Data communications between an airplane Airbus A350 and the ground infrastructure

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Abstract— **The main purpose of this work was to evaluate the benefits of the Wi-Fi Gatelink and the AMEX over IP selectable options, and to define communication profiles to transmit data items over IP networks. Taking into account the normal utilization of TAP's long haul fleet, data scenarios were built in order to assess the expected throughput requirements. Supported by measurements performed in Lisbon airport ramp and hangar, the throughput achieved by Wi-Fi (IEEE 802.11a, b, g) and cellular (GPRS, EDGE, UMTS) communication technologies allowed to conclude that the Wi-Fi Gatelink option should be selected. Moreover, taking into account the technologies available in each operational scenario (including Wi-Fi), and the characteristics of the data items, four communication profiles were defined: Flight, Ground and Flight, Ground, and Ground (large and low priority data). Analysing the costs per MB associated to each transmission technology, as well as the expected amount of data transmitted using AMEX over IP, allowed to calculate savings of about 6700€ to 26800€ per year, for each aircraft. Finally, an analysis of the impact of e-Operations on passengers' connectivity revealed that the forecasted amount of data to be transmitted regarding e-Operations is not large enough to have a significant impact.**

Index Terms—**A350, Wi-Fi, Cellular, AMEX, IP connectivity, Throughput.**

I. Introduction

Recently with new aircraft programs arising, there has been a tremendous amount of data being collected on the aircraft. In addition, airlines are starting to deploy other applications that have traditionally been paper-driven for maintenance. These issues have driven the airlines to look at wireless automation to support maintenance. Focus for these applications has been primarily on ground connectivity. Cellular and Wi-Fi Gatelink are the two primary means of collecting data from the aircraft for maintenance. Additionally, the transmission of faults information during flight, over aircraft communication systems, is also becoming widely used.

Automating the aircraft and certain flight and maintenance operations processes has been a goal of the airline industry. However, in many ways, the automation of the aircraft has only just begun, as general estimates typically put the adoption of technology for aircraft anywhere from 5-15 years behind that of the average Fortune 1000 company. Albeit, future aircraft would require very high-speed connectivity in order to support the new operational models that would bring lower costs to the airlines [1]. Within this next generation aircrafts is the future Airbus A350. To make the A350 an integrant part of the extended airline network, Airbus provides several technologies (Cellular, Wi-Fi, SATCOM SwiftBroadband, Wired Ethernet, ACARS) to enable multiple connectivity with the ground infrastructures. However not all the technologies available are included in the basic offer of the aircraft.

This paper presents an introductory study regarding the acquisition of the Wi-Fi Gatelink and the Avionics Messaging EXchange (AMEX) over IP technology selectable options. It also defines recommended communication profiles to transmit data items over IP networks, and identifies the main characteristics to take into account when contracting cellular and Wi-Fi services in the context of a Service Level Agreement (SLA). Additionally, a study on the impact of e-Operations on PAX (passengers) in-flight connectivity is also provided.

These objectives were accomplished through the definition of data scenarios and thus assessing the minimum transmission requirements for each of the operational scenarios, and comparing them with the expected performance of the available technologies. For this work development, a partnership was established with TAP, a Portuguese airline. The collaboration had the important role of providing assistance on several technical details and insights on the aircraft technologies, and operational scenarios, as well as supporting the measurements campaign performed. In spite of the results achieved being within the scope of TAP's operations, any airline operator can apply the methodology used throughout this work.

The article is structured as follows: Section II provides an insight of the aircraft network fundamental concepts, and presents the different communication technologies available; Section III explains how the throughput requirements for the operational scenarios were computed; Section IV assesses about the Wi-Fi Gatelink acquisition, defines communication profiles, and draw recommendations regarding Wi-Fi or cellular SLAs; Section V regards the AMEX over IP acquisition, following by an analysis on the impact of e-Operations on PAX connectivity; Section VI summarizes the main conclusions from this study and provides future work suggestions.

II. Fundamental Concepts

A. Aircraft Domain

According to [2], aircraft systems and networks can be divided into four main domains: Aircraft Control Domain (ACD), Airline Information Services Domain (AISD), Passenger Information and Entertainment Services Domain (PIESD) and Passenger Owned Devices Domain (PODD). The PIESD and the PODD domains are dedicated to passenger's connectivity, thus a detailed explanation is not on the scope of this work. On the other hand, the ACD and the AISD domains comprise and support dedicated flight, maintenance and cabin operations. The ACD can be divided into the ACD and the ACD IS (Aircraft Control Domain – Information System).

The ACD integrates the Flight and embedded control systems, as well as the core cabin systems, and it is basically constituted by the aircraft modular components. The ACD IS integrates two gateway functions covered by Secure Communication Interfaces (SCIs) and one Avionics Server Function Cabinet (ASFC). The ASFC is dedicated to host applications that interact with the avionics modular components from the ACD. It is based on a cabinet design and it is also responsible for management the allocated resources to each functions. The applications hosted in the ASFC are classified within three different functions domains, however only the Flight Operations and Maintenance functions domains are related with sending/receiving data to/from the ground, therefore relevant for this work.

