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USING BROADBAND SATELLITE SYSTEMS TO SUPPORT AERONAUTICAL COMMUNICATIONS

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ABSTRACT

In this paper we discuss the possibility of using a broadband satellite-based system to support aeronautical communications. First, we investigate the applications and service requirements for current and future aeronautical communications. Then the communication system and network architecture are outlined and some of the system components are discussed in detail, including the satellite transmission channel, the airplane on-board network, and various aspects of the aeronautical terminals. Finally we present a simulation analysis of the system with the focus on meeting the Quality of Service requirements for the identified service categories.

1 INTRODUCTION

Air travel has become an integral part of our lives. Since the inception of the airline industry, airlines have recognized the critical importance of reliable communications to the safe and profitable provision of commercial airline service. Accordingly, in 1929, the developing airline industry in the United States agreed to cooperate in the establishment of a shared, industry-owned communication system to provide industry communications. For over 70 years, the airline industry has continuously improved and managed the evolution of the communications system into what is now the largest private network of its type in the world. [1]

World airline passenger traffic growth is currently approximately 6% per annum and this figure is likely to drop only slightly in the next fifteen years. Every year over 48 million flights take place in US alone including commercial, military and general aviation flights. As air traffic volume has steadily increased, assuring the safety and efficiency of the US National Airspace System (NAS) and the broader worldwide airspace system has become one of the foremost systems engineering challenges of the 21st Century. [2]

Recognizing the potential for significant improvements in over-ocean coverage afforded by the use of satellite technology for aeronautical communications, the airline industry is developing a design for a global satellite-based communications system to meet the needs of the aviation industry. The expected advantages of the satellite systems for aeronautical communications also include high communication capacity, low message propagation delay, suitability to free flight concepts, and economic benefits.

The remainder of the paper is organized as follows: in section 2, we investigate the applications and services for aeronautical communications, with special emphasis on traffic characteristics for the identified service categories. In section 3, the network architecture is explained. Some of the system components are discussed in detail, including the satellite constellation and the network on-board the airplane. In section 4, we focus on the terminal design and link budget for satellite link. In section 5, we build several simulation scenarios and analyze the system performance. Finally, we outline some conclusions and ideas for future work.

2 APPLICATION AND SERVICE REQUIREMENTS

The aeronautical satellite communication system will provide, on a global basis, an integrated communications transport system for:[3]

Safety Communications:

- ☐ Air Traffic Services (ATS)
  Air traffic control, weather and flight information services
- ☐ Aeronautical Operational Control (AOC)
  Dispatch, flight planning, weather, maintenance communications involving safety and regularity of flight, and independent company communications required by federal aviation regulations

Non-Safety communications:

- ☐ Aeronautical Administrative Communications (AAC)
  Cabin provisioning, passenger-related and other company communications not directly associated with safety and regularity of flight
- ☐ Aeronautical Public Correspondence (APC)
  Public correspondence, personal communication by/for passengers and crew

The service performance is designed to comply with the recommendations of the Future Air Navigation Subcommittee (FANS) of the International Civil Aviation Organization (ICAO) which include:[1]

Availability:	99.99%

Response Time (MAX) Data:	1 second
Response Time (MAX) Voice:	2 seconds
Message Transit Time (MAX):	10 seconds

2.1 APPLICATION CATEGORIES

The types of applications, which must be supported in the aeronautical communications, can be divided into two categories: safety communications and not-safety communications. The aeronautical satellite communication system is normally used for communications related to the safety and efficiency of flight, but non-safety communications could be permitted on a non-interference basis, when priority and preemption can guarantee the precedence of the safety communications. [4]

The safety communications are currently performed by the National Airspace System, which consists of both ground-to-ground and air-to-ground communication systems. Ground-to-ground communication systems interconnect all ground facilities to each other. Air-to-ground (A/G) communication systems provide pilot-to-controller (specialist) communications. The safe separation of aircraft during flight is the essential task performed by air traffic control (ATC). Currently ATC services depend on air/ground voice communication between pilots and the air traffic controllers established principally via ground based VHF and UHF radios. These links support all phases of flight including ground movements; departures and arrivals; and en route. Furthermore, A/G communications are used to transmit instructions and clearances, provide weather services and pilot reports.

