AERONAUTICAL BROADBAND COMMUNICATIONS VIA SATELLITE

M. Werner, M. Holzbock
DLR Oberpfaffenhofen
Institute of Communications and Navigation
{Markus.Werner,Matthias.Holzbock}@dlr.de

ABSTRACT

The paper discusses various aspects of aeronautical broadband satellite communications (AirCom). A range of applications and services is identified and categorized into the scenarios of in-flight entertainment, in-flight office, telemedicine, flight security, and flight logistics & maintenance. A number of operational and planned AirCom systems are presented. A structured overview of key issues and respective steps for the system design of an AirCom system is given.

It is intended to provide a generalized baseline for a systematic AirCom design process and reflect some recent, ongoing and planned R&D activities in the field. System aspects are discussed in detail, comprising for example constellation candidates, the aeronautical satellite transmission channel and various aspects of the aeronautical terminal. The paper concludes with an outlook on integrated system design methodology and on the envisaged development of an AirCom design tool (ADT).

1. INTRODUCTION

The demand for making air travelling more pleasant, secure and productive for passengers is one of the winning factors for airlines and aircraft industry. Design studies for airlines and first market entries of in-flight network companies show the necessity for high data rate communication services for airliners, with an obvious trend to Internet applications.

In an aeronautical scenario global (or at least multi-regional) coverage is essential for providing continuous service. Therefore satellite communication becomes indispensable, and together with the ever increasing data rate requirements of applications, aeronautical satellite communication meet an expansive market. According to analysts, the addressable market amounts to $70 billion through the next ten years [1].

It can be clearly anticipated that any early-to-market entry will take an evolutionary approach extending currently existing systems and services, for instance by bundling some narrowband Inmarsat (GEO) or Globalstar (LEO) channels. Observing ongoing global R&D, test & demonstration, licensing and spectrum regulation activities in the field, one finds Boeing as a key player, with the *Connexion by Boeing*™ system/service being the most obvious initiative.

However, as the envisaged satellite systems haven't simply been designed for broadband aeronautical communications, such approaches reveal several deficiencies and/or limitations if one aims at a future-proof system solution in the longer term. For instance, two particularly striking deficiencies with GEO satellites are the coverage problems at higher latitudes (important near-polar long-haul flight routes!) and the extreme antenna steering requirements at lowest elevation angles (i.e., again at higher latitudes).

In the light of this, a coordinated effort of the satellite and aircraft industry together with relevant research institutes seems to be of strategic importance. In particular, aiming at a longer-term satellite system solution that is tailor-made for aeronautical broadband communications, we see an urgent need for basic research work that has to be driven by medium-term industry exploitation plans from the beginning. Parts of this research work are currently being started on a project basis. This paper intends to give an overview of some recent, ongoing and planned R&D activities in the field, with particular emphasis on selected system design issues.

2. MARKET, APPLICATIONS AND SERVICES

2.1 Market Issues

A central issue affecting the addressable market(s) is in how far the underlying business case combines separate market segments which are potentially closely related to the *aeronautical broadband satellite communications (AirCom)* segment in a narrow sense. For instance, a case could be made for a combined aeronautical communication/navigation system business case, or one that brings together AirCom with the extension of "classical" air traffic management (ATM) tasks, or maybe all three of them. Other possible combinations are with S-UMTS, S-DAB, maritime or land-mobile segments.

Lacking sufficient reliable information or data on such issues, we only consider the AirCom segment in a narrow sense throughout this paper. The following two subsections identify application categories and offered services which we think identify this segment.

Two key observations concerning the "geographic market" are (i) the pronounced asymmetry of market opportunities between northern and southern hemisphere (partly just a result of our earth's "continental layout"), and (ii) the fact that a significant share of the addressable market is at higher (northern) latitudes, especially with the important long-haul intercontinental flight routes between the European, North American and East Asian regions. Both observations are illustrated in Figure 1, although its view is Europe-centric; the underlying flight route investigations have been performed within the European ACTS project ABATE and have been used for design and dimensioning studies of an aeronautical subsystem of the EuroSkyWay satellite communications system [2].

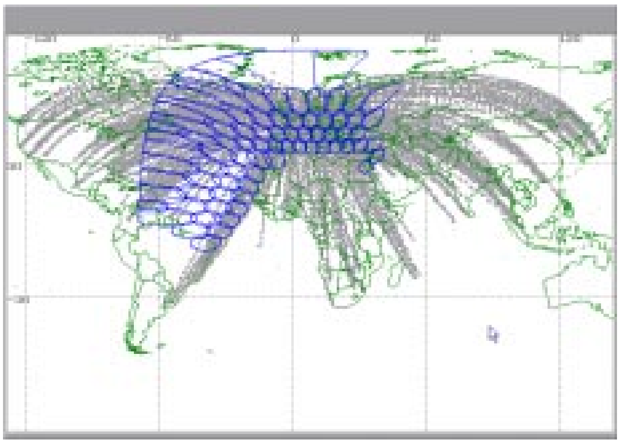

FIG 1. ABATE coverage and flight route density [2]

2.2 AirCom Application Categories

With respect to the aeronautical *communications* sector in the narrow sense as explained and dubbed *AirCom* above, and based on earlier investigations [3], we propose to subdivide the range of applications into the following five categories:

- infotainment,
- (in-flight) office,
- telemedicine,
- flight security,
- logistics & maintenance.

As for the infotainment category, today's in-flight entertainment (IFE) systems are in the majority characterized by one-way services like a limited number of pre-recorded movies or music channels, short screen "news" and rudimentary travel info, all together coming from an on-board storage medium and presented at a fixed time. In many cases, "interactivity" is limited to the freedom of selection between several channels and *re*-action on the offering by tuning in and out. Upcoming features like a suspend/resume function while viewing a video introduce first simple forms of interactivity, and are usually limited in access (e.g., first/business class). Anyway, compared to what modern users are getting acquainted to at home or while moving on ground, and especially taking into account the potential of and demand for all kind of Internet-based services with all their projections into the future, such type of IFE may be regarded as out-of-date. Currently, Internet access for www applications and email seems to be the most attractive and fashioned feature to be provided to aircraft passengers, but the list of services is manifold. Moreover, infotainment (making air travelling more pleasant) is only one of the driving applications for high data rate links to airliners.

Making air travelling more secure for the passengers brings about two other application scenarios: telemedicine and flight security. The attractiveness of telemedicine for airliners is twofold. The possibility to ensure e.g. a video link to a medical expert team on ground and transmit online various vital parameters of an injured passenger will give medical assistance far beyond today's first aid facilities. This may on the one hand attract passengers to airlines providing such a service and on the other hand reduce flight interruptions because of medical emergencies. Bringing a patient of an in-flight emergency to the next airport lasts in adverse cases several hours and immediate medical expert help can save life. Moreover, flight interruptions are very expensive (about 100000 US$ depending on the aircraft size) and are occurring due to medical emergencies about once a month at Lufthansa [4]. Also the age of aircraft travelers shifts to older people, so it is obvious why available services such as oral support and first aid instructions by a medical expert on ground are successfully used by more and more airlines. For this reason, plans for the A380, the new wide-body aircraft of Airbus, show a first aid separate cabin equipped with medical facilities going beyond the 'Doctors Kit' available today. Such a facility is substantially enhanced by powerful communication and data transmission capabilities and can then guarantee that emergencies are diagnosed by medical experts.

