., 2016); Sensitive to CSI inaccuracies (Windpassinger et al., 2004); High power consumption (Qiao et al., 2018); Experiences some diversity penalty (Windpassinger et al., 2004) |
| VP | Enhances the channel inversion performance and provides performance close to capacity (Li A and Masouros, 2015); Simple encoding technique (Peel et al., 2005); Minimizing the transmit power (Chae et al., 2008); Compared to the DPC, it provides full diversity order with considerably less complexity (Taherzadeh et al., 2007); Capability to mitigate IUI (Peel et al., 2005) | Computationally complex and involves searching for various perturbation vectors to lower the initial vector norm (Masouros et al., 2013); Cannot be used with adaptive modulation (Li A and Masouros, 2015); Performance degradation in the case of a limited feedback scenario (Du et al., 2019); Vulnerable to CSI imperfections and incorrectly scaled power factors (Lu AA et al., 2019) |
| LRA | Significantly reduces the benchmark sphere encoding's search complexity (Guenach, 2019); In channels with poor conditions, it performs better than TH (Guenach, 2019); Extensively used in the real-world systems (Zhang L et al., 2016); Provides excellent performance with minimal computational complexity (Wübben et al., 2011) | Requires perfect CSI at the transmitter (Chen R et al., 2012); Computational complexity depends upon the corresponding reduction criteria (Zu and de Lamare, 2012) |

implementation algorithm known as the THP. The THP can be used in MIMO systems to eliminate the subchannel interference. Despite having a lower performance than the DPC algorithm, THP has a practical implementation. Compared to linear precoding techniques, the THP is more complex, but it effectively avoids noise amplification.

The VP approach provides a simple encoding strategy and is considered a generalized THP algorithm. The VP algorithm offers a full diversity order with much less complexity compared to the DPC approach.

The LR algorithm's fundamental idea is to use $\boldsymbol{H}$ as the foundation of a point lattice and take the advantage of the discrete behavior of digital information (Wübben et al., 2011). The LR algorithm has several definitions, each with corresponding reduction criteria, such as the Brun reduction (BR), the Seysen reduction (SR), the Lenstra–Lenstra–Lovász (LLL) reduction, the Korkine–Zolotareff reduction (KZR), the Minkowski reduction (MR), and the Gauss reduction (GR) (Albreem et al., 2021).

Fig. 11 compares the performance of DPC and THP in an MU-MIMO scenario ($N_\mathrm{T}=U=4$) with each user having a single antenna.

The results are reproduced from Cho et al. (2010) using MATLAB R2017a. As can be observed, the DPC outperforms the THP; however, the transmitted power of the DPC is higher. Using modulo operations while precoding contributes to the THP's decreased transmit power.

### 6.3 Discussion on precoding techniques for enabling IFC

The accurate nature of CSI is vital to the effectiveness of any precoding technique. CSI can be acquired through feedback in frequency division duplex (FDD) or reverse channel estimation in TDD. In the context of IFC, the channel can be modeled as a free-space path loss, with line-of-sight (LoS) communication. Unlike the rich scattering channels in the conventional wireless communication networks, the A2G channel exhibits weak scattering properties. As aircraft do not abruptly change their altitude,

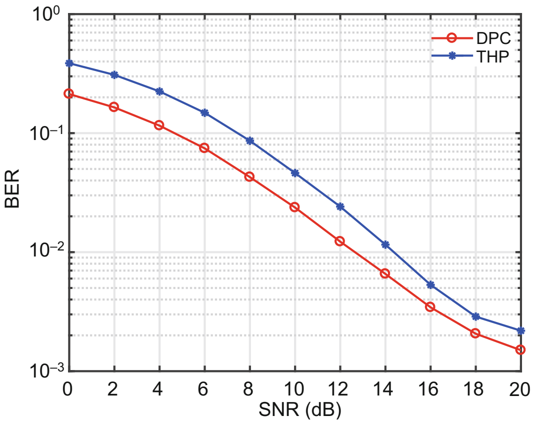

**Fig. 11 Performance comparison of DPC and THP**

direction, or speed, a codebook-based approach can be employed in conjunction with the precoding techniques (MF, ZF, and DPC) discussed in the previous subsection. Although the nonlinear precoding techniques outperform the linear precoding techniques, they are highly sensitive to CSI inaccuracies and require perfect CSI knowledge at the transmitter.

Similarly, in the case of a large number of aircraft being served by a BS, RZF may be used due to its ability to eliminate inter-user interference (IUI). Likewise, THP can be employed since it can avoid noise amplification, mitigate interference, and cancel inter-symbol interference (ISI). However, it is more complicated and expensive when compared to linear precoding. MF and ZF precoders may not be used in this scenario, since ZF has a noise amplification issue and MF is unable to suppress residual IUI. Another practical challenge in ensuring a reliable and efficient IFC is the determination of a precise number of antennas that can be deployed at the BS as well as at the aircraft, since the computational complexity is directly related to the number of antennas at the transmitter (BS) and the receiver (aircraft).

Furthermore, maintaining a balance between the complexity and performance is essential for an efficient precoder. Regretfully, in comparison to more complex precoders (nonlinear), low-complexity precoders (linear) exhibit inferior performance. On the other hand, it is more challenging to implement a complex precoder design practically. Although different precoding techniques are under consideration for enabling IFC through the utilization of STP techniques, the capabilities and limitations of an optimum precoder can only be confirmed through real-time test beds.

## 7 BF techniques

BF is an STP (transmit diversity) technique to improve signal quality and system reliability. In BF, the antenna array transmits or receives radio frequency (RF) signals directionally by modifying its phase and amplitude at each antenna element. BF allows for the phase and/or amplitude control of transmitted signals depending on the channel environment and intended use. In Wang JY et al. (2009), Chen L et al. (2011), Tsang et al. (2011), Hur et al. (2013), Sun et al. (2014), and Han et al. (2015), a detailed overview of BF types and architectures was presented, whereas a brief description of the digital and hybrid BF including the simulation-based link-level performance can be found in Bogale et al. (2016, 2017) and Ahmed et al. (2018).

According to their structural design, popular antenna arrays are either uniform linear arrays (ULAs) or uniform planar arrays (UPAs). UPAs lead to smaller antenna array dimensions, which allows for the integration of more antenna components into a manageable array and the implementation of 3D BF (BF in the elevation domain). Hence, they are more favorable for mmWave MIMO channels. Element arrangements for antenna arrays include localized and interleaved modes. Localized arrays perform better and offer more support for systems with significantly larger angles-of-arrivals (AOAs) (Zhang JA et al., 2015). Despite having a narrower beam width, interleaved arrays are more difficult to construct due to space limitations.