The safety communications also include new application scenarios, which make air traveling more secure for the passengers. Video, audio and avionic data transmission may be useful to prevent or analyze aircraft accidents. Flight data, cabin and cockpit video can be sent to ground and stored for a certain time. In case of aircraft disaster, these data can give helpful information for resolving hijacking or analyze aircraft failures faster and more precisely, before the "black box" is found.

Another important application is logistics and aircraft maintenance information, which is not observable to the passenger, but can reduce on-ground time and ease maintenance of the aircraft. For example, when the cabin crew or automated sensors recognize faulty equipment, maintenance crew on ground can prepare the repair and organize replacements parts in advance, based on detailed fault identification data being transmitted immediately.

Non-safety communications can make air traveling more pleasant, secure and productive for passengers. Today's in-flight entertainment (IFE) systems only include a limited number of pre-recorded movies or music channels, short screen "news" and rudimentary travel info. All these one-way services are come from an on-board storage medium and presented at a fixed time. In recent years, some airline companies introduce new in-flight entertainment, such as direct TV, Internet applications and so on.[5] But those services are limited in access (e.g., only in some particular airline and for first/business class). In the other end, modern users can get various entertainments at home or while moving on ground. 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, IFE is only one of the driving applications for high data rate links to airliners.

Non-safety communications are more important for the business traveler. The time those travelers spend on board an aircraft can 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 carry a mobile computer and over 80 percent a mobile phone. 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.[6,7]

2.2 SERVICE REQUIREMENTS

Based on the previous discuss, these two application categories, safety and non-safety communications, include a range of particular communication services. Table 1 assigns to each application category respective key services. Some services fit into more than one category. Moreover, not all services will be permanently required. In case of an emergency, for instance, the shutdown of passenger services for the benefit of flight security applications is acceptable. From a system design viewpoint, this immediately relaxes the worst-case data rate demand of the aircraft communication system.[8]

Table 1. Categorized Services

Category	Services
Safety Communication	Cabin survey, cockpit survey, flight recorder data transmission, weather services, aircraft maintenance data
Non-safety communication	WWW, email, live TV, phone, fax, video-conferencing, file transfer, intelligent travel information, gambling

The next step is to derive the individual traffic statistics for the identified service categories. Table 2 contains a list of traffic parameters for possible communication services. The usage parameters are estimated currently. The second column shows how frequently an application may be used. The numbers apply for business travelers. It is assumed that the video conferencing services will only apply to dedicated corporate aircraft. The third column shows the average duration of the usage of an application. The fourth and fifth columns show the bit rates required by the applications. Here, forward link means the direction towards the aircraft, and return link means data rate from aircraft. The last column indicates the burst which is defined here as peak bit rate divided by the average bit rate.[8]

2.3 SERVICE DIMENSIONING

The system dimensioning process can be structured in several steps:

- ❑ Determination of gross traffic per aircraft using the multi-service model
- ❑ Determination of the timely and locally varying traffic, depending on the flight path and flight schedule, assuming also a service roll-out scenario for different airlines and aircraft types.
- ❑ Identification of potential serving satellites and their coverage areas.
- ❑ Mapping and traffic allocation of aeronautical communications traffic to the satellite systems.

The traffic generated and received by a single aircraft is a function of the distribution of passengers among first, business and economy class, the duration of the flight, the physiological flight time, and the set of available services. The traffic should be described as superposition of the traffic generated by each passenger according to the characteristics of the desired services in terms of data rate and QoS parameters.

