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Modelling and Evaluation of the Required Communication Performance of Air-Ground Data Links based on Erasure Codes

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ABSTRACT

The modernization of Air Traffic Management (ATM) operations in Europe and the U.S.A. is underway to accommodate the increase in air traffic. The changes, expected to be rolled out by the mid-2020s, include shifting from voice-based communications to data-based communications. The International Civil Aviation Organization (ICAO) has standardized the Required Communication Performance (RCP) as the metric to measure the performance of data communications.

The RCP metric has been used by Eurocontrol and the Federal Aviation Administration to produce the requirements of the Air Traffic Control (ATC) data-centric communications to support the future ATM. Also, the emerging unmanned aviation is in the process of being integrated in the same airspace as commercial aviation. ICAO has proposed the RCP to measure the performance of the Command and Control (C2) communications. The RCP metric is applied to the end-to-end communication but also to sections of it. The bottleneck of the future ATC and C2 communications has been identified as the air-ground data links. They are the less performant part of the end-to-end path and yet, the strictest requirements have been allocated to them. An issue with the RCP metric is that it uses parameters related to the application layer performance rather than common terms when defining a link, like average packet loss ratio or delay.

The first objective of this thesis is to provide the tools to calculate the RCP performance of the air-ground data links and then obtain the link parameters' values that meet the ATC and C2 RCP requirements. The second objective is using a performance improving technique to exploit the aeronautical multi-link scenario to reduce the individual link parameters' value required to meet the ATC and C2 RCP requirements.

In this thesis, a novel equation model is proposed to calculate the performance provided by the air-ground data links. The advantage of this model over other methods such as emulation or measurement is that calculation is the fastest to produce the results. Also, this model is independent from the physical and link layer protocols. The model is used to fulfil the first objective, applying it to calculate the air-ground data link parameters that meet the ATC and C2 RCP requirements. Multi-link performance improving techniques are reviewed and optimal block erasure codes over multiple links, named Multi-Path Erasure Coding (MPEC), is chosen to achieve the results of the second objective. A novel equation model is proposed to calculate the performance of multiple links using MPEC. This model has the same advantages as the single-link version. Using MPEC, the air-ground data link requirements are reduced if multiple independent links are available. The drawback of MPEC is the requirement of multiple links and the increased bandwidth consumption.

The results of applying the single link model to estimations of the real air-ground data links show that it is highly unlikely that the current satellite links meet the data-centric ATC and C2 requirements. However, the L-Band Digital Aeronautical Communication System (LDACS) link is likely to meet the ATC requirements over continental airspace. The model is then used to calculate the link requirements for new links for each airspace domain. For ATC communications, the requirements are: a bit rate of at least 116 kbps, a packet loss ratio of the links in the 10^{-3} order, a maximum latency of 400 or 1200 ms (depending on the airspace domain) and a link availability of 99.995%. The C2 requirements are even stricter with a bit rate requirement of 4.4 Mbps, an average packet loss ratio in the 10^{-11} order, maximum latency of 160 ms and availability of 99.9995%. The link requirements are above the values of current technology.

The link requirements can be reduced using MPEC. The new requirements are calculated using the MPEC model. For the ATC communications, with two links the average packet loss ratio is reduced by one order of magnitude. Adding a third link further reduces requirements, so that the 5% of the packets can be transmitted with a delay 4 to 8 times higher than the requirements for a single link (depending on the airspace domain) and the availability required is 99.998%. Additional links further reduce the loss requirements. The C2 link requires an average packet loss ratio in the 10^{-2} order with 5 links. The required values for the link parameters when using MPEC are lower than for single-link communications. They are achievable by the air-ground data links that will support the data-centric ATC and C2 communications.

The work in this thesis provides the models to design and evaluate the RCP performance of the air-ground data links both individually and using the MPEC technique. No model was previously available for a fast calculation. The results of applying the model provide the community with useful target values for the next generation of air-ground data links to meet the ATC requirements as well as a proposal for unmanned aircraft.

ZUSAMMENFASSUNG

Um den Anstieg an Flugverkehr in Europa und den USA zu bewältigen ist die Modernisierung des Air Traffic Management (ATM) unumgänglich. Die Veränderungen, welche in den 2020er Jahren erwartet werden, beinhalten einen Wechsel von Sprachkommunikation zu Daten-basierter Kommunikation. Die ICAO (International Civil Aviation Organization) hat, „Required Communications Performance“ (RCP) als Metrik festgelegt um die Leistung von Daten basierter Kommunikation zu messen.

Die RCP-Metrik wurde von Eurocontrol und der Federal Aviation Administration verwendet, um die Anforderungen der datenzentrischen Kommunikation der Flugsicherung (ATC) zur Unterstützung des zukünftigen ATM zu erstellen. Ebenso ist die aufkommende unbemannte Luftfahrt dabei, im selben Luftraum wie die kommerzielle Luftfahrt integriert zu werden. Die ICAO hat vorgeschlagen, dass die RCP die ‚Command and Control‘ (C2) Kommunikation misst. Die RCP-Metrik wird auf die, end-to-end‘ Kommunikation, aber auch abschnittsweise angewendet. Das Nadelöhr der zukünftigen ATC- und C2-Kommunikation wurde als Luft-Boden-Datenverbindung identifiziert. Sie sind der schwächste Teil des ‚end-to-end‘ Pfads, und dennoch wurden ihnen die strengsten Anforderungen zugewiesen. Ein Problem der RCP-Metrik besteht darin, dass beim Definieren einer Verbindung Parameter verwendet werden, die sich auf die Leistung der Anwendungsschicht beziehen, und nicht auf allgemeinere Begriffe wie die durchschnittliche Paketverlustrate oder Verzögerung.

Das erste Ziel dieser Arbeit ist es, die Werkzeuge bereitzustellen, um die RCP-Leistung der Luft-Boden-Datenverbindungen zu berechnen und daraus die Werte der Verbindungsparameter zu erhalten, welche die Anforderungen von ATC und C2 RCP erfüllen. Das zweite Ziel ist die Verwendung einer leistungsverbessernden Technik, um das aeronautische Multi-Link-Szenario zu nutzen, um dadurch den Wert der einzelnen Verbindungsparameter zu reduzieren, welcher für die Erfüllung der Anforderungen von ATC und C2 RCP erforderlich ist.

In dieser Arbeit wird ein neuartiges Gleichungsmodell vorgeschlagen, um die durch die Luft-Boden-Datenverbindungen bereitgestellte Leistung zu berechnen. Der Vorteil dieses Modells gegenüber anderen Methoden wie Emulation oder Messung besteht darin, dass die Berechnung um Ergebnisse zu erhalten am schnellsten ist. Des weiteren ist dieses Modell auch unabhängig von den physischen und ‚link-layer‘ Protokollen. Das Modell wird verwendet, um das erste Ziel zu erreichen; Die Luft-Boden-Datenverbindungsparameter zu berechnen, welche die ATC- und C2-RCP-Anforderungen erfüllen. Die Multi-Link-Performance Verbesserungstechniken werden überprüft und es werden optimale ‚block erasure codes‘ über mehrere Links (Multi-Path Erasure Coding (MPEC)) ausgewählt, um die Ergebnisse für das zweite Ziel zu erreichen. Es wird ein neuartiges Gleichungsmodell vorgeschlagen, um die Leistung mehrerer Verbindungen mit MPEC zu berechnen. Das Modell hat die gleichen Vorteile wie die Single-Link-Version. Bei Verwendung von MPEC werden die Anforderungen an die Luft-Boden-Datenverbindung reduziert, wenn mehrere unabhängige Verbindungen verfügbar sind. Die Nachteile von MPEC sind das Erfordernis mehrerer Verbindungen und der erhöhte Bandbreitenverbrauch.

Die Ergebnisse der Anwendung des Single-Link-Modells auf Schätzungen der realen Flug-Boden-Datenverbindungen zeigen eine große Unwahrscheinlichkeit, dass die aktuellen Satellitenverbindungen die datenzentrischen ATC- und C2-Anforderungen erfüllen. Trotzdem ist es wahrscheinlich, dass die L-Band-Verbindung für ein digitales Luftfahrtkommunikationssystem (LDACS) die Anforderungen der ATC im kontinentalen Luftraum erfüllen. Das Modell wird dann dazu verwendet, um die Anforderungen neuer Verbindungen für jede Luftraumdomäne zu berechnen. Für die ATC-Kommunikation gelten folgende Anforderungen: Eine Bitrate von mindestens 116 kbps, ein Paketverlustverhältnis der Links in einer 10-3 Reihenfolge, eine maximale Latenzzeit von 400 oder 1200 ms (abhängig von der Luftraumdomäne) und eine Verfügbarkeit der Links von 99,995%. Die C2-Anforderungen sind strenger mit einer Bitratenanforderung von 4,4 Mbps, einem durchschnittlichen Paketverlust-Verhältnis in einer 10-3 Reihenfolge, einer maximalen Latenz von 160 ms und einer Verfügbarkeit von 99,9995%. Die Verbindungsanforderungen liegen über den Werten der aktuellen Technologie. Die Verbindungsanforderungen können mit MPEC reduziert werden. Ferner werden die neuen Anforderungen mit dem MPEC-Modell berechnet. Bei der ATC-Kommunikation wird mit zwei

Verbindungen das durchschnittliche Paketverlustverhältnis um einen Großteil reduziert. Durch das Hinzufügen einer dritten Verbindung werden die Anforderungen weiter reduziert. Somit können die 5% der Pakete mit einer um das 4- bis 8-fach höheren Verzögerung als die Anforderungen an einzel-Link Verbindung übertragen werden (je nach Luftraumdomäne) und die Verfügbarkeit beträgt 99,998%. Zusätzliche Links reduzieren die Verlustanforderungen weiter. Die C2-Verbindung erfordert eine durchschnittliche Paketverlustrate in einer 10-2 Reihenfolge mit 5 Verbindungen. Die erforderlichen Werte für die Verbindungsparameter unter Verwendung von MPEC sind niedriger als für die Einzelverbindungskommunikation. Sie sind durch die Luft-Boden-Datenverbindungen erreichbar, die die datenzentrierte ATC- und C2-Kommunikation unterstützen.

Diese Arbeit stellt die Modelle zur Verfügung, mit denen die RCP Leistung der Luft-Boden-Datenverbindungen sowohl einzeln als auch mit der MPEC-Technik entworfen und bewertet werden können. Für eine schnelle Berechnung stand bisher kein Modell zur Verfügung.

Die Resultate des angewendeten Modells liefern nützliche Zielwerte für die nächste Generation von Luft-Boden-Datenverbindungen, um die Anforderungen der ATC zu erfüllen, sowie für einen Vorschlag für unbemannte Flugzeuge.

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LIST OF ACRONYMS

Acronym	**Definition**
ACARS	Aircraft Communications Addressing and Reporting System
ACTP	Actual Technical Communication Performance
AOA	Autonomous Operations Area
AOC	Aeronautical Operations Communications
APT	Airport
ATC	Air Traffic Control
ATM	Air Traffic Management
ATN	Aeronautical Telecommunication Network
ATS	Air-Traffic Services
ATSU	Air-Traffic Services unit
BER	Bit Error Rate
BGAN	Broadband Global Area Network
bps	Bits per second
C2	Command and Control
CDF	Cumulative Distribution Function
COCRv2	Communications Operating Concept and Requirements for the Future Radio System version 2
CPDLC	Controller-Pilot Data Link Communication
CSP	Communication Service Provider
CTMC	Continuous-Time Markov Chain
DTMC	Discrete-Time Markov Chain
ECTP	Expected Communication Technical Performance
ENR	En Route
ESA	European Space Agency
ESP	Encapsulating Security Payload
FAA	Federal Aviation Administration
FCFS	First Come First Served
FEC	Forward Error Correction
GEO	Geosynchronous orbit
HMAC	Hash Message Authentication Code
ICAO	International Civil Aviation Organization
IETF	Internet Engineering Task Force
IPS	Internet Protocol Suite
IPsec	Internet Protocol security
ISO	International Organization for Standardization
JARUS	Joint Authorities for Rulemaking of Unmanned Systems
LEO	Low-Earth orbit
LDACS	L-Band Digital Aeronautical Communication System

Acronym	**Definition**
LDACS1	L-Band Digital Aeronautical Communication System (option 1)
LDACS2	L-Band Digital Aeronautical Communication System (option 2)
GOLD	Global Operations data Link Document
MPEC	Multiple Path Erasure Coding
MPTCP	Multi-Path Transmission Control Protocol
MTU	Maximum Transmission Unit
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
ORP	Oceanic, Remote, Polar
OSI	Open Systems Interconnection
PDF	Probability Density Function
PEP	Performance Enhancing Proxies
pFH	Probability per flight hour
PMF	Probability Mass Function
pT	Probability per transaction
RCP	Require Communication Performance
RCTP	Require Communication Technical Performance
RPAV	Remotely Piloted Aircraft Vehicle
SANDRA	Seamless Aeronautical Networking Through Integration of Data Links, Radios and Antennas
SBB	Swift Broadband
SBD	Short Data Burst
SESAR	Single European Sky ATM Research
SLA	Service Level Agreement
TCP	Transmission Control Protocol
TMA	Terminal Maneuvering Area
UAV	Unmanned Aerial Vehicle
UDP	User Datagram Protocol
VDL2	Very High Frequency Data Link Mode 2

GLOSSARY

Air-ground data link. A *data link* that allows the *aircraft end systems* with the *ground end systems* to *communicate*.

Air-to-ground (A2G). In the direction from the *aircraft* to the *ground*.

Air traffic management (ATM). The dynamic, integrated management of air traffic and airspace including *air traffic services*, airspace management and air traffic flow management (safely, economically and efficiently) through the provision of facilities and seamless services in collaboration with all parties and involving airborne and ground-based functions.

Air traffic control (ATC) service. A *service* provided for the purpose of: a) preventing collisions: 1) between aircraft, and 2) on the manoeuvring area between aircraft and obstructions; and b) expediting and maintaining an orderly flow of air traffic.

Air traffic services unit (ATSU). A generic term meaning variously, air traffic control unit, flight information centre or air traffic services reporting office.

Aircraft. Any machine that can derive support in the atmosphere from the reactions of the air other than the reactions of the air against the earth's surface.

Aircraft end system. A *node* in the *aircraft* that *communicates* with the *ground end systems* by means of *transactions*.

Availability (*A*). The probability that an *operational communication transaction* can be initiated when needed while meeting the *continuity* and *integrity* requirements.

C2 landing service. A set of *transactions* that support the command and control operation to land an unmanned *aircraft* with a remote pilot in control.

Communicate. Transfer of information.

Continuity (*C*). The probability that an *operational communication transaction* can be completed within an associated value of *transaction time*.

Data. Application layer *protocol data unit*.

Data link. A channel that connects two nodes and enables them to forward packets to each other.

Direct wireless link. An *air-ground data link* that transmits the *protocol data unit* wirelessly and directly without means of any relay.

Ground. On the Earth's surface.

Ground end system. a *node* in the *ground* that *communicates* with the *aircraft end systems* by means of *transactions*.

Ground-to-air (G2A). In the direction from the *ground* to the *aircraft*.

Integrity (*I*). The probability of one or more undetected errors in a completed communication *transaction*.

Link parameters: The parameters that define the performance of a *data link*.

Message: Used as synonym of *data*.

Network: A set of *nodes* and links that provides connections between two or more defined points to facilitate telecommunication between them.

Node: a device that can *communicate*.

Operational communication transaction: The process a human uses to initiate the transmission of an instruction, clearance, flight information, and/or request, and is completed when that human is confident that the transaction is complete.

Protocol Data Unit: A unit of information exchanged between peer protocol layer entities.

Satellite link: A wireless *air-ground data link* that uses a satellite as a relay between the *aircraft* and the *ground*.

Service: A service is a set of ATM-related *transactions*, both system supported and manual, within a data link application, which have a clearly defined operational goal.

Transaction: See *operational communication transaction*.

Transaction time (*T*). The time elapsed until completion of an *operational communication transaction*.

NOTATION

Symbol	**Definition**
A	Availability (RCP parameter)
$A2G$	Air-to-ground
Av	Link availability (link parameter)
B	Bit rate
C	Continuity
E	Set of e
$G2A$	Ground-to-air
I	Integrity
K	Probability that a message is received
L	Set of l
N	Average number of transactions per flight hour when the transaction might happen
PLR	Average packet loss ratio
R	Random variable of the random delay uncorrelated with the previous' packet's delay
T	Transaction time
$T_{95\%}$	Transaction time for continuity 95%
T_{C}	Transaction time for a continuity C
X	Random variable of the random delay correlated with the previous' packet's delay
b	Size of the IPv6 packets including headers, in bytes
c	Constant delay
e	Number of encoded packets over a link
h	Index of the last previously correctly transmitted packet
i	packet index transmitted over a link
j	Last successfully transmitted packet index in a sequence
k	Number of IPv6 packets in a message
l	Link identifier
q	Queuing delay
n	Total number of encoded packets
$p_{y,z}^{\{l\}}$	Probability of link l changing from state y to state z
PB	Subscript for packet bundling
pT	Probability per transaction (unit)
pFH	Probability per flight hour (unit)
r	Random delay
r'	Value of the random delay air-to-ground plus ground-to-air with 99% probability.
req	Requirement or required
s	Transmission delay
t	time the packet enters a link
x	Link state

Symbol	**Definition**
y	An index without a specific meaning
z	An index without a specific meaning
Γ	Number of encoded packets successfully sent over a specific link
Δ	Minimum value of the random delay
Φ	Sequence of packets
Ψ	Sum of the probability of all the sequences that share the same combination of delivered and undelivered packets until the last delivered packet
Ω	Set of sequences
β	Time passed since the beginning of a message transmission
γ	Number of packets received over a link
δ	Number of the message retransmission
ε	Encoding plus decoding time
η	Total number of encoded packets received at the decoder
θ	Sequence of encoded packets transmitted over a link
λ	Retransmission timeout
μ	Transition rate of a state
π	Steady-state probability
σ	Standard deviation
τ	Time between the delivery of a packet and the beginning of the message’s transmission
ω	Subset of links that meet the continuity and integrity requirements on their own

[ ] Used to group operations.

( ) Used to indicate the dependencies of a variable or function.

{ } Used to join one or more variables into a set.

E(f): Expected value of *f*.

Pr(*f*): Probability of *f*.

· Symbol of the product operation

1. INTRODUCTION

1.1. Overview

The modernization in the Air Traffic Management (ATM) to accommodate the increasing number of aircraft has led to the modernization of Air Traffic Control (ATC) communications. In the mid-2020s ATC air-ground communications will shift from being mostly voice-based to being mostly data-based. The performance requirements of those communications are already available in [1]. However, the requirements of the air-ground data links that will support them are not. Thus, it is unknown whether existing air-ground data links will be usable or what characteristics should newly deployed links have.

The first objective of this work is to provide the tools to calculate the communication performance based on the air-ground data link parameters' values and to use them to define the future air-ground data link. A model is proposed to calculate the performance provided by an air-ground data link. Then, the model is used to calculate the air-ground data link parameters' values needed to meet the communications requirements of future data-centric communications. The results show that the required link performance is higher than the performance provided by current technologies, and in line with some of the future air-ground data links.

The second objective is to reduce the air-ground data links' requirements calculated as part of the first objective by exploiting the multi-link scenario. Of all the techniques reviewed, one is chosen and a model to calculate the performance using it over multiple links is developed. The results show that the technique chosen to combine the multiple links reduces the average packet loss ratio and delay requirements of the links to values closer to the existing technologies, at the expense of increasing the required link availability and overall bandwidth consumption.