Several studies have been undertaken to classify BF techniques according to their features or characteristics. Some researchers categorized BF techniques based on their physical properties such as switched and adaptive BF (Gotsis and Sahalos, 2011). Hur et al. (2013), Bogale and Le (2014), Ali et al. (2017), and Rao et al. (2021) proposed another classification based on signal processing, which includes analog, digital, and hybrid (analog and digital combined) BF techniques. The next subsection will explore various BF techniques, which are illustrated in Fig. 12.

### 7.1 Switched and adaptive BF

With switched BF, the system chooses from several preconfigured patterns to point the main lobe toward the intended direction. The Butler matrix

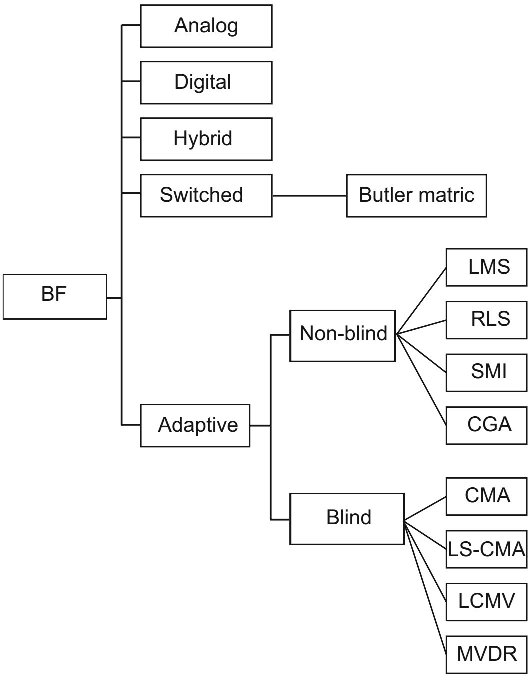

**Fig. 12 Classification of BF techniques**

is one of the most widely used switched BF mechanisms. Interested readers can find an in-depth review of the Butler matrix's functioning in Ren et al. (2016). The Butler matrix has become a popular choice for MIMO BF networks (which consists of hybrid couplers and phase shifters (PSs)) in electronically scanned arrays due to its adaptability and simplicity for multi-beam antennas (Fakoukakis et al., 2015).

A switched beam system requires a switching network to obtain the desired signal from a specific terminal. The selected beam might not point in the desired direction. Researchers have proposed many methods to resolve this problem, such as the ones mentioned in Huang ZE and Pan (2015) and Tiwari and Rao (2015). Additionally, a beam often supports multiple mobile stations as well.

Systems with adaptive BF arrays have the capability of creating a unique beam for each user. Adaptive array processors are used to generate weight vectors to control the phase and amplitude spreading. Adaptive BF facilitates the creation of specific beam shapes, and the main lobe remote sensing enables the main lobe direction toward the desired user while staying null toward other users.

The BS must update the mobile station's location for adaptive BF to work. However, accurate localization is difficult to achieve due to the possibility of process overload from multiple real-time mobile stations. Due to the difficulty of anticipating the direction-of-arrival (DOA) of received signals, an adaptive BF system is substantially more difficult to design than a switched BF system. Perfect adaptive beams, however, aim to significantly improve the offered power resources and lessen user interference. The DA2GC networks, which have LoS characteristics with a small user base (the number of planes), might be thought of as a perfect candidate for adaptive BF, even though it is challenging to implement.

Non-blind adaptive and blind adaptive algorithms are the two primary types of adaptive BF (Thangavel, 2015). In non-blind adaptive algorithms, the array weights are updated continually using a reference signal. By comparing the responses to the reference signal after each iteration, the error signal is used to update the weights in the algorithms. The least-mean-square (LMS), recursive-least-square (RLS), sample matrix inversion (SMI), and conjugate gradient algorithm (CGA) are a few examples of well-known non-blind adaptive algorithms (Ali et al., 2017).

On the other hand, the word "blind" makes it obvious that these algorithms can learn without any prior statistical knowledge. To improve the signal strength to the desired terminal and minimize the interference from other terminals, blind algorithms focus on re-establishing some downlink signal physical properties. Examples of well-known blind adaptive algorithms are the constant modulus algorithm (CMA) and the least square constant modulus algorithm (LS-CMA) (Bhotto and Bajic, 2015). In both approaches, nulls are created by adaptively modifying the antenna array configuration in the direction of a known interference source. Minimum variance distortionless response (MVDR) (Zou and He, 2013) and linearly constrained minimum variance (LCMV) BF (Rasekh and Seydnejad, 2014) are other well-known techniques based on the null steering strategy. Table 7 presents a brief comparison of switched and adaptive BF in terms of coverage, cost, complexity, number of users, interference cancellation capability, and power consumption.

## 7.2 Analog BF

The input signal is phase-shifted or scaled using analog techniques (like low-PS) in analog BF. Analog BF is recommended over digital for applications

**Table 7 Comparison between switched and adaptive BF**

| Parameter | Switched BF | Adaptive BF |
|---|---|---|
| Interference cancellation capability | Faces challenges in separating the desired signal from the interference signal | An efficient technique for reducing interference and noise while enhancing the desired signal |
| Complexity | Easy to implement | Difficult to implement |
| Cost | Inexpensive, needs only couplers and PSs | Expensive as signal processing is required |
| Coverage | Can accommodate more users | Accommodates fewer users as a result of DOA estimation and user localization |
| Number of users being served per beam | More than one | Only one |
| Power consumption | High (the emitted beam might not point in the intended direction) | Improved utilization of power resources |

Sources: Ali et al. (2017); Rao et al. (2021)

requiring cost-effective solutions, since a comparable system may be designed with inexpensive PSs (Ali et al., 2017; Rao et al., 2021). More than 50 years ago, analog BF was proposed, and some contemporary analog BF antennas have been developed which provide continuous BF. Venkateswaran and van der Veen (2010) proposed analog BF for MIMO communications using phase-shift networks to eliminate undesirable signals in the analog domain and to minimize the required analog-to-digital converter (ADC) resolution. It is difficult to control the nulls' direction in the analog domain.