When different types of flights are concerned, short and medium haul flights should be focused on needs for business and information type of services. Long haul flights should include also entertainment type of services, in order to offer a complete set of services. The dimensioning of a satellite system providing aeronautical services requires an in-depth analysis of the airline passenger traffic with the region of coverage. Global trends in air-traffic have been identified which allow system-dimensioning activities to be performed such as spot-beam allocation. Traffic routes both within and to/from Europe have been identified so that aeronautical service requirements within the coverage region may be identified. Europe is and will continue to be the world's largest market for international passenger traffic. Traffic between Europe and the Americas is and will remain to be a dominant market route. The north Atlantic corridor between the UK and North America is identified as being an important route regarding European international passenger traffic.

Table 2. Traffic Characteristics

Service, Application	Application frequency	Mean Holding time	Data rate return link	Data rate forward link	Burst rate
Video surveillance	Permanent	Unlimited	64 kb/s	-	1.0
Aeronautical Surveillance	Permanent	Unlimited	100 bps	100 bps	1.0
Video conference	0.01/flight	15 min	16+384 kb/s	16+384 kb/s	3
Telephony	2/h	3 min	9.6 kb/s	9.6 kb/s	2.857
Video telephony	0.01/flight	5 min	16+64 kb/s	16+64 kb/s	1.0
Shared Applications	0.01/flight	15 min	384 kb/s	384 kb/s	2.5
Document mail service (email, short messaging paging)	5/h	0.25 s	16 kb/s	16 kb/s	1.0
File transfer	5/h	4 s	144 kb/s	144 kb/s	20
Internet	2/h	30 min	16 kb/s	144 kb/s	20

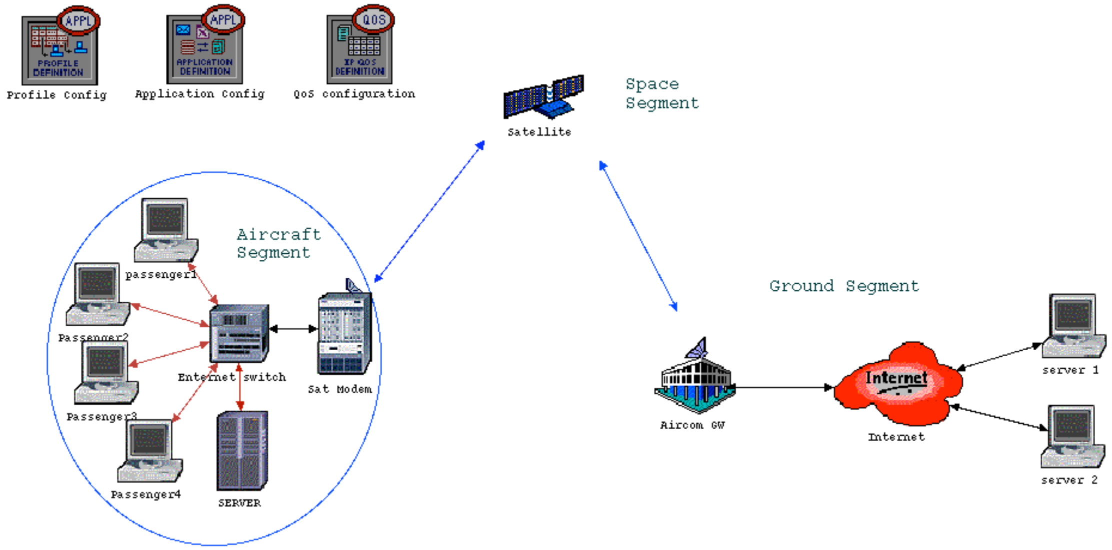

Figure 1. Network Architecture

3 NETWORK ARCHITECTURE

The design of the overall network architecture and related protocols obviously depends so closely on the addressed market, specific application scenario, and the choice of satellite constellation and key technology equipment. Although protocol issues in ground based networks are well understood, additional challenges with communicating in the space environment require consideration of more constraints as well as compatibility with ground networks.

The aeronautical satellite communication system we consider here will be composed of three major subsystems:

- Avionics and cabin system
- Space segment for interconnection of the cabin with the terrestrial telecom networks
- Ground Segment supporting the integrated cabin services. The ground segment provides the interconnection to the terrestrial personal and data networks as well as the Internet backbone.