The main novelty of this work is that with the proposed models, the performance of the air-ground data links can be calculated in the Required Communication Performance (RCP) metric proposed by the International Civil Aviation Organization (ICAO) [2]. The models are also used to calculate the air-ground data link parameters' values that support the future of ATC communications. The technique chosen to exploit the multi-link scenario is shown to provide a substantial increase in performance.

The following sections of this chapter first introduce the background of the work, then the two objectives and finally the scope of the thesis. Chapter 2 covers the traffic model and the data-centric requirements. The air-ground data link model and the literature review of the existing and future links are presented in Chapter 3. Then, in Chapter 4, the model to calculate the expected performance is proposed and used to calculate the performance of the reviewed links as well as the new link requirements. The model using MPEC and the results derived from it are given in Chapter 5. In Chapter 6, a technique named "chain and fragmentation" is studied to improve the performance by concentrating the data in as few packets as possible. Finally, the thesis conclusions are presented in Chapter 7.

After this overview of the thesis, the next section provides the background of the data communications used. The modernization of the ATM includes changing from voice-centric to data-centric communications and a new metric to measure the performance in which the proposed performance models are based on.

1.2. Background on data communications

The expected increase of air traffic has triggered a modernization of the communications. In 2008, the most likely expected growth in Europe of number of flights was 80% by 2030 [3]. However, the financial crisis forced the expectations to be revised. In 2013 the most likely expectation of growth was 50% by the year 2035 [4]. To support more aircraft in the skies, ATC communications have been planned to progressively change from the voice-centric based communications to data-centric based. The performance of the future data-centric communications is expected to support more demanding ATM operations, reducing the workload on the pilots and allowing higher aircraft density. The schedule for this change is different depending on the region. The Federal Aviation Administration (FAA) in the

U.S.A. aims for deployment sometime in the mid-2020s [5]. In Europe the change is being implemented by the SESAR joint undertaking, with the current target date being year 2024 [6].

Currently, communication exchanges between the aircraft and the ground are mostly done with voice communications, except for the Aircraft Communications Addressing and Reporting System (ACARS) and the Controller–Pilot Data Link Communications (CPDLC). When using ACARS or CPDLC, data is transmitted over the air-ground data links implemented following the Aeronautical Telecommunication Network (ATN) architecture, using the Open Systems Interconnection (OSI) protocol stack. The combination of ATN and OSI is referred to as ATN/OSI [7]. The low performance of the existing ATN/OSI air-ground data links relegate them to support only non-critical ATM operations. To support the new ATM operations, data-centric communications require new links with increased performance. New air-ground data links like L-band Digital Aeronautical Communication System (LDACS) are planned to be implemented using the Internet Protocol Suite (IPS) protocol stack, referred to as ATN/IPS [8]. The European project SANDRA has worked in the integration of the future seamless aeronautical network supporting the ATN/IPS protocol suite [9]. Using ATN/IPS provides protocols for multicast, quality of service, mobility and security that are required for the future ATN. Also, it should allow cost savings as a wide range of commercial off-the-shelf products and of qualified personnel are available [10].

Data communications are also very relevant for the future integration of unmanned aviation in ATC controlled airspace. Unmanned aircraft are expected to use the same airspace as commercial aviation in the future, as it would open many new possibilities such as unmanned aerial transport of freight. Any aircraft, regardless of its means of control, must follow the rules of aviation and thus unmanned aircraft are expected to be as safe as manned aircraft [11] [12]. For this reason, civilian Unmanned Aerial Vehicles (UAV) and Remotely Piloted Aircraft Vehicles (RPAV) are still operated exclusively in segregated airspace. Removing the pilot from the aircraft makes the ground control critical until the aircraft can autonomously behave just like a manned aircraft. Until the autonomous control systems of UAV and RPAV are safe enough, the data link is critical to safely perform Command and Control (C2) operations.

The requirements for data communications to support the ATM and C2 operations must be expressed with a numeric metric that allows the certification of the communication systems to support the future communications requirements. ICAO has adopted the RCP metric [2] for both ATM [13] and unmanned operations [12]. The RCP metric consists of four parameters: transaction time, continuity, integrity and availability. The transaction time and continuity parameters impose requirements on how fast the transaction must be successfully completed. The integrity parameter states the acceptable number of undetected errors. Finally, the availability parameter sets a requirement on how often the system must be ready to perform the operation.

The requirements for the future data-centric communications that support the ATM operations have been defined by Eurocontrol and the FAA in the Communications Operating Concept and Requirements for the Future Radio System version 2 (COCRv2) document [1]. To the knowledge of the author, this is the most up-to-date requirements document publicly available. The requirements in COCRv2 have been defined for both ATC and Aeronautical Operations Communications (AOC). Those requirements are given for the following conditions: the different airspace domains of operation, the time frame of implementation and the segment of the whole communication path. The work in this thesis is focused in the requirements of air-ground ATC services allocated to the air-ground data links.

Communication requirements for UAV and RPAV operations have not yet been defined. As the regulatory agencies are still working on it, the most demanding phase (landing) requirements are estimated. The quality of service level required has been obtained in COCRv2 based on the harm done to the safety of flight due to failure of the supported ATM operation. The severity has been categorized by most regulatory bodies in different hazard levels (from no effect to catastrophic) that depend on the increased crew workload and possibility of human injury or death. A maximum occurrence frequency of failure of operation is then given for each hazard level. The same procedure is followed to estimate the C2 requirements.

In Chapter 2, the background on data communications is further explained. The traffic is modelled after the transactions as described in the ICAO documents and using the ATN/IPS protocol stack. The RCP metric parameters are detailed, and it is explained how the required values can be obtained. Finally, the requirements are given for the ATC and C2 services.

In this section the future data communications are described. The requirements they impose on the air-ground data links are expressed with the RCP metric. However, whether the existing or future air-ground data links meet those requirements is not yet discussed. Obtaining the answer to that is the first objective of this thesis, as explained in the next section.

1.3. Objective 1: The future air-ground data link

The requirements for future ATC and C2 services are given with a metric whose parameters describe the characteristics of the data exchange between the end systems. Thus, it is not straight forward to verify whether an air-ground data link (already existing or being designed) characterized with different parameters meets the requirements allocated to it. Thus, the first objective of this thesis is 1) to provide a model to calculate the performance provided by any air-ground data link, 2) to use this model to calculate whether the existing links meet the requirements and 3) to use the model to calculate the parameter values of a link that meets the data-centric communication requirements. The results of objective 1 are illustrated in Figure 1. The arrows in the figure indicate what inputs are needed to reach the results, with a different colour for each result. The chapters where the inputs and results are developed are indicated in the figure. The following paragraphs explain how the inputs are obtained and how they are used to reach the results.

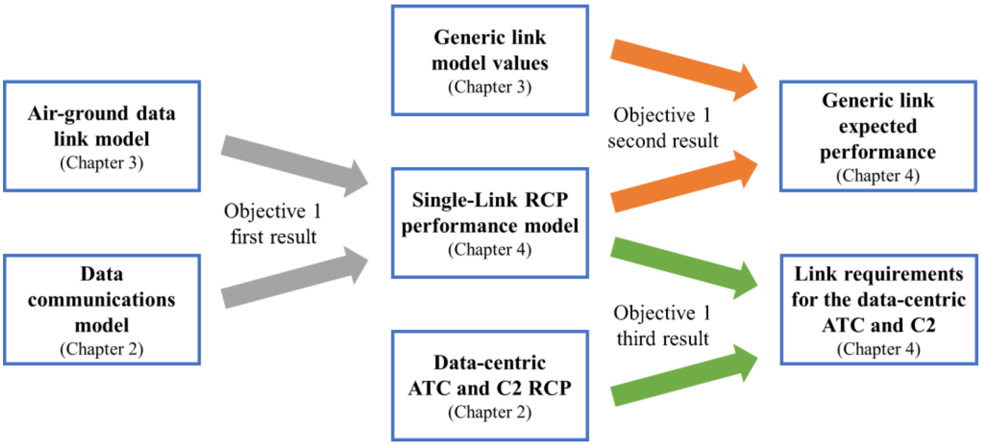

Figure 1: Objective 1 results

The Single-Link RCP performance model provides the means for calculation of the performance. Other options exist to evaluate the suitability of a link such as simulation and measurement. Calculation is the fastest of the methods and it provides results that can be used to make high-level decisions during the design phase. Then more precise, slower methods such as simulation or emulation can be used. Measurement takes the longest to produce results and it requires the link to be operational, but it provides the best statistics.

To meet the objective, the air-ground data link is modelled. The link model has parameters to characterize the availability of the link, the correlated packet loss and the correlated packet latency. The availability of the link is based on the uptime. The packet loss is modelled using a continuous time Markov chain of two states, one in which all the packets are forwarded and another in which they are all dropped. As opposed to discrete time Markov chains, the state changes are triggered by the time passed rather than an event such as a packet transmission. Thus, the correlation between the losses is independent of the traffic sent over the link. The latency is modelled as the sum of the following contributions: queuing time, service time, constant delay and random delay. The queuing system's policy is first-in first-out. The service time is deterministic, and it based on the packet size and the link's bit rate. The constant and random delay conform a random variable that comprises the contributions of other physical and link layer effects such as propagation delay and link retransmissions caused by collision with another sources' traffic.

A literature review is performed to identify the air-ground data link model values of existing and future ATN/IPS based air-ground data links. The existing links are Inmarsat Swift Broadband (SBB), Iridium Short Burst Data (SBD) and the future links are Iridium Certus and L-Band Digital Aeronautical Communication System (LDACS). There isn't much information on Iridium Certus as the link technology is proprietary and it is still under deployment. Whereas LDACS is still being defined, several publications are available that describe the performance. Since all the values are not available for any of the links, three link profiles (named "generic links") are proposed as approximations using the available information. When no information is available, then the value of the parameters is obtained assuming that it is like other air-ground data link technologies.

A model composed of equations is proposed to calculate the expected performance using the RCP metric from the air-ground data link model parameters and the traffic model. The model is named "Single-Link RCP performance model". To calculate the transaction time and continuity parameters, the equations provide the probability that the message is correctly received for each value of transaction time. The RCP availability parameter is the same as the link's availability parameter. Given the link model, the integrity value is always zero.

The Single-Link RCP performance model is used to calculate the performance provided with the "generic link profiles". On one hand, neither of the generic satellite links meets the required continuity of any of the ATC services. On the other hand, the direct wireless generic link (based on LDACS) meets the transaction time and continuity requirements of all the ATC services. The availability value depends on the deployment of the real system, but it is likely to be achieved as the gap between existing air-ground data links is only one order of magnitude (from existing 99.99% availability to the required 99.995%). However, direct wireless links are only usable when within range, in the case of LDACS that is 200 nautical miles (~370 km), so the link would be unavailable in oceanic and remote areas. The C2 landing service requirements are not met by any link.

Using the Single-Link RCP performance model, the parameters' values of the air-ground data links that meet the RCP requirements are calculated. One set of values is calculated for the ATC requirements of each airspace domain and the C2 landing service. Any link with equal or better performance than the proposed links, meets the RCP requirements. The link requirements to support the C2 landing service are unattainable, with packet loss ratio of the 10^{-11} order. The values obtained for the ATC links are achievable since existing technology meets them individually, but having a single link meet all of them (bit rate, delay, packet loss and link availability) would require planning in the new deployments.

The air-ground data link model and the literature review of existing and future air-ground ATN/IPS links are provided in Chapter 3. The RCP performance model, the expected performance of the generic links and the link parameters' values required to meet the RCP requirements are provided in Chapter 4.

The Single-Link RCP model is a useful tool to determine whether a link meets the RCP requirements and to calculate the link parameters' values to meet the RCP requirements. The new air-ground data links must meet the performance requirements to support the future data-centric communications or a way to reduce the requirements must be found. The latter is the second objective of this thesis and it is presented in the next section.

1.4. Objective 2: Reducing the individual link requirements

The results from the work done for objective 1 indicate that a highly performant link (low latency, low loss) is required to meet the ATC requirements. If LDACS performs like the Direct Wireless generic link based on it, then the technology is well positioned to support the ATC requirements over continental airspace. The question remains for oceanic flight. The European Space Agency is working on a new satellite link named Iris [14] and Iridium Certus will soon be available. However, neither the performance nor the full characterization of those links is yet available. Therefore, it cannot be assured at this time that the RCP requirements will be met by any link.

Objective 2 is 1) to propose a technique to exploit the multi-link scenario, 2) to provide a model to calculate the increase in RCP performance with that technique, 3) to evaluate the performance provided by multiple generic links using the model, and 4) to use the model to calculate the reduced link requirements that meet the data-centric communication requirements. The results of objective 2 are illustrated in Figure 2. The arrows in the figure indicate what inputs are needed to reach the results, with a different colour for each result. The chapters where the inputs and results are developed are indicated in the figure. The following paragraphs explain how the inputs are obtained and how they are used to reach the results.

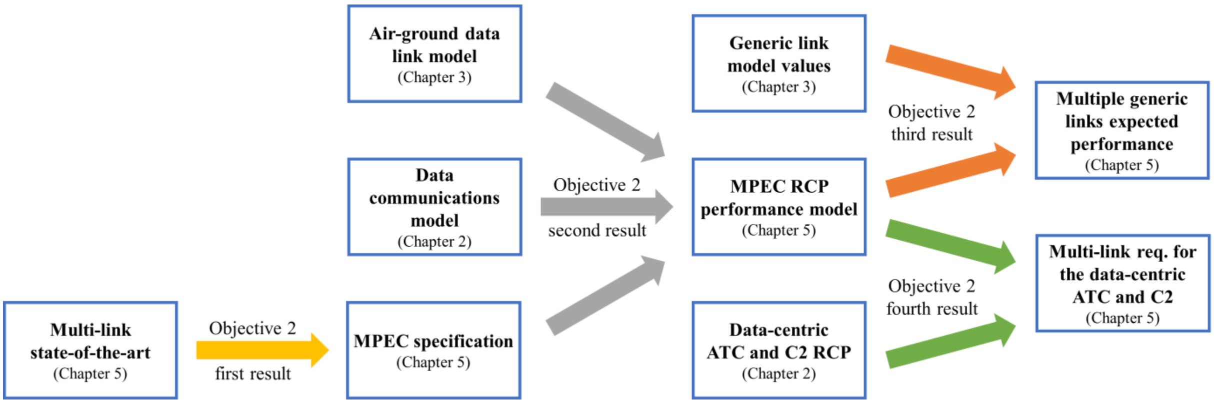

Figure 2: Objective 2 results

A literature review is done to compare and propose a technique to exploit the multi-link scenario as part of objective 2. Increasing the performance of links for air-ground data communications has been proposed by repeating the message over multiple links [15]. More efficient techniques have been proposed for other scenarios such as video streaming like using multiple links and an optimal erasure code [16]. Those techniques are reviewed in the state-of-the-art section in the multi-link performance chapter (Section 5.2). After analysing their suitability and comparing their performance, one technique is chosen to exploit the multi-link scenario and reduce the link requirements. That technique is using optimal erasure coding over multiple links. For the rest of the document, this is referred to as Multi-Path Erasure Coding (MPEC).

With MPEC, an optimal erasure code is used to recover the losses. Normally when losses happen retransmissions are triggered, and the latency is increased by the round-trip of the link. This value is generally high for satellite and wireless links, for example a geostationary-satellite-based link has a minimum round-trip time of about half a second because of propagation. With an optimal erasure code, the original data lost in the transmission can be recovered at the receiver if the losses don’t exceed the amount of redundancy. Thus, the probability of loss is reduced, and retransmissions occur less often with erasure coding (how often depends on the amount of redundancy), at the cost of pre-emptively consuming more bandwidth. The correlation in the losses makes the redundancy less useful as bursts are harder to recover. Transmitting over multiple links reduces the correlation; it is a way of implementing spatial diversity. Additionally, the impact of correlation in latency caused by effects such as congestion is also reduced.

The feasibility of deploying MPEC is discussed. The erasure coding encoder and decoder functions would have to be implemented at the link edges. However, it is possible that the ground stations are not collocated, adding an extra delay to the transmission. Also, being a new technology for aeronautical communications, it would require going through a regulatory process. The author of this thesis met with a group of regulators from the European Aviation Safety Agency and the results of the meeting are explained in this document. From a regulator’s perspective there is no issue with MPEC that would prevent its certification, but it would have to be proven that it provides an advantage and that it does not interfere with on-going operations. The first step would be to deploy the technique for non-critical communications before attempting certification for critical communications.

The second part of objective 2 is to obtain a model to calculate the RCP using MPEC. A model is proposed to calculate the expected performance using the RCP metric from the air-ground data link model, the MPEC parameters and the traffic model. This model is named “MPEC RCP performance model”. It follows the same approach to calculate the continuity as the Single-Link RCP performance model but instead of requiring all packets sent over the link to be received, a message is correctly received if enough encoded packets have been timely transmitted over all the used links. The availability is calculated with the contributing links’ availability. The performance terms of transaction time and continuity of repeating the whole message over multiple links, as proposed in the literature [15] for aeronautical communications is compared to MPEC using the new model to show the gain in performance of the latter.

The third part of objective 2 is to evaluate the performance of multiple generic links. The “generic link profiles” are based on information found on real air-ground data links. Whereas these links are unique, it could be possible that two flows of data are independent when transmitted over the same link, if for example different frequencies were used. Without discussing whether this independence would be possible, the minimum number of equal but independent satellite links to meet the ATC continuity requirements using MPEC is calculated. The results show that for some ATC services more than eight links would be needed: an unfeasible scenario. Thus, MPEC doesn’t increase the performance enough to be a valid strategy to use these links to meet the ATC requirements.

The last part of objective 2 is to use the MPEC RCP model to calculate the link characteristic requirements using MPEC. The requirements of the new air-ground data links are lower if multiple links are used with MPEC. The results when determining the requirements with MPEC show that to meet the ATC requirements, having two equal but independent links reduces the packet loss ratio requirements by about one order of magnitude. Adding a third link reduces the delay requirements so that the 5% of the packets can be transmitted with a delay 4 to 8 times higher than the requirements for a single link (depending on the airspace domain). More links further reduce the loss requirements. The C2 landing requirements for a single link are almost impossible to meet. However, the single link requirement of packet loss ratio in the 10^{-11} order becomes manageable at the 10^{-2} order with 5 links using MPEC. The drawback of using MPEC is having to implement multiple links, an overall increase of the bandwidth consumption and an increase of the availability requirement of less than one order of magnitude. However, its benefits make it worth consideration for deployment.

