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DRIVERS AND ELEMENTS OF FUTURE AIRBORNE COMMUNICATION NETWORKS

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Abstract

The drivers of future airborne communication capacity are mainly aeronautical passenger mobile communication needs, but also Air Traffic Control (ATC), unmanned aircraft systems integration, airline communications including air health management, as well as weather and scientific mission data dissemination. The increasing variety and volume of personal mobile applications are estimated to cause capacity requirements to a *per-passenger* level of mega-bits per second that may be of the same order of magnitude as capacity related to ATC and avionics *per aircraft*. Consequently, three key elements of future Airborne Communication Networks (ACN) are derived, which include photonic high-capacity communication links, hybrid photonic / radio-frequency diversity networking and high-altitude platform stations for permanent ACN-to-internet connectivity.

1. INTRODUCTION

Novel requirements in both the civil and military aviation sector call for larger Airborne Communication Capacities (ACC) for Air Traffic Management (ATM) and mission data dissemination. Further ACC demand is created by the widespread use of internet-enabled mobile devices by both business and leisure passengers, and other state-of-the-art IT-based technologies. Terrestrial global mobile data traffic is predicted to increase 18-fold within the next four years, strongly driven by a new generation of tablet PCs and smartphones [1], which are also expected to drive the bandwidth demand for airborne communication in the future. Along with an estimated increase in Revenue Passenger Kilometers (RPK) of 4.8 to 5.1% p.a. [2] [3], this user category will generate a high demand for ACC. In addition, fierce competition exists over communication bandwidth with terrestrial telecommunication providers. The limited spectral bandwidth within available atmospheric windows imposes an increasingly efficient frequency use, as well as a rethinking of allocation and utilization, and consolidation of the available spectrum.

Today, communication systems aboard aircraft are spectrally and spatially separated, and strict adherence to licensed frequencies must be ensured. ATM-related communication is facilitated using HF and VHF[1] voice and data links with relatively low bandwidth [4]. Especially in the mobile communications market, satellite communication (SatCom) fulfills a crucial role due to near-global coverage and large overall transmission capacity. However, accessible bandwidth is a scarce commodity and signal travel delays are relatively large due to geostationary distances of large communication satellites. On the other hand, airborne mobile services based on cellular technology, as provided by Aircell [5], are restricted to domestic operations due to range limitations. Concepts that incorporate High-Altitude Platform Stations (HAPS) to provide mobile communication services with wide local coverage are being considered for terrestrial wireless applications [6], and these could prove advantageous for airborne communications as well.

The idea that aircraft themselves can be networked in order to bridge limited communication ranges and to consolidate communication channels originated at the NASA Small Aircraft Transport System (SATS) planning conference in 1999 [7]. This could be facilitated using mobile Internet-Protocol (IP) based networking [8], and the concept became known as the Airborne Internet (A.I.). Moreover, in commercial aircraft design, there is an overall trend towards “e-enabled” aircraft that support IT-based services like Electronic Distribution of Software (EDS), Air Health Management (AHM), and data-centric Air Traffic Control (ATC) which rely on electronic networks [9]. Currently, the SANDRA project in the EU [10] and the Airborne Networking [11] project in the USA are working towards future implementations of networks which support such concepts.

The aim of this paper is to analyze the drivers and determine the elements of future Airborne Communication Networks (ACN), in order to derive promising pathways and means to address the forthcoming challenges. Especially frequency licensing is a fundamental problem in case of large bandwidth communications. Thus, we see large potential in airborne networking using free-space optical (FSO) links due to vast available bandwidth, and believe that technology today is sufficiently advanced for employment in such an environment in the foreseeable future. The paper is organized as follows: In order to estimate technological and topological requirements for future ACN, several drivers were identified and rated by estimated near-future bandwidth requirements as well as time criticality. These drivers are discussed in the following section. Subsequently, a concise review of existing evolutionary ATM modernization programs is given. Last but not least, selected elements of potential future ACN are discussed, with regard to network architectures and topologies, technology, as well as physical limitations.

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[1] (Very) High Frequency.

2. DRIVERS OF FUTURE ACN

The identified drivers of future ACN are mobile Aeronautical Passenger Communication (APC), ATC, unmanned aircraft systems integration, airline communications including AHM, as well as weather and scientific mission equipment data dissemination. Each of these drivers will be discussed below, and a quantification of data capacity requirements is attempted.

2.1. Aeronautical Passenger Communication

The last decade has seen the introduction of game-changing wireless communications devices, like the so-called smart-phones and the iPad™ tablet computer. According to [1], in 2011 only 12% of mobile phones were smart-phones, but these generated 82% of communication traffic. These figures are expected to rise, supporting disproportionately high growth in overall data traffic. Mobile communications technology is constantly evolving in order to keep up with the increasing transmission capacity demands of mobile devices. Moreover, in an increasingly connected world, consumers of terrestrial mobile services are becoming accustomed to 24/7 connectivity. This demand is already reflected in the offering of wireless mobility services in business and commercial aircraft by SatCom. Depending on the type of mobile content, different connectivity demands arise. Four types of content, i.e. voice, music, video, and data in general, were defined and are discussed in the following.