3.1 SATELLITE CONSTELLATION

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. A key issue for the success of such systems is the passenger acceptance. It is believed that the ease of access to the service can be predominantly achieved by wireless techniques as the passengers are used to from their daily life.

However, a GEO solution for the purpose of future broadband communications to aircraft in flight reveals several deficiencies and limitations. 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).

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 tend to increase while moving to lower orbits. Satellite handover will become a major issue, and inter-satellite links may be necessary at least for LEO constellations to provide connectivity over large ocean areas. With an appropriate non-GEO satellite constellation, coverage and extreme antenna steering requirements problems could be avoided, and in particular coverage with clearly higher elevation angles could be realized in near-polar regions.

3.2 ON-BOARD NETWORK

The service scenario considers travelers in aircraft on the move. In the future, airliners will provide a variety of entertainment and communications equipment to the passenger. Since people are becoming more and more used to their own communications equipment, such as mobile phones and laptops with Internet connection, either through a network interface card or dial-in access through modems, business travelers will soon be demanding wireless access to communication services. So far, GSM telephony is prohibited in commercial aircraft due to the uncertain certification situation and the expected high interference levels of the TDMA technology. With the advent of spread spectrum systems such as UMTS and W-LAN, and low power pico-cell access such as Blue tooth, this situation is likely to change, especially if new aircraft avionics technologies are considered, or if the communications technologies are inline with aircraft development.

When wireless access technologies in aircraft cabins are envisaged for passenger service, the most important standards for future use are considered to be: UMTS with UTRAN air interface, Blue tooth, and W-LAN IEEE 802.11b. Of course, these access technologies will co-exist with each other, beside conventional IP fixed wired networks. The wireless access solution is compatible with other kinds of IFE, such as live TV on board or provision of Internet access with dedicated installed hardware in the cabin seats. Hence, it should not be seen as an alternative to wired architecture in an aircraft, but as a complementary service for the passengers. [8,9]

4 LINK BUDGET AND TERMINAL DESIGN

4.1 TERMINAL ANTENNA

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 beam widths. 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.

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 angle differs from antenna bore sight 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.

Beside beam agility requirement, the pointing, acquisition and tracking (PAT) strategy for the antenna is another requirement. Generally, PAT algorithms can be categorized in open loop or closed loop systems, or a combination of both strategies. 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. [10,11]

4.2 LINK BUDGET

Modulation technique is a key consideration. This is the method by which the analog or digital information is converted to signals at RF frequencies suitable for transmission. Selection of modulation method determines system bandwidth, power efficiency, sensitivity, and complexity. For the purposes of link budget analysis, the most important aspect of a given modulation technique is the Signal-to-Noise Ratio (SNR) necessary for a receiver to achieve a specified level of reliability in terms of Bit Error Rate (BER).

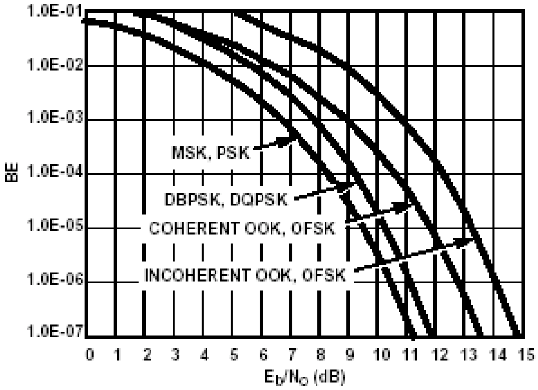

Figure 2. Probability of Bit error for common modulation methods [12]

Eb/No is a measure of the required energy per bit relative to the noise power. A graphical of Eb/No vs. BER is shown in figure 2. In our applications, we choose 10^{-8} as the maximum BER that we can tolerate. From the figure, we find that for QPSK modulation, a BER of 10^{-8} requires an Eb/No of 13 dB. Eb/No is independent of the system data rate. In order to convert from Eb/No to SNR, the data rate and system bandwidth must be taken into account as $\mathrm{SNR} = (E_b/N_0) * (\mathrm{DataRate}/\mathrm{Bandwidth})$. Thus from table 3, a SNR of 13 dB is required to establish suitable quality for digital transmissions. The equivalent isotropic radiated power (EIRP) and figure of merit (G/T) of the antennas are decided by taking account of these values and the capability of the satellite. Table 4 shows a typical example of link budget.