Although analog BF needs only one RF chain and therefore is easier to implement in terms of hardware, it has a considerable performance penalty because only the input signal's phase can be controlled. Furthermore, it does not appear to be straightforward to extend the approach to multiuser systems, and hence it cannot be employed in mmWave MU-MIMO systems.

### 7.3 Digital BF

RF chains and specialized baseband are needed for digital BF to regulate the phase and amplitude of the beam. Numerous tools are included in digital BF, such as nulls to increase signal-to-interference-noise ratio (SINR), programmable antenna radiation pattern management, adaptive beam steering, and DOA estimation. The only way to obtain these benefits is by using digital technology. To achieve many high-gain beams without compromising the SINR, digital BF is typically preferred. Digital BF is divided into four categories: single adaptive beam, single fixed beam, single fixed beam with many users, and single Chebyshev dynamic beam with multiple users (Rao et al., 2021). In digital BF, the weight vectors of the input signal are combined to produce the desired output. Mixers, power amplifiers, and DACs are what make up the foundation of a basic digital BF system. Each antenna array component in digital BF needs to be reinforced by a unique RF chain, which is expensive to implement when there are multiple antennas. However, digital BF outperforms analog BF in terms of performance.

### 7.4 Hybrid BF

Hybrid BF is an effective, economical, and reliable technique for future wireless networks because it can deliver higher data rates with a lower probability of error (Islam et al., 2016). Hybrid BF concepts, which combine digital and analog BF, have been demonstrated as being beneficial by Hur et al. (2013), Bogale et al. (2015), and Ying et al. (2015). While the digital BF component produces baseband signals, the analog BF section addresses RF chain effects by reducing the number of ADCs/DACs, which increases the output of power amplifiers.

The three main advantages of hybrid BF are reduced hardware costs, increased energy efficiency, and support for mmWave-based MIMO communication. The mmWave signals face several challenges during propagation, such as extremely high path loss, inability to pass through thick surfaces, ease of fading, and absorption by atmospheric gases. Hybrid BF techniques can be employed to overcome these challenges, as designing array antennas for this range of frequencies is quite difficult (Bogale et al., 2015). Research communities have proposed numerous hybrid BF architectures/techniques. Interested readers can refer to Nwalozie et al. (2013) and Ahmed et al. (2018) for an in-depth review of hybrid BF. A brief comparison between notable BF techniques is given in Table 8.

## 8 STP for inflight broadband connectivity—the current research work

The MIMO theory was supported by Bell Laboratory layered space–time (BLAST) communication systems (Su et al., 2013), which demonstrates that the MIMO architecture's capacity is, in fact, much higher than that of the SISO architecture. Since then, an enormous amount of research has been undertaken (and is being done) to develop various spatial multiplexing and diversity techniques to maximize the potential of MIMO in terrestrial wireless networks.

The research on MIMO channels for single-user and multiuser systems until the year 2003 was summarized by Goldsmith et al. (2003). This interest grew even more once the number of antennas per device increased and the advantages of MIMO became more apparent. Currently, MU-MIMO with very large antenna arrays is a key component of the 5G new radio (NR) cellular standard published by the 3rd Generation Partnership Project (3GPP)

**Table 8 Comparison of notable BF techniques**

| Technique | Basic working principle | Merit | Demerit | Remark |
|---|---|---|---|---|
| Switched BF (Kutty and Sen (2016) and Rao et al. (2021)) | The user can choose from a variety of specified beams in the desired direction. When creating the same, the Butler matrix structure is preferred, and PS and hybrid couplers make up the system | Can accommodate more than one user per beam, easy implementation, practical approach, better coverage, and cost-effective | It is quite possible that the selected beam is not exactly pointing in the intended direction. Less interference and noise cancellation capability; High power consumption | Suitable for narrow beam switching systems |
| Adaptive BF (Das (2008) and Rao et al. (2021)) | This technology may create a unique beam specifically for each user through the utilization of weight vectors generated by adaptive array processors. It is possible to create specific beam shapes that aim at the desired mobile station while avoiding the interfering sequence | Single user per beam; Less power consumption and uniform coverage area | Difficult to implement user localization for a large number of users; Expensive | Suitable for DA2GC communication networks |
| Analog BF (Islam et al. (2016), Ali et al. (2017), and Rao et al. (2021)) | PSs are used to alter the phase of input signals to steer the beams in the desired directions. Uses a single RF chain with many analog PSs | Simple hardware architecture; Minimal power usage; Minimum baseband processing requirement | Poor performance, low antenna gain, and difficulty in reconfiguration as it is not very flexible | Mostly chosen for radar systems and short-range communications |
| Digital BF (Albert and Chen (2016), Islam et al. (2016), Ali et al. (2017), and Rao et al. (2021)) | Employs a unique digital baseband and an RF front end for each antenna. The system is made up of analog building blocks and ADCs | Optimal performance; Greater flexibility since it allows for the option to change the number of beams or elements | Costly, high power consumption, and sophisticated architecture; High baseband signal processing requirement; Spacious (needs more space) | Best suited for implementation at the BS. Suitable for airborne networks being LoS, and smaller number of users (aircraft) |
| Hybrid BF (Nwalozie et al. (2013), Ying et al. (2015), Islam et al. (2016), Bogale et al. (2017), Ahmed et al. (2018), Guha et al. (2018), and Rao et al. (2021)) | Combines digital and analog BF, and has multiple analog subarrays with their digital chains. Analog subarrays are used to group antenna elements. Each subarray antenna elements share all other components except for one PS, which is assigned to a single antenna element | Cost-effective, less power requirement compared to digital one. More flexible than analog BF, comparable to digital BF in terms of performance | Less flexibility and power loss in the combining stage | Suitable for MIMO systems with multiple antennas |

(ETSI, 2020). Heath et al. (2016) discussed signal-processing techniques for mmWave systems. The 5G beam management procedures were discussed in Giordani et al. (2019). The relationship between the optimal capacity of LoS MIMO channels with antenna element separation was studied by Gesbert et al. (2002) and Bohagen et al. (2007, 2009). Particularly, Gesbert et al. (2002) analyzed the best possible antenna element separation in the situation of parallel transmitter and receiving antenna arrays, while Bohagen et al. (2007, 2009) presented a typical non-parallel/arbitrary 3D alignment issue. Additionally, effective transceiver architectures, beam design approaches, and the performance advantages that MU-MIMO and SDMA can deliver in mmWave deployments have all been well investigated by the research community (Kulkarni et al., 2016; Sohrabi and Yu, 2017). The viability of implementing the MIMO concept in airborne networks was investigated in Gans (2009), where two F-35 fighter aircraft, each with 12 antenna elements, communicate with each other. When the distance between the aircraft is within a particular range, it is shown that the MIMO channels greatly increase the capacity compared to the single-antenna scenario. Although by increasing the distance between aircraft, the MIMO capacity is reduced, and it always remains higher than that of the single antenna system. In Kyritsi and Chizhik (2002), a free-space near-ground MIMO link experiment was conducted at Bell Labs to analyze the link's capacity dependency on the polarization of the electric field, distance, and antenna array layout.