Video, audio and avionic data transmission may also be an issue to resolve or analyze aircraft disasters. Flight data, cabin and cockpit video can be sent to and stored for a certain time on ground. In case of aircraft disaster, these data can give helpful information for resolving hijacking by being 'live on board' or analyze aircraft failures faster and more precisely, before the 'black box' is found.

Focusing on one of the airlines most worthy assets - the business traveler - , the time being spent on board an aircraft has to be made more productive. Design studies show that airlines are thinking of a new kind of office class. Almost one half of aircraft passengers are business travelers. Over 70 percent of them is carrying a mobile computer and over 80 percent a mobile phone [5]. The aircraft office for this user group raises some other design and technical challenges. While Internet access for passengers being on a vacation trip has to be available on installed terminals - e.g. in seat, the business user on board wants to connect his own equipment to the communication network, and power for this equipment has to be provided. Although a standardized in-seat terminal would ease electromagnetic compatibility problems, the need for a private workspace supporting the connection of own equipment will prevail from the airline customers' view. This brings about the interesting question of applicable protocols. Mobile IP may provide not only the possibility of getting access with personal equipment to Internet and work on the familiar desktop, it could also serve to extend the "personal network", for instance a company's VPN, to everywhere in the sky.

Finally, also logistics and aircraft maintenance information, which is not observable to the passenger, but can reduce on-ground time and ease maintenance of the aircraft, should be mentioned as important application class. As an example, uploading the audio and video servers can replace difficult distribution services of bringing the changing entertainment programs on board. While in a first step a plain multicast transmission of these programs to selected airplanes can replace copying data on tapes, in the future one may also think of even more adaptive video and audio programming solutions with respect to the single customer. Finally, if the cabin crew or automated sensors recognize faulty equipment, maintenance personal on ground can prepare the repair and organize replacements parts in advance, based on detailed fault identification data being transmitted immediately.

TAB 1. Categorized AirCom services

Category	Services
Infotainment	www, email, live TV, gambling, phone, intelligent travel information
Office	email, www, phone, fax, video-conferencing, file transfer
Telemedicine	video conferencing, vital data trans-mission
Flight security	cabin survey, cockpit survey, flight recorder data transmission
Logistics & maintenance	video and audio server upload, aircraft maintenance data

2.3 AirCom Services

The five application categories entail a range of particular communication services which in turn drive related technical requirements. Table 1 assigns to each application category respective key services; obviously, some services fit into more than one category. Moreover, not all services will be permanently required. In case of an emergency or disaster, for instance, the shutdown of infotainment and office services for the benefit of telemedicine or flight security applications is acceptable. From a system design viewpoint, this immediately relaxes the worst case data rate demand of the aircraft communication system.

From the identification of relevant services it is a natural step in top-down system design to subsequently extract and specify the respective technical requirements. As a first approach in the considered AirCom scenario, Table 2 provides a classification into

- availability in terms of flight duration (long, medium, short haul flights),
- data rate requirements (system design oriented),
- delay, delay jitter, BER (user-oriented QoS),
- required protocols and data formats,

indicating some key service requirements in a qualitative manner. Identifying which services are (not) required with a certain flight duration category is particularly important for user/terminal capacity estimations and thus basic input information for the capacity dimensioning process, besides the usual data used there (number and location of users/terminals, activity, etc.). Besides that, this may also result in different aeronautical terminal types for long- and short-haul flights.

3. OPERATIONAL AND PLANNED SYSTEMS

In this section, we present a small collection of planned commercial systems/services for broadband satellite communications to airliners, and some currently operational systems or services that may be regarded as predecessors. Finally, we point at some trials or demonstration flights that have already been performed or announced by airline companies, featuring AirCom services and/or related technology.

3.1 Operational Systems and Services

SITA AIRCOM-I

SITA is a leading provider of global telecommunications and information solutions to the air transport industry [6]. Founded by member airlines in 1949, it now runs global integrated voice and data networks to serve airlines, aerospace companies, air-freight organizations, travel and global distribution companies, airport authorities and governmental organizations. Besides their *VHF AIRCOM* system based on hundreds of VHF ground stations world-wide, they operate the *SATELLITE AIRCOM* system providing voice/fax and data services mainly to long haul aircraft. With *AIRCOM-I*, this service offering is complemented for short and medium haul aircraft using new equipment reduced in size, weight and cost. The nearly global spot beam coverage is achieved using geostationary Inmarsat-3 satellites at 54°W, 15.5°W, 64°E, and 178°E. Both passenger communications and airline operational traffic are served. Among other equipment, a specific aircraft requirement is a 6dBi intermediate gain antenna.

Together with AirTV, a global media satellite service dedicated to the airline industry, SITA has recently entered into an agreement to jointly offer Internet and real-time TV and audio services over a four satellite broadband network (press release May 2000). The service should be available by the last quarter of 2002.

Racal MCS-3000/6000

Designed for the Inmarsat GEO satellite network, Racal Avionics together with Honeywell offer the MCS-3000/6000 multi-channel aeronautical satellite communications terminal [7]. It provides basically 2/5 voice/fax and 1 data channels and supports PC modem communications. For passengers, telephony, fax, PC data and value added services (such as flight, car rental, hotel reservation services, in-flight shopping) are supported, and for the cockpit crew, voice and data operational/administrative services are available.

“Airborne multimedia services” and “new terminals under development for high data rate aerosatcom” are mentioned as ongoing activities without further details [7].

TAB 2. Service requirements (-- to ++ increasing requirements)

service	flight duration category	bit rate	delay/ jitter	BER	protocol / data format	remark
phone	all	--	++/++	o	GSM, ISDN	
fax	long	--			ISDN	
gambling	all				TCP/IP, mobile IP	
email	all	--	--		TCP/IP, mobile IP	
www	all	o	--		TCP/IP, mobile IP	
intelligent travel information	all	o	--		TCP/IP, mobile IP	special www service
file transfer	long		--		FTP, TCP, mobile IP	
vital data transmission	all	o	o			
cabin/cockpit survey	all		o			
flight recorder data	all		+			
maintenance data	all		--			
video-conferencing	long		++/++	o		
audio server upload	all		--	--	MP3	multicast
video server upload	long		--	--	MPEG	multicast
live TV	long		++	o	MPEG	broadcast

3.2 Planned Systems

Connexion by Boeing™

Boeing has recently unveiled plans to provide live TV/audio and real-time high-speed Internet (data) services to commercial airlines, business jets and government customers [1]. Rollout is foreseen to start on North American routes by 2001 and to be expanded to other global flight routes through 2005. Currently, Boeing is in negotiations with airlines, service and content providers on further steps in the introduction of this service. Two-way broadband connectivity shall be delivered directly to airline seats to provide passengers with personalized and secure access to the various forms of content via their own laptop. Initially, an asymmetric available bandwidth of 5 Mb/s receive and 1.5 Mb/s transmit per aircraft is envisaged. Customer airplanes will be equipped with a Boeing proprietary phased array receive and transmit antennas. Boeing claims that this antenna technology "provides dramatically faster data transmission capability than currently exists today", besides the enhanced response to directional changes by electronic instead of mechanical steering. However, the initial design and development of the mentioned antenna has been carried out in 1986, and several critical issues concerning antenna technology and design will certainly have to be addressed in ongoing work. Some first investigations in this direction are presented in Section 4.6.