Table 3. Typical bandwidths for various digital modulation methods

Modulation Method	Typical Bandwidth
QPSK, DQPSK	1.0 x Bit Rate
MSK	1.5 x Bit Rate
BPSK, DBPSK, OFSK	2.0 x Bit Rate

Table 4. Link Budget

Return link budget

Uplink: aircraft to satellite

Transmission Power	20	dBW
Antenna Gain	35	dBi
EIRP	55	dBW
MAX. Space Loss	214	dB
Frequency	29.6	GHz
Range (10^o elevation)	42800	Km
Receiver G/T	11	dB/K
Bandwidth	5	MHz
Received C/No	80	dBHz

Downlink: satellite to ground

Transmission Power	20	dBW
Antenna Gain	12	dBi
EIRP	32	dBW
MAX. Space Loss	210	dB
Frequency	19.9	GHz
Range	38030	Km
Receiver G/T	30	dB/K
Bandwidth	5	MHz
Received C/No	80	dBHz

Forward link budget

Uplink: ground to satellite

Transmission Power	20	dBW
Antenna Gain	50	dBi
EIRP	70	dBW
MAX. Space Loss	213	dB
Frequency	29.6	GHz
Range	38000	Km
Receiver G/T	2	dB/K
Bandwidth	20	MHz
Received C/No	86	dBHz

Downlink: satellite to aircraft

Transmission Power	20	dBW
Antenna Gain	35	dBi
EIRP	55	dBW
MAX. Space Loss	211	dB
Frequency	19.9	GHz
Range	42800	Km
Receiver G/T	14	dB/K
Bandwidth	20	MHz
Received C/No	86	dBHz

It is found that the most critical link is downlink from the satellite to the aircraft. In aeronautical satellite communication systems, generally speaking, the total link quality is mostly dependent on a G/T of an aircraft antenna. In our simulations, the aircraft antenna has a maximum value of G/T=14dBK, so the total C/No can reach 86dBHz, which has a sufficient link margin.

5 SIMULATION RESULTS

The system performance is analyzed by using a discrete event simulation model. We focus on the performance and communication capabilities for the identified services categories.

5.1 SINGLE AIRCRAFT SCENARIO

In this simulation, a K/Ka-band satellite in geosynchronous orbit operates in the microwave switch mode, in which it behaves as a bent-pipe transponder. Its spot beam is used to establish the communication link between the satellite and the fixed ground terminal, which provides the interconnection to the control center and Internet backbone. The aircraft, which includes on-board network, communicates with satellite by its phase array antenna. Various communication services with different priority are simulated in our scenario.

The satellite steerable antenna is used to establish the link between satellite and aircraft. The benefit of using the steerable antenna is that it removes the restriction that the flight path be within geographically fixed spot beam contours, allowing the aircraft to fly anywhere in the western hemisphere. Use of the steerable antenna introduces the additional system complexity of requiring the antenna to continuously track the aircraft. The antenna has a 3dB contour of 450 kilometers, which coupled with a maximum aircraft ground speed of 1200 km/h, results in a low dynamic tracking requirement. In practice, this tracking is accomplished by multiplexing aircraft positioning information with data stream transmitted from the aircraft to the fixed terminal. At the fixed terminal the positioning information is then demultiplexed and transmitted via the public switched telephone network to the satellite control station, where the controller is then commanded to point the steerable antenna to the aircraft location.