One of the restrictions for using MPEC is that all the packets must be equally sized. Different solutions when this is not the situation are available in literature [17]. The “chain and fragmentation” technique consists in merging all the packets and then chunking them into equally sized packets. When used to reduce the number of packets to the minimum possible, here it is referred to as “Packet Bundling”. The results if applying this technique with MPEC show an improvement of less than order of magnitude in the average packet loss ratio requirement of the new links. The benefit of using Packet Bundling without coding is also analysed using the generic links. The results using the technique are the improvements on the single-link performance and the link parameters requirements’ reduction using MPEC. The inputs necessary to reach obtain these results are illustrated in Figure 3; the arrows in the figure show what inputs are used for each result:

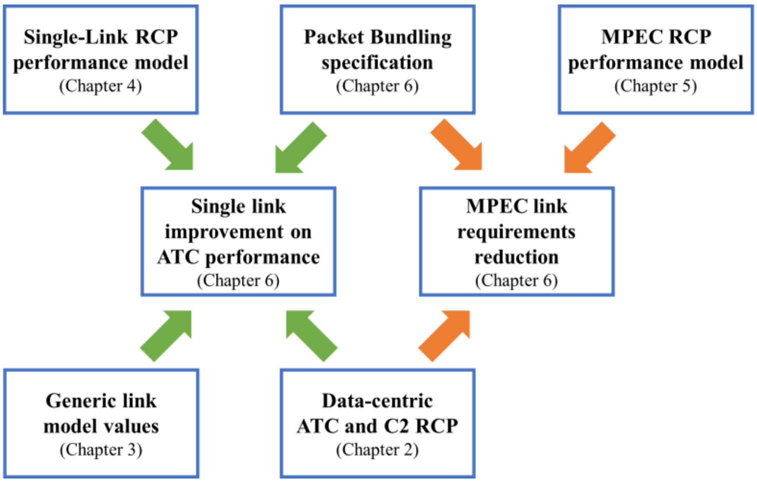

Figure 3: Packet Bundling results

All the MPEC work is presented in Chapter 5. The application of Packet Bundling and its impact on the air-ground data links requirements are discussed in Chapter 6. With all the objectives and content of the thesis are described, the next section explains the scope constraints when developing the work.

1.5. Scope constraints

This scope of this thesis is limited to the two objectives described in this introduction chapter. For each objective, the relevant standards are reviewed, the state-of-the-art is reviewed, the means to fulfil the objectives are proposed and the results of their application are presented and analysed. Some constraints to the scope are explained in the following chapters and summarized here.

First, the relevant communications are those with the strictest requirements, transmitted over a data link, and involving an aircraft and its ground counterpart. The performance of aeronautical voice communications has already been studied for decades, so it is not covered here. Aeronautical data communications performance is measured with the RCP metric from ICAO; no other metrics are considered.

The strictest performance requirements are those related to safety of flight communications. For ATM operations, this corresponds to ATC communications. Because the unmanned aircraft are also in the process of being introduced in the same airspace as commercial aviation, C2 communications are also in scope. The RCP values considered are for the data-centric period. The most up-to-date ATC requirements publicly available, to the best knowledge of the author, are found in the COCRv2 document [1], named “phase 2 requirements”. No C2 requirements are yet available.

The performance requirements are given in COCRv2 separately for the different parts of the end-to-end communication path. The strictest requirements are allocated to the air-ground and air-air links. Air-air data links are still in a very early stage and left out-of-scope of this thesis. Thus, the ATC services requirements in scope are those for air-ground data communications, data-centric (phase 2) and allocated to the air-ground data link. The requirements for the air-air ATC services and for the Autonomous Operations Area (AOA) domain requirements are excluded.

The physical and link layer protocol are abstracted in the air-ground data link model to make it usable for all the technology choices. If the model is used to calculate the required link parameters, the obtained values can be used to adjust the physical and link layer choices. The network and transport layers protocols used are defined by ICAO. Two transport protocols can be used, the User Datagram Protocol (UDP) or the Transmission Control Protocol (TCP). The delay-sensitive communications in scope are assumed to be using UDP. Therefore, the impact of using TCP in the transport layer on the Single-Link RCP model and the MPEC RCP model is out-of-scope.

Modelling the traffic generated by the end-systems is out-of-scope of this thesis to limit the complexity of the analysis. Because of this, the assumption that no queueing occurs at the aircraft and ground link gateways from the traffic generated by services at the end-systems is made to develop the Single-Link and MPEC RCP performance models. Note that the effect of traffic generated by other aircraft and transmitted over shared resources of the air-ground data link is included in the air-ground data link model as part of the random delay.

Using MPEC provides advantages at a cost. Deciding whether to use MPEC or a single highly performant link (low latency, low loss) is different for each deployment and the decision would likely involve economic factors, spectrum availability regulations and other non-scientific aspects. Thus, it is out of scope of this work.

All the scope constraints described here affect the content of the thesis. When any of the above constraints is relevant it is mentioned in the text. The different parts of the thesis are described in the next section.

1.6. Publications

The presentation of the topic of this thesis was published by the author in [18]. On that paper, the RCP metric is reviewed and the idea of using multiple links and erasure coding to increase the RCP performance are presented. The emulator used to verify the RCP models in the thesis was developed in the European project ACROSS; the emulator's design was presented in [19].

The work leading to the results of the single-link case for the ATC services are published in [20]. Those results correspond to the thesis' objective 1 results. The results of objective 2, using MPEC to reduce the individual links requirements are published in [21]. Some paragraphs or phrases of those two publications are also used in this report to present the concepts and results.

1.7. Thesis outline

The remainder of the thesis is structured as follows:

Chapter 2 introduces the aeronautical data communications. The protocols of the different layers of the ATN/IPS are explained. The performance requirements for the aeronautical data communications are expressed with the RCP metric. The parameters of the metric a method to derive new requirements are described. Then, the requirements of the future data-centric ATC and the C2 services are provided.

Chapter 3 presents the air-ground data link model with parameters for the link's availability, packet losses and latency. A review of the literature is done to characterize existing and future air-ground data links. Since there are no values for all the link parameters, three links are defined based on the available information. Those are named "generic links" and they are later used to evaluate their expected performance.

Chapter 4 addresses the performance of single-link communications (objective 1). The Single-Link RCP performance model is proposed to evaluate the performance of any link using the RCP metric and the air-ground data link model from Chapter 3. Using the model, the performance of the generic links is evaluated and the link parameters' value requirements to meet the ATC and C2 RCP are calculated.

Chapter 5 is concerned with the reduction of link requirements in the multi-link scenario (objective 2). There is a literature review of different techniques used to increase the performance by adding redundancy. The selected technique is named Multi-Path Erasure Coding (MPEC). The MPEC RCP performance model is proposed to calculate the performance of multiple links using MPEC. The model is then used to evaluate the performance of multiple generic links. Then, the model is used to obtain the link parameters' value requirements when multiple links are used. Those results are compared to the single link case from Chapter 4.

Chapter 6 discusses the issue of different-sized packets when MPEC is used. A technique named “packet bundling” is used to concatenate the packets and fragment the result in the minimum number of equally-sized packets. Packet bundling improves the performance when used over multiple links but also over a single link.

Chapter 7 concludes the thesis discussing the results and the proposed tools for the development, implementation and evaluation of air-ground data links for aviation.

2. FUTURE AIR-GROUND DATA COMMUNICATIONS

2.1. Introduction

Air Traffic Management (ATM) operations are supported by both voice and data communications. When the aircraft and ground crews exchange information, they mostly use voice. Non-critical operations are sometimes supported by data communications. The current communication system cannot safely accommodate the expected grow in air traffic [22]. A change to data-centric communications will support this increase after the modernization of the Air Traffic Control (ATC) data communication systems. The Federal Aviation Administration (FAA) has planned the change around the mid-2020s [5] and the SESAR joint undertaking in Europe towards the year 2024 [6].

In this chapter, the traffic characteristics and performance requirements of the data-centric communications are presented. The performance requirements are stated using the Required Communication Performance (RCP) metric. The values provided correspond to the most demanding operations using data communications: ATC operations for civilian aviation and landing operations for unmanned aviation.

Section 2.2 describes the protocol stack of the data-centric Aeronautical Telecommunication Network (ATN). The network and transport layer are taken from the Internet Protocol Suite (IPS) protocol stack, referred to as ATN/IPS [8]. Voice-centric data communications were implemented using the Open Systems Interconnection (OSI) protocol stack, referred to as ATN/OSI [7]. The application layer is modelled based on the transaction definition from ICAO GOLD [13]. The link and physical layers are not detailed because they are not defined in the protocol stack and they are abstracted in the air-ground data link model in Chapter 3.

Then, the RCP metric is discussed in Section 2.3. This metric has been adopted by the International Civilian Aviation Organization (ICAO) to measure the performance of aeronautical communications [2]. The metric consists of four parameters: transaction time, continuity, integrity and availability. The definition of each parameter is revised, and changes are proposed to clarify the terms. Then, the procedure to obtain the values is explained; the highest the impact of failure is on the safety of flight, the highest the requirement is.

The characteristics of the data-centric communications for Air Traffic Control (ATC) operations are presented in Section 2.4. The most recent, publicly available RCP values for the air-ground data link have been published by EUROCONTROL and the FAA in the Communications Operating Concept and Requirements for the Future Radio System version 2 (COCRv2) document [1]. The average number of packets and average packet size are also obtained from COCRv2, but the values are adjusted to consider the ATN/IPS protocols instead of the ATN/OSI.

The unmanned aviation communication requirements haven't yet been defined by the regulatory agencies. Thus, the RCP values and message characteristics for the most safety-critical operation (landing) are defined in Section 2.5 based on information available from different sources.

2.2. Protocol stack

2.2.1. The Aeronautical Telecommunication Network

The network used to communicate the aircraft and the ground is implemented using the Aeronautical Telecommunication Network (ATN). When the ATN was conceived, ICAO adopted the Open Systems Interconnection (OSI) protocol stack designed by the International Organization for Standardization (ISO). At that time, the OSI protocols were well defined and they could easily be adapted to the aeronautical applications [23]. The combination of the ATN using OSI is referred to as ATN/OSI [7].

With the modernization of the ATN described in Section 1.2, the ATN/OSI protocol stack will become obsolete. The protocols are not good enough to support the next generation services. What is more, the developing costs of a new version are high because ATN/OSI is only used for aeronautical networks. The International Civilian Aviation Organization (ICAO) has proposed to change the protocol stack to implement the Internet Protocol Suite (IPS) defined by the Internet Engineering Task Force (IETF), defined for the ATN as ATN/IPS [8]. IPS provides the protocols for multicast, quality of service, mobility and security that are required for the future ATN. Also, IPS is broadly widespread so commercial off-the-shelf products are available, and it also opens access to a larger pool of qualified personnel for maintenance and development of products. This will provide a reduction of the costs. New air-ground data links, like L-band Digital Aeronautical Communication System (LDACS) are planned to support ATN/IPS. Thus, there is a transitional period in which the ATN/OSI and the ATN/IPS will co-exist.

The protocols specified in the ATN/IPS are in the network and transport layers (see Figure 4). The protocols are the same as specified by the IETF. However, ICAO specifies a subset of protocols and options of those protocols that must be used in the ATN. For example, ICAO adopts Internet Protocol version 6 (IPv6) as its network layer protocol in all the air-ground ATN/IPS networks. Implementation of the Internet Protocol version 4 (IPv4) is not considered by ICAO, even if it is allowed in ground networks. The use of the IPS for ATN is fully specified in the Manual for the Aeronautical Telecommunication Network (ATN) using Internet Protocol Suite (IPS) Standards and Protocols [8].

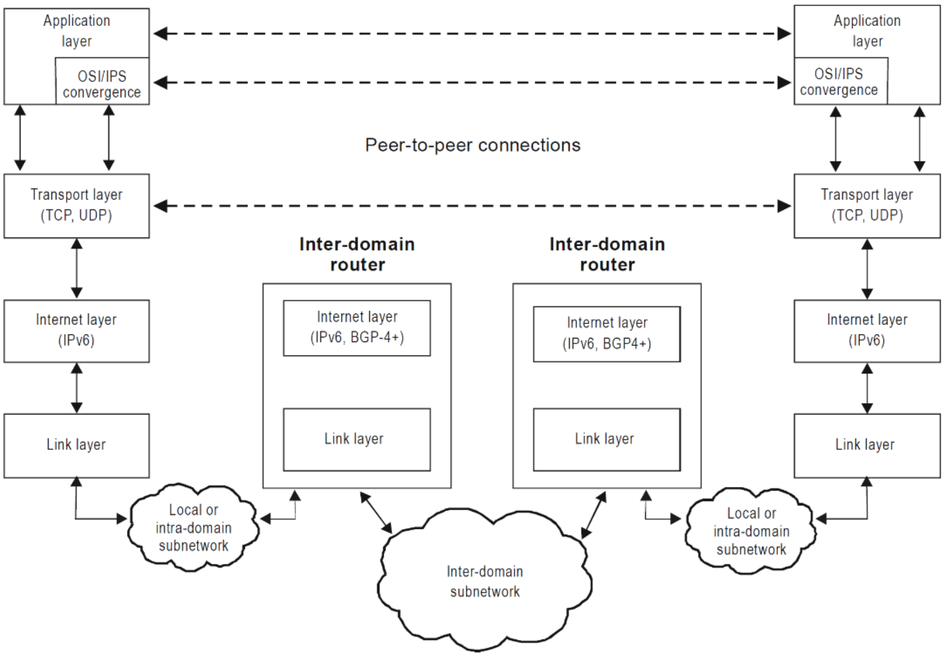

Figure 4: ATN/IPS protocol stack [8].

A representation of the future ATN/IPS network is illustrated in Figure 5. The aircraft and ground end systems communicate with each other using the IPS transport and network protocols. The exchanged data is transmitted over the multiple air-ground data links that connect the aircraft with the ground network. The quality of service, mobility and security protocols described in [8] are provided to the air-ground links by the “aircraft gateway” and “ground gateway”. These elements could be implemented with one or more nodes. For example, in the ACROSS project testbed [19], quality of service is implemented in one router and the mobility and security protocols together in a separate router.

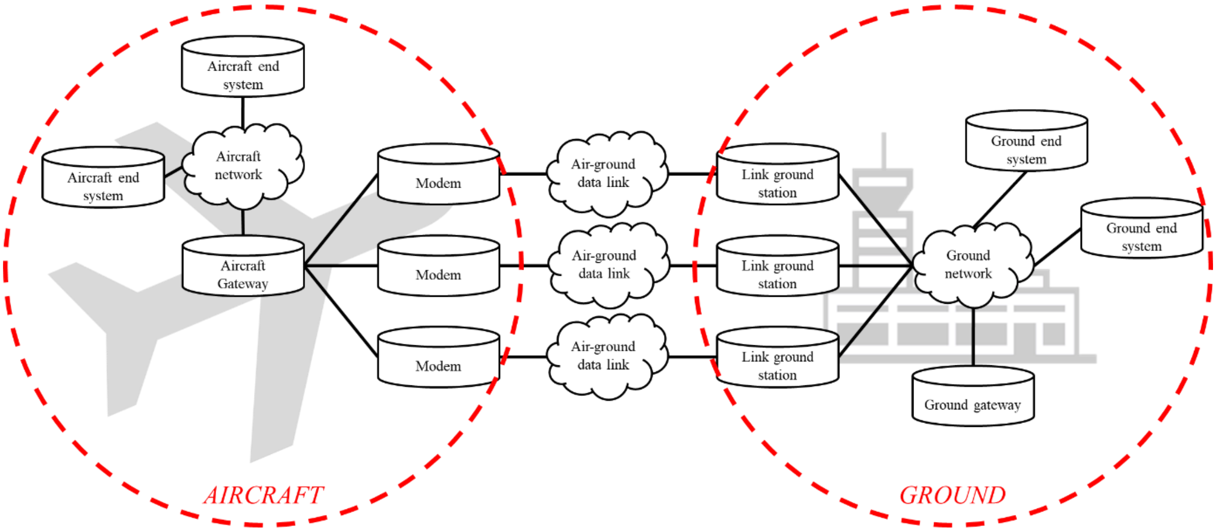

Figure 5: ATN/IPS network representation.

The integration of the future ATN/IPS network has been studied in the SANDRA project, covering aspects such as quality of service, network mobility, enhanced transport protocols and header compression [9]. An important aspect of quality of service is having enough bit rate to transmit all the traffic generated. Normally, traffic from different aeronautical service domains (e.g. ATC or Aeronautical Passenger Communication APC) are physically segregated, meaning that different links are used to transmit. In SANDRA it was explored to logically segregate the traffic using different Internet Protocol security (IPsec) security associations over the same physical link with a strict prioritization of safety traffic (e.g. ATC) versus passenger traffic (e.g. APC) as an alternative to that inefficient use of resources. However, the certification issues with this concept make it difficult to be implemented in a real scenario. Network mobility was also studied with the implementation of the NEtwork MObility (NEMO) protocol [24] and the impact of pre-emptively handover traffic between links before moving out of coverage. The results of the project were presented in [25].

The top layer in the protocol stack is the application layer. It is defined by ICAO for both ATN/IPS and ATN/OSI as an exchange of messages between the end systems and its characteristics are explained in the next section.

2.2.2. Application layer

The performance requirements of the air-ground communications are defined using the Requirement Communication Performance (RCP) metric. The RCP parameters refer to the performance of the transactions. A transaction (or operational communication transaction) is *"the process a human uses to initiate the transmission of an instruction, clearance, flight information, and/or request, and is completed when that human is confident that the transaction is complete"* [2]. At application layer, the transaction is the exchange of messages (i.e. the application layer protocol data unit in the ATN/IPS protocol stack) between the air and ground end systems.

In ICAO GOLD [13], the exchange of a message between a transmitter and a receiver is acknowledged upon correct reception. The transmitter will retransmit the message after a timer expires if the acknowledgement has not been received (see Figure 6).

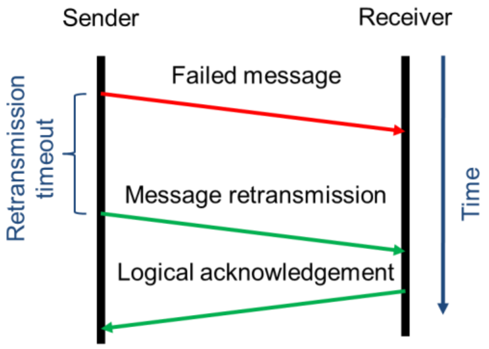

Figure 6: Retransmission logic of the transaction model.

Transactions are presented as an exchange of two messages in ICAO GOLD [13]. The side initiating the operation (aircraft or ground) is called initiator and the other side the responder. A request message is sent from the initiator. Following the correct reception of the request, the responder replies with a reply message (see Figure 7). In this thesis, these exchanges are named *bidirectional transactions*.

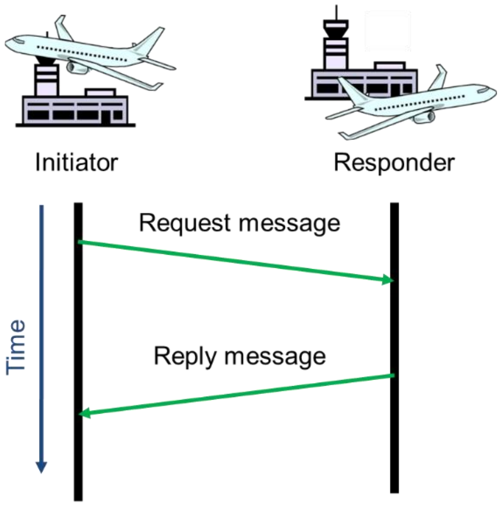

Figure 7: Bidirectional transaction representation.

Surveillance operations like fuel reports are described in ICAO GOLD [13]. The communication consists in a message called notification, sent from the aircraft to the ground. While the word transaction is not used for these communications, the same metric parameters as the RCP are used. Therefore, in this thesis, these exchanges (regardless of the direction) are named *unidirectional transactions*. Their representation is shown in Figure 8.

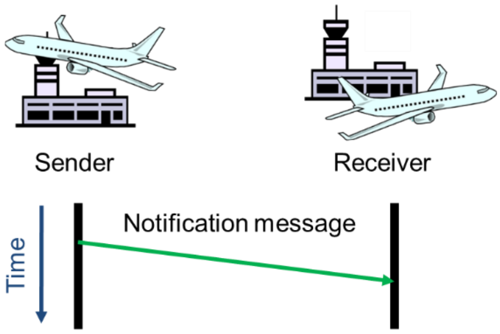

Figure 8: Unidirectional transaction representation.