The AISD is made of one Open world Server Function Cabinet (OSFC), docking stations for the Electronic Flight Bag (EFB), among other components. The OSFC is dedicated to host applications of the AISD (with exception for Electronic Flight Bag applications) and to interface with the entertainment domain and IP communication means. Just like the ASFC it is based on a cabinet design. The applications hosted by the OSFC are classified within four different domains (Flight Operations, Cabin Operations, Maintenance, Resources).

To enable IP connectivity, the A350 provides cellular connectivity through the Terminal GPRS/UMTS Client Unit (TGCU), wireless Wi-Fi connectivity through the Terminal Wireless LAN Unit (TWLU), and wired connectivity (Ethernet). The TGCU provides connectivity for 850/ 900/ 1800/ 1900 MHz quad-band GSM GPRS/EDGE, for 850/ 1900/ 2100 MHz tri-band UMTS, and it is expected that HSDPA, HSUPA, HSPA+ and LTE connectivity become available in the near future. The TWLU provides acceptable performance for IEEE 802.11a (5 GHz frequency band), but it is optimized for IEEE 802.11b/g (2.4 GHz frequency band). Moreover, SATCOM SwiftBroadband (SBB) connectivity is also available through a high gain antenna (like the Cobham HGA 7001). Regarding non-IP technologies, small amounts of data from the ACD/ACD IS domains can be transmitted through Aircraft Communications Addressing and Reporting System (ACARS) network (legacy SATCOM systems or VHF communication systems). During the ground phase all of the technologies are available, in contrast with the flight phase, where only SATCOM SBB and ACARS network are available.

All IP traffic is managed by the Information Management Air-ground Communication System (IMACS) and routed through the Communications Router Module (CMR). Both of these systems are hosted on the AISD domain. Nevertheless, for traffic coming from the ACD IS domain, an IP communication channel is not the only option. Legacy systems like ACARS networks can be used (and in some cases, must be used) instead of IP networks. For direct uplink into the ACD IS domain only ACARS networks can be used. Yet on downlink, there are several options that must be considered. Exporting the data from the ACD IS domain into the AISD domain and transmit it over an IP network is a possible solution where, independently of the packet size, traffic would flow from the aircraft, over an IP network, into the airline network. On the other hand, depending on the packet size, AMEX could be used to transmit data over ACARS network or if chosen by airlines, AMEX over IP could also be used. Using AMEX would mean the following:

- Packets smaller or equal to 100 KB could be transmitted over ACARS network.
- Packets smaller or equal to 2 MB could be transmitted using AMEX over IP through an IP network.
- Media Independent Aircraft Messenger (MIAM) could be employed. Utilizing MIAM means that a compression rate ranging from 40% to 60% is achievable, depending on the data item (size and type). When using AMEX over IP, the employ of MIAM would result in a bandwidth saving, in contrast with transmitting data that was directly exported from the ACD IS.
- The airline would have to contract a third party ground AMEX DataLink Service Provider (DSP) network, or implement its own ground AMEX network. If the airline chooses to contract a third party then, when employing the AMEX over IP solution, the traffic would flow over a IP network into the airline network, then from the airline network into the third party ground AMEX DSP network, and finally from the third party network into the ACARS server inside the airline network. For AMEX over ACARS, traffic would flow through the ACARS network, from the aircraft to the third party ground AMEX DSP network and finally to the airline network.

Besides all these communication links that can be established, there is also another way to download and upload data into the aircraft. As a last resort or as an airline operational option, data can be directly uploaded or downloaded through a USB flash drive or an external hard drive.

B. Communication Technologies

Wireless technologies, identified in the previous aircraft domain sub-section as possible solutions to transmit data over IP networks, were analysed considering metrics as the throughput and security robustness. Based on the literature ([3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19]), the conclusions achieved were summarized on Table I.

TABLE I. Communication Technologies: Theoretical and Practical Bit Rates, and Security Evaluation

Technology	Theoretical bit rate	Practical bit rate	Security
GSM	14.4 Kbps	N/A	Insecure.
GPRS	170 Kbps	40 – 50 Kbps	Relatively secure, however it is likely to lose this status in the future.
EDGE	473 Kbps	270 Kbps	Same as for GPRS
UMTS	2.0 Mbps	384 Kbps	Secure.

HSPDA	1.8 – 84.4 Mbps (Depending on the HS-DSCH category)	1 – 6 Mbps (HS-DSCH category 8, and depending on the transmission conditions)	Same as for UMTS.
HSUPA	0.71 – 17.25 Mbps (Depending on the E-DCH category)	1 – 1.5 Mbps (E-DCH category 6, and depending on the transmission conditions)	
LTE (DL)	10 – 300 Mbps (Depending on the device category)	N/A	More secure than UMTS. However the flat-IP based architecture results in more security risks.
LTE (UL)	5 – 75 Mbps (Depending on the device category)	N/A	
802.11b	11 Mbps	5.8 Mbps	Accordingly to the security standard (WEP, WPA, WPA2, or IEEE 802.11i) being used can be considered from insecure to highly secure.
802.11a	54 Mbps	24.7 Mbps	
802.11g	54 Mbps	24.7 Mbps	
Satcom SBB	432 Kbps per channel (up to 4 channels)	N/A	Secure

III. Operational and Data Scenarios

Data scenarios were defined in order to identify the throughput requirements for each of the operational scenarios. Then by comparing it with the performance of the technologies available, it will be possible take conclusions about the Wi-Fi Gatelink and AMEX over IP selectable options.