2.1.1. Data

The delivery of data packets through the internet is facilitated using Internet Protocol (IP). IP is a best effort delivery scheme, were bitrates as well as delivery times are variable. Transmission Control Protocol (TCP) is dominantly used for data transfer, which handles functions like error control. Acknowledgement packets are returned by the recipient to confirm packet arrival, which requires an un-congested return path in the network. In the case of a packet loss, data is retransmitted which may introduce large end to end delays [12]. In the case of internet browsing, real-time data delivery is less critical than in the case of voice communications, streaming audio or video. However, packet loss altogether is generally intolerable, and sufficiently large bandwidth on the order of 1 Mbps is desirable for a pleasing user experience [13].

2.1.2. Voice

Voice transmission might be considered the most traditional service in mobile communication. As such, the required bandwidths are moderate. Sophisticated encoding and compression schemes exist, based mainly on distortion-tolerance of human speech recognition. However, it is required that the data stream arrives in a synchronized and timely fashion, and signal delays should be limited to fractions of a second. Efficient speech coding uses compression algorithms to achieve fair speech quality at few kbps data rates in mobile networks [14]. However, larger bandwidth for high quality speech (e.g. Adaptive Multi-Rate - Wideband: up to 23.85 kbps [15]) is desirable for a more pleasant communications experience on the one hand, and increased clarity and distinctness in safety-critical communications on the other. Time delays depend on network type and need to be considered in packet-switched networks and especially in satellite telephony with more than 200 ms signal path delay. Bi-directional voice services need to be near real-time, so generous pre-buffering is not an option. Subsequently, the coding algorithms (codecs) should be disruption-tolerant in case packets are lost. For example, User Datagram Protocol (UDP) may be used for speech transmission, and enhanced by Real-time Transport Protocol (RTP), which adds Quality of Service (QoS) feedback methods [12].

2.1.3. Music

Music contains a broader spectrum of acoustic frequencies and as such requires higher bitrates for decent audio quality. The ubiquitous mp3-standard, for example, delivers quality practically indistinguishable to uncompressed audio at a bitrate of 128 kbps [16]. An internet connection with sufficient capacity along with pre-buffering of streamed audio/music is desirable in order to assure hop-free listening experience. Digital satellite radio broadcast is a bandwidth-efficient alternative, but it doesn’t offer “on-demand” delivery.

2.1.4. Video

A typical uncompressed, high definition video has a raw data rate up to about 600-800 Mbps [12]. Data rates are reduced to more manageable numbers by sophisticated audio and moving image compression techniques. In case of high capacity data storage media like Bluray®, the focus is on perceivably loss-less compression. In this case, bitrates are reduced to up to 54 Mbps [17], including audio. Distribution of video to mobile electronics demands much lower bitrates, as well as buffering techniques in case of bitrate fluctuations. Depending on video resolution and audio quality, bandwidth requirements may still be moderate to large, in terms of typical contemporary wireless transmission rates, for real-time delivery. Compression ratios up to a factor of 60 are feasibly with tolerable impact on image quality [18]. This means that a bitrate on the order of 10 Mbps is necessary for high definition video transmission. In case of low definition video, a bitrate on the order of 1 Mbps can be assumed. Bitrates are expected to rise in the future due to quality evolution and new technologies like 3D, albeit improved compression algorithms are being developed with an expected 50% improvement in compression ratio [19]. Some current mobile devices, like the 3rd generation iPad™ tablet computer, offer resolutions already superior to full-HD video. For audio and video, Real Time Streaming Protocol (RTSP) may be used, for example. Satellite television is a bandwidth-conserving alternative, but again without “on-demand” capabilities.

2.1.5. Estimation of Capacity Requirements

As outlined above, the increasing variety and volume of mobile applications, such as personal management and social entertainment, drives the growth of mobile traffic data. Today, video-on-demand services dominate traffic in cellular mobile networks, accounting for more than 50% of traffic in 2011, with mobile web/data applications close behind and mobile-to-mobile communications coming in third. This trend is expected to continue, with an expected 70.5% of video traffic in 2016 in terrestrial wireless networks [1]. According to TNS [20] the highest growth potential and frequency of usage is attributed to video calling, watching live TV as well as streaming or downloading video/TV.

Of course, the cabin of an aircraft is a slightly different setting. Aircraft operators already offer off-line streaming audio and video for in-flight entertainment, and

Data Usage	Assumed % of PAX	Approx. Data Rate	Weighted Data Rate
Rare use of email and the internet	65 %	Negligible	0.00 Mbps
Email, web-browsing, social networking, internet shopping	25 %	1 Mbps	0.25 Mbps
Multimedia applications	10 %	10 Mbps	1.00 Mbps
Average *per passenger*	100 %	1.25 Mbps	
Average *per 300-PAX aircraft*	100 %	375 Mbps	

TAB 1. Estimated onboard data traffic for a 300-passenger aircraft.

passengers might choose to use these services instead of on-line services. Moreover, certain services may be made available via on-board servers as well, for example travel-relevant data including gate changes, connecting flights scheduling, or digital tourist guides for the destination area, et cetera. Furthermore, passengers are divided into business and leisure travelers, with differing interests. A business traveler might be more concerned with mobile office applications, as opposed to in-flight entertainment services. In order to estimate a plausible per-passenger bandwidth requirement, it is necessary to understand and asses possible mobile user behavior on-board the aircraft.