If more complex operations that require multiple exchanges (3 or more ways) are defined, then they should be broken down into a composite of unidirectional and bidirectional transactions. For the remainder of the document, when it is not specified, all transactions are considered unidirectional.

The messages generated by the application layer are encapsulated in by the transport protocol. The transport layer of ATN/IPS is presented in the next section.

2.2.3. ATN/IPS transport layer

In the ATN/IPS, the transport protocols are Transmission Control Protocol (TCP) and User Datagram Protocol (UDP). Both protocols are part of the ATN/IPS standard [8] and so applications might choose either for transport. TCP is a connection-oriented transport protocol that provides reliability whereas UDP is connectionless and lightweight. TCP's main advantage over UDP is the assurance of delivery of all the data. However, TCP does not provide any control over the time until the delivery. TCP's main disadvantage with respect to UDP is overhead. The UDP header is 8-bytes long and TCP's is between 20 and 60 bytes. Also, before beginning data transmission with TCP a connection must be established, thus delaying the transmission of data. This is especially problematic when transmitting urgent data over satellite communications, a link type commonly used for aeronautical communications. Because of the high latency of geostationary satellites, when used to establish a TCP connection at least 500 ms are needed just because of the propagation delay. Alternatively, the TCP connection can be established from the beginning and kept alive, but this approach consumes additional bandwidth due to signalling. Therefore, TCP is better suited for bulk transmissions and UDP is better suited for delay-sensitive applications.

The communications considered in this thesis (see Sections 2.4 and 2.5) are composed of short messages that have are subject to strict time requirements, so it is assumed that UDP is used as transport protocol. According to [10], Boeing and Honeywell (two important aeronautics industry members) are already favouring UDP over TCP. Thus, the performance of communications using TCP as transport protocol are out-of-scope of this work. If TCP would be used, the Single-Link RCP model (Section 4.3) and the MPEC RCP model (Section 5.4) would have to include the delay of establishing the connection when calculating the delay incurred by any message. The queuing delay at the link could increase because of the signalling. The different TCP congestion control mechanisms and the retransmissions of lost packets would have to be modelled.

The UDP datagrams are encapsulated by the ATN/IPS network protocols. The next section introduces them and shows the UDP datagram with all the network headers.

2.2.4. ATN/IPS network layer

The main network protocol in the ATN/IPS is the Internet Protocol version 6 (IPv6). IPv6 is connectionless network protocol that provides no assurance of delivery. In addition to IPv6, more protocols are defined for specific functions such as mobility and security.

The Mobile IPv6 (MIPv6) protocol [26] has been proposed by ICAO to provide mobility to the network layer. With this protocol, the mobile node (the aircraft node) has two addresses. One, the care-of-address is the IPv6 address provided by the access router of the air-ground data link. Second, the home address which is an IPv6 with a prefix located in the network of the Home Agent. The Home Agent is a fixed ground entity, part of the MIPv6 protocol. Whenever a corresponding node (the ground node) communicates with the mobile node, it always uses the home address. Thus, the packet is always routed through the Home Agent. The Home Agent encapsulates the packet to send it to the current care-of-address of the mobile node. Whenever the mobile node changes its care-of-address, it notifies the Home Agent. Using this protocol, an additional IPv6 header is added to the packet for tunnelling. The IPv6 addresses are conceived as both identifiers of nodes but they also indicate the location of the node in the network. With MIPv6, the aircraft is always identified with the same address (home address) while changing location. The main issue with this protocol is an increase in the end-to-end delay because all packets must go through the Home Agent. For example, if an aircraft registered to a Home Agent in the Germany is flying over Australia and it communicates with a ground node in Australia, the packets must be transmitted first to the Home Agent in Germany and then back to Australia. Changing Home Agent also means changing the home address. Since the thesis focuses on the air-ground data link requirements rather than the end-to-end, the impact of MIPv6 in the end-to-end latency is out-of-scope of the thesis.

The Internet Protocol security (IPsec) security architecture [27] must be implemented on all nodes. When IPsec is used between two routers (IPsec gateways), the packets sent between the IPsec gateways are protected. From [27], that protection is “access control, connectionless integrity, data origin authentication, detection and rejection of replays (a form of partial sequence integrity), confidentiality (via encryption), and limited traffic flow confidentiality”. In the thesis, encryption is assumed not to be used; voice communications are currently unencrypted to allow anyone receiving a message to see it regardless if they were the intended receivers, so it is likely that most data communications remain unencrypted. When no encryption is used, then the Encapsulating Security Payload (ESP) protocol [28] provides authentication and integrity.

The ESP protocol header has a field named “Security Parameter Index” to authenticate the packet as belonging to a protected path between two IPsec gateways. Another field named “Sequence number” is used to avoid repeated packets. Integrity is provided by the ESP protocol with the “Integrity Check Value” field, to avoid unauthorized manipulation of the data including the ESP header. For IPsec without encryption, ICAO has selected the Hash Message Authentication Code (HMAC) “AUTH_HMAC_SHA2_256-128” algorithm [29]. The HMAC algorithm calculates a new string of bits or hash (in this case, 256 bits long, but truncated to 128 bits) using the packet’s bits and a key shared by both IPsec gateways. When the IPsec packet is received at the IPsec gateway, the hash is recalculated and compared to the hash in the packet. If both hashes match, the packet is highly unlikely erroneous. Changes in the packet data (intentional or unintentional) are detected with this, but no correction capabilities are provided.

In addition to the ESP header, the ESP protocol adds a trailer with padding to make the packet multiple of 4 bytes. It is assumed that ESP is used in tunnel mode with MIPv6 providing the outer IPv6 header to reduce the overhead. The packet structure is shown in Figure 9.

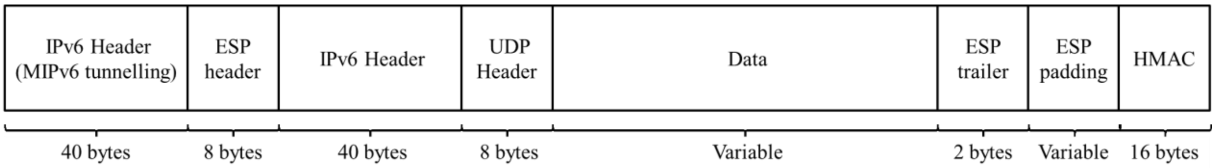

Figure 9: Packet structure

ICAO has selected in the ATN/IPS manual the Internet Key Exchange Protocol Version 2 (IKEv2) [30]. The two gateways authenticate each other either using a pre-shared key or the combination of public signature key and certificate. IKEv2 is used to share secret information such as the keys used by ESP protocol to calculate the hash.

Each message is encapsulated in UDP datagrams and then in *k* IPv6 packets of size *b* bits. This is shown graphically in Figure 10; in the case of this figure, the message is split in 3, but depending on the service it could be a different number. If the size of the resulting IPv6 packets is bigger than the Maximum Transmission Unit (MTU) then the sender must adjust the packet size. Given that the path between the aircraft and ground end systems is composed of several links whose MTU is unknown, it is assumed that all links support at least the minimum MTU required by IPv6, 1280 bytes [31].

The ATN/IPS doesn’t specify the protocols used in the lower layers. After seeing all the packet’s structure, the next section covers an important aspect of ATN/IPS, the overhead generated by all the headers as shown in Figure 9.

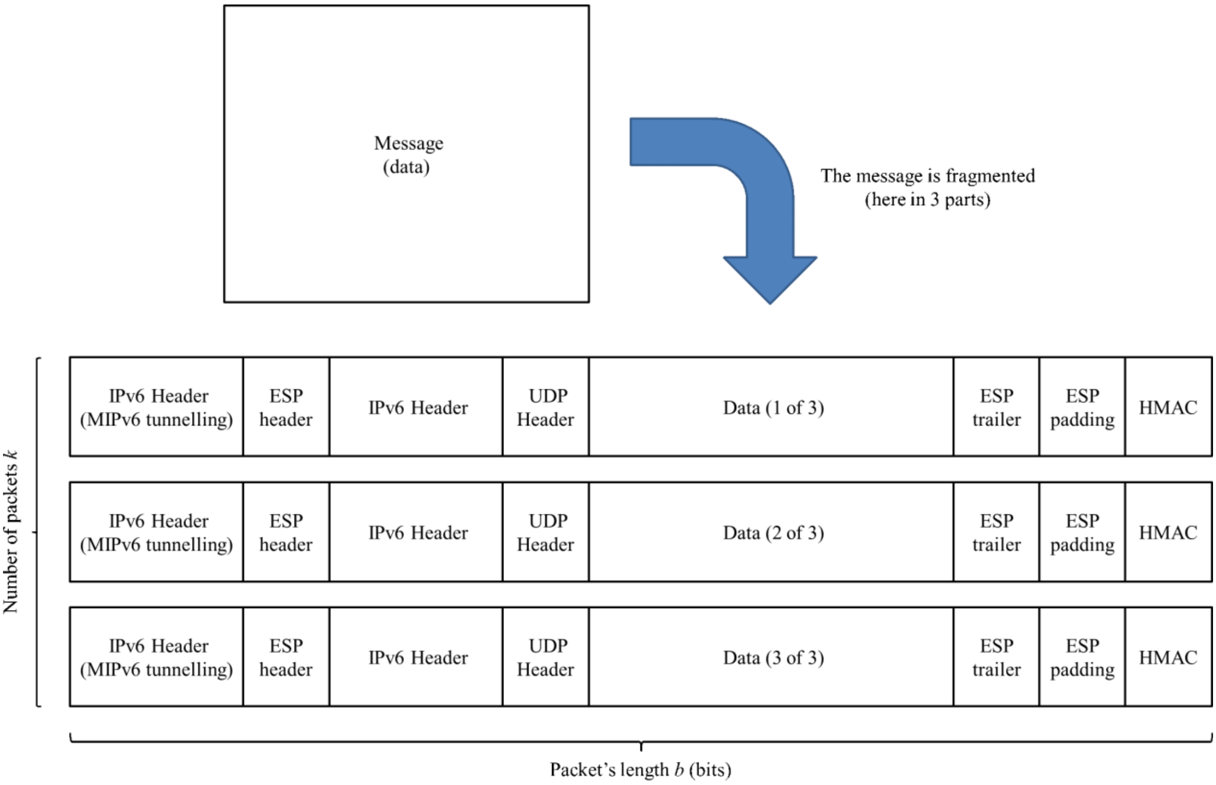

Figure 10: An encapsulated message with k=3

2.2.5. Overhead

The use of ATN/IPS causes a significant overhead in the ATC communications. The ATN/OSI headers' total length for most ATC services is 77 bytes [1] and the ATN/IPS headers' length is between 114 and 117 bytes (see Figure 9), depending on the padding added by the ESP trailer. Therefore, with ATN/IPS there is a ~50% increased overhead with respect to ATN/OSI. The increased overhead is a problem for packets with a data length much smaller than the headers' length. For example, for the ACL service data size per packet is 16 bytes (see Table 4): with the ATN/OSI the headers are 83% of the packet and with ATN/IPS it is 88%. If we look at the D-ALERT service (air-to-ground) with 923 bytes of data, with ATN/OSI the headers are 7.7% and with ATN/IPS they are 11.3% of the total length. The conclusion in [32] is that, the benefits of using ATN/IPS without reducing the overhead are not worth the cost. Whether or not those values are acceptable is debate out-of-scope of this thesis.

Overhead is important for the performance of the future air-ground data communications because transmitting additional data generates additional transmission delay and consumes more bandwidth. As a link's bandwidth utilization increases, the queuing delay also increases. The additional delay incurred by the packets makes it harder to meet the future latency requirements.

ICAO proposes to reduce the overhead using RObust Header Compression (ROHC) [33]. ROHC reduces the header size by storing on the decompressor the fields of the headers that have the same value on every packet of a stream, so that those fields are not transmitted. ROHC reduces the size of changing fields by predicting their value at the decompressor. A full packet is periodically sent to refresh the decompressor. The performance achievable by ROHC for the aeronautical communications has been discussed in [34] and its implementation was tested in the SANDRA project [35] showing promising results. The use of ROHC is optional according to the ATN/IPS manual [8], so it is not considered in the calculations of this thesis. When ROHC is used over the air-ground data link, it changes how losses occur. Depending on the ROHC mode used, if the periodic refreshment packet is lost, then all packets are either lost or they are delayed until a retransmission of the refreshment packet is requested and received. Also, the first packets when a new stream is transmitted are bigger until the compressor stops sending the constant fields, thus increasing the latency of the packets.

2.3. Required Communication Performance metric

2.3.1. Overview

In the previous section, the protocol stack was described. However, that only covers the traffic characterization. The performance requirements are given at the application layer by the Required Communication Performance (RCP) metric.

The RCP metric is defined by ICAO as "*a statement of performance requirements for operational communication in support of specific ATM functions*". An ATM function is the same as an ATM operation. Thus, the RCP is used to establish the adequate level of safety and efficiency required from the communications to support an operation. When defining the requirements using the RCP metric, all the elements involved in the communication, including the humans, are considered. The RCP has been proposed by ICAO for both civilian passenger/transportation aircraft [2] and Unmanned Aerial Vehicles [12]. In the next section, the metric's parameters are described.

2.3.2. RCP metric parameters

The RCP consists of four parameters: transaction time, continuity, integrity and availability. The following definitions have been provided by ICAO in the RCP document [2]:

- **Transaction time (*T*).** The maximum time for the completion of the operational communication transaction after which the initiator should revert to an alternative procedure.
- **Continuity (*C*).** The probability that an operational communication transaction can be completed within the transaction time.
- **Integrity (*I*).** The probability of one or more undetected errors in a completed communication transaction.
- **Availability (*A*).** The probability that an operational communication transaction can be initiated when needed.

ICAO GOLD [13] has a slightly different approach for the transaction time. The definition shown in the previous list is called "expiration time" (again, to be met with probability C). Then, a smaller value of time is given that must be met by 95% of the transactions, called "nominal time". Having those two definitions provides higher detail of the requirements of the time taken to complete the operational communication transaction, since two conditions are imposed rather than just one. In fact, this is setting restrictions on the shape of cumulative density function of the time spent to complete a transaction, one at the 95% probability and one at the C probability. The original definitions of continuity and transaction time are worded such that it is easily understood that only one value for each parameter is possible. A rewording of the definitions to clarify that each value of continuity is linked to a specific value of transaction time was proposed by the author in [18] and they are repeated just below. These are the definitions that are used in the remainder of this work:

- **Transaction time (*T*).** The time elapsed until completion of an operational communication transaction.
- **Continuity (*C*).** The probability that an operational communication transaction can be completed within an associated value of transaction time.

The availability definition is also reviewed. If ICAO's definition is read strictly, being capable of initiating the communication regardless if there is any path performant enough to meet the requirements, is enough to consider the communication as available. Implicitly, the meaning could include the condition that the transaction can be initiated while meeting the required performance. Thus, the definition of availability is rephrased to, as proposed by the author in [18]:

- **Availability (*A*).** The probability that an operational communication transaction can be initiated when needed while meeting the continuity and integrity requirements.

This definition of availability is used for the remainder of the thesis. Note that the new definition does not require all transactions to be successfully completed but only with the probabilities imposed by the other requirements.

The next two sections explain specific cases of applying the RCP metric. First, when the requirements are allocated only to the technical part of the communication and then the RCP for unidirectional transactions.

2.3.3. Required Communication Technical Performance

When removing the human contribution to the communication performance, only the technical contributions are left. The requirements applied only to the technical part, have been named Required Communication Technical Performance (RCTP) by ICAO. Figure 11 (taken from ICAO GOLD [13]) shows the elements of communication that contribute to the RCTP: the aircraft systems, the Communication Service Provider (CSP) systems (i.e. the air-ground data link) and the Air-Traffic Services unit (ATSU) systems. A CSP is an organization that manages commercially one or more air-ground data links.

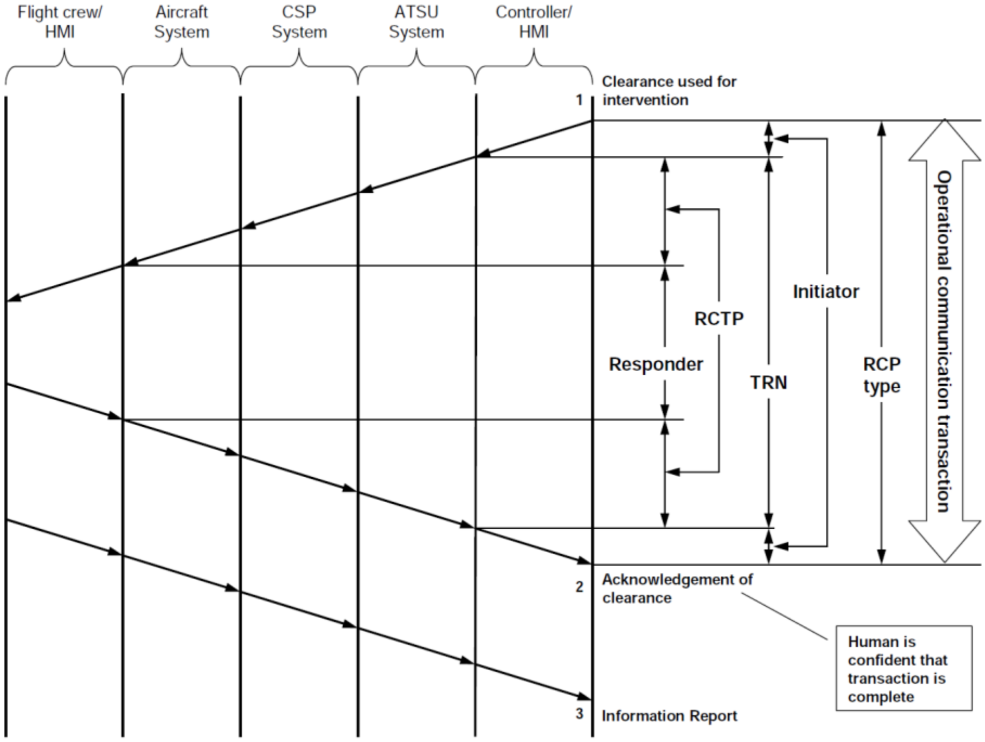

Figure 11: RCP allocation to the different elements of the communication as shown in ICAO GOLD [13].

The RCTP parameters are the same as for the RCP: transaction time, continuity, integrity and availability. Those parameters measure the performance at application layer (both for ATN/OSI and ATN/IPS) and indirectly impose requirements on the quality of the air-ground data links used for the communication. For example, link parameters such as latency or packet loss ratio have an impact on the transaction time.

2.3.4. Required Surveillance Performance

Surveillance operations are announcements that aircraft make to notify the ground (and presumably other aircraft) of their status, like for example position reports. The exchange of information is unidirectional albeit signalling could be required in the opposite direction. The performance metric for surveillance operations' communications is introduced as Required Surveillance Performance (RSP) by ICAO [13]. The RSP is the same as the RCP for just one direction; the same metric parameters (time, continuity, integrity and availability) are used. However, the use of the word "transaction" is not used. In this document the RSP will be treated as RCP for unidirectional transactions.

2.3.5. Determining the requirements

After having defined the metric, this section explains how the values of the parameters are found. The stringency of the requirements specified using the RCP depend on the operation the RCP is related to. The RCP is defined to ensure that an adequate level of safety and efficiency is achieved. The severity of failure of the operation supported by the service determines the values chosen for each of the RCP parameters.