A. Data Categories

The applications hosted by the ACD IS and the AISD domains, use the aircraft transmission network to send or receive data items. In order to classify these data items, several parameters have been defined:

- Operational Domain: Distinguishes if the data is relevant to the Maintenance domain, Flight domain, or Cabin domain.
- Priority: Different data have different priorities. Three levels of priority have been defined:
  - High priority data is mandatory to be transmitted,
  - Medium priority data is strongly recommended to be transmitted,
  - Low priority data should be transmitted.
- Size: The size of a data item to be transmitted can differ between a wide range of values, depending on the application that is generating or receiving the data item. Hence, data have been divided in five sizes:
  - Small – 0 to 100 KB,
  - Medium – 100 KB to 2 MB,
  - Large – 2 MB to 10 MB,
  - Very Large – 10 MB to 100 MB,
  - Extra large – 100 MB to 1 GB.
- Security Sensitiveness: Defines how sensible is the information being transmitted in terms of security. There are three ranges of sensitiveness: High, Medium, and Low.
- Dataflow: identifies if the data traffic is downlink or uplink.
- Phase: identify whether a specific type of data is to be transmitted only during flight, only when aircraft is on ground, or on both situations.

B. Data Scenarios Definition

The innovation that characterizes the new Airbus A350 results in a lack of information. Size values provided for those data items, as well as the number of times that some items are transmitted in each of the different operational scenarios, are based on assumptions and on the experience obtained from the operation of Datalink applications already in place. Given these considerations, the definition of the amount of data to be transmitted in the operational scenarios, considers three data scenarios: a best-case scenario, a typical-case scenario, and a worst-case scenario. In addition to these scenarios, high priority, medium priority and low priority data, are to be distinguished.

For a best-case scenario, it is always considered the minimum amount of times that a data item can be transmitted, as well as the minimum size interval possible for each data item. Furthermore, when referring to Field Loadable Software (FLS) data items, low priority is always considered, and the size is always equal or smaller than 50 MB.

A typical-case scenario implies that for each item it should be considered an average maximum size, and an average maximum number of transmission times, which can be extracted from (1) and (2).

$$Avg_{Size} = (Max_{Size} + Min_{Size}) \times \frac{1}{2} [MB] \quad (1)$$

$$Avg_{N\ times} = (Max_{N\ times} + Min_{N\ times}) \times \frac{1}{2} \quad (2)$$

Where:

- Avg_{Size} regards a data item average maximum size;
- Max_{Size} is the upper limit of the maximum size interval, and Min_{Size} is the upper limit of the minimum size interval that a data item can have;
- $Avg_{N\ times}$ corresponds to the average number of times that a data item is to be transmitted;
- $Max_{N\ times}$ is the maximum number of times that a data item might be transmitted;
- $Min_{N\ times}$ is the minimum amount of times that a data item might be transmitted.

Also regarding the FLS data items in a typical-case scenario, the average size (according to Airbus FLS size predictions) and the number of items distributed according to its priority, can be calculated using the following expressions:

$$FLS_{Size} = 0.95 \times 50 + 0.04 \times 200 + 0.01 \times 1000 \ [MB] \quad (3)$$

$$High_{priority\ items} = Avg_{N\ times} \times \frac{1}{2} \quad (4)$$

$$Medium_{priority\ items} = (Avg_{N\ times} - High_{priority\ items}) \times \frac{1}{2} \quad (5)$$

$$Low_{priority\ items} = Avg_{N\ times} - High_{priority\ items} - Medium_{priority\ itmes} \quad (6)$$

Where:

- FLS_{Size} regards the FLS data items average maximum size, and according to Airbus [20], the FLS data items are expectable to have the following probability distribution:
  - 95% will have a size smaller than 50 MB;
  - 4% will be between 50 MB and 200 MB;
  - 1% will be higher than 200 MB.

  However, to calculate the FLS_{Size} the values taken into account were the upper limit of the size intervals defined. For the 1% of FLS data items with a size higher than 200 MB, the upper limit chosen is the same defined for the Extra large size. Hence the average maximum size expected for FLS data item is of 65.5 MB.
- $High_{priority\ items}$ is the average number of high priority FLS data items;
- $Medium_{priority\ items}$ is the average number of medium priority FLS data items;
- $Low_{priority\ items}$ is the average number of low priority FLS data items.

For a worst-case scenario, it is always considered the maximum amount of times that a data item could be transmitted and the maximum size interval available for each item. Moreover FLS items are always considered with High priority and its maximum size is of 65.5 MB (the same as in the typical-case scenario).

C. Operational Scenarios

Concerning TAP's A350 expected line of operations; several different operational scenarios can be defined in which data has to be exchange with the ground infrastructures. Based on the data scenarios considerations and on the expected aircraft ground time, minimum throughput requirements were defined for the operational scenarios.

1) Transit in Portugal: regards a transit in Lisbon or Oporto. Short and Long transits can be distinguished based on the aircraft ground time. According with [21] a Short transit takes around 34 minutes and a Long transit is around 62 minutes.