Connexion by Boeing™ plans to lease multiple transponders of Loral's geostationary Telstar satellite fleet providing C band and Ku band coverage not only over the continental United States, but also over Europe, Asia, South America, northern and South Africa. Given each of these regions, airplanes on most national or continental flights cruise at low to mid latitudes and thus the minimum elevation angle requirements between aircraft and GEO satellite seem to be moderate at a first glance. More severe challenges in terms of coverage and antenna steering angles, however, come along with some important intercontinental flights (e.g. US-Europe, Europe-East Asia, US-Asia) using routes at higher (northern) latitudes, and this huge market may be reason enough to also think of non-geostationary alternatives in the longer term. Related issues are discussed in Section 4.4.

Inmarsat I-4 / B-GAN

With its fourth generation of satellites, the *Inmarsat I-4*, Inmarsat plans to build *a Broadband Global Area Network (B-GAN)* to be operational during 2004. According to announcements, plans are to deliver Internet and intranet content and solutions, video-on-demand, video conferencing, fax, email, voice and LAN access at speeds up to 432kbit/s virtually anywhere in the world via notebook or palm top computers [8]. Interoperability with the current I-3 satellite network is foreseen, thus allowing seamless migration to the new services.

In Flight Network (IFN)

Barely a year after the launch of this initiative it has recently (April 2001) been announced to be canceled "due to slower than anticipated market development" [9]. The venture failed to win a major customer, even for trials, and to attract support from Internet and telecommunications companies [9]. Nevertheless, we think it is worth summarizing some of its key drivers and goals, being more than just reminiscence of a particular ceased venture. Rather it should contribute with some interesting aspects related to satellite-based AirCom as a business sector in general.

In Flight Network had been formed as a joint venture by News Corporation and Rockwell Collins, aiming at a global in-flight entertainment system based on a broadband, Internet-like architecture to be deployed in phases starting late 2001. IFN's business model was advertiser-oriented, providing a flexible framework for tailored delivery of advertisements via full-motion broadcast video channels or Web-based video spots or banner ads. A wide range of programming adaptation was foreseen, for instance with respect to flight duration, origin and destination, global or regional interest, and flight segments. The joint venture aimed at combining News Corporation's interests in providing content with taking advantage of Rockwell Collins' existing Integrated Information System (I2S) as an on-board computing and software platform to base IFN development upon.

IFN content for passengers, as well as maintenance diagnostics and navigation and flight plan data would be exchanged via a low-power microwave airport gatelink system while the aircraft is on ground. Data with real-time requirements (weather info, news, email and Internet access) could be transferred via the satellite system, where IFN announced to use “proven, existing satellite communications facilities and digital broadcasting technology”. At a first glance, this obviously meant use of geostationary satellites not only for broadcast services, but also for broadband Internet data in the forward link. However, IFN had also announced plans to cooperate with Globalstar and Qualcomm, carrying the respective return link over the global LEO system, and also using the Globalstar network as an independent two-way channel for email, Internet access and other applications with moderate data rate requirements. The main driver for this strategy was to avoid both, (i) long waiting times until deployment of new satellite networks and (ii) large investments in expensive new antennas.

3.3 Airline Trials and Demonstration

SAS

Scandinavian Airlines (SAS) is the first airline in the world to test wireless email and Internet for passengers onboard an aircraft. The test will begin during 2001. Referring to an SAS press release (01-01-24) SAS has signed an agreement with Telia and Seattle-based Tenzing Communications Inc. to test Tenzing’s communications system for wireless Internet access onboard aircraft. SAS passengers will gain access to email and Internet via portable PC or Mac.

During the test, passengers will be able to send and receive email and have access to the Internet via an Internet server onboard the aircraft. A LAN (local area network) based on IEEE 802.11b technology, the first standard developed for wireless networks, will be installed in the cabin.

Passengers will gain access to the SAS website and other travel-related Internet portals. The onboard server is linked via Inmarsat satellites to a ground station when the aircraft is airborne and the content is transmitted and updated at regular intervals.

SAS is also working to find a solution so that passengers can gain access to their own company’s email system behind a firewall. In the future, Tenzing also foresees being able to implement broadband connections onboard aircraft using advanced satellite technology.

Lufthansa FlyNet

At the end of the year 2000 Lufthansa was able to demonstrate successfully TV and fast Internet access on a private Airbus A340 equipped with an aeronautical terminal antenna of Boeing. The coverage restricted system was able to receive 400 TV channels and allowed online access.

Lufthansa's Chairman of the Executive Board Jürgen Weber announced last November "... With an eye on customers, Lufthansa is developing ‘services for mobile people’: Under the ‘FlyNet’ label, it is set on becoming the first airline to lay on live TV and Internet access for passengers in the aircraft cabin...".

This enthusiastic statement was modified and more careful prognoses now state that it will take until 2005 to equip Lufthansa's complete long-haul fleet with the regarding technology provided that broadband satellite systems will come operational till this date.

Table 3 finally assembles the (available or planned) service profiles in keywords, mainly using the respective companies’ announcements and news, and tries to classify them according to the application categories identified in Section 2. This gives a first impression that the infotainment sector gains a lot of interest, probably due to enormous market expectations. However, the office sector and the more customer-oriented elements of the airline logistics services start to catch up, whereas the remaining two sectors are certainly more driven by systematic planning, administration and international coordination under the dictate of much more critical “quality of service” requirements than infotainment and office applications. Sophisticated telemedicine will certainly become an on-board essential one day, but the development and service provision can of course not be driven by market competition and Internet hype alone.