Similarly, the capacity of airborne MIMO systems has been investigated in Su et al. (2013) using various alignments of linear transmitter and receiving antenna arrays. Tadayon et al. (2016) investigated the technical perspectives for the utilization of LTE infrastructure for A2G communications. The authors highlighted that the challenges like channel impairments, a high amount of interference, handover number, and Doppler shift faced by existing cellular-based DA2GC can be overcome by using MIMO, BF, and multi-beam technologies. Vondra et al. (2018) suggested the utilization of several antenna beams pointed at diverse aerial sites to address these challenges in LTE-based DA2GC networks. To minimize the capacity loss caused by intersecting beams, the authors suggested a coordinated resource-allocation strategy that includes spectrum allocation, beam selection, and capacity planning. However, a snapshot model without considering the aircraft's mobility was taken into account. In Koutsopoulos and Tassiulas (2002), an adaptive resource-allocation scheme in the SDMA-based terrestrial network was proposed. Channels for users were allocated based on their spatial separation, while BF weights and transmission rate were adjusted for each user. Lu Y and An (2008) proposed an adaptive BF to decrease the interference from other airplanes. They exploited finite-length snapshots to create beam patterns that can form nulls toward interfered airplanes, while the main lobes were shaped toward the served airplane. In this way, BER can be significantly reduced. The use of ZF BF and a low-complexity airplane grouping technique in the context of SDMA in airborne communication was investigated in Bai L et al. (2013). The authors confirmed that more antenna elements can increase the SDMA gain, while a smaller inter-site distance (ISD) can increase the SDMA efficiency.

BF techniques in the aeronautical communications were studied by Erturk and Aksan (2016). The authors suggested a tool that makes use of the Euler angles and positional data to enable real-time link budget analysis of DA2GC. Furthermore, this tool offers an entire set of mathematical models for a BF algorithm. Another BF algorithm for 2D antenna arrays in the DA2GC scenario was suggested in Tart and Trump (2014). The algorithm can suppress the interfering signals significantly, while the serving signal was affected only minimally. Dinc et al. (2017) proposed a multiuser beamforming (MUBF) technique for creating a distinct beam for each aircraft to use the available spectrum optimally. The accessible bandwidth in a single beam may be used again since MUBF permits simultaneous transmission to multiple aircraft. However, even by using advanced techniques of MUBF together with SDMA, the capacity available per airplane can be significantly limited if beams for two or more airplanes interfere with each other. The performance of 4G- and 5G-based DA2GC networks was compared to satellite-based A2G communication in Vondra et al. (2017). Based on the 3GPP LTE standard, which is commonly employed in terrestrial networks, the 4G DA2GC network uses BF in the three horizontal 120° sectors to minimize the interference between the two neighboring ground stations (GSs). The maximum modulation available for this 4G network is 64 QAM. On the other hand, 5G DA2GC systems are empowered by advanced communication techniques like SDMA together with BF. In this way, each airplane can have a separate beam such that the MUBF allows the reusing of all available bandwidth in every single beam. Moreover, the higher-order modulation 256 QAM is employed.

This article lists certain challenges associated with DA2GC in addition to numerical and simulation analysis. The 5G DA2GC network, which primarily employs coordinated beam-steering and MU-MIMO, achieves the highest capacity. A 5G DA2GC-based network can deliver >130 Mbit/s to aircraft connected to it for around half of the flight's duration if the ISD is 200 km and the bandwidth is 20 MHz. On the other hand, the signal quality and the overall capacity of the 4G-based DA2GC network are substantially reduced by interference, which lowers the network's overall capacity. Consequently, with the same arrangement, only 16 Mbit/s is possible for 50% of the flight time. Even while satellites offer a high-quality signal link, the capacity is shared by several airplanes, limiting the total capacity accessible for one aircraft to a maximum of 40 Mbit/s for 50% of the flying duration.

Research on using STP techniques for enabling IFC using DA2GC networks is still in its early stages due to several reasons/challenges that are highlighted in the succeeding section. Similarly, contemporary research on A2G communications focuses on low-altitude unmanned aerial vehicles (UAVs) (a few hundred meters), while commercial aircraft typically fly at a height of between 9 and 12 km (Mozaffari et al., 2019).

## 9 Open research challenges and future directions

### 9.1 Advanced communication technologies and techniques in STP for enabling IFC

Although using STP in airborne networks has many advantages, there are still several challenges that need to be addressed, such as hardware constraints, energy efficiency, pilot contamination, efficient precoding, channel estimation, user scheduling, and signal detection. These challenges must be thoroughly investigated and put to the test in a real-world environment before we realize the benefits of STP that have been promised. Furthermore, thorough research is essential before integrating emerging technologies into our current wireless system, particularly in airborne networks. Below are some potential research directions in this area:

1. Hardware impairments. STP systems employ a large number of antennas to reduce the effects of noise, fading, and interference, which increases the hardware cost and overall system complexity. MIMO systems should be built using inexpensive and compact components to lower the hardware's size, power consumption, and computational complexity to be used in airborne networks. However, the inexpensive equipment will aggravate hardware shortcomings including phase noise, amplifier distortion, magnetization noise, and in-phase and quadrature (IQ) imbalance, which requires special attention. The influence of hardware impairment can be reduced with the right usage of compensating algorithms, even though it cannot be entirely erased. A good field for research in STP is the design of these compensation algorithms.

2. Pilot contamination. As there are a finite number of orthogonal pilots that can be employed at any given moment, pilot contamination becomes one of the main challenges to implementing an STP system. Pilot contamination raises interference and lowers possible throughput. Although many studies have been conducted to mitigate the implications of pilot contamination, it is still vital to use optimization strategies to further minimize such effects (Köse et al., 2022). Therefore, finding efficient means of reducing the pilot contamination effect is a vital topic to investigate.