TABLE II. DATA RATE MINIMUM REQUIREMENTS FOR A TRANSIT IN PORTUGAL

	Transit	Best-case (Mbps)	Typical-case (Mbps)	Worst-case (Mbps)
Downlink	Short	0.437	0.624	0.975
	Long	0.240	0.342	0.535
Uplink	Short	0.628	1.885	2.671
	Long	0.345	1.034	1.465

2) Transit in an Outstation: regards a transit outside of Portugal.

TABLE III. DATA RATE MINIMUM REQUIREMENTS FOR A TRANSIT IN AN OUTSTATION

	Transit	Best-case (Mbps)	Typical-case (Mbps)	Worst-case (Mbps)
Downlink	Short	0.029	0.090	0.191
	Long	0.016	0.050	0.105
Uplink	Short	0.040	0.087	0.102
	Long	0.022	0.048	0.056

3) Line Inspection: are the lightest of all types of inspections and the ones that are performed more often. This inspection can occur in Portugal or any outstation, and takes around 6 hours.

TABLE IV. DATA RATE MINIMUM REQUIREMENTS FOR A LINE INSPECTION

	Best-case (Mbps)	Typical-case (Mbps)	Worst-case (Mbps)
Downlink	0.122	0.839	1.570
Uplink	0.056	0.170	0.243

4) Light Inspection: are periodicaly, usually takes one full day, and must be performed in Lisbon, inside the Hangar.

TABLE V. DATA RATE MINIMUM REQUIREMENTS FOR A LIGHT INSPECTION

	Best-case (Mbps)	Typical-case (Mbps)	Worst-case (Mbps)
Downlink	0.031	0.217	0.397
Uplink	0.038	0.116	0.195

5) Heavy Inspection: are periodicaly, usually takes one week, and must be performed in Lisbon, inside the Hangar.

TABLE VI. DATA RATE MINIMUM REQUIREMENTS FOR A HEAVY INSPECTION

	Best-case (Mbps)	Typical-case (Mbps)	Worst-case (Mbps)
Downlink	0.019	0.135	0.253
Uplink	0.034	0.248	0.444

6) Aircraft on Ground (AOG): refers to when an aircraft has a failure and for safety reasons cannot fly. The amount of time necessary to troubleshoot and perform maintenance to the aircraft cannot be determined and strongly depends on the failure/malfunction occurred. For that reason it is extremely difficult to evaluate the minimum throughput requirements.

7) Flight: refers to a flight scenario. Here one can distinguish 2 types of needs: data with high priority that must be transmitted as soon and as fast as possible, and data that does not have high priority and for that reason can be transmitted along the flight. For that reason there is no minimum thourghput requirement, but rather an amount of data that must be transmitted.

IV. GROUND CONNECTIVITY ANALYSIS

A. Performance Measurements

In order to provide more reliable performance bandwidth values in the operational scenarios, practical "last mile" measurements were performed, instead of only relying in the expected practical or even theoretical values. All measurements were made on the ramp area of Lisbon airport (on a gate and on an open apron), and inside the hangar in the three different central lines (CL) where the A350 will be performing light and heavy inspections. The tests performed inside the hangar took place while normal maintenance operations were happening, and the hardware used as a client was as near as possible to the location where the A350 Wireless Airport Communication System (WACS) antenna will be, under a real aircraft. The tests performed in the airport also took place while normal boarding/landing operations were happening, and as before, the hardware used as a client was under an aircraft, as near as possible to the location of the A350 WACS antenna.

Regarding cellular communications measurements, it was used the Ookla Speedtest application (accordingly to [22] represents a reasonable accurate characterization of the "last-mile" performance) connected to a Speedtest server located in Lisbon. This application was running on an Apple Iphone 4, which has the following cellular and connectivity specifications: support for GSM/GPRS/EDGE (850, 900, 1800, 1900 MHz) and for UMTS/HSDPA/HSUPA (850, 900, 1900, 2100 MHz), where the maximum HSPDA performance is of 7.2 Mbps and the maximum HSUPA performance is of 5.76 Mbps. In the scope of this project, measurements were made using EDGE and using HSPA. While doing the HSPA tests the Iphone was connected to a network with a HSPDA 7.2 Mbps (HS-DSCH category 8) and HSUPA 2.0 Mbps (E-DCH category 6) as maximum allowed theoretical performance.

Concerning the Wi-Fi measurements, the server and the client side used the Iperf application and had to be previously configured. Two different configurations were used regarding the hangar and the airport measurements:

1) *Hangar:* To implement the server side functionalities, Iperf was installed in TAP central network server. As for the client side, it was used an Apple MacBook Pro 9,2 with a 2.5GHz processor (Core i5 "Ivy Bridge" I5-3210M), 4GB of RAM memory, and a BCM4331 Wi-Fi chipset which allows to achieve a maximum data rate of 450Mbps. Due to hardware constrains, the radio interface used to connect the client to the APs (Access Points) was IEEE 802.11n (instead of IEEE 802.11 a, b, or g) supporting theoretical data rates of up to 217 Mbps. However in order to extrapolate the obtained results for the IEEE 802.11 g standard, an evironment factor related to the downgrade performance of IEEE 802.11n results was calculated and then applied to the effective throughput of IEEE 802.11g (which accordingly to [23] is never higher than 24.7 Mbps if TCP is being used).