TAB 3. Service profiles of available or planned systems/trials

	Infotainment	Office	Tele-medicine	Flight security	Logistics & maintenance
SITA AIRCOM-I (existing)	telephony fax modem (access to ground-based value-added services) (planned:) email Internet access multi-channel live TV, video&audio			ground-to-air voice calling service	data (AOC&AAC) cabin and flight crew applications
Racal MCS-3000/6000 (existing)	telephony fax modem (access to ground-based value-added services)				data (AOC&AAC) cabin and flight crew applications
Connexion by Boeing™ (planned)	email www *- surfing* *- stock trades* *- reservations* live TV news&info intelligent travel info *- airport/flight maps* *- gate information* *- destination info (weather, reservations, etc.)* e-commerce *- shopping* *- duty-free*	email reports company news			crew info *- enhance operational efficiency on ground and in air* carrier information *- travel planning* *- travel support* *- frequent flier mileage*
Inmarsat I-4/ B-GAN (planned)	voice&fax email www LAN access video-on-demand	B2B sector services intranet video conferencing			
In Flight Network (IFN) (planned earlier & canceled)	email www live TV recorded video recorded audio voice over IP	business channels in multiple languages			cabin and flight crew applications maintenance diagnostics navigation databases flight plan data passenger services
Lufthansa FlyNet	live TV www				
SAS (planned 2001)	wireless email and www				

4. SYSTEM DESIGN: KEY ISSUES

This section provides a structured overview of key issues and respective steps for the system design of an AirCom satellite communications system. The different issues are discussed at a different level of detail, reflecting the somewhat unbalanced depth of earlier and ongoing R&D work on the topic. However, it is not the only intention here to give a kind of R&D or project status report, but also to provide a generalized baseline for a systematic AirCom design process.

4.1 Market Entry Options and Business Case Implications

Different market entry options and reference business cases must be taken into account in an initial stage of AirCom system design.

Market entry options immediately drive technology and frequency band used. The evolutionary path leads via C/Ku band and existing GEO transponders, whereas the "revolutionary" path may target from the beginning at advanced Ka band technology and the design of a tailor-made, potentially non-GEO system.

Concerning the business case(s), it is very important to have a clear perspective early enough on how far the AirCom broadband communications market in a narrow sense will be targeted in combination with other potential market segments like navigation, air traffic management, etc.

4.2 Frequency Band and Spectrum Regulation

In order to satisfy increasing data rate requirement and to overcome restricted bandwidth availability at lower frequencies, broadband services have to operate more and more at higher frequency bands. Aeronautical channel characterization measurements have proven that frequencies up to Ka band and above are suitable for aeronautical communication systems [10]. In-flight multimedia service demonstrations at K/Ka band validated that technology is manageable and a system is operable at these frequencies [11]. On the other hand, in the short/medium term the way to future broadband AirCom will most likely lead via available transponders/systems and "cheaper" antenna technology, giving some preference to C and Ku bands.

Regarding possible frequencies for aircraft multimedia services in the mid- and long-term future, several questions arise. As a matter of fact, current FCC regulation on Ku band often explicitly phrases "mobile (excluding aeronautical) ...". Consequently, current tests or trials using available Ku band antennas need a dedicated trial license. So what is the future of Ku band in this game? And in general, can the broad service spectrum as identified in Section 2 be properly covered by current allocation classifications (FSS, mobile, broadcast, etc.) at all, or is there a demand to look at dedicated allocation for satellite aircraft services? The fact that Boeing had representatives at WRC 2000 in Istanbul to work toward getting spectrum for data services to aircraft in flight [12] may be interpreted as strong interest in that direction; at least it shows that such issues need to be addressed soon. This becomes even more delicate if one opens the broadband aircraft scenario not only to GEO satellites but also alternative constellation approaches in the longer term. Similar questions as with the narrowband big LEO/MEO systems may become important, like mobile vs. fixed and primary vs. secondary classification, band sharing, interference issues, link budgets, and global vs. regional harmonization.

4.3 Aircraft and Flight Characteristics

The major interest here is in (i) geometric/geographic aspects of single flights, in (ii) global/regional flight route statistics/data, and in (iii) geometric implications from aircraft body structure; (i) and (iii) are in combination important for all later design issues where relative geometric position and attitude (changes) of aircraft and satellite(s) play a role, like effective coverage, antenna pointing, and link shadowing, whereas (ii) provides essential input information for satellite spot beam antenna design and for capacity dimensioning.

4.3.1 Flight Characterization

4.3.1.1 Per Aircraft

For our purposes, relevant flight characteristics of a single aircraft fall in two categories: (i) identification of different generic flight phases over time, and (ii) description of aircraft position and attitude as a function of time. From both, typical worst-case situations (in terms of line-of-sight conditions to a satellite) can be extracted that are important for later design issues, such as constellation choice and terminal antenna design.

A "flight" in generalized sense can be subdivided into the following flight phases:

- on-ground (standing)
- taxiway
- take-off
- ascending
- cruising
- course changes
- descending
- waiting loops
- landing

The position and orientation (or attitude) of the aircraft as a rigid body in three-dimensional space have a major impact on the view angles under which a satellite is seen from the aircraft. Being time-dependent, both must thus be thoroughly considered through all flight phases. It is obvious that worst-case situations (in terms of position/orientation in space) will encounter that have a significant impact

- on the satellite constellation design, mainly via the *minimum elevation angle* ε_{min} as key system parameter,
- on the design of the terminal antenna, mainly in terms of radiation characteristic, selected technology and PAT (pointing, acquisition & tracking),
- and on the location/placement of the terminal antenna(s) on the aircraft's fuselage (which is of course in close relationship to the last item).

From the viewpoint of the aircraft (more precisely, from its center of mass or the antenna center, depending on the issue considered) any other point in space can be located at a *relative* position. Taking such an "aircraft-centric" view with the aircraft's center defining the origin of a respective coordinate system, the "absolute" position of the aircraft (in a geocentric coordinate system, for instance) is no longer required for calculation of distance and view angle to other points in space. A unique description of the aircraft's own orientation in space (attitude), however, is indispensable to properly define such a aircraft-centered coordinate system, and must particularly provide the "anchoring" with respect to the fundamental geocentric references, usually earth center and north directions.

A customary approach for attitude determination and control of both airplanes and satellites is the *roll-pitch-yaw (RPY)* convention, used by most of today's IRS (inertial reference system). It defines roll, pitch and yaw axes of a rigid body as follows:

- x^{body} = roll axis, positively forward (in flight direction)
- y^{body} = pitch axis, positively to the right (w.r.t. flight direction)
- z^{body} = yaw axis, positively downward (towards earth center)

The attitude of the body in space is then described by the corresponding angles, each defined positively clockwise around the respective axis:

- α = roll angle, positively right wing down, from the horizon, range –180°...180°
- β = pitch angle, positively nose up, from the horizon, range -90°...90°
- γ = yaw angle, positively eastwards, from the north direction, range -180°...180°

A formal vector geometric introduction of the related terminal-centered coordinate system proves to be helpful when the aircraft is only considered as an attitude-changing rigid body carrier for one or more mounted terminal antennas, and when detailed calculations of distances and antenna view angles towards the satellite(s) are performed [13].

4.3.1.2 Global/Regional Flight Routes

Flight route statistics/data are relevant to get (series of) snapshots of airplane distribution in the service coverage area, which are essential input information for satellite antenna spot beam design and overall system capacity dimensioning. Usually, the latter will be based on some worst case situation extracted from the snapshots.

A simplified minimum set of data describing a global or regional flight scenario could be based on

- departure and destination airport locations,
- related departure and arrival times (either from exact time tables, or as a flight frequency model),
- a simple model for cruising speed (e.g., simply a constant speed derived from the flight distance divided by the flight duration, neglecting any influences from other flight phases),
- a simple model for geographic flight routes (e.g., each flight following a great circle between start and destination).