The common approach to determining the requirements is to classify the hazard impact on the safety of flight when the operation fails and then relate this to a maximum acceptable occurrence rate. This is shown in documents for civilian aviation (ICAO [2], FAA and EUROCONTROL [1]) and unnamed aerial vehicles by the Joint Authorities for Rulemaking of Unmanned Systems (JARUS) [36].

The first step when defining the requirements is to perform a safety assessment. The safety hazard effect is ranked in one of five classes (no safety effect, minor, major, hazardous or catastrophic) depending on the impact. An example of the description of the effect and how to map it to a hazard class is found in the COCRv2 [1] and replicated here in Table 1.

Effect on:	**Hazard Class**				
	No safety effect	**Minor**	**Major**	**Hazardous**	**Catastrophic**
General		Does not significantly reduce system safety. Required actions are within operator's capabilities.	Reduces the capability of the system or operators to cope with adverse operating conditions to the extent that:	Reduces the capability of the system of the operator's capability to cope with adverse conditions to the extents that:	Total loss of system control such that:
ATC	Slight increase in ATC workload	Slight reduction in ATC capability, or significant increase in ATC workload	Reduction in separation as defined by a low/moderate severity operational error or significant reduction in ATC capability	Reduction in separation as defined by a high severity operational error or a total loss of ATC	Collisions with other aircraft, obstacles, or terrain
Flying public	• No effect on flight crew • Has no safety effect • Inconvenience	• Sight increase in workload • Slight reduction in safety margin or functional capabilities • Minor illness or damage • Some physical discomfort	• Significant increase in flight crew workload • Significant reduction in safety margin or functional capability • Major illness, injury, or damage • Physical distress	• Large reduction in safety margin or functional capability • Serious or fatal injury to small number • Physical distress/excessive workload	Outcome would result in: • Hull loss • Multiple fatalities

Table 1: Description of hazard severity as found in COCRv2 [1].

Because fault-free systems do not exist, failures are bound to happen. Thus, a tolerance is allowed on the failure of operations based on the safety impact; the more hazardous a failure is, the less often must it occur. Table 2 shows the acceptable probability of occurrence per flight hour based on the hazard classes from COCRv2 [1]. For unmanned aerial vehicles, JARUS has a similar table but the occurrence depends on characteristics of the aircraft (e.g. weight).

Hazard Class	Safety Objective	Definition
No Safety Effect	Frequent	≥ 1 occurrence in 10^{-3} per flight hour
Minor	Probable	≤ 1 occurrence in 10^{-3} per flight hour
Major	Remote	≤ 1 occurrence in 10^{-5} per flight hour
Hazardous	Extremely Remote	≤ 1 occurrence in 10^{-7} per flight hour
Catastrophic	Extremely Improbable	≤ 1 occurrence in 10^{-9}per flight hour

Table 2: Safety objective definitions as found in COCRv2 [1].

The acceptable probability of occurrence is given in "probability per flight hour". Since the probability per transaction fits better the RCP definitions, a change must be applied, based on the number of transactions in each relevant flight hour. Take P_{FH} as the probability of failure per flight hour, P_{T} the probability of failure per transaction and N the average number of transactions per flight hour during the flight phases when the transaction might happen, (1) and (2) are the relations between P_{FH} and P_{T} (obtained from [37]).

$$P_{FH} = 1 - (1 - P_T)^N \tag{1}$$

$$P_T = 1 - (1 - P_{FH})^{1/N} \tag{2}$$

After following this procedure, the required values of the RCP are found. The RCP parameters can also be found to show the expected and actual values provided by the links, as explained in the next section.

2.3.6. Expected and Actual Communication Technical Performance

The RCP metric defines the communication requirements to ensure the safety and efficiency of flight. However, the parameters of the metric can be used also to describe the expected performance that a system will provide, or to evaluate the actual performance provided. This is a very important part of the global use of the RCP metric for communications. Being able to estimate the expected technical performance of the system is a key element of the design and dimensioning of the communications system. Evaluating the actual technical performance of an existing system is needed to determine its compliance with the requirements and if adjustments must be made.

As taken from [19], "when the RCP parameters are used…

- … to express the technical requirements, we speak of *Required Technical Communication Performance* (RCTP). The values of the RCTP are *defined*.
- … to estimate the expected technical performance provided, we speak of *Expected Technical Communication Performance* (ECTP). The values of the RCTP are *calculated*.
- … to reflect the actual technical performance provided, we speak of *Actual Technical Communication Performance* (ACTP). The values of the ACTP are *measured*."

The ECTP values are calculated using a theoretical model or through simulation. The ACTP values are measured by logging the performance of an existing communications system.

2.4. Future ATC air-ground data communications

This section lists the air-ground data link requirements for the future data-centric ATC communications and the traffic characteristics. Depending on the operation supported by the communications the RCP values of transaction time, continuity, integrity and availability will differ. The requirements found in different documents such as ICAO GOLD [13] and 9869 [2] have the transaction time values ranging from 10 to 400 seconds. The technical allocation of these transaction times is also in the order of tens and hundreds of seconds. While these numbers might seem ridiculously high to users of terrestrial links, they are not for current aeronautical data communications users, who are used to data links having very low data rates (e.g. 1200 bps with Iridium).

The COCRv2 document from Eurocontrol and the FAA contains the RCP values for the operations with the future data-centric communications. Even though the document dates to 2007, to the knowledge of the author of the thesis, it is the most up-to-date requirements document publicly available. SESAR's projects 15.02.04 [38] and 15.02.06 [39] have recently produced new RCP requirements. However, the deliverables with the requirements are not publicly available. If those requirements become the norm in Europe, all the results obtained in Chapter 4 (single-link), Chapter 5 (multi-link) and Chapter 6 (packet bundling) could be recalculated to meet them; all the models and techniques proposed in this work are valid regardless of the set of RCP requirements.

In COCRv2, the requirements are given for each ATC and AOC service, considering that all operations that are part of the same service have the same requirements. The requirements specified in COCRv2 are presented in multiple tables depending on where the requirements are allocated (end-to-end or the data links), the airspace domain (APT, TMA, ENR, ORP and AOA), and when are they valid (phase 1 for voice centric from 2005 and phase 2 for data-centric from 2020). The airspace domains are defined in COCRv2 as [1]:

- Airport domain (APT) consists of an area 10 miles in diameter and up to ~5000 ft consisting of the airport surface and immediate vicinity of the airport.
- The Terminal Maneuvering Area (TMA) domain consists of the airspace surrounding an airport, typically starting at ~5000 ft up to ~FL245, that is the transition airspace used by Air Traffic Control (ATC) to merge and space aircraft for landing or for entrance into the En Route domain. The TMA domain typically radiates out ~50 nautical miles from the center of an airport. The COCR assumes that the airspace used in departure and arrival phases of flight are identical except for the direction of flight.
- The En Route (ENR) domain consists of the airspace that surrounds the TMA domain starting at ~FL245 to ~FL600 and is the continental or domestic airspace used by ATC for the cruise portion of the flight. It also includes areas to the lower limits of controlled airspace (e.g., 1,500 feet) where an airport or TMA does not exist. At the ATSU level, the COCR assumes this domain to have a horizontal limit extending 300 nautical miles by 500 nautical miles.
- The Oceanic, Remote, Polar (ORP) domain is the same as the ENR domain, except that it is associated with geographical areas generally outside of domestic airspace. The COCR assumes this domain to have a horizontal limit extending 1000 nautical miles by 2000 nautical miles.
- The Autonomous Operations Area (AOA) domain is a defined block of airspace which is associated with autonomous operations where aircraft self-separate (i.e., Air Traffic Control is not used). The defined block may change vertical or horizontal limits or usage times based on, among other factors, traffic densities. The COCR assumes this domain to have horizontal limits of 400 nautical miles by 800 nautical miles.

The focus in this thesis is in the air-ground data link requirements for the data-centric communications, that is phase 2 air-ground ATC services in COCRv2. Thus, of all the ATC services, requirements related exclusively to air-air communications such as AOA domain requirements and the AIRSEP, AIRSEP SURV, C&P SURV, ITP SURV, M&S SURV and PARIAPP SURV services are not considered. The A-EXEC as it is no longer considered by SESAR and excluded. The considered services and their requirements are taken from COCRv2 and listed in Table 3.

Table 3 is organized with each ATC service in one row and the RCP parameters in columns. The Transaction Time T requirements are given for all ATC-controlled airspace domains (APT, TMA, ENR and ORP) whereas the other RCP parameters (Continuity C, Integrity I and Availability A) are the same regardless of the domain. The $T_{95\%}$ columns contain the transaction time requirements for 95% continuity and the T_C columns, the transaction time requirements for the continuity value from column C. For the DSC service, the values in COCRv2 for $T_{95\%}$ were higher than the values of T_C; this is assumed to be a typo, so the values have been swapped in Table 3. The transaction time requirements provided in Table 3 correspond only to one-way requirements, even for bidirectional transactions. Thus, the requirements must be met for both the air-to-ground and ground-to-air directions for bidirectional transactions.

ATC service	$T_{95\%}$ (APT)	$T_{95\%}$ (TMA)	$T_{95\%}$ (ENR)	$T_{95\%}$ (ORP)	C	T_C (APT)	T_C (TMA)	T_C (ENR)	T_C (ORP)	I	A
ACL	1.4	1.4	1.4	5.9	0.9996	5.0	5.0	5.0	16	$5\cdot10^{-8}$	0.9995
ACM	1.4	1.4	1.4	5.9	0.9996	5.0	5.0	5.0	16	$5\cdot10^{-8}$	0.9995
AMC	3.8	3.8	3.8	-	0.996	8.0	8.0	8.0	-	$5\cdot10^{-4}$	0.9965
ARMAND	-	-	4.7	-	0.996	-	-	13.6	-	$5\cdot10^{-4}$	0.995
C&P ACL	-	2.4	2.4	5.9	0.9996	-	7.8	7.8	16.0	$5\cdot10^{-8}$	0.9995
COTRAC (int.)	-	2.4	2.4	5.9	0.9996	-	7.8	7.8	16.0	$5\cdot10^{-8}$	0.9995
COTRAC (wil.)	-	2.4	2.4	5.9	0.9996	-	7.8	7.8	16.0	$5\cdot10^{-8}$	0.9995
D-ALERT	2.4	2.4	2.4	5.9	0.9996	7.8	7.8	7.8	16.0	$5\cdot10^{-6}$	0.9995
D-ATIS (arr)	2.4	2.4	2.4	9.2	0.996	7.8	7.8	7.8	24.0	$5\cdot10^{-8}$	0.995
D-ATIS (dep)	2.4	2.4	2.4	9.2	0.996	7.8	7.8	7.8	24.0	$5\cdot10^{-8}$	0.995
DCL	9.2	-	-	-	0.9996	24.0	-	-	-	$5\cdot10^{-8}$	0.9995
D-FLUP	2.4	2.4	4.7	9.2	0.996	7.8	7.8	13.6	24.0	$5\cdot10^{-4}$	0.995
DLL	1.4	2.4	4.7	9.2	0.9996	7.8	7.8	13.6	24.0	$5\cdot10^{-8}$	0.9995
D-ORIS	-	2.4	2.4	9.2	0.996	-	7.8	7.8	24.0	$5\cdot10^{-8}$	0.995
D-OTIS	2.4	2.4	2.4	9.2	0.996	7.8	7.8	7.8	24.0	$5\cdot10^{-8}$	0.995
D-RVR	1.4	1.4	2.4	9.2	0.996	5.0	5.0	7.8	24.0	$5\cdot10^{-8}$	0.995
DSC	-	-	9.2	16.0	0.9996	-	-	24.0	22.2	$5\cdot10^{-8}$	0.9995
D-SIG	4.7	4.7	-	-	0.996	13.6	13.6	-	-	$5\cdot10^{-8}$	0.995
D-SIGMENT	2.4	2.4	2.4	9.2	0.996	7.8	7.8	7.8	24.0	$5\cdot10^{-8}$	0.995
D-TAXI	2.4	2.4	-	-	0.9996	7.8	7.8	-	-	$5\cdot10^{-8}$	0.9995
DYNAV	-	-	4.7	9.2	0.996	-	-	13.6	24.0	$5\cdot10^{-4}$	0.995
FLIPCY	2.4	2.4	2.4	5.9	0.9996	7.8	7.8	7.8	16.0	$5\cdot10^{-8}$	0.9995
FLIPINT	2.4	2.4	2.4	5.9	0.9996	7.8	7.8	7.8	16.0	$5\cdot10^{-8}$	0.9995
ITP ACL	-	2.4	2.4	5.9	0.9996	-	7.8	7.8	16.0	$5\cdot10^{-8}$	0.9995
M&S ACL	-	2.4	2.4	5.9	0.9996	-	7.8	7.8	16.0	$5\cdot10^{-8}$	0.9995
PAIRAPP ACL	-	2.4	-	-	0.9996	-	7.8	-	-	$5\cdot10^{-8}$	0.9995
PPD	4.7	4.7	4.7	9.2	0.996	13.6	13.6	13.6	24.0	$5\cdot10^{-4}$	0.995
SAP (Setup)	-	2.4	2.4	-	0.9996	-	7.8	7.8	-	$5\cdot10^{-8}$	0.9995
SAP (Report)	-	2.4	2.4	-	0.9996	-	7.8	7.8	-	$5\cdot10^{-8}$	0.9995
SURV (ATC)	0.4	1.2	1.2	1.2	0.99996	3.2	8.0	8.0	8.0	$5\cdot10^{-8}$	0.99995
URCO	2.4	2.4	2.4	5.9	0.9996	7.8	7.8	7.8	16.0	$5\cdot10^{-6}$	0.9995
WAKE	0.4	1.2	1.2	-	0.9996	3.2	8.0	8.0	-	$5\cdot10^{-8}$	0.9995

Table 3: Data-centric ATC air-ground data link performance requirements

Of all the requirements in Table 3, the strictest is the ATC surveillance (SURV) service RCTP. The transaction time requirements for SURV services are related to the aircraft separation requirements. It is expected that air traffic continues to grow and thus the separation must be reduced to accommodate the new aircraft. A publication by SESAR in 2016 [40] reflects that initial tests with Inmarsat's Swift BroadBand satellite system meets the SURV transaction time requirements. However, the trial's length did not produce an amount of data big enough to be statistically meaningful to say that the ACTP meets the RCTP.

To calculate the ECTP of the air-ground data links when used to support the future ATC services, it is necessary to know the number of packets per message *k* and the length of each packet *b*. In addition to the RCTP requirements, COCRv2 provides an estimation of the values for each service when transmitted over an ATN/OSI network. The number of ATN/OSI network Protocol Data Units (i.e. packets) and their size in bytes are obtained from COCRv2's table 6-15 [1]. The values given are averages and already consider the ATN/OSI headers' sizes. However, the protocol stack considered in this thesis is the ATN/IPS (see Section 2.2).

The number of packets per message *k* and the length of each packet *b* (in bytes) are given in Table 4. Each row corresponds to one of the ATC services also found in Table 3. The subscript of *k* and *b* indicates the protocol stack (ATN/IPS or ATN/OSI). The "OSI data" column corresponds to the data length of each OSI packet (i.e. length without headers). All columns are given for the air-to-ground (A2G) and ground-to-air (G2A) directions. All lengths are given in bytes.

To obtain the ATN/IPS values for *k* and *b*, the following conversion procedure is applied. The SURV service is associated to ADS-B messages; the application layer size of the ADS-B message is 28 bytes (headers excluded). The WAKE service is assumed to have the same size as SURV. The DLL service includes 76 bytes of headers and the rest, 77 bytes. After only the data size is left (i.e. OSI data column in Table 4), the final packet size can be obtained adding the UDP header, IPv6 header, ESP header and trailer and MIPv6 tunnelling IPv6 header as explained in Section 2.2.4. However, for resulting packets bigger than the minimum MTU (see Section 2.2.4), the packet number and size are obtained by adding all the data together and selecting the minimum number of packets that after equally spreading the data are sized below the minimum MTU of 1280 bytes. The use of ROHC is optional according to the ATN/IPS manual [8], so it is not considered here when calculating the packet sizes. For example, in the ground-to-air direction, there are three COTRAC (int.) OSI packets of size 1969 bytes each, with 1892 bytes of data each. The total data size is $3 \cdot 1892 = 5676$ bytes. If divided in four packets, the each would carry 1419 bytes of application data, more than the maximum 1280. When divided in five ATN/IPS packets, each carries 1136 bytes of data. To this number, we add the headers and trailers described above $1136 + 8 + 40 + 10 + 16 + 40 = 1250$ bytes. Because the packet is padded to be multiple of 4 bytes, 1250 bytes become the final packet size of 1252 bytes.

ATC service	**A2G k_{OSI}**	**A2G b_{OSI}**	**A2G OSI data**	**A2G k_{IPS}**	**A2G b_{IPS}**	**G2A k_{OSI}**	**G2A b_{OSI}**	**G2A OSI data**	**G2A k_{IPS}**	**G2A b_{IPS}**
ACL	2	93	16	2	132	2	93	16	2	132
ACM	1	88	11	1	128	1	126	49	1	164
AMC	0	0	0	0	0	1	89	12	1	128
ARMAND	1	88	11	1	128	1	260	183	1	300
C&P ACL	2	93	16	2	132	2	93	16	2	132
COTRAC (int.)	4	1380	1303	5	1160	3	1969	1892	5	1252
COTRAC (wil.)	2	1380	1303	3	984	2	1613	1536	3	1140
D-ALERT	1	1000	923	1	1040	1	88	11	1	128
D-ATIS (arr)	3	93	16	3	132	5	100	23	5	140
D-ATIS (dep)	2	96	19	2	136	3	101	24	3	140
DCL	2	88	11	2	128	1	117	40	1	156
D-FLUP	3	129	52	3	168	5	190	113	5	228
DLL	1	222	146	1	260	1	491	415	1	532
D-ORIS	3	93	16	3	132	9	478	401	9	516
D-OTIS	3	107	30	3	144	11	193	116	11	232
D-RVR	3	121	44	3	160	4	116	39	4	156

ATC service	A2G k_{OSI}	A2G b_{OSI}	A2G OSI data	A2G k_{IPS}	A2G b_{IPS}	G2A k_{OSI}	G2A b_{OSI}	G2A OSI data	G2A k_{IPS}	G2A b_{IPS}
DSC	4	87	10	4	124	3	96	19	3	136
D-SIG	3	129	52	3	168	4	1340	1263	5	1128
D-SIGMENT	3	129	52	3	168	4	130	53	4	168
D-TAXI	1	98	21	1	136	2	132	55	2	172
DYNAV	1	82	5	1	120	1	515	438	1	552
FLIPCY	1	173	96	1	212	1	105	28	1	144
FLIPINT	1	2763	2686	3	1012	1	143	66	1	180
ITP ACL	2	93	16	2	132	2	93	16	2	132
M&S ACL	2	93	16	2	132	2	93	16	2	132
PAIRAPP ACL	2	93	16	2	132	2	93	16	2	132
PPD	1	277	200	1	316	1	105	28	1	144
SAP (Setup)	2	100	23	2	140	2	95	18	2	132
SAP (Report)	1	107	30	1	144	0	0	0	0	0
SURV (ATC)	1	34	28	1	144	0	0	0	0	0
URCO	1	34	5	1	120	1	98	21	1	136
WAKE	1	34	28	1	144	0	0	0	0	0

Table 4: Average number of packets *k* and average packet size *b* per ATC message

This section covered the requirements and traffic characteristics of the future air-ground data-centric ATC communications. Those are not the only requirements for the future data-centric communications. The requirements and traffic characteristics of unmanned aviation are described in the next section.

