Airplane-Aided Integrated Networking for 6th Generation Wireless - Will It Work?

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With the increasing demand for wireless connectivity, communication technology is moving towards the integration of terrestrial networks with space networks. The creation of this Integrated Space and Terrestrial Network (ISTN) is of critical importance for industries such as logistics, mining, agriculture, fishery and defense. However, a number of grand technological challenges have to be overcome for ISTN through low-cost airborne platforms and high data-rate backbone links. This article discusses a pair of bottlenecks that severely limit the ISTN capacity and reviews the family of wireless communication technologies suitable for supporting such backbone links. A novel ISTN architecture that makes use of the civil airliner networks to form a low-cost airborne network is proposed. Combined with the emerging high-speed long-range millimeter wave (mm-wave) communication systems as the backbone and access links, the proposed architecture is capable of supporting a high-capacity ISTN at a low cost. Some key technologies, which enable the realization of such a high-capacity low-cost ISTN, are also suggested.

Introduction

Since its roll-out commences from the first quarter of 2019, the 5th generation (5G) mobile communication technology promises significantly increased capacity, massive connections, and compelling new applications. However, the 5G wireless systems are still ground-based, having the same coverage problems as other terrestrial networks. Space communication networks are complementary to terrestrial networks as they provide vast communication coverage for people and vehicles at sea, as well as in remote rural areas and in the air. Clearly, future information networks must seamlessly integrate space networks with terrestrial networks, which may become the ambitious target of the 6th generation (6G) wireless systems [1, 2].

The envisaged 6G wireless systems are expected to support truly global wireless communications anywhere and anytime. Hence, an Integrated Space and Terrestrial Network (ISTN) is expected to be at the core of 6G communication systems. How to build a high-capacity yet low-cost ISTN is thus of significant importance to the development of global 6G communication systems.

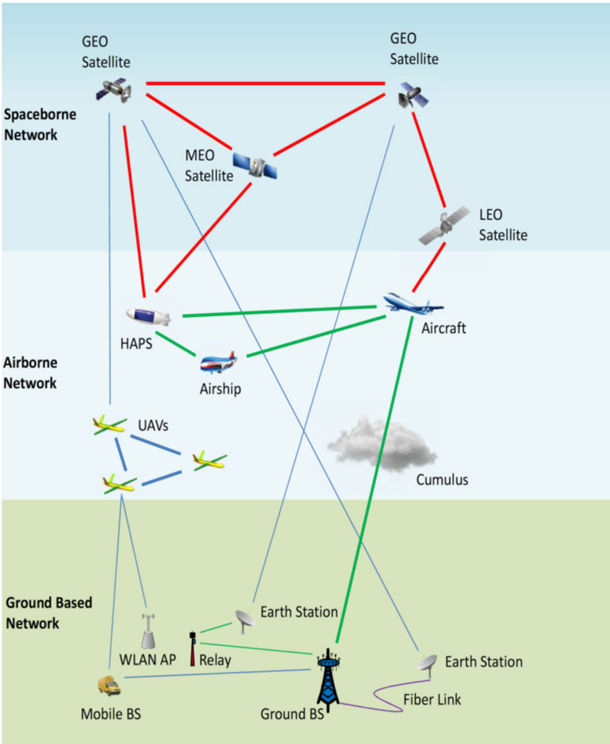

***Figure 1** Typical ISTN architecture with various communication links connecting the major nodes.*

An architectural illustration of a typical ISTN is shown in Figure 1, which can be divided into three layers. The spaceborne network layer consists of various orbiting satellites such as the Geostationary Earth Orbit (GEO) satellites, Medium Earth Orbit (MEO) satellites, and Low Earth Orbit (LEO) satellites operating at different altitudes. The airborne network layer makes use of various aerial platforms including stratospheric balloons, airships and aircrafts, Unmanned Aerial Vehicles (UAVs), and High-Altitude Platform Stations (HAPSs). The ground-based network layer includes the satellite networks' ground infrastructure, cellular networks, Wireless Local Area Networks (WLANs) and mobile ad hoc networks. Major nodes in these networks include satellite stations, cellular Base Stations (BSs), mobile satellite terminals, relays and WLAN access points (APs).