3. User scheduling. Since the BS has a limited number of antennas, user scheduling is necessary if there are more users than antenna terminals. By scheduling users who are experiencing favorable channel conditions, the throughput of the STP system can be enhanced. However, this approach ignores and never schedules users at the edge who are having bad channel conditions. Fairness among all users must be maintained to enhance the overall system performance.

Numerous studies have been done to develop an effective user-scheduling algorithm; however, they have not yielded optimum results (Chataut and Akl, 2020). It is necessary to undertake further research to come up with a scheduling algorithm design that is efficient and fair with the capability of providing an increased data rate while ensuring equity across users (aircraft).

4. Multiple aircraft antennas. Currently, STP systems that have multiple antennas cannot be supported by aircraft. It would be difficult for aircraft manufacturers to develop less expensive, lighter, and more compact antennas that can support this technology. Therefore, a promising field for future research would be efficient transceiver design with low complexity, high performance, and multiple antennas.

5. Security. An airborne network's physical layer security is still in its infancy and has to be further investigated. It is necessary to develop techniques for securing communication between aircraft and DA2GC networks.

### 9.2 Aircraft mobility modeling

Fig. 13 illustrates the seven phases of an aircraft's flight pattern, including taxiing, take-off, climb, cruise/enroute, descent, approach, and landing.

Since the aircraft fly at various altitudes during these phases, the modeling of the aircraft is affected, and as a result, the total flight pattern cannot be modeled using a single mobility model. The aircraft mostly operate at lower stratospheric altitudes and have LoS propagation characteristics. Therefore, the cruise/enroute stage can be modeled as linear uniform motion or free-space loss since no structures or objects could obstruct the linkages. Similar to that, the modeling of aircraft can be done using the improved semi-Markov smooth mobility and Poisson process models (Li J et al., 2012). Due to the precise random scheduling of events and the known average time between occurrences, the Poisson process may typically be used during the take-off and approach phases. Similarly, the improved semi-Markov smooth mobility model strives to replicate aircraft mobility based on the fundamental law of aerodynamic motion, and as a result, it can be applied to all seven phases of aircraft movement. The aircraft's mobility characteristics may be referred to as pseudo-linear because it follows a relatively linear route without changing its direction or motion parameters. However, establishing reliable connectivity platforms involves taking into account the research challenges posed by ultra-high speed, 3D movement characteristics, and environmental effects. Likewise, examining various path-loss models under varied operating conditions has the potential to be a fascinating field for future research.

### 9.3 Attenuation modeling of DA2GC networks

Propagation in DA2GC networks exhibits the LoS characteristics and can be modeled as free-space

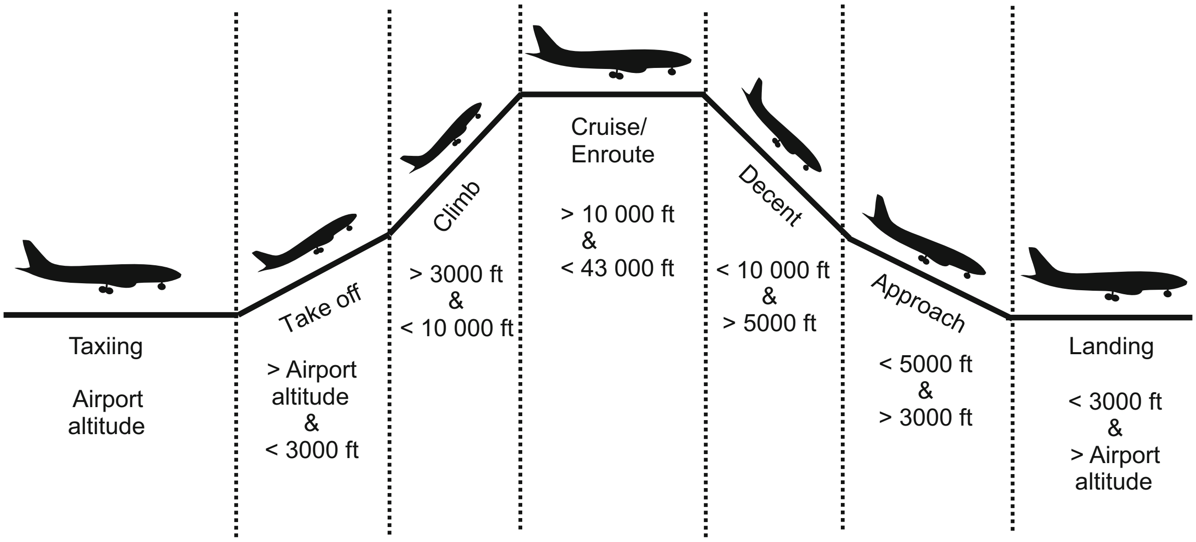

Fig. 13 Phases of the aircraft flight (100 ft=30.48 m)

loss. However, rain attenuation, particularly for communication with a frequency >5 GHz, is the principal obstacle in tropical and equatorial locations. At the high-frequency bands, free-space path loss and rain attenuation lead to considerable signal loss and pose a danger to the system's accessibility, especially in tropical regions where annual rainfall rates are significant. Additionally, the raindrops cause electromagnetic (EM) wave energy to be absorbed and scattered. As a result, Ku/Ka-band broadcasting services frequently face connection outages, particularly on rainy days. Therefore, to determine how exactly the IFC network will perform in real-world scenarios, elements, like expected rain fade duration, rain time, and frequency-dependent rain attenuation, should be considered along with the free-space path loss (Samad et al., 2021; Zarkadas and Dimitrakopoulos, 2021; Alozie et al., 2022).

To effectively determine the link's attenuation owing to rain, it is required to comprehend the rain drop size distribution (DSD). Although several studies have been carried out to explore, parameterize, and quantify DSD from different regions, there are still significant ambiguities regarding the temporal variability of DSD and their dependence on various types of rainfall and climatological regimes. A better slant path rain attenuation model is required, especially for regions with significant rainfall, in addition to the exact attenuation estimation. This is because the currently available models (about temperate regions) often have lower prediction accuracy. Similarly, significant uncertainties regarding equatorial regions exist where only limited experimental data on DSD are readily available. In light of the experimental database that is currently available and several well-known DSD models from the established literature, it is interesting to explore further and estimate the inherent characteristics of DSD when modeling the STP-based DA2DC network. In addition, attenuation induced by atmospheric gases, particularly oxygen absorption, should be taken into account due to the extensive distance of aeronautical networks. The operating frequency significantly influences the oxygen absorption.