A more detailed investigation of related issues and review of available database material is required and envisaged in ongoing and future work.

4.3.2 Aircraft Characteristics

Here we focus on some relevant characteristics of an aircraft's rigid body geometry, inspired by its inherent impact on effective line-of-sight view conditions from a point on the fuselage surface where a potential antenna may be mounted. Figure 2 illustrates four potential positions A, B, C, D for an antenna mounted on the aircraft. At positions A - C the antenna would be mounted directly on top of the aircraft's fuselage, whereas at position D it would be mounted at the top of the tail structure.

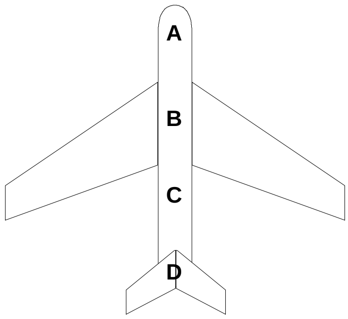

FIG 2. Potential antenna positions (top view)

Due to size and weight of mechanical antenna steering equipment position D is only possible with electronically steered antenna(s). In case of a tail-plane at the top of the tail structure, as typically encountered with some smaller or older airplanes, this could be mounted flat on the tail-plane. For larger modern airplanes with the tail-plane typically at the height of the fuselage, a flexible microstrip antenna adapting to the surface of the tail structure could be a solution. These are, however, issues for further detailed investigations, also taking into account potential pointing problems resulting from more pronounced vibrations of the tail structure as compared to the fuselage. In the current context it remains only important to notice that such an exposed antenna position inherently provides advantages from a line-of-sight blockage viewpoint.

For antenna positions A-C, shadowing through the tail structure may be severe. Table 4 summarizes the respective shadowing angles for various types of aircraft. More precisely, the maximum tail-plane elevation ε_{TP} and the maximum tail structure elevation ε_{TS} in degree are listed, both measured from the reference plane which is defined by the antenna center and the roll and pitch axis vectors of the aircraft. Values <0 for ε_{TP} mean that the tail-plane of the respective aircraft is at the height of the (vertical center of) fuselage and thus below the reference plane (antenna on top of fuselage!).

TAB 4. Shadowing angles of airplane tail structures in degree

Antenna position	A		B		C	
Shadowing angle	ε_{TP}	ε_{TS}	ε_{TP}	ε_{TS}	ε_{TP}	ε_{TS}
Airbus						
A340-200	<0	10	<0	15	<0	30
A340-300	<0	9	<0	14	<0	26
A320-200	<0	11	<0	18	<0	29
A321-100	<0	12	<0	15	<0	25
A310	<0	13	<0	20	<0	35
Boeing						
747-400	<0	9	<0	15	<0	
737-300	<0	12	<0	20	<0	30
737-400	<0	12	<0	19	<0	30
737-500	<0	13	<0	20	<0	30
Dornier						
328 turbo-prop	14	15	20	22	30	33
Fairchild						
Metro 23 turboprop	1	10	2	14	3	19
Cessna						
CitationJet	12	14	18	19	28	30
Citation S/II	4	15	7	21	8	34
Model 560 Citation V	4	15	7	21	8	34
Citation VI	15	15	20	20	36	36

4.4 Satellite Constellation Issues

4.4.1 General Considerations

For the near-term future and any evolutionary approach towards aeronautical multimedia communications, a broadband network based on geostationary satellites seems to be the first option. At least predecessor systems and/or services are available today that are mainly based on the (Inmarsat) GEO satellite networks. Moreover, with the demise and/or the continued financial problems of some current narrowband non-GEO constellations, understandably there is some general discouragement in the satellite telecommunications community concerning the question of constellation alternatives.

However, a GEO solution for the purpose of future broadband communications to aircraft in flight does also exhibit a number of specific problems and drawbacks, so that a mid- or long-term system design should not be done without an unbiased and comprehensive study of all pros and cons.

With a LEO or MEO solution, in particular, potential system capacity limitations and latency for real-time communications could be reduced. On the other hand, besides system costs, especially networking complexity tends to increase while moving to lower orbits; satellite handover will become a major issue, and intersatellite links may be necessary at least for LEO constellations to provide connectivity over large ocean areas. In any case, a LEO or MEO constellation design for broadband aeronautical communications may differ significantly from the big LEO MSS case in dependence of the concrete market segments, service profiles and other key requirements and constraints, so that it is worth being studied in more detail if a competitive non-GEO solution is feasible.

As already mentioned, the main critical issues in a GEO system are the coverage deficiencies at higher latitudes and the extreme antenna steering requirements at lowest elevation angles (i.e. again highest latitudes), and this in the light of the important near-polar flight routes in the northern hemisphere. With an appropriate non-GEO (LEO, MEO, or HEO) satellite constellation these problems could be avoided, and in particular coverage with clearly higher elevation angles could be realized in near-polar regions.

In the following, we will restrict to consider a MEO solution as the most promising alternative to a GEO system, mainly because it can be regarded as a somewhat reasonable trade-off between (i) coverage/elevation statistics provided, (ii) system complexity, costs and resource utilization (better than LEO), and (iii) moderate latency, acceptable also for real-time services (a significant drawback for HEO here).

4.4.2 Coverage Issues

The minimum elevation angle ε_{min}, one of the key parameter for satellite system design, is usually a parameter of earth-space geometry and related to terminal or user *positions* on earth only, but not to terminal or antenna *orientation*. The (nominal service) coverage area of a satellite is defined as the area containing all locations on earth from which the satellite is seen with an elevation angle larger than ε_{min} against the horizon. In the aeronautical communications scenario, however, it is important to consider *relative elevation angles* with respect to the *virtual horizon* of the attitude-changing aircraft, which is the plane defined by the roll and pitch axes of the aircraft body. Assuming an antenna mounted on top of the aircraft with its boresight direction parallel to the yaw axis, i.e. perpendicular to the virtual horizon, the relative elevation angle of a point in space can very easily be translated into the 90°-complementary *off-boresight* or *steering* angle of the antenna.

For further considerations, let us assume a phased-array antenna mounted o top of the aircrafts's fuselage at position A, with a rotational-symmetric (around the yaw axis) radiation pattern and a 3dB-steering range of, say, +-70°. This yields a minimum relative elevation of +20°. In order to derive the effective (nominal) minimum elevation angle (from horizon) for satellite coverage under *permanent* line-of-sight conditions, in general a “worst-case overlay” of both body structure elevation angles and RPY attitude has to be considered for all flight phases where service shall be available. With the assumed antenna position A, however, any body structure blockage is outside the steering range of the antenna. Moreover, during the cruising flight phase for instance, pitch values are usually negligible with respect to standard roll angles of 25° during maneuvers. Thus the worst-case situation arises when the aircraft is at the edge of (nominal) coverage, its flight vector is orthogonal to the line between aircraft and satellite, and a maneuver requires rolling to the opposite side from satellite direction. Then the minimum relative elevation angle of 20° and the maximum roll angle of 25° add positively up to a 45° requirement for the nominal minimum elevation angle of the system in order to guarantee permanent visibility. From Figure 3, finally, one gets an impressive confirmation of the earlier statement that a GEO system solution faces severe coverage problems at higher latitudes; with a 45° minimum elevation requirement, it can only cover locations up to approximately 40° latitude. Compared to that, a MEO approach does not yield so much smaller footprints, but with a reasonable constellation design, permanent coverage up to high latitudes can be achieved with a moderate number of satellites.