Although substantial efforts have been invested in integrating space networks with ground-based networks [3, 4], there are still a number of grand challenges in constructing the global high-capacity ISTN at a low cost. The predominant bottlenecks are the bandwidth available for high-speed aerial backbones and the Area Spectral Efficiency (ASE) of Direct Air-to-Ground (DA2G) communications between the airborne and ground-based networks, both related to the airborne network.

Aerial backbones rely on high-speed wireless links to connect the major nodes in the ISTN. They play a pivotal role in the ISTN by handling the aggregation and distribution of various data flows such as voice, video, Internet and other data sources. As the airborne network is an indispensable intermediate layer between the spaceborne and the ground-based networks, high-speed, flexible and all-weather aerial backbones constitute the most critical infrastructural elements in building the airborne network.

Frequency reuse can be readily achieved in ground-based cellular networks by limiting the coverage area of each cell with the aid of power-control, hence limiting the interference from each other. However, this is hard to achieve for space and terrestrial networks because the satellite is far away from the ground. The coverage of a narrow communication beam becomes very wide when it reaches the ground. This will result in low ASE because many users have to share the bandwidth in a large area. For example, the spot beams from a pair of Ka band GEO satellites in Australia's broadband satellite system, known as Sky Muster, have a 325 km radius for the central region and 125 km radius for coastal areas [5].

There are some ISTN architectures proposed in the literature, such as the extended space network [6] which can be integrated with the mobile wireless networks to provide comprehensive services and global access. However, existing ISTN architectures rely on dedicated aerial platforms for connecting the space networks with the terrestrial networks, which are likely to be the most costly part in the ISTN infrastructure. Additionally, no flawless solution has been provided for the high-speed aerial backbones or for attaining a high area spectral efficiency.

This article proposes a novel architecture for realizing a high-capacity low-cost ISTN by exploiting the existing civil airliner network and mm-wave links. Such an architecture is capable of breaking the above-mentioned bottlenecks at low cost. The civil airliner network covers a large fraction of the global land and sea surface and has sufficient plane density for forming a major part of a dynamic opportunistic airborne network. The mm-wave links can potentially provide very high bandwidth for both the backbone and access to ISTN services.

Aerial Backbone Options for ISTN

In the traditional terrestrial telecommunication infrastructure, the backbone network mainly relies on single-mode fiber as its primary data link. However, the ISTN cannot rely on this fixed infrastructure for the airborne network. Instead, it requires wireless backbone links with a capacity comparable to optical fibers that can operate under any climatic conditions, anywhere and anytime.

Early efforts on wireless backbones were primarily based on microwave links. They are not affected by harsh weather conditions, but their major disadvantage is their limited transmission rate constrained by the limited spectrum. One of the well-known microwave aerial backbones is the Common Data Link (CDL) [7] developed by the US Defense sector in the early 1990s, which uses the Ku frequency band (12-18 GHz) and offers a 274 Megabits per second (Mbps) data rate over a distance of several hundred kilometers. CDL is widely used for providing point-to-point communications from aircraft to the BS on the ground as well as for controlling the aerial platforms. After shifting to the Ka frequency band (26-40 GHz), the advanced CDL improved the data rate to 3 Gbps. Unfortunately, this is still far from sufficient, since hundreds of Gbps data rates are required for integrating space networks with terrestrial networks.