2) *Airport ramp:* The Iperf application was configured in the same way, being the only differences in the hardware. To act as the server a MacBook Pro (the one used as client before) was used, connected to the network through 1 Gbps Ethernet. And to act as client it was used a Toshiba Satellite L750 with a 2.30GHz processor (Core i5 "Sandy Bridge" I5-2410M), 6GB of RAM memory, and an Atheros AR9002WB-1NG Wireless Network Adapter which achieves a maximum data rate of 150Mbps. Furthermore, the client and the APs where connected through IEEE 802.11g.

Due to configuration problems, Wi-Fi measurements using the Iperf application were only preformed in the uplink direction. However inside the hangar there was also a possibility to perform Wi-Fi measurements by using an internal application called Ookla NetGauge. This application uses similar technology to the Ookla Speedtest application mentioned before and is installed in an internal server inside TAP's network.

Table VII presents the average results computed in each of the locations. The traffic direction is identified Ground-to-aircraft or Aircraft-to-ground. Ground-to-aircraft refers to downlink in the aviation definition or uplink in the telecommunications definition, and Aircraft-to-ground is the opposite.

TABLE VII. AVERAGE MEASURED PERFORMANCES

Traffic direction	EDGE (Kbps)	HSPA (Mbps)	W-Fi (Mbps)*
Ground-to-aircraft (Hangar)	CL2: 30.8 CL5: 40.8 CL9: 38.8	CL2: 2.083 CL5: 1.559 CL9: 1.610	CL2: – CL5: 5.9 to 13.6 CL9: 4.5 to 10.5
Ground-to-aircraft (airport ramp)	Gate: 25.8 Open apron: 17.6	Gate: 2.753 Open apron: 2.290	–
Aircraft-to-ground (Hangar)	CL2: 14 CL5: 17 CL9 19.6	CL2: 1.429 CL5: 0.985 CL9: 1.597	CL2: – CL5: 8.6 to 19.9 CL9: 3.2 to 7.4
Aircraft-to-ground (airport ramp)	Gate: 4.2 Open apron: 4.6	Gate: 1.171 Open apron: 0.832	Gate: 20.525 Open apron: 8.893

B. *Results Analysis*

The measured results achieved for EDGE were much lower than what would be the practical performance expectations and the signal strength was very inconsistent especially in the outdoor environment (airport ramp scenarios). In relation to HSDPA (HS-DSCH category 8) and HSUPA (E-DCH category 6), the expected practical bit rates could be considered within the minimum accepted performance to satisfy the demand. The measured results achieved were consistent and within the expected practical performances. However, considering that HSPA, HSPA+, and LTE technologies will not be offered on the A350 at Entry Into Service (EIS), then these technologies can only be considered for future upgrades. At EIS, UMTS will be the cellular communications technology available that will provide the higher throughputs.

To analyse if Wi-Fi Gatelink is required to satisfy the throughput performance requirements of each operational scenario, it is necessary to define a base referential (Table VIII) of those requirements. The base referential should be composed by the most demanding performance by surrounding scenario (hangar or airport). Thus if the performance values of the available technologies could satisfy the base referential then also every other throughput necessity in any of the operational scenarios would be satisfied.

TABLE VIII. MOST DEMANDING PERFORMANCES BY SURROUNDING

Surrounding	Traffic direction	Operational scenario	Data scenario	Throughput (Mbps)
Hangar	Aircraft-to-Ground	Light Inspection	Best-case	0.031
		Light Inspection	Typical-case	0.217
		Light Inspection	Worst-case	0.397
	Ground-to-Aircraft	Light Inspection	Best-case	0.038
		Heavy Inspection	Typical-case	0.248
		Heavy Inspection	Worst-case	0.444

* Values presented in Table VII, regarding Wi-Fi measured results for traffic inside the hangar correspond to the raw estimations for the IEEE 802.11g standard throughput performance, instead of the actual measured results.

Airport ramp	Aircraft-to-Ground	Transit in Portugal (Short)	Best-case	0.437
		Line Inspection	Typical-case	0.839
		Line Inspection	Worst-case	1.570
	Ground-to-Aircraft	Transit in Portugal (Short)	Best-case	0.628
		Transit in Portugal (Short)	Typical-case	1.885
		Transit in Portugal (Short)	Worst-case	2.671

When comparing the most demanding requirements presented on Table VIII with the expected performance of the available cellular technologies (GSM, GPRS, EDGE, and UMTS) one can conclude that a stand alone option of cellular technologies is not enough to satisfy the requirements. Hence Wi-Fi must be selected.

Wi-Fi performance will be highly dependent on the distance between the A350 and the AP. For IEEE 802.11 a, b, and g the variation of the expected practical performance with the distance to the AP is illustrated on [12]. From those results one can conclude that as long as the A350 is not more than 60 meters away from the AP then Wi-Fi should be enough to fulfil the bit-rate requirements. Furthermore the measured results were clearly superior to the requirements from the base referential, being the only exception the throughput results achieved in central line 2 (CL2). However CL2 results can be explained by the lack of coverage in that area of the hangar, a problem expected to be mitigate before the EIS of the A350's to TAP. In fact, the currently Wi-Fi network will be upgraded (in the hangar environment as well as in the airport) in terms of coverage and performance. Hence it is expected for the throughput performances to be even higher.