### 9.4 Channel estimation

Precise CSI is required for BF, signal detection, and resource allocation in STP systems (supplementary materials, Section 6.1). The pilot overhead increases significantly because the user terminal needs to estimate the signal from many BS antennas. An efficient channel estimation approach with acceptable pilot overhead is thus a promising research topic, especially for the FDD system. Similarly, the channel in DA2GC networks can be modeled as a free-space path loss with LoS communication during the on-air stage of the flight. Contrary to the rich scattering channels generally found in conventional wireless communication networks, the DA2GC channel exhibits weak scattering properties. As aircraft do not abruptly change the altitude, direction, or speed, the channel can be estimated by the automatic dependent surveillance-broadcast (ADS-B) system (Erturk and Aksan, 2016). This system periodically (every 0.4–0.6 s) broadcasts flight-related data like direction, altitude, ground speed, and position. ADS-B signal can be detected in the 500 km range with significant accuracy compared to radar-based air traffic control (ATC) systems. ADS-B position data can be used by the BF stage since aircraft do not move randomly. Hence, channel estimation (channel gain matrix) and beam search using ADS-B need to be further explored. Another exciting area of research is the use of machine learning and deep learning techniques to predict statistical channel characteristics. For signal recognition, BF, channel estimation, and user scheduling, several studies have recently been conducted to examine machine learning and deep learning (Neumann et al., 2018; Soltani et al., 2019; Hu et al., 2021).

### 9.5 Doppler effect

In contrast to what is found in terrestrial cellular networks, the Doppler effect can be an even more severe offender when the airplane is in-flight since the fading is occurring at a genuinely rapid rate, which leads to adverse inter-carrier interference (ICI) (Tadayon et al., 2016). Specifically, two adverse effects emerge when using multicarrier modulation, such as orthogonal frequency division multiplexing (OFDM). First, the ICI caused by the Doppler shift can be more devastating owing to the closely spaced subcarriers. Second, channel estimation gains acquired by transmitting reference signals may change frequently throughout a symbol because channel fading occurs quickly and the coherence time is substantially shorter than the symbol length.

An aircraft traveling at a 12-km altitude at a speed of 800 km/h can experience a Doppler shift as high as $f_{\max} = \pm 4$ kHz when the GSs are 100 km apart, demonstrating the severity of the issue (supplementary materials, Section 6.2). The detrimental impact of this unwanted shift can only be eliminated for typical OFDM setups with an inter-carrier spacing of 15 kHz by allocating approximately 30% of the spectrum as a guard band between each pair of adjacent subcarriers. These factors prevent our most modern cellular network from providing safe connectivity to devices moving >300 km/h. When it comes to IFC, an aircraft travels at nearly three times this speed, making the Doppler shift a greater threat (Dahlman et al., 2011).

### 9.6 Frequent handoff

High airplane speed poses another issue known as frequent handoff. If done frequently, handoff might degrade communication quality, resulting in temporary service outages and squandering of important resources on managing assignments that could otherwise be used to serve another user. To illustrate this issue numerically, at a height >9 km, assuming a nominal 100 km cell size, an airplane with a cruise speed of 900 km/h has as short as 400 s to reach the coverage area of a specific cell. In the case of IFC, reducing cell size increases the number of GSs, resulting in higher costs and complexity. Also, increasing the cell size will increase the number of serving aircraft in a cell, which can degrade the overall system efficiency by sharing resources. Furthermore, in the presence of atmospheric turbulence (like rain and fog), increasing the BS tilt angle (to increase the cell size) drastically increases the attenuation. Designing efficient handoff mechanisms in different environments can be a fascinating research topic.

### 9.7 Efficient precoding techniques

So far, linear precoding techniques have dominated most STP research efforts. To find less-complicated variations of nonlinear precoders, such as the DPC and THP, investigations are being carried out. However, there is a lot of potential for advancement in terms of finding nonlinear precoders that perform well and are as sophisticated (computationally intensive) as linear precoders.

Additionally, there is a wealth of literature that uses deep learning to address the precoding issue in mmWave MIMO systems (Huang HJ et al., 2019). However, there is a noticeable absence of research regarding the utilization of AI technology in typical sub-6 GHz MIMO systems. As a result, there are plenty of research opportunities to apply AI techniques/technologies (like machine learning and deep neural network (DNN)) to develop a simple but high-performance precoder. Also, machine learning can be used to determine the appropriate algorithm rather than depending solely on data estimation. Similarly, employing the virtual channel model (VCM) to develop distinctive precoding algorithms is a fascinating area of research.

### 9.8 Aircraft antenna designing

The direction and characteristics of the aircraft antenna (gain, azimuth, beam width, and polarization) play a vital part in determining the overall network capacity. The aircraft antenna's position also has a significant impact, which should be placed in the best feasible location to minimize the interference with other aircraft systems. Owing to the dynamic nature of airborne networks, another untouched avenue for future research involves designing antennas for enabling IFC leveraging STP techniques in conjunction with the mmWave frequency spectrum.

### 9.9 Beam steering

The idea behind beam steering is to continuously adjust the amplitudes and phases of the array elements while following an airplane in the sky to ensure that it remains confined inside the main lobe of the antenna (supplementary materials, Section 6.3). However, beam steering can occasionally result in a declining return for the system. This occurs when the aircraft is elevated at an excessively low angle and is situated far from the serving BS (for instance, on top of further cells). The aircraft can now experience interference from other BSs using the same frequency. Network-wide coordination among BSs is needed to avoid this situation. However, because BSs may be tens of kilometers away, such coordination is a difficult and expensive task. Additionally, it can lower the SE. It is interesting to research the development of efficient beam-steering algorithms and antenna arrays.

### 9.10 Spectrum extension and regulations

The available spectrum is very limited, and more spectrum is required to offer adequate service quality. Also, spectrum harmonization across different countries is essential for a reliable IFC and effective DA2GC. Although mmWave communications provide promising advantages (supplementary materials, Section 6.4), mmWave-based IFC still faces several challenges that must be addressed. The Tx/Rx antenna beam alignment requires more effective BF training and tracking methods due to the increased mobility of aircraft. Additional consideration must be given to Doppler frequency offset adjustment at the Rx terminal. Communication networks' spectrum efficiency can be considerably increased by combining mmWave and SDMA. Investigating how SDMA and mmWave might coexist for IFC may be a significant field of study, considering that SDMA is capable of supporting multiple users using the same TF resource.