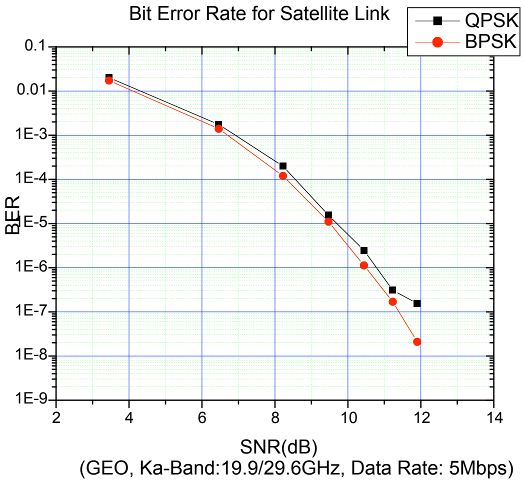

Figure 3. Bit Error Rate for Satellite Link

Based on the link budget and system architecture, we first investigate the channel condition by using different modulation method. The aircraft is flying from Los Angeles to New York with one stop at Denver. The duration of the flight is about 3.5 hours. We focus on the link from satellite to aircraft. As shown in figure 3, the relation between BER and SNR matches the theory result, which is shown in figure 2. Moreover, from the trend of the curve, a SNR of 13 dB can reach the BER requirement ($<10^{-8}$).

Next, we investigate the TCP performance in the aeronautical satellite communications system.[13,14] In this scenario, there is an Ethernet LAN on the aircraft, which connects to the ground network via GEO satellite. The client on the aircraft will download files from the ground server by using FTP during the flight. The TCP in the client is configured as in table 5.[15,16] For each scenario, the forward link has data rate 5Mbps. Both the client and the server have TCP buffer size of 65536 bytes.

Figure 4 shows the TCP performance for the satellite link with FTP file size of 1.6MB. We can see that the response time to download a file increases exponentially with the BER. That's because the TCP congestion window cannot recovery quickly when there are lots of packet losses (high BER). For same BER, the Windows Scaling and SACK have better performance than Reno, Tahoe and Default configuration, where Default TCP need the largest response time to download the same file. The differences of response time are more obvious when the BER becomes large.

Figure 5 shows the same configuration but with the file size of 10MB. The difference of the response time for those TCP flavors are more obvious especially in cases of high BER.

Table 5. TCP Configuration Description

Default	Slow Start and Congestion Avoidance
Tahoe	Fast Retransmit
Reno	Fast Retransmit and Fast Recovery
SACK	Selective Acknowledge
Window Scaling	SACK and Window Scaling

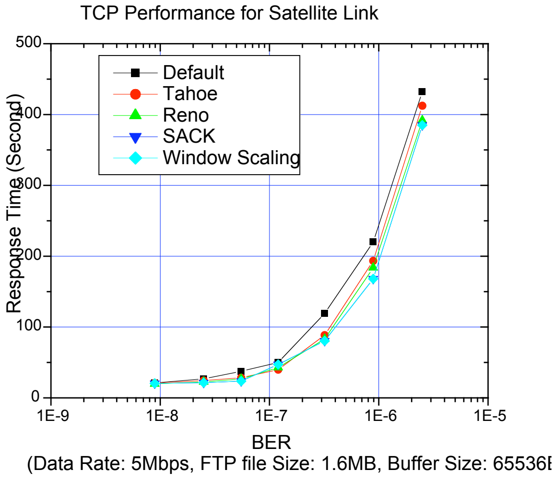

Figure 4. TCP performance for satellite link (1.6MB)

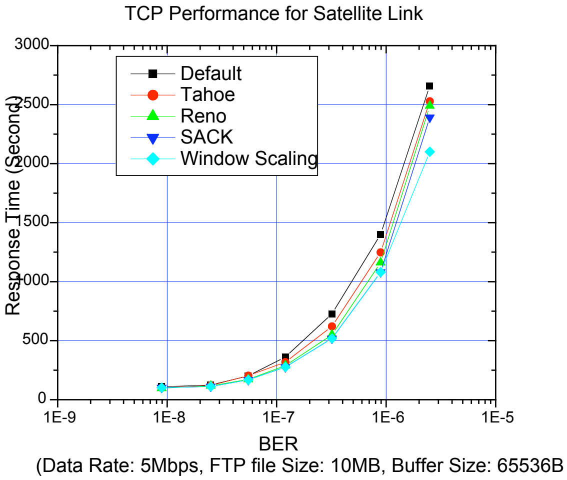

Figure 5. TCP performance for satellite link (10MB)