Free Space Optics (FSO) links constitute excellent solutions for connecting satellites in space. The first FSO link was developed by the US Defense Advanced Research Projects Agency (DARPA) through its "Free Space Optical Experimental Network Experiment (FOENEX) Program" from 2010 to 2012, which provides a data rate of 10 Gbps equivalent to an optical 10 Gigabit Ethernet (GbE) interface. Upon using Wavelength-Division-Multiplexing (WDM), the data rate can be further improved to 100 Gbps. Due to the low absorption and scattering loss in space at an altitude of 1000 km (for LEO) to 40,000 km (for GEO), the high-speed FSO links are capable of serving as viable backbones for interconnecting the spaceborne platforms over tens of thousands of kilometers [8]. Unfortunately, FSO links cannot propagate through cloud, fog, rain or snow efficiently. During dense cloudy (or foggy) conditions, when the visibility is less than 50 m, for instance, the attenuation of an FSO link may be in excess of 350 dB/km. This means that for about 40% of the time in some regions the FSO links cannot be used in the airborne network or for interconnecting the aerial and terrestrial networks.

In order to develop a high-speed all-weather mobile backbone transmission network, DARPA established the "100G RF Backbone Program" at the beginning of 2013 [9]. The goal of the project is to design, build and test an airborne Radio Frequency (RF) communication link that has both a 'fiber-optic-equivalent' capacity and a long reach. The attainable data rate is as high as 100 Gbps at 200 km for air-to-air links and 100 km for air-to-ground links from a high-altitude (e.g., 20 km) aerial platform. The link is expected to provide an all-weather (cloud, rain and fog) capability, while maintaining a beneficial throughput and link range. The mm-wave technology has been identified as the best choice for realizing the 100 Gbps RF backbone as there is 10 GHz bandwidth in the 71-76 and 81-86 GHz E-band. The atmospheric attenuation is below 0.3 dB/km and the total atmospheric and cumulus loss (assuming a 50 km link distance) is estimated to be only about 10 dB in the E-band [9]. High-gain power amplifiers and high-gain angularly selective antenna arrays can be used with the aid of beamforming to combat the relatively high path loss of long links. Additionally, multiple data streams can be supported, using Spatial Division Multiple Access (SDMA) and Line-Of-Sight Multiple Input Multiple Output (LOS-MIMO) technologies [10], to increase the ASE as well as the total capacity.

Link Budget Parameters	**71-76 GHz Band**		**81-86 GHz Band**	
	Input	**Output**	**Input**	**Output**
Transmit Frequency [GHz]	73.5		83.5	
Channel Bandwidth [GHz]	5		5	
Path Length [km]	100		100	
Transmit Antenna Aperture [m]	0.3		0.3	
Receive Antenna Aperture [m]	1.8		1.8	
Antenna Efficiency	0.55		0.55	
P1dB Output Power [dBm]	43		43	
Back-off for 64QAM [dB]	-10		-10	
Transmit Power [dBm]		33.0		33.0
Other Transmitter Loss [dB]	-1.8		-1.8	
Transmitter Antenna Gain [dBi]		44.7		45.8
EIRP [dBm]		75.9		77.0
Path Loss [dB]		169.8		170.9
Atmospheric and Cloud Loss [dB][9]	7.9		8.2	
Total Loss [dB]		-177.7		-179.1
Receiver Antenna Gain [dBi]		60.2		61.4
Received Power [dBm]		-41.6		-40.8
Receiver Noise Figure [dB]	6		6	
Other Receiver Loss [dB]	-1.8		-1.8	
Thermal Noise Power [dBm]		-76.9		-76.9
Signal-to-Noise Ratio Required [dB]	27.0		27.0	
Receiver Sensitivity [dBm]		-41.9		-41.9
Link Margin [dB]		0.3		1.1