The potential frequency ranges for IFC and the best way to harmonize the frequency bands that will be used for DA2GC communications are two other unresolved issues/uncertainties. Since the spectrum will always be a valuable resource, dynamic spectrum management strategies can also be investigated for interference cancellation and reuse as the aircraft travels between nations.

### 9.11 ST OWC for IFC

The name "OWC" refers to optical transmission, in which the propagation medium is guided infrared (IR) spectrum between 0.3 and 394.7 THz, visible light (VL) spectrum between 394.7 and 833.3 THz, or ultraviolet spectrum between 750 THz and 30 PHz. A general classification of OWC includes visible light communication (VLC), optical camera communication (OCC), light fidelity (LiFi), free-space optical communication (FSOC), and light detection and ranging (LiDAR) (supplementary materials, Section 6.5). Terrestrial point-to-point FSOC systems are operated at the IR, VL, and UV frequencies. LoS and non-line-of-sight (NLoS) optical communication links with high data rates can be provided through UV communication (Xu and Sadler, 2008).

Among all the OWC technologies, FSOC is a potential candidate for the provision of IFC. Laser technology is used in FSO systems to transmit signals. FSO systems provide long-distance communication by optical BF. Over 300 GHz, which is completely unregulated globally, is the frequency used by FSOC. Recent FSOC systems can achieve data rates comparable to that of fiber optics (Kaushal and Kaddoum, 2017). Tsai et al. (2015) established a 40 Gbit/s FSO link with a 20-m communication range. The LEO–LEO connection additionally succeeded in reaching 5.6 Gbit/s (Kaushal and Kaddoum, 2017).

It is simple to deploy FSOC systems. As a result, the use of FSO in air–ground connectivity can be a suitable supplementary option and is a fascinating topic. The integration of MIMO and OWC technologies for enabling IFC is a potentially interesting topic for future research because MIMO is currently a proven technology in RF-based communication systems. Due to the narrow beamwidth of light-emitting diode (LED) receivers and their limited angles of view, the coexistence of MIMO and OWC will require extra care because even a slight misalignment between a transmitter and a receiver can quickly break down the communication.

### 9.12 Orthogonal time frequency space (OTFS) modulation for IFC

The OTFS technique, which modulates data in the delay-Doppler (DD) domain rather than the traditional TF domain (supplementary materials, Section 6.6), has been proposed for high-mobility wireless applications and has gained global recognition (Hadani et al., 2017; Wei et al., 2021). Although the name "OTFS" was initially introduced in 2017, foundational research on channel properties in the DD domain may be traced back to the 1960s (Bello, 1963). Although the DD domain communication has demonstrated enticing advantages over its usual TF domain counterpart, its fundamental constraints remain unclear in the literature. Despite prior studies conducted on attainable rate analysis for OTFS modulation, further investigation is needed to advance the information-theoretical understanding. The capacity scaling rule for MIMO-OTFS has not been substantially investigated in the literature, although it is crucial for future wireless communication, including IFC. Furthermore, security and privacy performance are important factors, especially in the context of IFC, which merits a deeper look.

OTFS modulation gives an immediate means to access the DD domain channel characteristics. However, numerous interesting DD domain channel features have yet to be fully used. For example, the commonly used channel model for OTFS modulation assumes that the channel geometry would remain unchanged for some time. However, this assumption may not hold for in-flight connectivity, where practical issues such as path live-or-die must be addressed. There are still issues for OTFS in fully copiloting the DD domain channel characteristics, which can be overcome by performing comprehensive real-world channel measurements for IFC.

The majority of prior research on OTFS modulation has focused on system architecture; there are still many important aspects of the DD domain communication that must be addressed. For instance, long latency might be a concern for OTFS transmission since the symbols received by the DD domain can only be acquired after all TF domain information symbols have been received, which takes longer than typical OFDM. As a result, designing low-latency OTFS receivers is essential. It is also interesting to compare the performance of OTFS and OFDM in terms of communication delay/latency in the context of STP-based IFC. Another point to consider is how to come up with good channel codes for OTFS systems, such as low-density parity-check (LDPC) codes, coupled codes, and Bose–Chaudhuri–Hocquenghem (BCH) codes.

Similarly, machine learning has demonstrated enormous potential in the design of wireless networks. Some basic works on machine learning-based OTFS designs have been published in Enku et al. (2021, 2022). However, many elements of OTFS modulation could benefit from machine learning. Furthermore, coupling OTFS with forthcoming new technologies like OWC, intelligent reflecting surface (IRS), and backscatter communications is critical for enabling IFC. Since the inception of OTFS, serving many users (using STP techniques) has been a hot issue. Numerous efforts have been made to address this issue, as described by Yuan et al. (2023); however, it remains unclear which domain (DD or TF) users should be multiplexed. Similarly, combining OTFS and STP in DA2GC networks for enabling IFC could be a fruitful area of future research, as joint signaling optimization in the delay, Doppler, and spatial domains is complex.

### 9.13 IRS

LoS communication allows for wave propagation over longer distances in IFC. However, due to the long distance between the airplane and the GS, the transmitted signal suffers from significant path loss and scattering from suspended particles, resulting in lower data rates and overall system performance. Environmental impediments like rain and fog might further reduce the transmitted signal. IRS scattering elements can be used to steer a signal in any desired direction, which may assist in mitigating these difficulties (supplementary materials, Section 6.7). Similarly, IRS can be used to overcome coverage concerns in DA2GC networks for long-haul flights over the ocean. IRS can be mounted on the ship or float below the water surface, to offer connectivity to planes (Nawaz et al., 2015; Mohsan et al., 2023).

However, significant obstacles in implementing IRS-assisted aerial networks, such as IRS reconfiguration (especially size), deployment, size optimization, and channel estimate, must be solved, and this is one of the fascinating future research avenues in the domain of IFC. Similarly, IRS can be built in a spherical shape to reflect impinging signals from all directions, which could be a potential study area for future advancements.