2.5. Future unmanned aviation air-ground data communications

There has been a huge increase in the civilian's interest for Unmanned Aerial Vehicles (UAV) and Remotely Piloted Aircraft Vehicles (RPAV) usage in the last few years. The irruption of these aircraft in the ATC controlled airspace would open many new possibilities such as unmanned aerial transport of freight. While UAV and RPAV are not yet allowed to fly alongside manned aircraft, the relevant regulatory bodies are working on making this happen. The objective of this section is to obtain the traffic characteristics and the RCP requirements of the UAV and RPAV communications to evaluate the air-ground data link parameters' required values, as with the ATC services from Section 2.4.

RCP for unmanned aerial operations have not yet been defined. Thus, in this section the requirements of the service supporting the highest-safety demanding operations are derived. Until the autonomous control systems of UAV and RPAV are safe enough, the data link is critical for the safe operation of those vehicles, so the most demanding service is related to Command and Control (C2) operations. A strategic command given to change the flight level when flying over the ocean will have lower requirements than that of an aircraft landing near a populated area, given the higher potential of harm when flying near people. Therefore, the RCTP values of the most demanding operation, landing the aircraft, are obtained from a mix of sources.

The first assumption is that the landing operation is very critical for life-safety. Even if no humans are on board the aircraft, landing would likely happen near people. Something going wrong could lead to a hazardous or catastrophic accident (see Table 1). However, loss of communications would not necessarily have hazardous or catastrophic consequences, as it is unimaginable that the aircraft is not equipped with a back-up automated landing system that could at least avoid damage on humans, even at the consequence of material loss. Therefore, the safety impact of loss of communications is considered as "major", as the safety margin would be highly reduced in this case (see Table 1).

During the European Commission co-funded ACROSS project the X-Plane flight simulator was used to simulate the remote monitoring and control of an aircraft [41]. The data required by the ground station to represent the flight as it was happening on the aircraft was 3965 bytes. To obtain the number of packets and their size, the same procedure as with the ATC traffic (see section 2.4) is followed. Assuming the aircraft is remotely piloted, an update rate of 20 Hz was selected. This matches the information regarding update rates in the bandwidth requirements estimation performed for the NASA [42], that states that the typical update rate for an UAV/RPAV goes from 1 Hz (fully autonomous) to 20 Hz (remotely piloted).

The strictest requirement for military UAV/RPAV C2 messages in North Atlantic Treaty Organization (NATO) standards is 200 ms [43]. This value has been proven to be tolerable for life-critical operations supported remotely by a human in the field of telesurgery [44]; remote telesurgery has been compared in literature to remotely piloting an aircraft in terms of lessons learnt regarding delay [45]. According to COCRv2, 80% of the transaction time is allocated to the data link for most services; here 160 ms.

If failure to complete a transaction would have a “major” impact, then the transaction time at the air-ground data link should not exceed 160 ms with a probability higher than 10^{-5} per flight hour (see Table 2). This probability can be changed into probability of failure per transaction using (2); considering that at 20 Hz, there are 72000 transactions per flight hour, thus $C=(1-10^{-5})^{1/72000}$. However, COCRv2 establishes an 80% allocation of the continuity probability to the data link. Therefore, the continuity requirement for the data link is obtained by elevating the continuity to the power of 0.8. The integrity and availability requirements should contribute to no more than 50% of the errors, assuming hazardous impact.

Parameter	**Value**
Operation	C2 operation: landing UAV/RPAV
Requirements applicable to?	RCTP requirements of the air-ground data link
Message size	3965 bytes
Network layer size	k = 4 UDP/IPv6 Packets b = 1108 bytes
Transaction frequency	20 transactions per second
Transaction time (Continuity) requirement	160 ms (0.9999999999 pT)
Integrity requirement	$7 \cdot 10^{-11}$ pT
Availability requirement	0.999995 pFH

Table 5: C2 landing operation traffic characteristics and RCTP of the air-ground data link

Given that a geostationary satellite links has a minimum propagation delay of roughly 250 ms, it is not possible to fulfil the requirements in Table 5 by a link of this kind. In fact, current UAV operations performed by the U.S. Air Force in Afghanistan are remotely piloted from a pilot at the Afghani airfield for landing and taking off using a direct air-ground link. However, when the UAV is cruising, and all mission decisions are strategic (i.e. not millisecond critical), then the control is given to pilots located in a base in Nevada, U.S.A. [46].

2.6. Summary

To develop the RCP performance models of Chapters 4 and 5 it is necessary to model the air-to-ground data links and the traffic requirements and characteristics. In this chapter, the traffic was modelled.

First, ICAO’s protocol stack for the future data communications, the ATN/IPS is described. This is a required step to characterize the traffic. Applications generate transactions that consist of one or multiple messages. Those messages are transmitted using the UDP transport protocol over an IPv6 network. The choice of using UDP is assumed in the thesis because it is lightweight and adequate for delay-sensitive applications. Neither UDP nor IPv6 implement reliability mechanisms. The IPsec protocol suite is used for security, including data integrity protection. The ATN/IPS is expected to provide a lower cost with respect to its predecessor (ATN/OSI) by opening aeronautical communications to be supported by commercial-of-the-shelf products.

The performance requirements are defined using ICAO’s RCP metric, which consists of four parameters: transaction time, continuity, integrity and availability. Transaction time and continuity control the probability of timely-delivery of the transactions. The result of applying the performance models to a link is a value for each of those parameters. Integrity is the maximum tolerable frequency of undetected errors. Availability is the portion of time when the link is operative and supports the communications. The values for the ATC services are obtained from literature. However, there are no available values for unmanned aviation. Therefore, a similar process to the one used to determine the ATC RCP values is followed to obtain the strictest communication requirements for unmanned aviation: the C2 landing service requirements.

The RCP parameters value requirements for the future ATC services and C2 landing service, and the traffic characteristics of all the services are provided. The performance of the air-ground data links must be compared to those values to determine whether the future data-centric communications are supported. To develop the performance models, a model of the air-ground data link is also needed. It is proposed in the next chapter.

3. AIR-GROUND DATA LINKS

3.1. Introduction

The air-ground data links are part of the communications path used to exchange information between the aircraft and the aeronautical ground systems, as represented in Figure 12. Those links connect the aircraft to the aeronautical ground network, a dedicated network comprising all aeronautical ground sites. All air-ground data links are wireless, but some connect the aircraft directly to the ground station (direct wireless links) and other use a satellite as a relay (satellite links), either in geosynchronous orbit (GEO) or low-Earth orbit (LEO). This difference is important for aeronautical communications as it makes a difference in the performance of the link as well as its coverage.

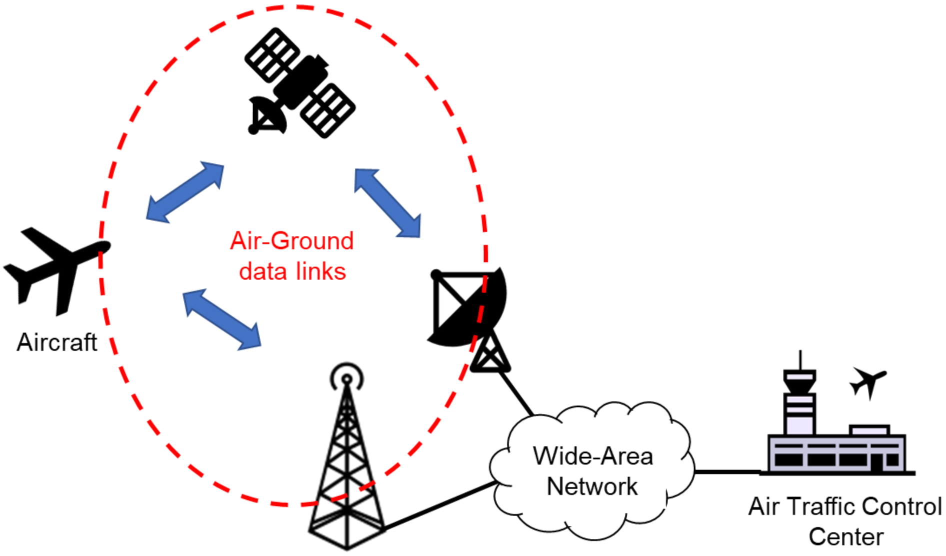

Figure 12: Air-ground data links in the end-end communications.

The first objective of this work is to provide a model to calculate the performance of the air-ground data links measured with the Required Communication Performance (RCP) metric. The RCP parameters refer to transaction performance, the application layer of the ATC and C2 communications (see Section 2.3). However, the parameters used to define the performance of data links are different. Thus, the first step before defining the RCP provided by the air-ground data links (as done in Chapter 4) is proposing a model of the air-ground data link. The objective of this chapter is to propose a detailed model of the air-ground data links while avoiding the necessity to include physical and link layer protocol parameters, as well as not modelling all other traffic sources using the link.

The air-ground data link model is presented in Section 3.2. The model characterizes the availability of the link and the impact on the packets forwarded over it. When the link is available, packets are either successfully delivered with some delay or dropped. The losses are modelled using a continuous-time Markov chain of two states to make them correlated but independent of the traffic profile. The latency of the link is modelled as the contribution of the queuing, transmission, constant and random delays.

In Section 3.3 the existing and planned data links are listed, and their parameters' values obtained from literature when available. The Aeronautical Telecommunication Network / Internet Protocol Suite (ATN/IPS) satellite links reviewed are Iridium Short-Burst Data (SBD), Inmarsat Swift BroadBand (SBB) and Iridium Certus. The ATN/IPS direct wireless links reviewed are Very High Frequency Data Link Mode 2 (VDL2) and L-Band Digital Aeronautical Communication System (LDACS).

There is not enough information to fully characterize all the links with the air-ground data link model. To make an analysis of the suitability of existing and future link technologies, link profiles based on the real technologies are proposed in Section 3.4. The information gaps have been filled with assumptions.

3.2. Air-ground data link model

3.2.1. Overview

The air-ground data link model proposed in this section and published in [20] makes no assumption on the physical and link layer protocols. Thus, the same model is usable for all the air-ground data links, regardless of the protocol choices. However, the link model parameters are not independent of those choices; the impact of the physical and link layer protocols affects the values of the parameters directly. For example, for a link that would use link-layer retransmissions as opposed to the same link without retransmissions, the losses value would be lower and higher latency values would be possible. The model covers three aspects of the data link: uptime, latency and losses.

The uptime of the air-ground data link is represented with the link availability parameter. The air-ground data links are not functional 100% of the time; maintenance or malfunction of the satellite/ground station are just a few of the causes that can make a link unavailable for even a few hours or days. If a packet is forwarded while the link is unavailable, it is lost. When the link is available, the packets either forwarded with delay or lost. The different stages modelled when the link is available are shown in Figure 13. The stages are applied to the packet in the order of the arrows from "ingress" to "egress".

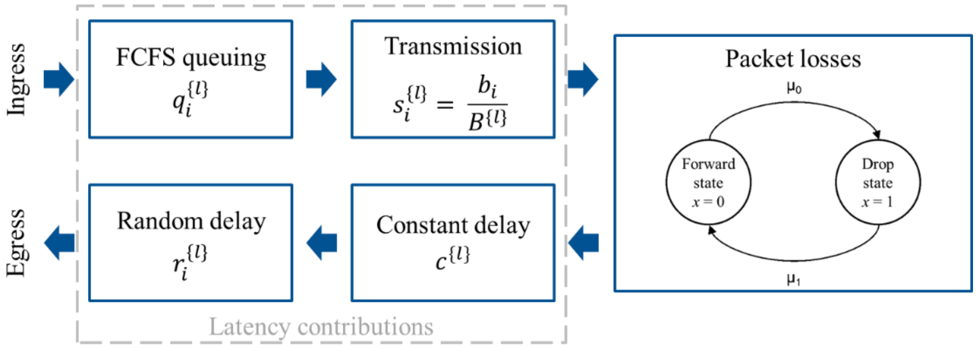

Figure 13: Air-ground data link model when available.

Losses are modelled using a continuous-time Markov chain. The state of the Markov chain x changes with the transition rate of its two states: μ_0 and μ_1. When packets are transmitted over the link and it is in Forward state, the packet is successfully transmitted over the link. If the link is in the Drop state, the packet is erased. The air-ground data link models in [34] and [47] use discrete-time Markov chains instead. However, using a continuous-time Markov chain the dependency from the packet interarrival process is avoided, as it was proposed for other applications using similar metrics such as video-processing [48].

Successfully forwarded packets are delayed. The latency for packet i in link l is modelled as the contribution of four parameters: queuing delay $q_i^{\{l\}}$, transmission delay $s_i^{\{l\}}$, constant delay $c^{\{l\}}$ and random delay $r_i^{\{l\}}$. Thus, packets that are transmitted while the link is in Forward state, will reach the egress side of the with an accumulated delay from all those parameters. The model has similarities the model used by NASA in their study of the link performance for the year 2060 [49]. NASA's model considers the contribution from queuing, transmitting and propagation delays. In the model of the thesis, the propagation delay is part of the constant delay. The congestion caused by other sources using the same channel (or spot beam) is part of their queuing delay in NASA's model whereas here it is part of the random delay. Thus, in the thesis model other sources of traffic sources are not modelled.

The link parameters that characterize the air-ground data link using this model are the link availability Av, the bit rate B, the transition rate of the Forward state μ_0, the transition rate of the Drop state μ_1, the constant delay c and the random delay r. How these parameters affect the packets sent over the link is explained in the following sections.

The following sections describe in detail all the parameters of the air-ground data link model presented here. The link availability is explained in Section 3.2.2. Packets sent over the link go over different stages (see Figure 13): the description of the Markov chain used to represent losses is given in Section 3.2.3 and the latency and the four contributions that make it up are given in Section 3.2.4.

3.2.2. Link availability

The air-ground data links are sometimes unavailable. Links are unavailable for several reasons, the most common being maintenance (planned) and failures (unplanned). To increase link availability, some links implement redundancy measures. For example, Inmarsat has two ground stations for each of its satellites.

When a link is unavailable, any packets transmitted over the link would be lost. The routers at the link edges are aware of the link unavailability status and thus no packets are forwarded over unavailable links. When a link is available, the packets forwarded over the link can either be lost or delivered with delay. The link availability is denoted as Av. It is the portion of time that the link is available.

When the link is available, packets are either erased or forwarded with delay. The next section covers the aspect of packet losses or erasures.

3.2.3. Packet losses

The packets forwarded over the air-ground data link when this one is available are either delivered error-free or lost. Normally, error detection is done by adding a checksum or a cyclic redundancy check. TCP and UDP implement a 16-bit checksum. Ethernet uses a cyclic redundancy check of 32 bits. With the protocols considered in this thesis (see section 2.2.4), traffic going over the air-ground data link have error detection implemented in the UDP checksum and in the hash generated with the Hash Message Authentication Code (HMAC) of the ESP header. This hash is a 128-bit field in the ESP header, calculated with a 256-bit hash algorithm. Normally, cryptographic hash functions are not used for error detection because of the larger length of the generated hash is bigger than the redundancy added with the other methods. However, when used the probability of undetected errors is negligible. Thus, the case that a packet is delivered with undetected errors is not considered in the model.

A common way to represent correlation or burstiness in wireless communications is the Gilbert-Elliott model. Gilbert's model from [50], in which each state is associated with either forwarding the packet or dropping it, has been suggested for aeronautical data links in [34] and [47]. The losses in Gilbert's model depend on the state of a Discrete-Time Markov Chain (DTMC). Changes in state happen at discrete time intervals, usually associated with the arrival of each packet. Using a DTMC means that the losses of the data link are dependent on the arrival processes, but the chosen model must not force the modelling of all the traffic sources (see in Section 1.5). An alternative definition, independent of the arrival process is using a Continuous-Time Markov Chain (CTMC), as proposed in [48]. The transitions between the states are triggered independently of the arrival process.

When the link is available, the losses are modelled using the Markov chain shown in Figure 14. The chain has two states: Forward and Drop states. The states are represented with x and numbered; in the Forward state (x=0) all packets are delivered while in the Drop state (x=1), all are lost. The transition rate is denoted μ_x. The inverse of the transition rate is the average time spent in the state. Thus, $1/\mu_0$ is the average time spent in the Forward state and $1/\mu_1$ is the average time spent in the Drop state. The steady-state probability and state transition probability formulas can be found in the Annex A.1, page 118. The average packet loss, also known as Packet Loss Ratio PLR is equal to the stationary probability of the drop state π_1, calculated with (44).

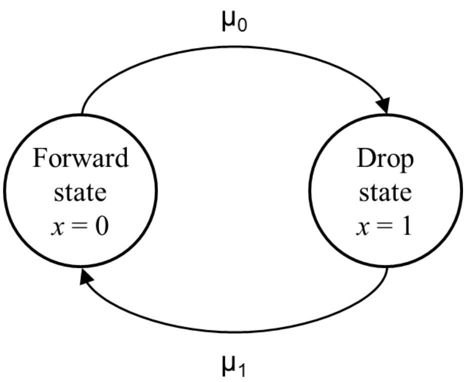

Figure 14: CTMC for link losses.

Packets are delivered at the egress edge delayed with respect to the time they arrive at the ingress edge when they the link is available and in the Forward state. The latency incurred by the packets is described in the following section.

3.2.4. Latency

The latency L of packets that are correctly transmitted (i.e. not lost) over the air-ground data link is the sum of all the delay contributions of the link l: queuing delay q, transmission delay s, constant delay c and random delay r. Thus, for packet i:

$$L_i^{\{l\}} = q_i^{\{l\}} + s_i^{\{l\}} + c^{\{l\}} + r_i^{\{l\}} \tag{3}$$

Any packet that is transmitted over the link while another packet is being serviced must wait in the queue. The time packet i arrives at the ingress node is named t_i and the time spent in the queue is denoted $q_i^{\{l\}}$. To reduce the complexity, the queue is modelled as infinite and with a first come first served policy (FCFS); the packets are served without any kind of prioritization.

Each packet is served in a deterministic time, the transmission delay $s_i^{\{l\}}$. Equation (4) provides the transmission delay calculated with the packet i size b_i (bits) and the bit rate $B^{\{l\}}$ of the link:

$$s_i^{\{l\}} = \frac{b_i}{B^{\{l\}}} \tag{4}$$

Note that with the link model shown in Figure 13, packets that are dropped are still queued and their transmission delay determines the time they spend in the queue. The link always adds a minimum delay to the successfully forwarded packets. This contribution is the constant delay and it is denoted as $c^{\{l\}}$. Propagation delay for wireless and especially for satellite links is the dominant contribution to this factor. However, several factors contribute to this delay like propagation time, link layer signalling, etc. What is important in the definition of the constant delay is that it is the sum of the fixed and the unavoidable contribution to the latency of all factors. An example to better illustrate this, follows. When sending data over a geostationary-satellite-based link connecting an aircraft and a ground station at a fixed location, there is propagation delay because of the distance between the aircraft and between satellite and between the satellite and the ground station. When the aircraft flies it moves and the distance changes, so the propagation delay changes. However, there is always a minimum distance between the aircraft and the satellite (when the aircraft flies at the maximum altitude right below the satellite). The propagation time corresponding to the minimum distance between the aircraft and the satellite plus the propagation time between the satellite and the ground station is the contribution of the propagation delay to the constant delay. The increase in the delay caused by propagation when the aircraft flies is variable, and it contributes to the random delay (see next paragraph). Since the physical and link layers are abstracted (see Section 1.5), the constant delay and the random delay parameters are used to model those effects.