***Table 1** Link budget calculation for air-to-ground link.*

To make it plausible that the mm-wave technology is potentially capable of supporting this ambitious high-speed long range aerial backbone, a rudimentary link budget calculation is provided in Table 1 for a 100 km air-to-ground link in the E-band using 64 Quadrature Amplitude Modulation (QAM) and operating at 27 dB received signal-to-noise ratio for achieving 10^{-6} uncoded bit-error-rate. With the 10 GHz total bandwidth and assuming 15% signaling overhead, greater than 50 Gbps data rate can be achieved with realistic transmitter and receiver antenna apertures and currently available 43 dBm solid state high power amplifier. By further exploiting dual polarization and/or LOS-MIMO, 100 Gbps data rate can be achieved. Upon using large antenna arrays, the required received power can be obtained even at a lower transmission power such as 27 dBm for each antenna element. This is a desirable solution, since MIMO technology can also be used for providing DA2G communications at a high spectral efficiency.

To summarize, Table 2 provides some comparative results for the above-mentioned backbone links in terms of their attainable data rate and communication range, using CDL, advanced CDL, FSO and FSO with WDM for an air-to-air link under clear weather conditions. Similarly, the data rates and range achieved using CDL, advanced CDL techniques, and mm-wave air-to-air links and air-to-ground links (assuming a 20 km airborne platform height) with a cloud layer underneath are also shown [9].

Link Type	**Capacity per Link (Gbps)**	**Range (km)**	**Conditions**
mm-Wave (Air-to-Ground) [9]	100	100	Clear weather and with cloud layer
mm-Wave (Air-to-Air) [9]	100	200	Clear weather and with cloud layer
FSO	10	>400	Clear weather only
FSO with WDM	100	>400	Clear weather only
CDL	0.274	>400	With cloud layer
Advanced CDL	3	≈350	With cloud layer
CDL	0.274	>400	Clear weather
Advanced CDL	3	>400	Clear weather

***Table 2** Comparison of various backbone links.*

New ISTN Architecture Based on Operational Civil Airliner Network

Figure 2 illustrates the proposed new ISTN architecture. To construct such a high-capacity yet low-cost ISTN architecture, we rely on a pair of key innovations. Firstly, mm-wave links based on antenna arrays may be used as the air-to-air and air-to-ground backbones (indicated by the green lines) to replace the conventional microwave links. This will significantly increase the available bandwidth and meet the data rate requirements. The FSO links (indicated by the red lines) serve as the high-speed links in the space network as well as between a satellite and an airborne platform. Secondly, the passenger airplanes may form a low-cost airborne network. Each airplane acts as both an end user to provide in-flight services and a relay node to provide networking/relaying functionality. At the same time, we invoke