For the purpose of this analysis we assume three different types of internet users (based on [21]). The described groups are distinguished by their involvement and consumption in terms of online activities (see TAB 1). They range from very rare to frequent users that employ the internet for a wide variety of services and applications. The first group is made up of those people that do not or only rarely use the internet for services such as email. The second group consists of those users whose major intention when using the internet is to access or exchange information. The third cluster contrasts the former two in that it represents frequent users of the internet for services going beyond information or knowledge seeking. For example, they are actively involved by running their own blog and employing various multimedia applications, and these types of applications are a main driver of data growth.

Building on these assumptions, TAB 1 shows the estimated data traffic for a wide-body aircraft with a seat capacity of about 300. Due to their specific online behavior, we assume that frequent users produce a traffic rate of about 10 Mbps per user compared to the moderate users with 1 Mbps. The rare users are assumed to have no impact on online services on-board the aircraft. Altogether, the required data traffic capacity therefore amounts to 375 Mbps for this specific case with fairly moderate assumptions. Existing mobile communications services, using SatCom or terrestrial infrastructure, are limited to bandwidths of currently few Mbps [5]. From these simple considerations, it is evident that any bitrate capacity that is made available for airborne mobile communication services will be embraced by passengers.

2.2. Air Traffic Related Services

Air traffic related services are here defined as voice communication between aircraft and ground controllers, as well as digital controller pilot data link communications (CPDLC). Also, the operation of UAS might be considered as ATC-related, however these aircraft are considered in a separate paragraph. Meteorological information, including clouds, precipitation, and wind shear as well as turbulence data are considered separately as well.

Traditionally, Air Traffic Services (ATS) including ATC relies on analog, amplitude modulated VHF radio communications. ICAO defines an Aeronautical Telecommunication Network (ATN) consisting of digital voice and data services between aircraft, and for air-ground operations, as well as provision for satellite services [4]. The VHF Digital Link (VDL) is defined to support data transmission rates of up to 19.2 kbps per channel, in the vicinity of ground stations. Digital speech transmitted over this link is encoded with a bitrate of 4.8 kbps. Also, HF Data Link (HFDL) aeronautical mobile service with limited capacity is available worldwide. In addition, provision for satellite based World Area Forecast System (WAFS) aeronautical meteorological weather data dissemination in the C-band with 9.6-kbps or faster data rates is provided. The planned L-band Digital Aeronautical Communication System (L-DACS) standard may support up to 275 kbps in data transmission with 75 Nm air-to-ground range [22] in the future.

In case of existing radiotelephone transmission, the acoustic frequency bandwidth is limited to 300–2700 Hz, whereas the bandwidth of human speech may span frequencies from 100 to beyond 7000 Hz [14]. For a clear and well-comprehensible speech quality, a broader acoustic spectrum and bandwidths of about 20 kbps would be desirable over a guaranteed channel. For data-based air traffic services, latency can be tolerated to a larger degree, but delivery should be near real-time. Relevant data like position, heading, and airspeed of near-by aircraft, approach data, weather information, etc. will require date rates which we assume to be comparable to the L-DACS specification.

2.3. Airline Communications

Limited data capacity is required in order to facilitate Airborne Operational Communication (AOC) and Airline Administrative Communication (AAC). Moreover, complex systems like aircraft engines include sensor suites used for health and status monitoring. Data can be disseminated wirelessly on ground after landing [23], or in real-time using SatComs or ACARS data links [24], for example for maintenance procedure optimization. Future health monitoring systems, including for example integrated structural sensors, may contribute to increasing amounts of data, and airborne networks could be used for dissemination. Raw data rates of vibration sensors, for example, can reach several Mbps for 100 sensors [25], but data reduction techniques would be used to extract relevant information. The overall data rates would depend on the amount of sensors, sensor types, as well as interrogation frequency, and are assumed to be in the range of a hundred kbps.

2.4. Emerging UAS Operations

The use of Unmanned Aircraft Systems (UAS) has proliferated in military applications in recent years. According to [26], UAS will dominate the Communications-on-the-Move (COTM) segment of satellite communications until 2020 due to large bandwidth demands especially of Intelligence, Surveillance and Reconnaissance (ISR) sensor data. The RQ-4 Global Hawk military UAS, for example, is able to transfer up to 47.9 Mbps of data via SatCom, and even 274 Mbps via air-to-ground links [27]. In general, for the safe operation of a UAS, the telecommand uplink (TC) and the telemetry downlink (TD), including some encryption overhead altogether require less bandwidth than the video and data content generated by mission-critical sensors.

The introduction of UAS technologies to a number of civilian applications is pending or under way, therefore additional communications capacities will be required in the near future. However, the mission-critical bandwidth requirements will vary according to type, mission, and size of the UAS, and most future UAS designs will probably not depend on satellite communications, but on short-range line-of-sight data links. Typical applications will be image acquisition for emergency response, pipeline monitoring, remote sensing and mapping, environmental monitoring, as well as crop and aquaculture monitoring. A viable assumption that can be made in order to estimate bandwidth requirements of a typical future UAS is that the disseminated data consists mainly of a high-resolution video stream with bandwidths around 10 Mbps. It is likely that only large and sophisticated UAS in long range operation in remote areas would benefit from an ACN.

A special class of UAS is represented by stratospheric High-Altitude Platform Stations (HAPS), which could be used as dedicated broadband communications relay stations for integration into an airborne network and for providing access to ground stations. HAPS will be considered further within the context of network architectures.