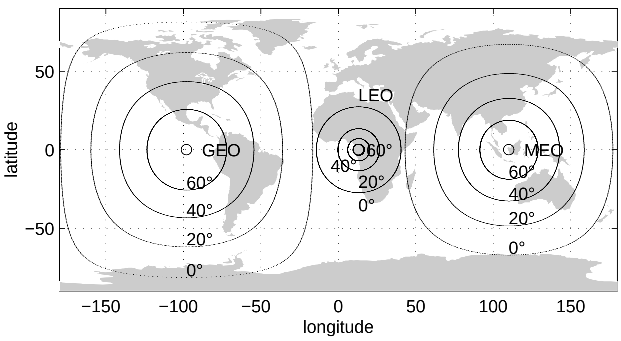

FIG 3. Coverage areas of satellites in different orbit types for several minimum elevation angles [17]

4.5 Aeronautical Channel Implications

The aeronautical transmission channel is crucial for the design of high-quality services. Frequencies at Ku band, K/Ka band and above are likely to be used since spectrum at lower frequencies is too limited for multimedia applications. In earlier work [10] the aeronautical channel has been investigated in K band at 18.685 GHz using a steered Cassegrain antenna with a beamwidth of 4.2°.

During normal flight cruising the aeronautical channel has been reported to be fairly constant in power, with very small fading following a Ricean probability density function with very high values of the Rice factor c up to 34 dB. This behavior can be observed in all situations where the antenna is in line-of-sight with the satellite, i.e., the path is not obstructed by any obstacle. Shadowing or diffraction of the radio signal may occur on ground by buildings when the aircraft is at the terminal or on taxiway. During the flight the signal may suffer diffraction or shadowing from the aircraft structure (tail, wings) during maneuvers or when the aircraft is cruising at low elevation areas of the satellite (near-polar areas with a GEO, for example). Figure 4 shows a typical measured power series with fading up to 13 dB caused by the wings during a 180° turn with a roll angle of 20°.

The radio signal at millimeter wavelength is also subject to atmospheric attenuation due to vapor and oxygen. These effects can be calculated statistically using the absorption and rain models of the ITU [14,15]. The attenuation depends mainly on the flight altitude, the region, and the weather conditions. The effect of wet antenna radomes have not yet been addressed thoroughly in the literature.

Shadowing and diffraction in aeronautical multimedia services will cause the radio connection to drop since the considered satellite systems will most likely not provide exhaustive link margins to compensate deep power fades. Thus the sources of shadowing have to be differentiated and appropriate countermeasures must be investigated.

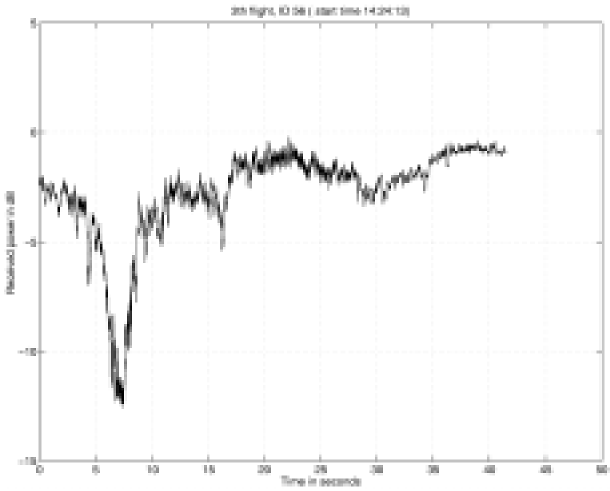

FIG 4. Shadowing of the signal due to airplane structure (wing)

4.6 Antenna Design and Technology

For a first assessment of suitability of antenna type and technology issues, the key parameters will certainly be the data rate and steering angle (mainly elevation) requirements. The critical case in operation arises when the maximum rate has to be provided at lowest angles, thus at the edge of beam coverage with smallest antenna gain.

4.6.1 Terminal Antenna

A detailed discussion of aeronautical terminal antenna design issues is given in [3]. To maintain the purpose of this paper to give an overall view, this section summarizes the crucial points.

Due to aerodynamic issues the outdoor part of the antenna design has to be minimal protuberant. For this reason, a minimized antenna size is advantageous, supported by the fact that the antenna size decreases for fixed gain at higher frequencies.

But concurring with this design issue, high data rates will require the use of high gain antennas with small beamwidths. To enable a continuous communication link, such antennas have to be pointed towards the satellite throughout all flight and on ground maneuvers of the aircraft.

As discussed previously an aircraft is a very agile, attitude changing vehicle. While in a land mobile scenario the angular change rates are the dominating factor for antenna beam agility design, in the aeronautical application the absolute values of the attitude angles are a technical challenge. In-cruise maneuvers lower (or increase) the virtual horizon of the aircraft by about 25 degrees, due to the aircraft's roll angle. This causes an additional reduction of the minimal elevation in e.g. North

Atlantic flight routes with communication to a GEO satellite, when the flight path is nearly orthogonal to the satellite's line of sight and the satellite is seen at low elevation. Therefore the antenna must provide full beam agility range.

Antenna beam agility is one of the most important technical issues for the realization of a broadband aeronautical communication link and has to be investigated taking into account aircraft's attitude changes, antenna technologies, antenna diversity and the optimal satellite constellation.

Electronically steered antennas lose antenna gain when the signal incident (line of sight) angle differs from antenna boresight and more than one antenna or a shaped antenna design is necessary. Mechanically steered antennas can cope larger agility ranges maintaining optimal antenna gain.

Non-GEO satellite constellations relax the minimal elevation and therefore the beam agility requirements for the antenna, but require more often satellite handover. If this handover has to be seamless, acquisition of and synchronization to the new satellite has to be made in very short time. Mechanically steered antenna hold in this matter the disadvantage of a finite beam velocity.

4.6.2 Terminal antenna PAT considerations

Beam agility requirements and the resulting optimized antenna design is only one topic to be investigated for an aeronautical terminal. An other one is the pointing, acquisition and tracking (PAT) strategy for the antenna. Generally, PAT algorithms can be categorized in open loop or closed loop systems, or a combination of both strategies [16].

While open loop PAT calculates the angle between the satellite direction and the mobile terminal by the knowledge of the mobile's attitude and position and the satellite position, closed loop strategies analyze the received signal strength and feed it back to a controller.