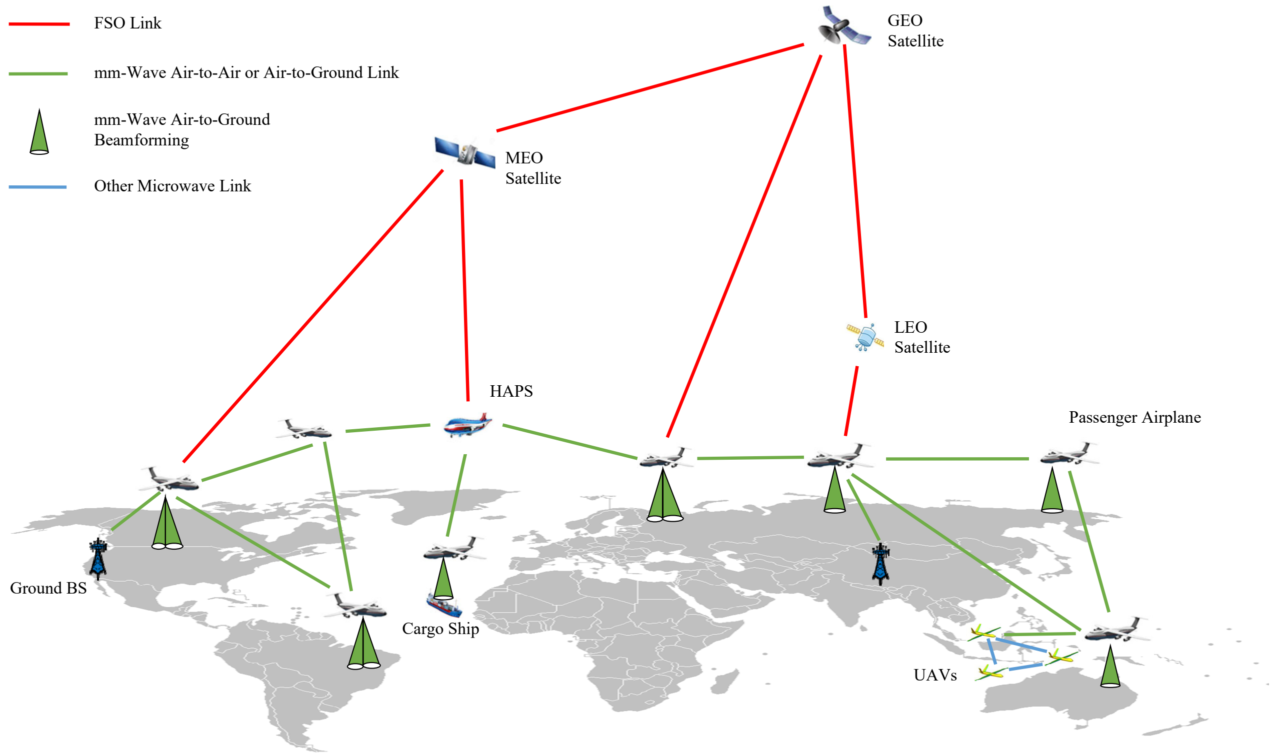

***Figure 2** New ISTN architecture based on mm-wave links and civil airliner networks.*

adaptive beamforming (indicated by the green cones) performed on the airplanes, to provide cellular air-to-ground coverage for relatively small cells capable of supporting a high ASE. Given a high-gain directional mm-wave beam and the relatively short distance from an airplane to ground compared to the distance from a satellite to ground, each beam only covers relatively small ground areas, hence the mm-wave spectrum can be tightly reused for achieving a high ASE expressed in bits/second/Hz/km^2. Naturally, having a smaller footprint on the ground requires more frequent handovers, hence substantial research is required for achieving an attractive trade-off between the ASE and the handover frequency. In the areas that the civil airliners cannot cover, dedicated HAPSs and/or airships may be used as the supplementary infrastructure. UAV networks can also be used to provide hot spot and emergency services.

Under this new ISTN architecture, using mm-wave links in the airborne network as well as between the airborne and ground-based networks will significantly increase the overall system capacity. Using mm-wave hybrid antenna arrays [11] may strike a compelling balance between the performance and cost. Using civil airliners as the main nodes for the airborne network will substantially reduce the cost of building a dedicated ISTN infrastructure. According to FlightAware, the world's largest flight tracking data company, there are on average tens of thousands of airplanes carrying over 1.2 million people in the sky at any given time [12]. These airplanes cover most of the land and sea globally and hence can provide networking services supported by the ISTN with vast coverage day and night. Because these airborne platforms are only about 10 km above the ground, the coverage area of a signal beam can be well controlled by using mm-wave hybrid antenna arrays for supporting a high user-density. Through joint signaling design, the cell formed by the airborne platform can also be integrated into the ground-based 5G cellular network, where mm-wave spectrum is also likely to be used for access. Therefore, this architecture can achieve seamless services across the whole network with substantially improved ASE.