2.5. Atmospheric Measurement Instrumentation

2.5.1. Meteorological Data

Modern airliners carry sophisticated weather radars which map extended areas with cloud coverage and precipitation data. Next-generation systems are even able to buffer radar scans in order to generate 3-dimensional weather data [28]. High-speed data links could enable the distribution of large amounts of such data to generate near-real time, visual weather information at high resolution, even to other aircraft without data-generation capacities. Due to the non-Cartesian geometry of a radar image, significant measured data might be mapped to a 3-D grid in a successive manner, using GPS referencing. The data could be sent over a data link to central servers for real-time processing and dissemination. According to [29], the Honeywell RDR-4000 weather radar stores volumetric weather data in a 1 million voxel, 640 nm x 640 nm x 60 kft grid corrected for earth-curvature, with a 30-second update rate. In a rough estimation, and assuming position and heading of the aircraft is otherwise known, this corresponds to a voxel-rate of 33 kilo-voxels per second with possibly 12 bits of information per voxel (i.e. 4 bits reserved for each hazardous weather, predictive windshear, and turbulence measurement data). Assuming a hypothetical data compression by a factor of ten, data generation rates on the order of 40 kbps per aircraft can be expected.

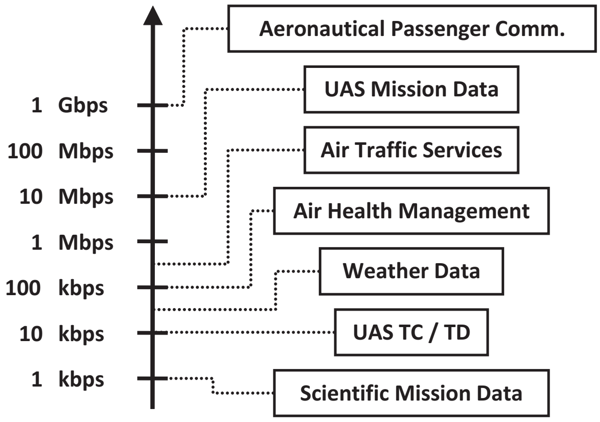

FIG 1. Possible communication capacity requirements of different applications.

2.5.2. Earth Observation Applications

Looking beyond air-travel related services, global climate monitoring as well as modeling is becoming increasingly important. Earth observation satellites are being used with great success, but ambiguities exist and data needs to be verified by earth-based measurements [30]. Moreover, airborne trace gas and air quality measurement campaigns are of great importance to the scientific community. Aircraft dedicated to scientific studies are available only in small quantities, operated for example by NASA [31] and DLR [32]. Therefore, commercial aviation lends itself to assist in climate studies due to the frequent operation along predictable routes. The In-service Aircraft for a Global Observing System (IAGOS) Project [33] operates six Airbus A340 aircraft (as of 2011), with plans to equip 10-20 aircraft with sensors in the future, each carrying trace gas, cloud particle and possibly aerosol measurement instrumentation. Currently data is collected after landing of the respective aircraft, but data dissemination via satellite or an airborne network is feasible, as data rates are low (on the order of 100 kbits/h, [34]). Furthermore, UAS with specialized payloads could collect and disseminate similar data additional on dedicated monitoring missions.

2.6. Overall Capacity Estimation

In the foregoing discussion, we made the effort to quantify bandwidth requirements that can be expected per aircraft in the near future. While it is impossible to accurately predict future demand quantitatively, it can be said that the capacities desired for mobile communications *per passenger* may be of the same order of magnitude as communications capacities related to ATC and avionics *per aircraft*. Therefore, the passengers' communications demand will be limited by the available bandwidth in the foreseeable future, and not the other way around. An illustration of potential future requirements for the services discussed is presented in FIG 1.

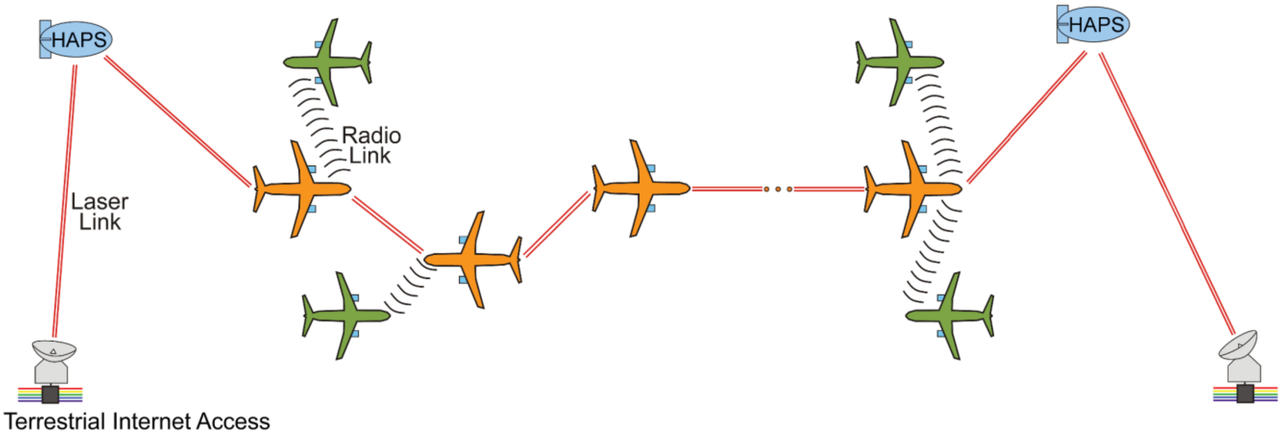

FIG 2. Proposed ACN topology. Optical links enable large-bandwidth access to the terrestrial internet via HAPS to ground stations. LaserComs are employed on large airliners, while smaller aircraft may use directive radio links with moderate bandwidths to connect to the network.