It is important to state, that if HSPA+ or LTE would be available by the time TAP acquire the A350's then it is most likely that their performances would be enough to satisfy the demand. This statement is based on the comparison between the requirements from Table VIII, the expected practical and theoretical peak bit-rate that these technologies can achieve, and the performance measured with HSDPA and HSUPA. In this case, the decision to select or not the TWLU will have to be supported by economic reasons.

C. *Communication Profiles*

Before addressing communication profiles, one should realize that despite USB being a valid option it should be always considered as a fall-back technology. The use of Satcom SBB is also constrained due to the high transmission costs and low transmission rates. As a consequence, most of the decisions about which transmission technology best fulfil the data categories will end up being between Cellular and Wi-Fi technologies.

Each data item can only be associated to one communication profile. Those associations take into account the technologies available in each of the operational scenarios and its capabilities, as well as on the characteristics of the data items. Thus, before defining the communication profiles, it was performed an analysis that allowed identifying the communication means that should be used in each operational scenario and for each data item (based on its size and priority). With reference to that analysis, it was possible to define the four communication profiles presented on Table IX.

TABLE IX. COMMUNICATION PROFILES DEFINITION

Communication profile	1st choice	2nd choice	3rd choice
Flight	Satcom SBB	–	–
Ground and Flight	Wi-Fi	Cellular	Satcom SBB
Ground	Wi-Fi	Cellular	–
Ground (large and low priority data)	Wi-Fi	–	–

In the extreme situation in which a data item is larger than 1 GB (not contemplated within the size category defined) it should not be sent over any communication profile. In that case, if the item has high priority then it should be stored and placed in the USB queue for a quicker retrieval at the aircraft. Else it should be stored normally and retrieved later.

D. *SLA Recommendations*

Service contracts with Wi-Fi and/or telecommunications service providers will have to be performed in order to have connectivity in the different operational scenarios (inside the hangar will be an exception as the service provider there is TAP itself). As part of those contracts, it is advisable to ensure at least the following three service parameters:

- The throughput provided should be at least enough to cover for the minimum data rates defined for each operational scenario worst-case.
- High availability regards a time frame (usually hours or minutes) in a year that the systems or services might not be available. However as the aircrafts are always flying to different locations (among TAP destinations) TAP has no interest for the service (Wi-Fi or cellular connectivity) to be available all the year. On the contrary it is recommended that the availability of the system to be negotiated accordingly with the average time that the aircraft spends on the ground on each location.
- For all scenarios where data items with high security sensitiveness are to be transmitted over Wi-Fi it is advisable to use Enterprise Wi-Fi Protected Access 2 (WPA2) and IEEE 802.11i (being the use of the Robust Security Network working mode more advantageous). Those characteristics are compliant with the recommendations from [24].

V. FLIGHT CONNECTIVITY ANALYSIS

A. *AMEX over IP*

AMEX over IP is an Airbus A350 selectable option. Due to the limited bandwidth available and the extremely high prices practised when transmitting over Satellite or ACARS networks the Flight scenario is the ideal scenario to take conclusions about the acquisition of AMEX over IP technology. One should have in mind that transmission from the ACD IS using IP communication means is only possible in the downlink direction (from the aircraft to the airline's network).

Three different options are identified in Fig. 1 for the transmission of data items from the ACD IS domain: AMEX over ACARS (red line), AMEX over IP (green line), No AMEX (blue line).

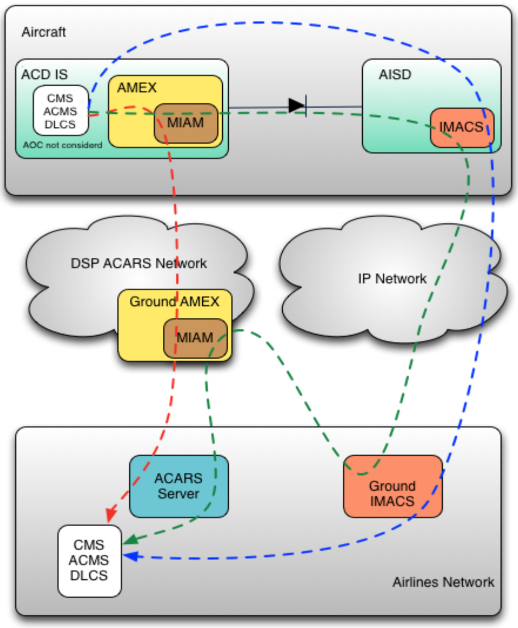

Figure 1. Data transmission options for data from the ACD IS domain

From the three data transmission methods identified in Figure 1, it was possible to define the following transmission scenarios:

- Scenario 1: Data items from the ACD domain of up to 100 KB are transmitted using AMEX over ACARS. Larger data items are sent through the No AMEX option.
- Scenario 2: Data items from the ACD domain of up to 100 KB are transmitted using AMEX over ACARS. Data items with a size ranging between 100 KB and 2 MB are transmitted using AMEX over IP, while for larger data items the No AMEX option is used.
- Scenario 3: Use AMEX over IP to transmit data items from the ACD domain with a size no larger than 2 MB. Larger data items are transmitted with No AMEX.
- Scenario 4: Sent all data through No AMEX.