The proposed integration of spaceborne and airborne networks along with ground based networks is capable of improving the global communication coverage and hence fulfils the main objectives of 6G networks. As an example of use cases of the proposed ISTN, passengers in an airplane can make phone calls and access the Internet using their mobile phones as if they were at home or at their workplace, enjoying better user experience and faster download speed than using the in-flight WiFi services available at the time of writing. Other use cases include smart farming, shipping, and tracking in sparsely populated areas. Rural and remote areas have been missing out the broadband dividends for many years due to the lack of connectivity. The main obstacle for rural broadband deployment has been the high cost of ground-based infrastructure. The proposed ISTN provides a solution with its vast coverage at low cost, bringing the smart farming and precision agriculture technologies to rural and remote farms to finally complete the rural "missing link" in global connectivity. For supply chain tracking and shipping applications, the low cost vast global connectivity will enable detailed tracking of containers at sea and livestock in rural and remote areas and close monitoring of their shipping and roaming conditions. Naturally, due to the mobility of passenger airplanes, a dynamic opportunistic airborne network can only provide "best-effort" rather than quality-guaranteed enhancement of the existing high-speed services. Therefore, there is a trade-off between the cost and the quality of services. Again, to provide more reliable service, a limited number of dedicated aerial nodes (HAPSs and airships) can also be deployed to supplement the scheduled civil airliners.

To demonstrate the potential performance improvement under the new ISTN architecture, Figure 3 shows the total system capacity as a function of the airliner density. We assume that a mm-wave link can achieve M×50 Gbps data rate, where M is the number of channels supported by using spatial multiplexing with the aid of mm-wave antenna arrays, and the Earth's surface area is 510 million km^2. The upper-bound of the total system sum-rate can be evaluated by calculating the number of airplanes operating globally at any given time multiplied by the maximum throughput of each airplane. We see that at an airliner density of about 20 airliners per 10,000 km^2, the ISTN can potentially achieve over 100 Peta bits per second (Pbps, 1 Peta bit = 10^{15} bits) total capacity. Figure 4 also shows the connectivity of a single airliner in terms of the number of serviced small cell BSs per square kilometer upon employing mm-wave beamforming using an N-element antenna array, assuming that the airliner is 10 km above the ground. Given the number of elements in the antenna array, the beamwidth of each mm-wave beam and hence the ground coverage area per link can be determined according to the typical airplane height. The number of small cells each airplane can serve may therefore be readily estimated. The figure indicates that having one small cell BS per square kilometer, which is similar to the BS density of the fourth generation (4G) mobile networks, can be achieved with the aid of about 100 antenna elements. A 30×30 element array mounted on an airliner is capable of serving over 10 small cell BSs per square kilometer. Each BS can offer access to mobile users in its serviced small cell of the ground-based network.

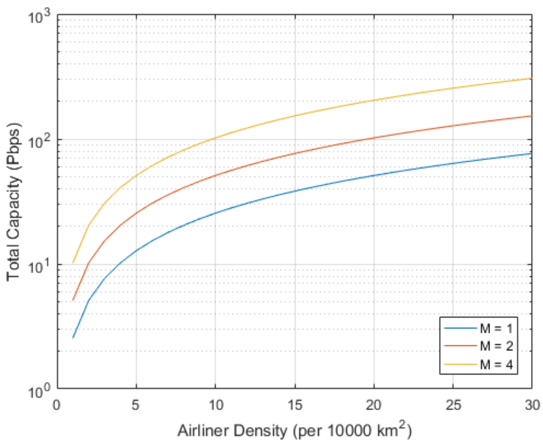

Figure 3 *Estimated total ISTN capacity.*

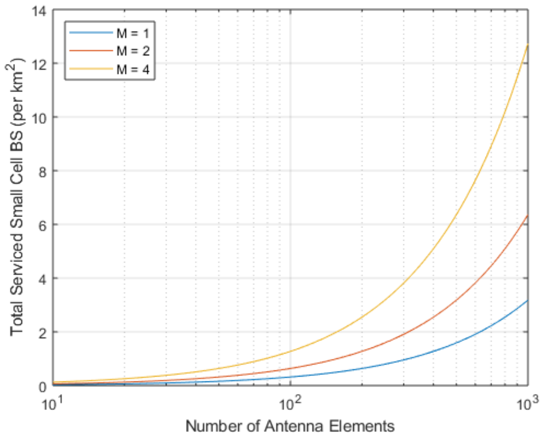

Figure 4 *Estimated connectivity of a single airborne platform.*

Key Enabling Techniques

To construct an efficient implementation of the proposed architecture, we envisage that the following six key technologies should be developed.