In conclusion, a moderate communications capacity should be reserved for operations-related data, with high quality of service and secure channels. For passenger communications, any increment in available bandwidth that can be provided is likely to be utilized in the future. In the following, we discuss technologies and concepts that may provide the required step-changes in communications capacity.

3. ELEMENTS OF FUTURE ACN

3.1. Relevant European Projects

Currently, programs like SESAR and NextGen are under way, with a focus on improving ATM to keep up with the rapid growth of commercial air traffic. The focus on the modernization of airborne communication systems for ATC is a key aspect, but these projects are not concerned with large capacity networking, or integration of different types of services into a single airborne networking system.

The NewSky project and its successor SANDRA address some of these questions. The NewSky project (2007–2009) analyzes mobile aeronautical communication networks for cockpit and cabin services which combine satellite and terrestrial data links. The project identified the need to integrate various individual communication systems and data links into one widespread common IP-based aeronautical network (IPv6), in order to reduce operational inefficiencies and incompatibilities of systems.

Applying these protocols takes account of the requirements different services impose on the system. NewSky's focus therefore was on specifying network and transport layer solutions with an emphasis on air-ground communications. The goal was to achieve cost savings, high reliability and aligning evolving technologies in an optimal way, i.e. ensuring interoperability. Furthermore, NewSky advocated “Networking in the Sky” and airborne mesh networks were analyzed.

The SANDRA project (2009–2013) continues to analyze seamless aeronautical networking through the integration of data links, radios and antennas. It addresses the integration of applications and services in terms of airline or airport operations, passenger services as well as cabin crew operations. Furthermore, at the network level the new system aims at ensuring the interoperability of network technologies via a common IP-based aeronautical network (IPv6).

However, neither NewSky nor SANDRA considers novel data links or network architectures, which this paper proposes in order to meet future bandwidth demands.

3.2. Key Elements of Future High-Bandwidth ACN

Up to now, we have discussed the drivers of airborne communications and possible future communications capacity demand in aviation, as well as existing projects of relevance. In order to meet future requirements, we propose ACN incorporating three essential elements,

- Photonic[2] high capacity communication links,
- Hybrid photonic / RF[3] diversity networking and
- HAPS-based ACN-to-internet connectivity,

as shown in FIG 2 and as described in the remainder of this paper. Such ACN would be formed between aircraft and would connect to the global internet via terrestrial access points. Due to limited range of broadband wireless connections, only the aircraft near the mainland could communicate directly with the access points. Aircraft over open seas, for example, would then form a chain or a mesh with the aircraft near the shore functioning as nodes to the ground infrastructure. A similar scenario was evaluated in detail within the NewSky project [35] for the important case of the North Atlantic corridor between Europe and the USA, with special attention to network load and timing considerations [36]. In this paper, fixed-location HAPS in the stratosphere are considered to provide high-bandwidth relay services and/or access to the terrestrial internet.

Such an ACN requires capabilities which are novel to the commercial aviation sector. The aircraft in such a network would be both customers of communications services, as well as resources to the network infrastructure itself. Aircraft would function as network nodes, supporting point-to-point communications as well as add/drop capabilities, which allow the multiplexing of a number of signals from

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[2] Technology for signal generation, transmission and processing at optical frequencies (approx. 10 – 1000 THz),

[3] Radio Frequency (approx. 3 kHz – 300 GHz).

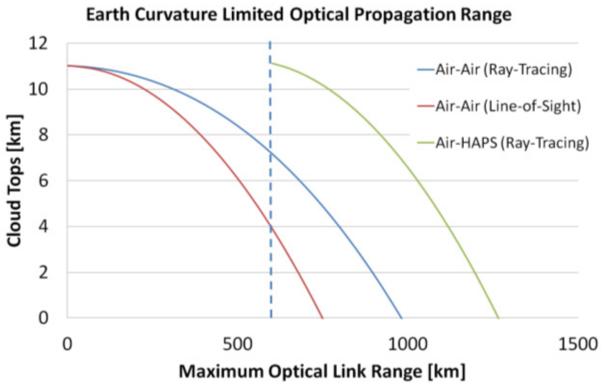

FIG 3. Maximum geometric range (aircraft-aircraft and aircraft-HAPS, with aircraft at 11 and HAPS at 25 km elevation, respectively) considering clouds. Ranges were calculated geometrically assuming vacuum transmission (i.e. line-of-sight), and by ray-tracing (i.e. considering atmospheric refractivity) following [45] and using [39].

different network participants into a single stream, and possibly the ability to buffer incoming and outgoing data streams. Furthermore, each individual aircraft may become a data resource by providing local weather data or other atmospheric data, as we discussed beforehand.

In addition to the topology of airborne networks, the physical layer of wireless communications is of highest interest. It determines range, achievable communications capacity, versatility, complexity, Signal-to-Interference Ratio (SIR), Bit-Error-Rate (BER), outage probability, resilience to atmospheric influences, applicability of radio frequency regulations, and possibility of electro-magnetic interference. Some of these aspects are discussed in the following.