In these figures, we can see that the window scaling and SACK appear to have similar performance. That is because in these scenarios, both the client and the server use a TCP buffer size of 65536 bytes. The congestion window of the TCP connection cannot be larger than the buffer size. We expect window scaling will have better performance than SACK when we have large buffer size. Figure 6 shows this effect. Here, when the client downloads a file of size 1.6Mb and the receiver's buffer size is less than 65536 bytes, the Window scaling and SACK have same performance. Actually window scaling is not used in this case. When the buffer size is larger than 65536 bytes, window scaling needs less time than SACK to download the same file. The difference in the response time will become more obvious in low BER and for bigger files.

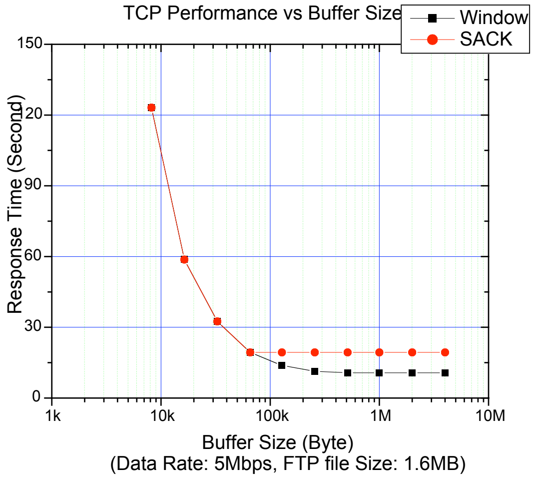

Figure 6. TCP performance with different buffer size

From the previous results, we can conclude that by using the satellite communications system with our configuration and system architecture, the basic communication requirements can be meet. Furthermore, if TCP/IP protocols are going to be adopted in this satellite system, some modifications of the protocol stacks would be necessary to achieve better performance.

5.2 MULTIPLE AIRCRAFT IN ONE SPOT-BEAM AND MULTIPLE SATELLITES

If we extend the analysis to the case where we have multiple aircraft and multiple satellites, two different scenarios need to be defined.

First, is the case where we have multiple aircraft in one spot beam of one satellite. In this scenario, the satellite spot beam is used to establish the communication between the satellite and multiple aircraft. In the forward link (from satellite to aircraft), we can use broadcast to communicate with all aircraft (TDM). In the return link from aircraft to satellite, we need some multi-access control (MAC) to share the capacity.[17]

If we have several spot beams and several satellites, handover between spot beams and possibly inter-satellite links are necessary to achieve global coverage and redundancy. In both cases, the system becomes much more complex than the one aircraft case. WE plan to address the design and system issues and performance analysis in later stages of this work.

6 CONCLUSIONS

We have discussed the first steps in defining a satellite-based solution to support broadband communications from commercial aircraft. A range of applications and services has been identified and categorized. Some design trade-off issues of the aeronautical satellite communications system have been discussed, with the focus on satellite constellations and aircraft on-board network. We presented a network architecture we are considering and a relevant simulation model. Based on the initial simulation results, we have seen that if TCP/IP protocols are going to be used in this scenario some modifications are necessary to achieve better performance.

A goal for future air traffic systems should be the support of new applications, global connectivity, seamless integration and interoperability, rapid reconfigurability and flexibility for future growth. Satellite systems could prove an enabling infrastructure well positioned to meet this aim. Future work will follow an integrated system design, with emphasis on multiple global satellite systems and spot beams to support multiple aircraft.

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