### 9.14 Cost–benefit analysis of airborne networks

There are a variety of stakeholders involved in the IFC market, and the major ones among them are listed below:

1. Airlines (main market player).
2. Aircraft manufacturer.
3. Connectivity platform operator (DA2GC network operator).
4. Onboard network operator (which needs a specialist operator having specialized knowledge to offer network inside the aircraft because the equipment placed on board is subjected to demanding and complicated compliance certification processes that comply with guidelines set by regulators). In some business models, the onboard operator can be the same airline.
5. Passengers.

The growing interest among all stakeholders in providing high-speed broadband connectivity has propelled this industry to new heights, resulting in a dramatic increase in its estimated value from 6.70 billion USD in 2023 to 11.79 billion USD by 2030 (Nalepka et al., 2023). However, it is believed that this forecasting would be heavily influenced by research trends and the significance of developments seen in the future years. To keep up with expected market trends, meet demands for high data rates reliably, and achieve critical deadlines in a highly sensitive industrial environment, dedicated business models are required.

To ensure seamless IFC services, the emerging DA2GC business environment needs the establishment of new business models with new responsibilities for present stakeholders, as well as the introduction of entirely novel entities (like cabin system providers or A2G network operators). For instance, the A2G network can be seen as a group of terrestrial and satellite operators for connectivity over the ocean. Aside from the business ecosystem and the regulatory environment, the DA2GC value chain is highly complex. Due to the engagement of several stakeholders and players, it is necessary to explore business models that clearly define the duties of partners and give opportunities for diverse participants to stimulate the market, in contrast to monopolistic solutions. Hence, innovative research directions and practical business models are of utmost importance for all DA2GC stakeholders.

Similar to the qualitative analysis, another unexplored area of research is the cost of connections, i.e., capital expenditure and operational expenditure (CAPEX/OPEX) of various business models. The whole communication network can be divided into three groups to determine its economic viability, as shown in Fig. 14.

Similarly, different revenue-generation models can be used for better insight into the economic viability of the overall system. Another area of research that could be pursued in the future is the cost–benefit analysis (by taking into account CAPEX and OPEX) for enabling IFC using the STP technology. Additionally, it would be interesting to compare the costs of the MIMO-based DA2GC with those of alternative connectivity platforms like satellites and AANETs.

### 9.15 Integrated network design

Satellites, terrestrial infrastructures (DA2GC), and AANETs all offer advantages and disadvantages in terms of cost, adaptability, flexibility, susceptibility, footprint, and overflight. As a result, designing integrated networks that combine many of these infrastructures to ensure precise, reliable, and uninterrupted coverage could be a hot research area. Some of the possible future research topics may include:

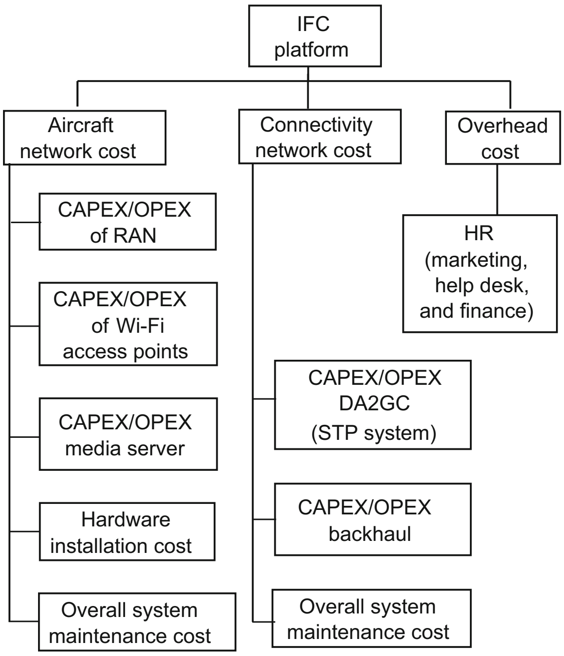

**Fig. 14 Cost breakdown of airborne network (DA2GC). RAN: radio access network**

1. Developing affordable and resilient dynamic networking solutions for heterogeneous (multilayer) networks (for example, regulating the seamless integration/disintegration of several aerial platforms);

2. Development of reliable methods of transmission for networks with extremely dynamic and weak connection characteristics;

3. Establishing efficient information-sharing and data transport across various networks;

4. Designing network operation control mechanisms under both multi-association and high-constraint situations. The multi-association implies that platforms are linked to service capabilities, flying patterns, and operational plans. The high constraint means that control techniques must adhere to strict safety constraints such as weather, trajectory conflicts, and topography.

## 10 Conclusions

This research work was concentrated on the application of STP techniques in airborne networks to enable IFC. The research study has aimed to develop a comprehensive understanding of the underlying concepts and theoretical principles behind STP techniques in airborne networks for enabling IFC. We have first conducted a thorough literature review and highlighted the challenges and limitations of STP-based A2G networks considering factors such as the environment, aircraft mobility, Doppler shifts, fading, and interference. In this regard, we have analyzed the leading approaches for enabling IFC along with their benefits and limitations. We have also presented a performance analysis that assessed the use of various STP techniques in airborne networks. The outcomes illustrated the efficacy of STP techniques in enhancing the performance and reliability of overall communication links. Finally, we have suggested potential areas for future research, such as exploring advanced communication techniques and technologies, aircraft mobility and attention modeling, channel estimation, Doppler effect, efficient precoding techniques, the effect of the aircraft antennas on connectivity, beam steering, spectrum extension and regulations, ST, OWC, OTFS, and IRS, and machine learning techniques may be explored further to streamline the use of STP techniques for a reliable IFC. The importance of conducting a cost–benefit analysis for DA2GC and integrated network design has also been emphasized.

### Contributors

Amjed ALI and Noor Muhammad KHAN designed the outline of the review. Amjed ALI conducted the literature survey and performed the comparison analysis. Amjed ALI and Noor Muhammad KHAN conducted the critical analysis of the literature. Amjed ALI drafted the paper. Noor Muhammad KHAN revised and finalized the paper.

### Conflict of interest

Both authors declare that they have no conflict of interest.

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## List of supplementary materials

1 Categories of CNS/ATM system

2 Leading approaches for the provision of inflight broadband connectivity

3 Capacity of space–time (ST) wireless communication systems

4 Linear precoding techniques

5 Nonlinear precoding techniques

6 Open research challenges and future directions

Fig. S1 Model decomposition when CSI is available

Fig. S2 OTFS implementation block diagram