3.3. Performance Limitations of Photonic / RF Airborne Communication Links

Available bandwidth for airborne communications is governed by the International Telecommunications Union (ITU), and only limited amounts are available to the aerospace sector. Within the VHF band, frequencies between 117.975 and 137 MHz are provided for aeronautical communications, with a range on the order of 200 Nm. In the HF band, frequencies between 2.8 and 22 MHz are reserved. Notwithstanding spectrum for radio navigation purposes, this amounts to roughly 40 MHz of bandwidth currently shared among all air traffic participants. Additional bandwidth is supplied by SatCom, which is a commodity that is non-exclusive to the aerospace sector. Also, the UAS community is currently pushing for spectral bandwidth for the safe operation of unmanned aircraft (WRC-12[4]).

With regard for the bandwidth demand derived earlier, we therefore require additional spectral domains for future ACN. The modulation bandwidth of an electro-magnetic wave is intrinsically limited by the Nyquist-Shannon limit [37]; practical wireless systems are further constrained by physical limitations like electronics and antenna bandwidth. In general it can be stated nonetheless that higher carrier frequencies allow larger modulation bandwidths, and thus larger data capacity. Also, the directivity increases with frequency, with a laser beam (ca. 200 THz) being the “extreme” example. Therefore, photonic links seem to be an essential enabler of future ACN.

However, higher frequency radiation is usually more susceptible to atmospheric impairments and geometric limitations. These aspects can be categorized as

- atmospheric extinction,
- atmospheric turbulence and
- line-of-sight limitations.

The ultimate range limit for a line-of-sight communication system is due to the curvature of the earth.

3.3.1. Atmospheric Extinction

Atmospheric windows exist in the visible (VIS) and infrared (IR) spectra, as well as the radio frequency spectrum, encompassing microwave (MW) and millimeter-wave (MMW) radiation. VIS and IR radiation are susceptible to scattering (molecular / aerosol scattering) and absorption (mainly water vapor and CO_2). MW and MMW radiation is affected mainly by water vapor and molecular oxygen. In addition, rain attenuation is considerable within a broad range of frequencies, which we neglect here as transmission above the troposphere is assumed.

3.3.2. Atmospheric Turbulence

In case of IR transmission, atmospheric clear air turbulence is a major factor, in addition to required beam pointing stability. Turbulence is caused by refractive index fluctuations in the atmosphere. While atmospheric turbulence decreases with altitude, boundary layer turbulence is of concern in case of a fast-moving vessel at high altitudes. Commercial systems, which compensate for turbulence-induced beam distortions by means of adaptive optics and gain control are already being marketed [38], so it is assumed that turbulence can be dealt with in the future.

3.3.3. Geometric Limitations

The maximum communication distance is restricted by the curvature of the earth in case of line-of-sight transmission. The atmospheric refractive index gradient allows for a moderate range enhancement by a factor of about 1.3 in the case of communicating stations at 11 km elevation each, due to refraction of the beams. Maximum transmission distance is shown in FIG 3, as function of cloud top elevation (i.e. we assume that radiation is obstructed by clouds). The refractive index structure for an optical beam in a model atmosphere [39] was assumed.

In perfect atmospheric conditions (i.e. cloudless sky), a maximum range of up to about 980 km is theoretically possible. A more realistic assumption is to take the tropopause as the lower limit of ray elevation. This leads to a feasible maximum geometric range of 700 km of an optical system, assuming cloud tops at 6 km elevation. In case of an aircraft-HAPS link, the geometrical range is more than 1000 km in this case. Radio-frequency radiation may penetrate clouds and could reach even further due to diffraction, but a discussion is beyond the current scope. It may be noted that GHz-systems also experience considerable attenuation by water droplets, limiting cloud penetration for large bandwidth RF links.

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[4] World Radiocommunication Conference 2012.

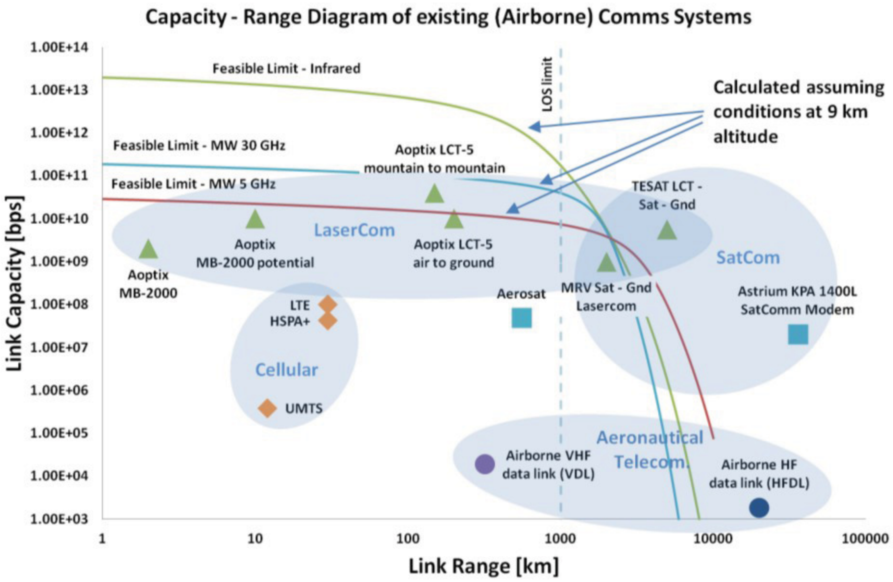

FIG 4. Feasible theoretical channel capacity at 9 km elevation, as function of distance for IR and MW systems, calculated using extinction coefficients from [46] and [44]. Capacity-range figures of different operational communication systems are also shown (references date from 2001-2011). Note that SatCom systems do not experience as much atmospheric attenuation, which partly explains the seemingly superior performance.