Dynamic Modelling of Spaceborne and Airborne Networks

Using civil airliners as the main infrastructure has the potential of substantially reducing the cost of building an airborne network, since only a limited number of dedicated HAPSs are necessary. However, the network of civil airliners exhibits certain dynamics. It is necessary to quantitatively analyze the performance of the dynamic network and to develop adaptive routing algorithms for ensuring the stability of the network.

The interactions between the airborne and spaceborne networks should also be investigated, especially in the context of LEO satellites, which change their locations at a high velocity. By modelling their orbits, density and the corresponding transmission rates of the LEO satellites, the network topologies and routing protocols of the airborne network can be optimized for satisfying the desired coverage and system capacity requirements.

High-Speed Long Range mm-Wave Transmission

In the last 5 years, mm-wave technologies have been significantly advanced, which makes them an attractive option for the airborne backbone. However, there are still numerous challenges to overcome before meeting the ISTN requirements. On one hand, higher data rates have to be achieved by using advanced technologies, such as in-band full duplex [13] and LOS-MIMO. On the other hand, to conquer longer communication distances, a sufficiently high transmit power is required. This calls for the employment of massive antenna arrays.

Since the topological structure of the airborne platform is in a constantly changing state, tracking the trajectory of the airborne platform in motion while supporting reliable continuous communications is also an open challenge. The design of Multi-Functional Antenna Arrays (MFAAs), for combining adaptive beamforming with space-time coding, spatial multiplexing and SDMA in the airborne environment also requires extensive study [11].

mm-Wave Aeronautical Communication Channel Models

In the proposed ISTN architecture, the intermediate airborne platforms are mainly passenger airplanes, hence maintaining reliable communications from/to the airplanes are of critical importance. As it is widely acknowledged, to design reliable aeronautical communication links, the performance must be evaluated in diverse operational conditions, such as en-route, arrival, take-off, taxi, and parking. With the adoption of mm-wave systems as both the air-to-air and air-to-ground backbones as well as the DA2G access links, in-depth understanding of the aeronautical mm-wave propagation characteristics is absolutely necessary.

At the time of writing, no aeronautical channel model is commonly available, especially not for mm-wave links. Some aeronautical channel models are available for the satellite-to-aircraft as well as air–to-ground links, but they have all been developed for the Very High Frequency (VHF) bands [14]. Assuming an mm-wave link in the E-band having a carrier frequency of 73.5 GHz, some key parameters used for modelling the mm-wave aeronautical channels are summarized in Table 3. Naturally, a plethora of other parameters should also be considered to construct realistic channel models, such as the Rician K-factor and the number of multipath components of Non-Line-Of-Sight (NLOS) channels, the size of mm-wave antenna arrays and their beam angles, just to mention a few.

Parameters	**Airplane Scenarios**			
	En-Route	**Arrival/ Take-Off**	**Taxi**	**Parking**
Carrier Frequency (GHz)	73.5	73.5	73.5	73.5
Airplane Velocity (mps) [14]	17 ~ 620	25 ~ 150	0 ~15	0 ~ 5.5
Doppler Frequency (kHz)	±4.6 ~ ±151.9	±6.1 ~ ±36.8	0 ~ ±3.7	0 ~ ±1.3
Maximum Delay (μs) [14]	6 ~ 200	7	0.7	7