However due to the high transmission costs associated with AMEX over ACARS, scenarios 1 and 2 are discarded. According to [25], when employing ACARS communication means an average cost of 1,844 €/KB can be assumed. Regarding Satcom SBB one should assume a cost value between 3 €/MB and 8 €/MB. It is important to state that these values strongly depend on specific SLAs between the airline and the service provider (e.g. [26] provides different values than [25]).

Scenario 3 and 4 differ in the transmission method concerning data items with a size of up to 2 MB. Scenario 3 transmission method, AMEX over IP, uses MIAM, which provides a compression performance that depending on the data items (size and type), no larger than 2 MB, can range between 40% and 60%. Scenario 4 uses No AMEX, thus there is no data compression.

In a downlink typical-case flight scenario, the amount of data available to be compressed with MIAM is 8.6 MB out of 31.25 MB. For the purpose of this topic, only the typical-case turns out to be relevant, as the number of flight cycles during an aircraft life spam would make the amount of data to tend to the typical-case. Accordingly with TAP 2013 statistics the long haul Airbus A330 fleet (which the A350 aims to replace) performed an average of 649 flight cycles per aircraft.

Using (7) it is possible to calculate the total amount of savings (in €) for an aircraft using the transmission scenario 3 instead of scenario 4, in one year.

$$Total_{data} \times Cost_{SBB} - (1 - G_{MIAM}) \times Total_{data} \times Cost_{SBB} = Savings \quad (7)$$

Where:

- $Cost_{SBB}$ = cost of transmitting data over Satcom SBB.
- G_{MIAM} = [0.4; 0.6] – MIAM compression performance.
- $Total_{data}$ = 5581.4 MB – average amount of data from the ACD IS domain and no larger than 2 MB sent by one aircraft during one year.
- $Savings$ – Total savings by each aircraft using AMEX over IP, in one year. Results are presented on Table X.

TABLE X. SAVINGS BY EACH AIRCRAFT USING AMEX OVER IP, IN ONE YEAR

		AMEX Compression Gain [%]				
		40	45	50	55	60
SATCOM SBB Cost [€/MB]	3	6698	7535	8372	9209	10047
	4	8930	10047	11163	12279	13395
	5	11163	12558	13954	15349	16744
	6	13395	15070	16744	18419	20093
	7	15628	17581	19535	21488	23442
	8	17860	20093	22326	24558	26791

When analysing the results, one should take into account that each value from the $Savings$ matrix represents the amount of money that is possible to save in that specific situation ($Cost_{SBB}$ and G_{MIAM}). Moreover, the cost of acquiring AMEX over IP, which is not a standard function of the aircraft, and the cost of contracting a Ground AMEX hosted at a DSP network (recommended solution by Airbus) or the cost of developing and integrating a Ground AMEX hosted at the airline's network, are not contemplated in Table X results.

B. Impact of e-Operations on PAX connectivity

Given the human demography, which is responsible for the location of major airports and air routes, air traffic is very heterogeneously distributed. The North Atlantic is the busiest oceanic airspace in the world, thus the North Atlantic Corridor (NAC) constitutes the worst scenario in terms of satellite channel occupation and availability.

According to [27] the NAC peak traffic density registered on 2001 was of 267 aircrafts. Also according to [28], in 2010 traffic over the US remained at similar levels between the years of 1999 and 2010. Consequently, one can conclude that if air traffic increased over the NAC is mainly due to the traffic increase over Europe. Based on [29], [30], [31], estimations for traffic growth over Europe and assuming that this traffic growth is reflected in the transatlantic traffic, it was possible to calculate an expected peak traffic density over the NAC for 2017 of 334 aircrafts. Nevertheless not all the aircrafts will be equipped with Satcom SBB by 2017 and consequently those aircrafts will be of no interest. According to [32], by the year of 2020 only 59% of all aircrafts will be using L-Band for in-flight connectivity. Consequently, it was considered that in 2017 an average of only 59% of aircrafts flying over the NAC would be using the Satcom SBB. Meaning that in 2017 the peak traffic density of aircrafts competing to use Satcom SBB over the NAC would be around 197.

The Inmarsat 4 Satellites narrow spot beams area over the equator is almost 3 times smaller than the NAC area. Considering that the 197 aircrafts are equally distributed over the 3 narrow spot beams, thus in a worst case there would be 66 aircrafts in a spot beam. For each narrow spot beam, Inmarsat states that the number of available channels is dynamically allocated according to the demand and can be as high as 90 channels (90 channels for uplink and 90 channels for downlink).

However due to the spatial distribution of the narrow spot beams more than 3 spot beams can be placed within the NAC area, as one spot beam is intercepted by other 6 spot beams. So in fact the area calculated for one spot beam actually corresponds to the area of one spot beam plus a percentage of area of another 6 spot beams. The percentage of area intercepted highly depends on the spot beam location. To put it simply, in terms of performance one can consider that the area of one spot beam actually corresponds to 2 or 3 spot beams. In that case, it is predictable that each aircraft will always have at least 2 channels available. Yet, the number of channels available can also be limited due to a number of reasons like: the fact that the aircrafts might not be equally distributed among the spot beams or even, that an increased demand in other parts of the world (covered by the same satellite) would reduce the number of channels available over the NAC area. Consequently, in this project it is considered as a worst scenario the case when there is only one channel available for downlink and another one for uplink for each aircraft.