3.4. Directive RF and Photonic Technologies

Research is actively seeking disruptive technologies which allow for spectrum- and bandwidth-efficient wireless communications, driven by growing capacity demands as well as increasing frequency congestion. This includes for example cognitive radio [40] and directive links. Cognitive radio is based on adaptive systems, which would allow a communications system to dynamically choose spectral bandwidth not currently in use by other parties. This radical approach would, however, rely on the lifting of licensing restrictions in the radio range.

Directive antennas, on the other hand, may use unlicensed spectrum, like IR or certain MW and MMW range bands. In addition, the directive nature alleviates frequency re-use in the same geographic location. Due to atmospheric effects and power limitations, directive antennas are necessary for long distance, high bandwidth communications, making mechanical or electronic beam steering a requirement. Unlicensed MW/MMW bands suffer from strong absorption, and do not lend themselves to this task.

As a consequence of the inherent limitations discussed above, we envision the use of unlicensed photonic links for future airborne network backbones in commercial aviation. RF links would still be required, in order to set up the network, for backward compatibility with existing infrastructure, and in cases where optical communication is hindered. Short range, MW/MMW directive links would be used as a complementary technology and integrated into the network structure.

3.5. State-of-the-Art and Technological Perspectives

Broadband wireless communication technologies are employed especially in commercial cellular applications and wireless LAN networking, in satellite communications, as well as in military fields. A technology screening was conducted, and the accessible capacity-range data were compared to feasibility-calculations considering realistic transmitter and receiver specifications for IR as well as MW systems at 5 and 30 GHz, respectively, assuming atmospheric conditions at 9 km altitude. The result is shown in FIG 4. The technologies were categorized as LaserCom (photonic), SatCom, and Cellular technologies. In addition, existing standard radio links used in aviation are included (the range figure in case of HF communications is half the circumference of the earth, assuming global coverage). Some SatCom systems perform even beyond the feasibility curves; however, vacuum propagation in this case leads to favorable conditions. The superior capacity, as well as theoretical potential, of the photonic systems is evident. This capacity is achieved although the antenna aperture diameter was assumed to be a factor of 5 smaller, and the power was assumed to be a factor of 1000 less, for the calculated IR link. The calculations suggest that Tbps-bandwidth photonic communication links are technically feasible in the future.

While MW-links could theoretically reach capacities beyond 100 Gbps, practical restrictions and licensing would severely reduce the potential capacity of individual links.

3.6. Network Architectures and Management

In fiber-optic networks, long-haul, Tbps-capacity optical communications is already established. The large technology base may provide Tbps, free-space optical capability to aircraft, using technologies outlined above. Due to the discussed link range limitations, each aircraft with optical terminals would function as a network node, with signal regeneration as well as add-drop-capability.

The function of HAPS would predominantly be to provide redundant access to the terrestrial internet at fixed locations, such as commercial airports with ground

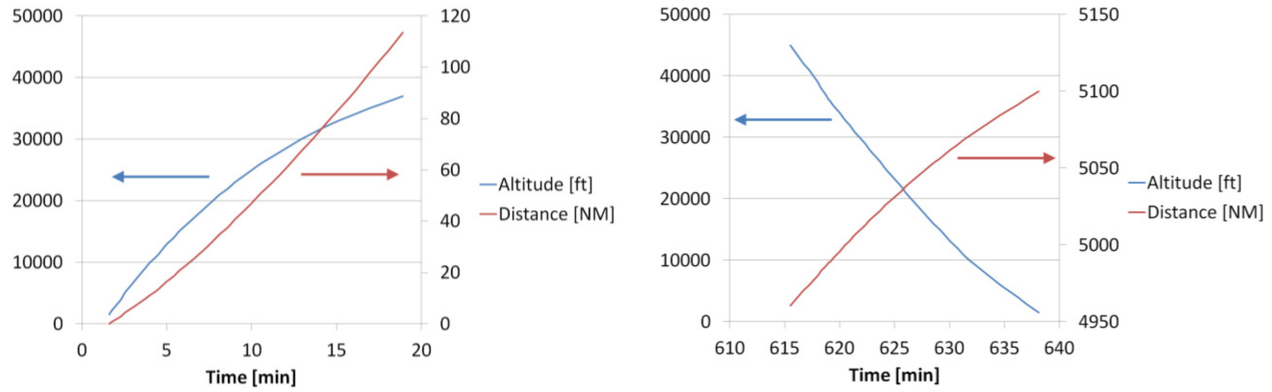

FIG 5. Ascent (left) and descent (right) phases on a typical mission of a twin-engine, long-range airliner [42]. Cruise altitude is reached after about 17 minutes time after takeoff. The descent phase from cruise to landing takes about 20 minutes.

communication terminals. The air-ground link must be realized with photonic technologies in order to transport the aggregated ACN data traffic with Tbps bandwidth. In order to establish permanent link access in the presence of clouds or dense fog, spatial distribution of both HAPS and ground terminals is required.