Table 3 *Key Parameters of mm-Wave Aeronautical Channels.*

Reconfigurable Conformal Antennas

In principle, the Effective Isotopically Radiated Power (EIRP) can be readily increased by employing the above-mentioned MFAAs. However, the very limited space, aerodynamic requirements and high cost render this impractical for most systems deployed on an airplane. A conformal antenna array is expected to meet the aerodynamic requirements at a lower cost. However, conventional conformal antenna systems fail to efficiently exploit the antenna aperture, hence severely limiting the power received. A solution to this limitation is the conception of a reconfigurable conformal antenna array relying on low-complexity MFAAs. Whilst being conformal to the surface of the mounting platform, the MFAA weights have to be dynamically controlled in situ to produce the optimum radiation characteristics to suit the radio environment. With the aid of sophisticated reconfigurability, the radiation patterns and polarization of all the elements within the line-of-sight of the chosen direction can be optimally adjusted for significantly increasing the size of the effective antenna aperture and for enhancing the radiation performance [15].

These sophisticated reconfigurable conformal antenna arrays conceived for mm-wave communications can indeed be mounted on the surfaces of airplanes. Therefore, developing low-cost high-gain reconfigurable conformal antenna arrays for the mm-wave frequency band that are suitable for the airplanes is vitally important both for the air-to-air and air-to-ground links for realizing the ISTN using the airliner network.

Three-Dimensional (3D) Networking and Optimization

In ISTN, we have to deal with complex networking issues, such as diverse types of communication links, various link delays, intermittent transmissions between satellites, a dynamically fluctuating topology, a high Doppler frequency and fading. To address these issues, the following research is needed:

- 3D (Space-Air-Ground) networking relying on the three layers of spaceborne, airborne and terrestrial links: 3D networking requires a comprehensive examination of the links between satellites, aircrafts and ground stations, all having different distances, delays, capacities and quality factors, whilst applying heterogeneous network design theory for global optimization.
- Optimizing a quasi-predictable network topology: In contrast to traditional ad hoc networking, the satellites and flights have fixed schedule and flight-path patterns. The network can be optimized by taking advantage of these quasi-predictable trajectories.
- Dynamic but quasi-predictable route selection: New network routing protocols can be designed to adapt to the dynamic but quasi-predictable network topology. The routes in the ISTN should be optimized in real time according to the network topology and channel conditions.

High-Speed Communication Protocol Optimization

The traditional TCP/IP protocol originally designed for fixed terrestrial networks cannot be readily adapted to the ISTN. Research on high-speed communication protocol optimization can be focused on providing the following solutions:

- Optimizing TCP for transmission over satellite channels: This includes optimizing the TCP flow control and congestion control protocols in the case of high bit error rates, as well as optimizing the TCP start up and acknowledgement mechanisms under the conditions of high latency.

- Overhead reduction: This includes packet header compression, since the satellite channels have a limited bandwidth. Sophisticated Automatic Repeat Request (ARQ) techniques and soft-packet combining may be invoked for improving the channel coding performance.
- Optimizing scheduling according to data attributes: Different applications such as browsing, voice, pictures, video and download, have different quality of service requirements in terms of their data rate, delay and error rate specification. It is necessary to design the corresponding communication protocols with quality of service assurance and realize it through the optimized scheduling of the resources.

Conclusions

In this article, we highlight two major problems, the bandwidth and the Area Spectral Efficiency (ASE) that have to be solved for building a high-capacity and low-cost Integrated Space and Terrestrial Network (ISTN). We propose a novel architecture based on the civil airliner network and mm-wave communication technology to realize a high-speed low-cost airborne network as the core of the ISTN. The airplanes in the airborne network are both the end users and the backbone nodes that provide high-speed links between an airborne platform and the BS on the ground. This novel architecture is capable of significantly improving both the bandwidth and ASE of existing satellite communication systems and hence the total capacity of the entire network. We also suggest a range of open research problems on a number of key technologies. Our hope is that the research community might become inspired to join forces in tackling these thrilling scientific challenges.

Acknowledgements

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