Regarding the amount of data to be transmitted, the worst case possible is the one where AMEX over IP is not used. In this case there will be 76,5 MB (or 612 Mbit) to transmit in the downlink direction and 40 MB (or 320 Mbit) in the uplink direction. Therefore the performance requirement for a long haul flight (time interval considered of 6 hours) is of 28,334 kbps in the downlink direction, and of 14,815 kbps in the uplink direction. One should have in mind that these results are representative of a worst case scenario (regarding data items, transmission method, channels availability, channel performance, and flight duration), thereby the 432 kbps provided by a single channel is more than enough to cover for all the e-operations connectivity needs.

The impact on PAX connectivity is not expected to be significant, except for when high priority data is to be transmitted. Traffic regarding PAX connectivity is expected to have the behaviour as Internet traffic patterns where download traffic outgrows upload traffic by a factor of 5 ([33]). As the amount of high priority data possible to be transmitted simultaneously in the downlink direction is not significant (between 0.32 and 0.5 MB, depending if AMEX over IP is used or no), the impact on upload traffic for PAX connectivity is expected not to be relevant. On the other hand, the amount of high priority data possible to transmit simultaneously on the uplink direction is very large (around 10 MB) and as so, in a worst-case scenario, it can have some significant impact on download traffic for PAX connectivity.

VI. Conclusions

The main objectives of this work were to provide conclusions regarding the Wi-Fi Gatelink and the AMEX over IP selectable options, as well as recommend communication profiles (through the IMACS parameterization) to transmit data items over IP networks. Moreover, identifying the main characteristics to be taken into account in the context of a SLA (when contracting cellular or Wi-Fi services), and assessing the impact of e-Operations on PAX connectivity were also within the scope of this work.

Regarding cellular communications throughput measurements, the average performances achieved were between 1.559 Mbps and 2.753 Mbps for HSDPA (category 8), and between 0.832 Mbps and 1.597 Mbps for HSUPA (category 6), while UMTS is only referred in the literature to support a maximum of 384 Kbps. HSPA (HSDPA category 8, and HSUPA category 6) could not satisfy the transit in Portugal worst-case scenario (2.671 Mbps) and the line inspection typical and worst-case scenarios (0.839 Mbps and 1.570 Mbps respectively). As a result it was possible to conclude that the cellular technologies available at EIS (GSM, GPRS, EDGE, and UMTS) are not valid as a stand-alone option for satisfying the transmission requirements.

In comparison with the results achieved for cellular technologies, the estimated Wi-Fi performance was superior to the throughput requirements in all scenarios. Average throughput performance values achieved were between 4.5 Mbps and 13.6 Mbps for download, and between 3.2 and 20.525 Mbps for upload (depending on the airport ramp or hangar location). In addition, the currently Wi-Fi network is expected to be upgraded (in the hangar and in the airport ramp) in terms of coverage and performance. Therefore the results achieved are merely indicative of the performance that could be achieved today, being higher performances expected with the future Wi-Fi network. Therefore the Wi-Fi Gatelink option should be selected, resulting in a joint solution (Wi-Fi and GPRS/EDGE/UMTS) that would provide enough throughput to overcome the demand requirements and even offer a large margin of growth.

Subsequently to the Wi-Fi Gatelink analysis, four communication profiles were defined. With reference to the key characteristics of each technology and the data items categories, the *Flight*, *Ground and Flight*, *Ground*, *Ground (large and low priority data)* communication profiles were established. Moreover it was recommended that, in the context of a SLA, the availability of a technology service (cellular or Wi-Fi) to be negotiated with reference to the average time that the aircraft spends on the ground on each location. The throughput provided should also be enough to satisfy the data rate requirements defined for each operational scenario worst-case, and Wi-Fi security recommendations previously provided should also be taken into account.

Concerning AMEX over IP, it was predicted it would be possible to save between (6698 € and 26791 €) per aircraft, in one year. However one should take into account that there is a cost associated with acquiring the AMEX over IP technology, and contracting a ground AMEX DSP (or implementing one). Therefore, TAP should assess if transmission costs savings are enough to cover for the cost of acquiring the AMEX over IP technology for each aircraft plus the cost of contract or implement a ground AMEX DSP.

With regard to e-Operations impact on PAX connectivity, it was important to take considerations about air-traffic density and its correlation with the expected Satcom SBB performance. By comparing the minimum throughput requirements for a 6-hour (continually transmitting) long haul flight with the 432 kbps provided by Satcom SBB the impact of e-Operations on PAX connectivity was expected not to be relevant. However in a flight scenario high priority data must be made available as soon as possible, which in the worst-case could lead to a momentarily significant impact on the download PAX connectivity (aircraft uplink direction).

For future work, one suggests performing new measurements tests when the upgraded Wi-Fi network within Lisbon airport and TAP's hangar becomes available. This will allow better evaluate the Wi-Fi throughput expected. Furthermore assessing the Wi-Fi availability and performance within the different outstations, as well as performing a cost/benefit analysis between Wi-Fi and cellular technologies, would be interesting to understand the dependency degree of the aircraft on cellular technologies.

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