Due to the complexity of the integration of optical terminals into airframes, a feasible approach would be to implement optical technology only into large commercial airliners, which form a high capacity backbone network, while smaller airliners could hook up to these network nodes using GHz-technology, as elaborated in Section 3.7. Data routing in ACN needs to be decentrally organized with each network node being aware of its current position in the network topology. In contrast to the multi topology routing described in [41] we do not have access to a fully meshed network, so resilience against changes needs to be additionally realized by other mechanisms. Routing as an issue for dynamic airborne networks has for example been comprehensively investigated such as in [36].

Such networks would have a number of inherent limitations. The network structure is dynamically dependent on the amount of available network nodes. This means that network access might be unavailable at times. Also, the nature of directive links would require knowledge about the current node infrastructure in order to form the ad hoc network, which is why RF-based technologies would be used in order to set up the high-speed network.

Another aspect is the fact that such networks would not be set up during cruise or descent phase of the aircraft, due to common detrimental meteorological conditions and possible safety concerns. In order to estimate the time and distance flown by a modern ETOPS aircraft, model calculations were performed [42]. This is shown in FIG 5. Calculations indicate that around 20 minutes of time would pass, and 120 Nm of distance would be travelled in both ascent and descent stage, before the aircraft would set up a broadband network connection. When initializing communications between two network nodes, such as when a new aircraft is to be integrated into a working topology, some form of boot strapping will be necessary, starting with low bandwidth, wide-angle modes and culminating in line-of-sight optical data links.

Safety and security issues also have to be taken into account as separate design concerns in network management. Regarding safety, even a temporary network failure for the intended use of the ACN for high reliability services like ATM or video transmission for UAS guidance represents more than just an inconvenience, but is generally inacceptable. Therefore, the network must have a layered structure of contingency solutions. From a physical infrastructure point of view, sufficient protection of passengers, crew and instrumentation from hazardous exposure to direct laser light is mandatory.

Regarding security, ACN only pose few problems not encountered in ground-based or satellite networks, with only the physical layer of the OSI network model being specific to the ACN proposed in this paper. Due to the highly dynamic nature of the network and the frequent instantiation of network nodes, ACN have to deal securely with handovers between network nodes of high data throughput. More specifically, as we frequently encounter the case of offline nodes entering the network anew, ACN require a distributed authentification and authorization protocol that does not require a central trusted authority. As far as the network security inside the network nodes (typically represented by aircraft) is concerned, the standard precautions apply as described in [9].

3.7. Network Topologies

In cellular networks, Mobile IP based data transmission is used. IP is a packet-based service that allows dynamic and resource-efficient routing through a network. Furthermore, mobile IP allows seamless internet connectivity in case of moving end-user devices. In this case however, the network infrastructure is largely static. In contrast, in Mobile Ad-hoc Networks (MANET), the infrastructure itself may change dynamically. Such networks have been investigated with regard to airborne networking recently, and even an aeronautical IP (aero-IP) has been conceived [43].

Network topologies describe the structure by which the nodes in a network are interconnected. A number of different of such topologies might be applicable the ACN, such as meshes, buses, trees, stars, daisy chains or hybrid combinations of these. When selecting a network topology, the physical limitations of the available technologies have to be taken into account. The ACN discussed in this paper mostly rely on free-space optical transmission technologies which are, by today's technological standards and those of the foreseeable future, bound to the use of sufficiently large optical apertures in the optical communication terminals. Due to space and aerodynamic requirements the number of such terminals to be integrated into an aircraft is limited. As shown in FIG 2, we suppose that our ACN incorporates various classes of capabilities of network nodes, those with RF antenna terminals only (aircraft with small bandwidth demand), and those with hybrid photonic / RF terminals (aircraft with large bandwidth demand and cross-connect capability). Accordingly, the simplest realization of a suitable topology for FSO ACN is a combined bus and hub network, involving a high bandwidth optical backbone implemented by a daisy chain of large airliners (i.e. bus) and radio wavelength branches leading to small aircraft nodes (i.e. hub).

4. CONCLUSIONS

In this paper, the drivers and key elements of future airborne communication networks were explored. Aeronautical passenger as well as airline communications, ATC, and atmospheric data dissemination were identified as major drivers. In order to meet the arising future capacity demands, we envision photonic broadband links for airborne communication networks. The technology necessary for large bandwidth optical communications already exists, with a broad technology base from the fiber optics communications field. The introduction of free-space optical links into airborne networks could enable multi-Gbps communication capacity per aircraft, with overall communication capacity within the Tbps range through the atmospheric channel. Broadband optical free-space communication has not reached wide market penetration in many feasible applications, due to atmospheric effects and outage possibilities in the troposphere. However, advantageous conditions are found within the stratosphere, concerning atmospheric extinction and clear air turbulence. HAPS would be needed as optical air-to-ground access nodes with spatial diversity for cloud mitigation. These HAPS could, for example, be placed above each major airport at stratospheric altitudes. Due to the nature of directive links, optical/GHz-RF hybrid solutions would be necessary in order to dynamically configure the ad-hoc network of aircraft by link initiation. The RF-portion of the network could be based on existing airborne communication infrastructure, while directive high-speed links could carry most of the traffic.

Additional future research on ACN might also include investigating possible business models and billing scenarios, as well as exploring the potential of applying ACN infrastructure to non-aviation related uses such as broadband coverage for sparsely populated areas.

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