Commercial airliners are equipped with highly precise IRS (Inertial Reference Systems) supported by GPS (Global Positioning System) data and attitude and position information is available on standardized interfaces (ARINC). In a GEO constellation, where the position of the satellite is fixed, the antenna pointing can be reduced to a simple matrix transformation, fed by this information and enhanced by some internal test or start-up calibration routines. Also a slow feedback of the received signal may be implemented, in order to compensate long term drifts, but for most avionic sensor systems even this feature can be abandoned. Pointing accuracy of about 0.1 degree and better can be reached [11].

More effort to the antenna pointing has to be spent in a non-GEO constellation. A pure open loop pointing like mentioned above needs a permanent update of the satellite positions. But even here the position information of the satellites can be made available or pre-calculated, for example GPS like, by transmitting actual satellite constellation information, which is analyzed by the terminal antenna PAT algorithm. Due to the fact that the aeronautical channel is suffering very rarely from fading and shadowing effects, a more closed loop focused strategy can be realized. Moreover the use of intelligent antennas for those constellations will improve the variety of strategies and ease aeronautical PAT realization.

Pure open loop PAT reduces acquisition and tracking to one single calculation. Therefore new terminal antenna pointing angles for a satellite handover can be determined before the handover and no satellite acquisition phase is necessary.

4.6.3 Doppler Shift

Another aspect of aeronautical terminal design varying from other mobile communication systems is Doppler shift, which is especially large because of the high aircraft speed and the high frequency bands to be used.

For example at Ka band and in a GEO constellation, the worst case (airliner flying in a jet stream directly towards or from the satellite) Doppler shift occurring is about 30 kHz and has to be managed by the frequency control of the aeronautical terminal [10]. For a non-GEO constellation, satellite velocity components have to be taken into consideration besides the aircraft's ones.

4.6.4 Satellite Antenna

Classical passive multi-beam satellite antennas require high mechanical effort for pointing and isolation. New active focal array fed reflector (FAFR) have up to now only been implemented at high frequencies with a very limited number of spot beams. Thus, recent satellite antenna technologies restrict system design to a limited number of spot beams and available power.

Moreover new technologies like SDMA (spatial division multiple access) for optimizing the use of radio spectrum may be applicable in particular for aeronautical systems and are topic of further research.

4.7 Service Link Design and Budget

Link design of the most important service link includes in particular selection/specification of modulation, coding, and multiple access schemes as well as filter design. Given the respective service link design parameters and the design parameters (or requirement specification) of both terminal and satellite antenna, a link budget for the service link can be calculated. Typically, this will be an iterative process.

4.8 Network Architecture and Protocols

The design of the overall network architecture and related protocols obviously depends so closely on the addressed market, concrete application scenario, choice of constellation and key technology equipment, etc., that a systematic approach requires most of the other steps to be taken first. However, it is helpful to have a kind of rough understanding from the beginning what "network architecture" covers and what are issues of relevance here. Figure 5 provides some illustrative indications, and a respective (only top-level) discussion can be found in [3].

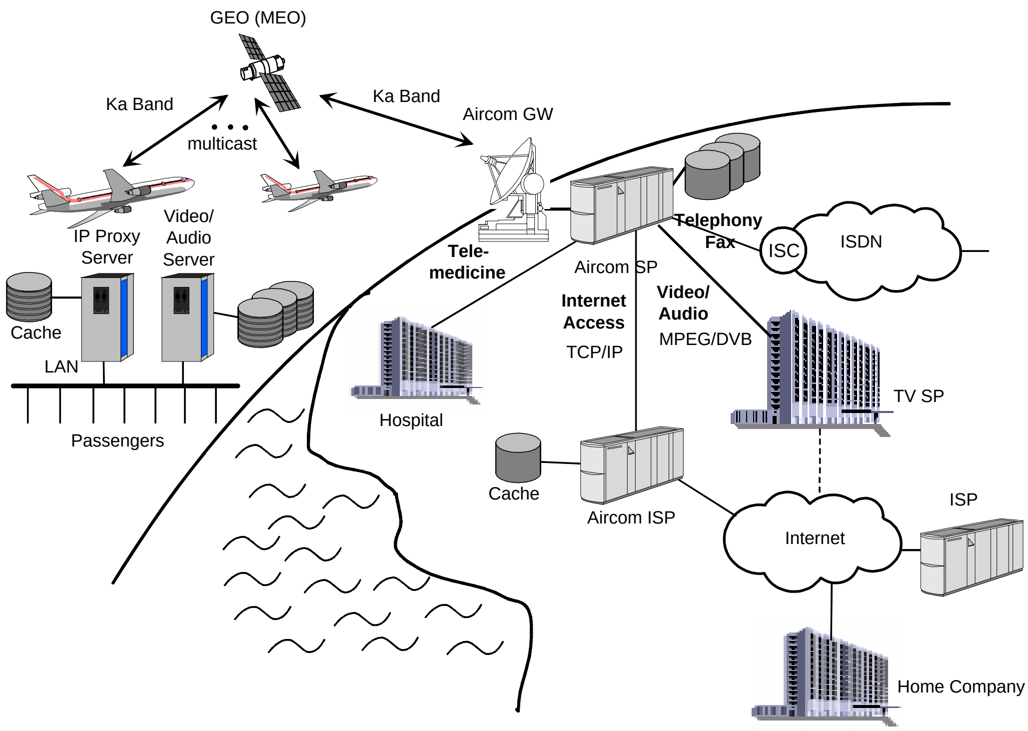

FIG 5. Network architecture and protocols

4.9 On-board Network

Another question is the type of LAN used in the aircraft. Basic choices will include the option of one integrated (e.g., all-IP LAN) network vs. several tailored sub-networks for the various service and application categories. An integrated solution could be based on Gigabit Ethernet, as well as on wireless concepts such as Hyperlan II.

Any wireless solution simplifies potential cabin or seat reconfiguration, reduces weight of communication infrastructure, but introduces possible electromagnetic interference. Relevant specifications and guidelines must be taken into account.

Recent demonstrations by SAS (cf. Section 3.3) already included a wireless on-board LAN based on the IEEE 802.11b standard.

The on-board network options remain a topic for further in-depth study. From our current perspective, relevant issues include

- wireline vs. wireless infrastructure,
- candidate wireless LAN standards,
- radiated power of wireless solutions,
- electromagnetic compatibility issues.

4.10 System Capacity Dimensioning

A last important aspect in AirCom system design is the capacity dimensioning process. Usually it requires a lot of input information from various earlier design steps, such as market/terminal figures, service profile and service bit rate specifications, flight route statistics, satellite constellation, satellite spot beam antenna design, etc. Figure 6 provides an overview of the general iterative satellite system design process with the capacity dimensioning playing a key role. Starting from a solid experience in spot beam capacity dimensioning for multiservice GEO systems [17], extensions and adaptations of the methodologies and models used there to the AirCom scenario are envisaged as one key area in further research work. In particular, the adaptation of an earlier developed linear scalable multiservice traffic model, summarized in illustrative manner in Figure 7, should be interesting.