The rest of the delay is caused by effects such as link layer retransmissions and the impact on the channel of other aircraft or ground sources. The contribution of those is modelled with the random delay. The random delay $r_i^{\{l\}}$, comprising the contributions of all the factors not covered by previous stages, is represented using a random variable, denoted $R^{\{l\}}$. Depending on the maximum value of the Probability Density Function (PDF) of $R^{\{l\}}$ and the time between two consecutively delivered packets (take h the last delivered packet before i), reordering could happen. The condition when this could happen is expressed as (5) and shown in Figure 15, with packet i having the minimum delay and h (i-1) the maximum possible.

$$\Delta_i^{\{l\}} = \left(t_i + s_i^{\{l\}} + q_i^{\{l\}}\right) - \left(t_h + s_h^{\{l\}} + q_h^{\{l\}}\right) < \max\left(R^{\{l\}}\right) \tag{5}$$

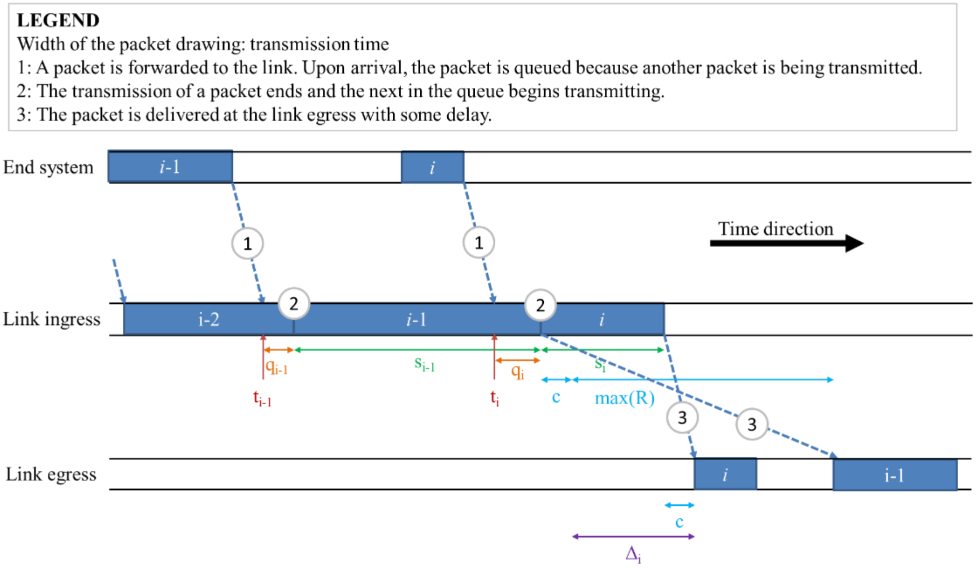

Figure 15: Example of random delay causing reordering (h = i-1)

Therefore, the random delay of the packet is correlated to the random delay of previously sent packets. The random delay follows the random variable $\mathrm{X}^{\{l\}}$ that depends on the values of Δ_i and r_h:

$$r_i^{\{l\}} \sim \mathrm{X}^{\{l\}}\left(\Delta_i^{\{l\}}, r_h^{\{l\}}\right) \tag{6}$$

Because the distribution of r_i depends on the value of r_h, then the probability $r_i^{\{l\}}$ taking the value y can be expressed with:

$$\Pr\left(r_i^{\{l\}} = y\right) = \sum_{z=0}^{\infty} \Pr\left(\mathrm{X}^{\{l\}}\left(\Delta_i^{\{l\}}, r_h^{\{l\}} = z\right) = y\right) \Pr\left(r_h^{\{l\}} = z\right) \tag{7}$$

Obtaining the PDF of the random variable R can be challenging. Public data to characterize the random delay is hardly available. Theoretical knowledge of the lower layers is not enough to predict the PDF, as other factors such as hardware, software and link usage by all users also have an impact. Thus, until a technology is deployed, it is only possible to estimate the random delay. For existing deployments, the PDF can be obtained from measurements or in existing literature. Obtaining the PDF of the random variable X in literature is virtually impossible. It also requires a big sample size to be obtained from measurements. Therefore, different approximations are proposed to derive X from R. With any of the proposed approximations $f_X = f_R$ whenever all the range of R is a valid value (i.e. when $r_h - \Delta_i \leq 0$).

The first approximation, named "optimistic", is obtained assuming that the probability of all the delay values of R that cannot happen if the order is maintained is assigned to the lowest possible value:

$$f_X(x, r_h, \Delta_i) = \begin{cases} f_R(x), & x > r_h - \Delta_i \\ F_R(r_h - \Delta_i), & x = r_h - \Delta_i \\ 0, & otherwise \end{cases} \tag{8}$$

The second proposed approximation, “conservative”, as the name suggest is more conservative; f_X is obtained by normalizing f_R for the remaining possible values:

$$f_X(x, r_h, \Delta_i) = \begin{cases} \dfrac{f_R(x)}{1 - F_R(r_h - \Delta_i) + f_R(r_h - \Delta_i)}, & x \geq r_h - \Delta_i \\ 0, & otherwise \end{cases} \tag{9}$$

The third proposal, “continuant”, assumes that the delay of two closely transmitted packets tends to be the same, so the probability is increased for the same random delay value as the previous packet:

$$f_X(x, r_h, \Delta_i) = \begin{cases} f_R(x), & x \geq r_h - \Delta_i \text{ and } x \neq r_h \\ F_R(r_h - \Delta_i) - f_R(r_h - \Delta_i) + f_R(r_h), & x = r_h \\ 0, & otherwise \end{cases} \tag{10}$$

In the “pessimistic” proposal, the probability of the values of R that cannot happen is assigned to the highest possible value:

$$f_X(x, r_h, \Delta_i) = \begin{cases} f_R(x), & x \geq r_h - \Delta_i \text{ and } x \neq \max(R) \\ F_R(r_h - \Delta_i) - f_R(r_h - \Delta_i) + f_R(\max(R)), & x = \max(R) \\ 0, & otherwise \end{cases} \tag{11}$$

The pessimistic proposal should not be confused with an upper bound. The only possible upper bound would be allocating all the probability to the highest delay recorded in R. Unless the values of X are found for all the relevant Δ_i and r_h, assuming the upper bound is the only way to ensure that the real performance will be better or equal to the calculated values. However, in a situation in which the random variable R has a wide range of values and the lower end has a high concentration of the probability, the results obtained using the model will be too far off the real values to be useful.

The approximations are used in this thesis only when evaluating the expected performance using the air-ground data links defined from the partial information available of existing technologies. That is, whenever the “generic links” are used; they are later defined in Section 3.4. Also, for those ATC services with one packet per message (k=1, see Table 4), no approximation is needed. The approximation choice does not change the equations of the Single-Link RCP model (Section 4.3) and the MPEC RCP model (Section 5.4). In this work, the optimistic approximation is used in those cases where the calculated performance is below the requirements to which it is compared, to show that even in the best-case scenario the requirements are not met. In any case, there is no “correct” approximation, so whenever one is used, the text explains why it is chosen.

3.3. Air-ground data link technologies

3.3.1. Overview

In this Section, the ATN/IPS air-ground data link technologies are reviewed with the objective of finding their profile according to the model from the previous section. Commercial, available air-ground links’ basic information can be found on the communication service provider’s websites, most of the time as a brochure of their services. More detailed information about existing and future technologies is usually found in papers, studies and research project reports.

The most accessible value for any link technology is the data rate. The link availability is also often provided for deployed links. Information about the link delay is more limited, with only an average, minimum and/or maximum values available. It is possible to find Cumulative Distribution Function (CDF) values of delay for applications running over a single link but always in the form of figures, not tabled values. Those figures are not ideal, as the contribution is more than just the air-ground data link and there is no information about correlation. The loss parameters' values are the hardest to find and when available, they are limited to uncorrelated values such as packet loss ratio or bit error rate.

The new generation of data links for aircraft will adopt the ATN/IPS protocol stack. On the satellite domain, two initiatives are on-going: Iris and Iridium Certus. On the direct wireless side, progress is less mature because a new ATN/OSI link has been recently deployed.

The European Space Agency (ESA) is developing Iris as part of the ARTES programme. The estimated date for deployment is 2028 [14]. For the short to medium term, ESA has partnered with the U.K. satellite operator Inmarsat to develop SBB as a precursor of Iris. Iridium currently provides safety aeronautical communications by means of the Iridium SBD service. The coverage of this service is global, as it consists of a constellation of Low-Earth orbit satellites. A new constellation of Iridium NEXT satellites was activated in 2019 [51]. It supports aeronautical safety communications since 2019 with data speeds of hundreds of kilobits per second, through the Iridium Certus services [52].

On the direct wireless side, the Very High Frequency data link mode 2 (VDL2) has been recently deployed and it is mandatory for all aircraft in Europe to be equipped with this link. Whereas the link uses the ATN/OSI, a technique for using VDL2 with IP has been proposed in [53]. The ATN/IPS technology replacement will be the L-band Digital Aeronautical Communication System (LDACS). It is expected that in 2022, ICAO selects one of the two candidate proposals for LDACS [54].

The Aeronautical Mobile Airport Communication System (AeroMACS) data link will also be used for aeronautical communications. In principle, it is irrelevant for the operations described in Chapter 2 because it is limited to airport communications when the aircraft is on the surface [55]. However, according to [56] AeroMACS could also be used during the landing, take-off and approach phases albeit only in the forward link direction. The values of the parameters of the link model from Section 3.2 when AeroMACS is used for these flight phases are not specified.

3.3.2. Inmarsat's Swift BroadBand

The SBB service from Inmarsat provides ATC-certified air-ground data communications since 2015 with four Inmarsat-4 geostationary satellites. The coverage is almost global, except for most of the area above 60º N and below 60º S [57].

The data rate for Inmarsat's SBB is 432 kbps with a high-gain antenna. Inmarsat claims meeting the RCP240 / RSP180 safety requirements [58], thus providing at least 99.99% link availability. There is no clear source stating the losses or latency of this link, though delay is estimated between 500 ms and 1500 ms. The available values using the air-ground data link model are collected in Table 6.

Parameter	**Value**
Bit rate *B*	432 kbps
Link availability *Av*	≥ 99.99%
Losses	*Unknown*
Constant delay	500 ms
Random delay	0-1000 ms *Probability density function unknown*

Table 6: Inmarsat Swift Broadband's link model values

3.3.3. Iridium Short Burst Data

Iridium's SBD service provides ATC-certified air-ground data communications since 2009 with sixty-six Low-Earth Orbit satellites positioned in six orbital planes. The coverage is global. Iridium SBD supports RCP240 and RSP180, so the link availability is at least 99.99% [58]. This is an improvement over an earlier measurement [59].

The bit rate of Iridium SBD is 1200 bps [60]. The packet loss ratio is between 2% and 3% [61]. Available figures for Iridium SBD suggest the smallest one-way latency to be in the order of 5 seconds [62]. A table of measurements is provided in [61] for the “modem processing delay”. However, the text seems to indicate that the values correspond to the end-to-end latency. A newer source for the delay is available [60] that provides in the form of a CDF (see Figure 16), with the average (2.7 s) and 95% (5.6 s) values given in text.

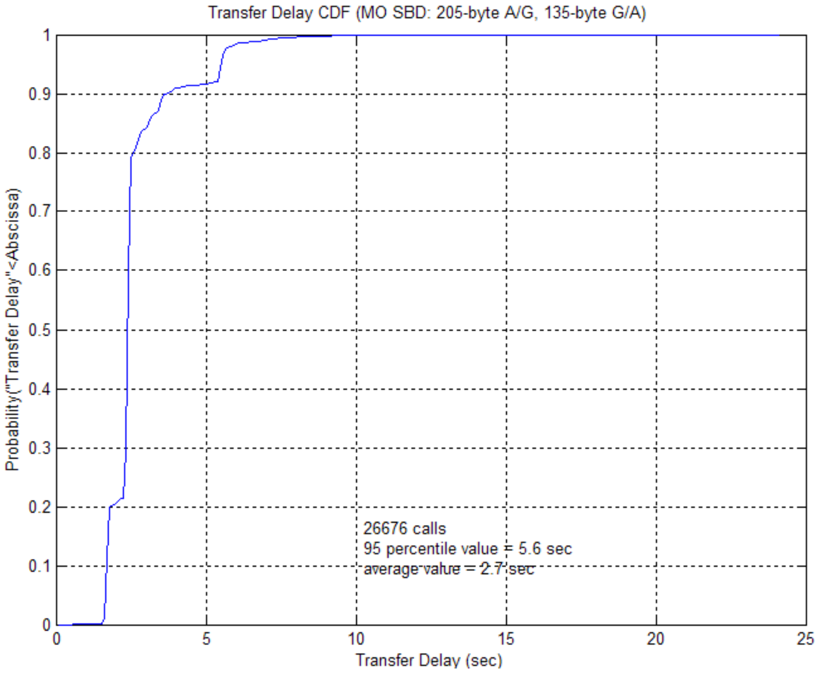

Figure 16: Iridium Short Burst Data delay, from [60].

The available values of Iridium SBD are collected in Table 7.

Parameter	**Value**
Bit rate *B*	1200 bps
Link availability *Av*	≥ 99.99%
Losses	Packet error ratio 2-3 % *CTMC transition rate matrix unknown*
Constant delay	*Unknown (see random delay)*
Random delay	Contribution to Figure 16 (the figure includes the transmission delay)

Table 7: Iridium Short Burst Data link model values

3.3.4. Iridium Certus

Iridium Certus is the name of the aeronautical communications service provided by Iridium’s next generation satellites, Iridium Next [52]. The satellites were launched between 2017 and 2019, completing a new constellation of 66 satellites (plus spares), like the previous Iridium constellation. The new service operates at much higher bit rate (up to 1.4 Mbps), but other factors such as availability or delay are still unknown as reflected in Table 8.

Parameter	**Value**
Bit rate *B*	≤ 1.4 Mbps
Link availability *Av*	*Unknown*

Parameter	Value
Losses	*Unknown*
Constant delay	*Unknown*
Random delay	*Unknown*

Table 8: Iridium Certus link model values

3.3.5. Very High Frequency Data Link mode 2

VDL2 is a direct wireless air-ground data link using the ATN/OSI that provides coverage to aircraft flying within 200 nautical miles of the ground station. Thus, the link is unavailable during oceanic flight.

The link has a maximum data rate of 31.5 kbps (10 kbps when the link is saturated) per channel. The delay of VDL2 depends much on the channel load. According to [37], it possible to support up to 8 seconds round-trip time for 95% of the transactions. The availability requirements for the aeronautical service providers is set to 99.99% [63]. ATN/IPS can be supported using specific mechanisms as proposed in [53].

Parameter	Value
Bit rate *B*	≤ 31.5 kbps
Link availability *Av*	99.99%
Losses	*Unknown*
Constant delay	*Unknown. See random delay*
Random delay	≤ 8 s with 95% probability (channel load 6 kbps) *Probability distribution function unknown*

Table 9: VLD2 link model values

3.3.6. L-band Digital Aeronautical Communication System

L-band Digital Aeronautical Communication System (LDACS) is the next generation air-ground data link. ICAO will select by 2022 one of the two candidate technologies: LDACS1 and LDACS2 [54]. Given the amount of research performed and the results shown, LDACS1 will likely be officially selected. LDACS will be a direct wireless link with 200 nautical miles coverage from each ground station.

In LDACS1, the corrected bit error rate after forward error correction of the receiver must be less than 10^{-6} [64]. Some of the contributions to the delay incurred by the packets over the LDACS1 can be obtained from literature. The LDACS1 transmission rate ranges from 303 kbps to 1373 kbps for the forward link and from 220 kbps to 1038 kbps for the reverse link [65]. The one-way propagation delay is 1.26 ms. The delay caused by congestion or process of the packets depends on the implementation of the LDACS1 system. The emulation of LDACS proposed in [66] has been implemented considering the remaining contribution to the latency (without retransmissions) for the forward link between 60 and 120 ms and for the reverse link between 120 and 180 milliseconds.

Parameter	Value
Bit rate *B*	220 to 1038 kbps (reverse link) 303 to 1373 kbps (forward link)
Link availability *Av*	*Unknown*
Losses	Bit error rate of 10^{-6} *CTMC transition rate matrix unknown*
Constant delay	60 ms (reverse link) 120 ms (forward link)

Parameter	**Value**
	Unknown contribution from packet processing.
Random delay	Uniform distribution between 0 and 60 ms. Random propagation delay between 0 and 1.26 ms based on distance to base station. *Unknown contribution from congestion.*

Table 10: LDACS1 link model values

The LDACS2 proposal defined in [67] is based on the All-purpose Multi-channel Aviation Communication System concept and architecture. It will provide a bit rate of 270 kbps and a bit error rate of 10^{-7}. Having the same range as LDACS1, it has the same propagation delay.

Parameter	**Value**
Bit rate *B*	270 Kbps
Link availability *Av*	*Unknown*
Losses	Bit error rate of 10^{-7} *CTMC transition rate matrix unknown*
Constant delay	*Unknown*
Random delay	Random propagation delay between 0 and 1.26 ms based on distance to base station. *Other contributions' weights unknown.*

Table 11: LDACS2 link model values

3.4. Generic air-ground data link profiles

There is not enough information available about the existing or future ATN/IPS links reviewed in the previous section to fully characterize any of them with the model proposed in Section 3.2. In this section, three profiles are defined to evaluate their performance to meet the requirements from Chapter 2. The profiles are based on the reviewed technologies and some assumptions made to find all the values of the profile. There are no profiles based on the VDL2 and Iridium Certus technologies. VLD2 is not fully an ATN/IPS link and there is barely any performance value of Iridium Certus. The profiles are referred to as *generic* links in the following chapters.

All the profiles are models based on assumptions and publicly available information. Thus, they don't fully represent any real technology. A thorough evaluation of the existing links from Section 3.3 is only possible with the collaboration from the communication service provides offering the data link services. Next section describes the first generic link, based on a geostationary satellite link.

3.4.1. GEO SatCom link profile

This profile is based on the data publicly available for Inmarsat's Swift Broadband collected in Section 3.3.2. The missing values are filled using the analysis of the traffic traces obtained in the SANDRA project [9]. In this European project, an Airbus A320 was flown over the skies of Bavaria to test the future ATN/IPS using an Inmarsat's Broadband Global Area Network (BGAN) link and an AeroMACS prototype [25]. Note that Inmarsat's SBB is the aeronautical version of BGAN. The traffic samples have been used to obtain a *very rough estimation* of the of the CTMC parameters defining the losses, the constant delay and the random delay. The samples used were obtained using an Inmarsat's BGAN background class connection.

The estimated values CTMC values are $\mu_0 = 0.1361\ s^{-1}$ and $\mu_1 = 2.3178\ s^{-1}$. The following criteria were applied to determine these values:

- A state change happens when a packet is correctly received and the next one is lost or vice versa.

- A state change happens at the time in the middle between the lost and received packets, measured at transmitting side of the link.
- The time spent at a state is the difference between two consecutive state changes.
- The sample of time spent at a state is invalidated if any of the transmitted packets during the duration of the state is further apart than 500 milliseconds from its previous and next packet.
- Long losses (>15 packets) are discarded as long interruptions were caused during the flight trial by manually disconnecting the aircraft network from the link.

To estimate the delay values, the difference between the sending time at the aircraft router and the reception time at the ground router are calculated. Then, the samples are processed to isolate the value of the constant and random delays. This is done by removing the impact of queueing and transmission delays.

The time spent in the queue was not measured during the trials, the packets that were queued are discarded from the traces. The samples are processed to discard packets for which the traffic load was higher than the bit rate supported by the link. Then, for each remaining packet the transmission time was independently subtracted, based on the measured bit rate of the channel and the packet size.