4.11 Integrated System Design: Methodology and Tool

Mainly based on the train of thought through Section 4, it is envisaged to follow a systematic and integrated system design methodology in future work, capturing in particular all relevant interdependencies and possible design loops in a modular way.

A more formal specification of the system itself and the system design process is foreseen as a baseline for the development of a modular software tool for AirCom system design, the Matlab-based *AirCom design tool (ADT)*, integrating a number of already available modules.

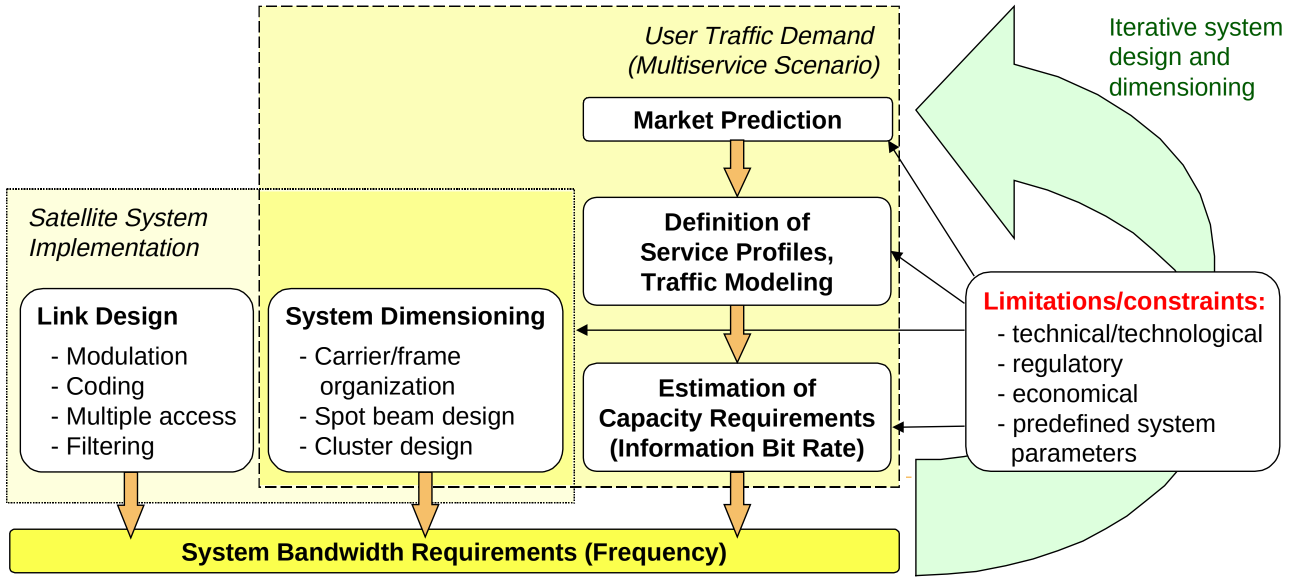

FIG 6. System dimensioning in the iterative system design process

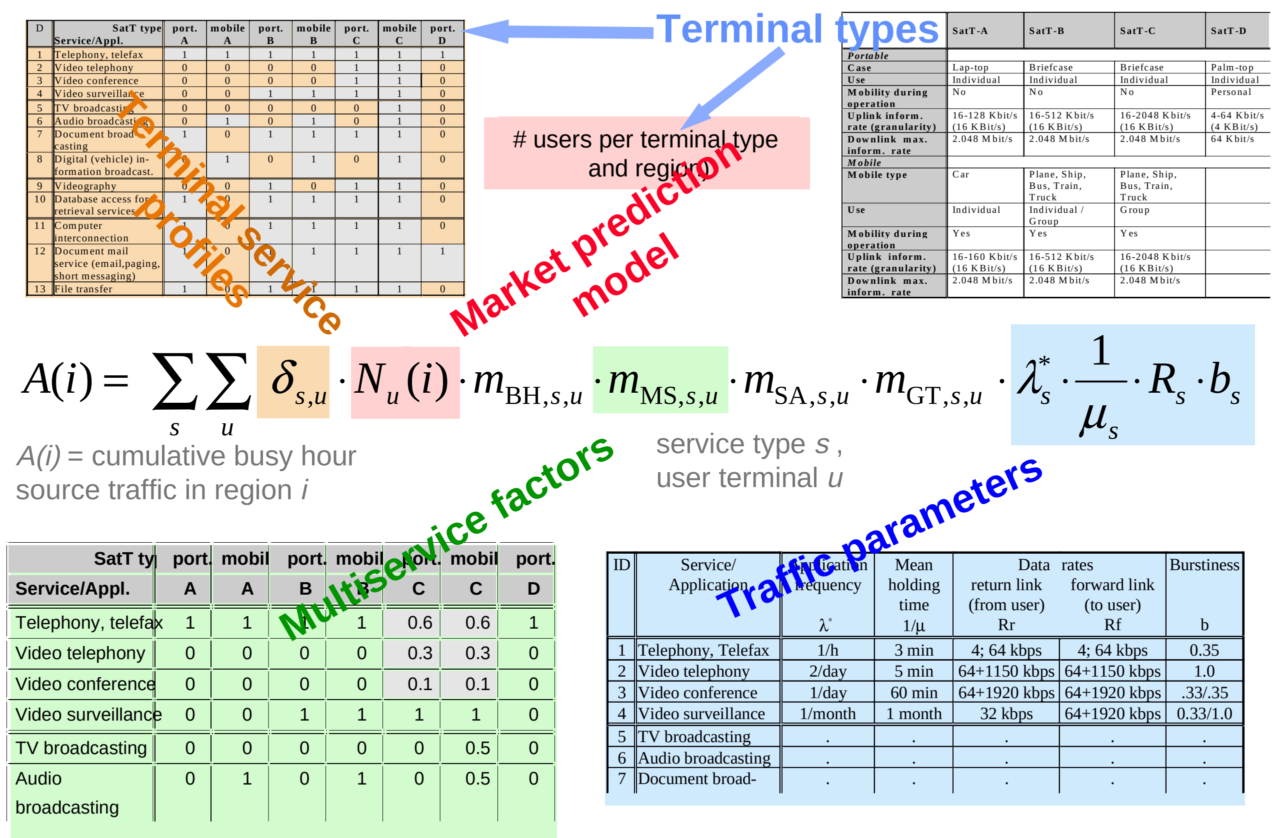

FIG 7. Components of the linear scalable multiservice traffic model for capacity dimensioning of broadband satellite systems.

5. CONCLUSIONS

We have discussed various aspects of aeronautical broadband satellite communications, dubbed AirCom. A range of applications and services has been identified and categorized into the scenarios of in-flight entertainment, in-flight office, telemedicine, flight security, and flight logistics & maintenance. A number of operational and planned AirCom systems have been presented. A structured overview of key issues and respective steps for the system design of an AirCom system has been given.

Future work will follow an integrated system design methodology and aims at the development of a dedicated software tool for AirCom design (ADT).

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