Unfortunately, the computer clocks were not synchronized using the Network Time Protocol or by any other means, as it was not required for the objectives of the SANDRA project. During the test runs, ping was used to measure the round-trip-time. Given that this value is measured in the same machine, there is no synchronization issue. The minimum estimated time is obtained halving the round-trip-time, at 355 milliseconds. As an approximation, the histogram of samples collected during different test runs are shifted to the minimum estimated delay.

Upon collection of all the delay samples, the histogram is calculated. The minimum value is taken as constant delay. The random delay probability mass function (PMF) is obtained shifting the histogram to have the first value at zero seconds. The PMF is shown in Figure 17 and the values are available in [68].

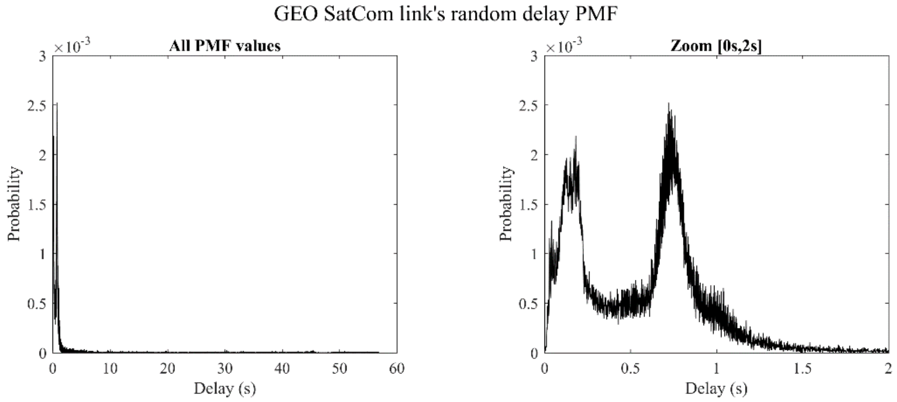

Figure 17: GEO SatCom link random delay PMF with all the values (left) and between 0 and 2 seconds (right)

The values of air-ground data link model parameters for the GEO SatCom link are based on Table 6 and the analysis above and collected in Table 12. Given the method used to obtain the values the loss and delay parameters, the GEO SatCom link values could be far from any real geostationary-based data link supporting ATC communications.

Parameter	**Value**
Bit rate B	432 kbps
Link availability Av	99.99%
Losses	$\mu_0 = 0.1361\ s^{-1}$ ($1/\mu_0 = 7.3475$ s) $\mu_1 = 2.3178\ s^{-1}$ ($1/\mu_1 = 0.4314$ s)

Parameter	**Value**
Constant delay	355 ms
Random delay	*r*’s PMF shape: Figure 17 and [68]

Table 12: GEO SatCom link model values

In addition to geostationary-based satellite links, there are also satellite links that use a constellation of LEO satellites to avoid hundreds of milliseconds in propagation delay. Next section presents a generic profile based on LEO satellites.

3.4.2. LEO SatCom link profile

This profile is based on the data publicly available for Iridium’s Short Burst Data collected in Section 3.3.3. The random and constant delay are obtained from a figure showing the measurement results of the link latency. Given that there is only a figure for the uncorrelated *PLR*, the CTMC parameters of the losses are obtained following the process described in Annex A.2, with *B*=1.2 kbps and *PLR*=3%, yielding the result of $\mu_0 = 0.0017$ s^{-1} and $\mu_1 = 0.0536$ s^{-1}.

The data to obtain the random delay is shown in Figure 16. However, the only source is the figure; no table of values is available to generate the PMF. Therefore, the values have been obtained by saving the figure into image file and the curve separated in linear sections. Each section’s end points are measured in pixels to approximate the value. Given the resolution of the file, 5 seconds correspond to 119 pixels and 10% probability to 47 pixels. Thus, each pixel corresponds to ~42 ms for the horizontal axis and ~0.213% probability for the vertical axis. The following table contains the beginning of each section. The corrected time column is obtained by subtracting the transmission time, considering an average packet size of 170 bytes (average between MO and MT from Figure 16).

Time (pixels)	**Time (ms)**	**Corrected time (ms)**	**Probability (pixels)**	**Probability (%)**
13	546	-587	1	0.21
36	1513	379	1	0.21
42	1765	631	94	20.00
52	2185	1052	101	21.49
60	2521	1388	376	80.00
86	3613	2480	423	90.00
94	3950	2816	428	91.06
128	5378	4245	433	92.13
134	5630	4497	459	97.66
145	6092	4959	464	98.72
190	7983	6850	468	99.57
195	8193	7060	469	99.79
241	10126	8993	470	100.00

Table 13: Linearization of the Iridium SBD delay in Figure 16

Given that the first row gives a corrected time below 0, it is ignored. The resulting CDF (Figure 18) looks like the one in Figure 16, but shifted (because of the correction) and linearized, as expected.

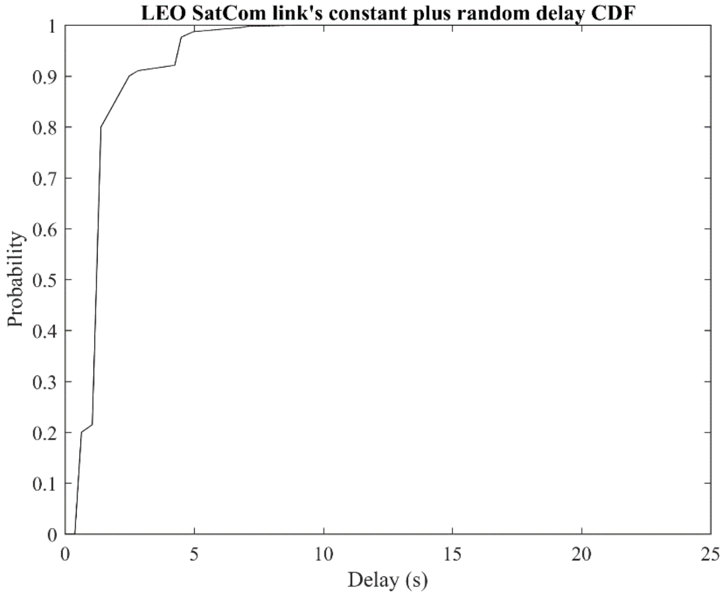

Figure 18: LEO SatCom link random and constant delay CDF.

The resulting PMF of the random delay (Figure 19) is obtained from taking the CDF (Figure 18) and shifting it to 0 (the minimum value is taken as constant delay). The values are available in [68].

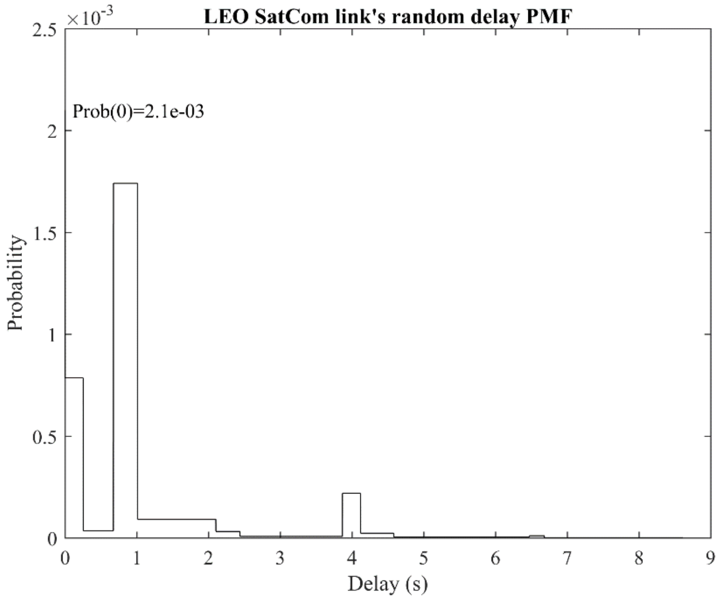

Figure 19: LEO SatCom link random delay PMF.

The values of air-ground data link model parameters for the LEO SatCom link are obtained from Table 7 and the analysis above and collected in Table 14.

Parameter	Value
Bit rate *B*	1.2 kbps
Link availability *Av*	99.99%
Losses	$\mu_0 = 0.0017\ s^{-1}$ ($1/\mu_0 = 588.2353$ s) $\mu_1 = 0.0536\ s^{-1}$ ($1/\mu_1 = 18.6567$ s)

Parameter	**Value**
Constant delay	379 ms
Random delay (distribution of R)	*r*’s PMF: Figure 19 and [68]

Table 14: LEO SatCom link model values

In addition to air-ground data links using satellites as relays, there are direct wireless links that connect the aircraft with the ground. Such a generic link is described in the next section.

3.4.3. Direct Wireless link profile

This profile is based on the data publicly available for LDACS collected in Section 3.3.6. Of the two candidates, LDACS1 is selected because the information available is more detailed than for LDACS2.

The selected bit rate value is the minimum bit rate of LDACS1: 220 kbps. The processing delay is considered of the order of 10 milliseconds (as in the emulation in [66]). This is added to the 120 ms already accounted in the constant delay. The random delay is represented with a discrete random variable of uniform shape, as the probability of arrival of the frames at any given time is the same. The choice of having a discrete random variable is simply because the resolution in which the requirements are expressed are milliseconds.

Since there is no LDACS link deployed yet, no information about availability can be found. However, all the communication service providers so far have a 99.99% availability, so it is reasonable to assume that this will be the minimum target for any future LDACS deployment. Given the future requirements, this value could be higher. To obtain the CTMC parameters the process described in Annex A.2 is followed, with B=220 Kbps and BER=10^{-6}, resulting in $\mu_0 = 0.0441\ s^{-1}$ and $\mu_1 = 9.8214\ s^{-1}$. The values of air-ground data link model parameters for the LEO SatCom link are obtained from Table 7 and the analysis above and collected in Table 14.

Parameter	**Value**
Bit rate *B*	220 Kbps
Link availability *Av*	99.99%
Losses	$\mu_0 = 0.0441\ s^{-1}$ ($1/\mu_0 = 22.6757$ s) $\mu_1 = 9.8214\ s^{-1}$ ($1/\mu_1 = 0.1018$ s)
Constant delay	130 ms
Random delay (distribution of R)	*r*’s PMF: Unif{0,59} ms

Table 15: Direct Wireless link model values

3.5. Summary

In Chapter 3 the air-ground data link model is proposed. The model abstracts the physical and link layers to make it technology independent. Therefore, the model is usable for all choices. The link parameters model the effects of those layers by adding losses and delay to the packets transmitted over the link.

The link availability *Av* is used to model the uptime of the link. The transition rate of the Forward state μ_0 and the transition rate of the Drop state μ_1 model the states of a continuous time-Markov chain used to determine whether packets are erased or forwarded. The advantage of having this model is that losses are modelled independent of the traffic profile. The latency of the link is a contribution of several factors: queuing delay q, transmission delay s, constant delay c and random delay r. To calculate the queuing and transmission delays, the link parameter of bit rate B is also defined. A review of the literature of the existing and future link technologies is done to obtain the values of the parameters of those links. The literature available falls short providing enough data to characterize them completely, either because the links are proprietary or because the future technologies are still not implemented.

To have fully characterized links, a new set of “generic” links are defined based on the reviewed technologies. Those generic links are used in the following chapters to evaluate the performance that the technologies could have if the generic links are close estimations of the reality. Two satellite links are defined, one based on a geostationary satellite and the other based on a Low-Earth Orbit satellite constellation. The third generic link is based on the future L-band direct wireless link.

In addition to the generic links being used to evaluate their performance, the air-ground data link model is used in Chapters 4 and 5 to develop the RCP performance models.

4. LINK PERFORMANCE FOR DATA-CENTRIC COMMUNICATIONS

4.1. Introduction

Usage of Air Traffic Management (ATM) operations with future data-centric communications are expected towards the mid-2020s (see Section 2.1). New air-ground data technologies have been proposed to meet the new communication requirements. Other links are already installed in many aircraft and new satellite links are being deployed as of 2018. Knowing the performance of the air-ground data links using the Required Communication Performance (RCP) metric is necessary to know whether a link meets the performance requirements. This information is needed when designing new air-ground data links, but also for existing technology to evaluate their suitability for supporting the future data-centric requirements. In this chapter, a new model is proposed to calculate the Expected Communication Technical Performance (ECTP) of any air-ground data link. With this model and the link parameters' values, the ECTP can be quickly calculated. Also, the link parameters' values required to meet the Required Communication Technical Performance (RCTP) can be obtained.

The state-of-the-art in Section 4.2 is a review of how the ECTP of links under design and the Actual Communication Technical Performance (ACTP) of existing air-ground data links have been obtained. To obtain the ECTP, three approaches are possible: emulation, simulation and calculation. Both emulation and simulation provide closer results to the real technology performance but with calculation, the results are obtained faster and with a lower implementation complexity.

The Single-Link RCP performance model proposed in Section 4.3 relates the traffic and link parameters to produce the values of the RCP performance parameters (continuity, transaction time, integrity and availability). To the best knowledge of the author, this is the first mathematical model available to calculate the ECTP. The model is validated with emulation and simulation.

The expected performance of the generic links is calculated in Section 4.4. The results show that the performance of both satellite links is insufficient to meet the ATC requirements from COCRv2 (see Section 2.4). The expected continuity is for all the services lower than 99%. The Direct Wireless link meets all the ATC requirements, but it only provides limited coverage applicable to the APT, TMA and ENR domains. The expected transaction time is in all cases greater than the C2 landing service requirements, meaning that none of the evaluated links can fulfil the requirements.

In Section 4.5, the link requirements to meet the ATC service RCTP from COCRv2 (Table 3) and the C2 landing service RCTP (Table 5) are obtained. The Single-Link RCP performance model is used to calculate the necessary values and the trade-off between the different link parameters. The results can be used as guidelines when designing new air-ground data links. The results are tied to the requirements used to obtained them, but the procedure described can be used for any other requirements, whenever they become available.

The results are analysed in Section 4.6 and the conclusions in Section 4.7. The expected continuity of the generic Direct Wireless link (see Section 3.4.3) supports the future ATC data-centric communications if the link availability is at least 99.995%. Neither of the generic satellite links from Section 3.4 meet the continuity requirements. These results indicate that new air-ground data links are required. The new link parameters' minimum values found using the Single-Link RCP performance model are achievable with current (yet undeployed) technology. The feasibility of a new link to meet the ATC service RCTP is discussed in detail in the analysis of results section. The link parameters requirements to meet the C2 landing service RCTP are several orders of magnitude higher than currently available. When the performance of a single link is not enough to meet the RCTP, the expected performance could be improved following the techniques presented in the next chapter.

4.2. State-of-the-art

There are multiple ways of obtaining the RCTP performance of the links. Measurements can be taken on while the link is being used. The link can be emulated to obtain a realistic approximation of the scenario under lab conditions. Simulation is faster than emulation albeit some aspects are modelled instead of represented with the real technology. With calculation, the RCTP are obtained through equations modelling the scenario.

The most accurate way of obtaining the performance provided by an air-ground data link is to measure it. It has been proved that both Iridium Short Burst Data (SDB) [59] and Inmarsat-4 Classic Aero [69] can meet the RCP240 and RSP180 requirements from ICAO GOLD [13]. Those requirements are precursors of COCR's data centric RCPs. The report on Inmarsat's Swift Broadband (SBB) service is not yet available, but some advance of the results can be found in [70]. A review of current and future air-ground data links capability to meet the current RCP has been done in [71]. Continuous monitoring of data communications performance has been done in the Auckland Oceanic Flight Information Region to determine the Actual Communication Performance (ACP) and ACTP of flights in the region [72]. Shorter measurements have also been performed using Inmarsat's SBB [40] and VHF Data Link Mode 2 [73]. However, they do not provide enough samples to be relevant in deciding whether the requirements are met or not. To reduce the impact of this small number of samples, an estimation method was proposed in [74] to determine the actual performance when a limited number of samples is available. Another disadvantage of measuring is that the link must be already deployed, so limited changes in performance are possible.

During the design phase of a new data link the only way to perform an evaluation with enough data is through emulation or simulation. This solution is way more cost effective than deployment and allows for a quicker change of the link's specifications after an adjustment in the requirements. The European Space Agency has used simulation as means to define the future satellite link to meet the COCR requirements [75]. In the DeSIRE 2 project, the communications of an unmanned aerial vehicle (UAV) have been modelled to certify the UAV, using the RCP, for the project's demonstration flight [76]. In the ACROSS project, an emulator was built to measure the performance in an environment with the ATN/IPS protocol stack implemented [19].

When calculating the performance using a mathematical model, the implementation of a simulator and simulation times are avoided. NASA has performed a study of the link performance for the year 2060 [49] using a different air-ground data link model and for a metric other than the RCP. To the best knowledge of the author, the model proposed in this thesis and published in [20] is the first model available to calculate the RCTP performance provided by a data link. The model is described in the next section.

4.3. Single-Link RCP performance model

4.3.1. Assumptions

The following assumptions are made to develop the model:

1. The ATN/IPS protocol stack is used as described in Section 2.2.
2. The air-ground data link can be characterized using the model described in Section 3.2.
3. To receive a message, all the IPv6 packets that compose it must be received.
4. The probability of having an undetected error is null.
5. The retransmission of a message does not invalidate the previously sent message.
6. The IPv6 packets forming a retransmitted message are unrelated to the IPv6 packets of previously sent messages. Thus, it is not possible to merge packets of multiple transmissions to restore a message.
7. Traffic services are considered in isolation.

The Single-Link RCP performance model is conceived as a set of equations that relate the traffic characteristics and the air-ground data link parameters to calculate the expected performance. For this, assumptions 1 and 2 are made to specify how to model the traffic and air-ground data link. Whereas some applications could perhaps work with partial information, in this model the worst case (all information is needed) is considered, hence assumption 3. Assumption 4 is done because the probability of undetected errors over the air-ground data links is null when using the model from Section 3.2, as reasoned in Section 3.2.3. The reason is that the Hash Message Authentication Code used in the network layer protocols (see Section 2.2.4) makes it negligible.

Assumptions 5 and 6 are made regarding the behaviour of the receiving application and how retransmissions are handled by it. When the timeout of λ seconds expires without having received confirmation of a correctly received packet, a retransmission is triggered by the source. However, the original packet might just be unusually late and still being delivered. With assumption 4, the receiver is considered to accept all messages regardless if they are late and a new transmission has already been triggered at the time of arrival. Assumption 5 is made because retransmitted packets might contain different information than the original packet, like a new timestamp or aircraft position, and it is assumed that the packets of different messages cannot be merged to reconstruct the message. Some applications might work without assumptions 4 and 5, but the model is made on the most restrictive terms to obtain a higher bound of the performance.

With the last assumption, it is assumed that the traffic from the different services does not interfere with each other. In other words, only one ATC service transmits at a given time. The issue with this assumption is that the impact on the queuing delay from other traffic is not accounted for. If the queuing delay increases because multiple services use the same link simultaneously the actual continuity decreases, and it is lower than the calculated continuity. Therefore, when this assumption is false, the expected performance is higher than the actual performance. The advantage of this assumption is that the Single-Link RCP model is independent of the traffic shape and load, reducing the complexity of the model and making the calculation faster. The obtained values represent the best performance possible provided by the links. In those scenarios where this assumption is false, the model provides a first approximation to the expected continuity. Then, the impact of the traffic and obtaining the variation on the results is best suited for other tools such as simulation or emulation.

Considering no knowledge of transmissions before the analysed transaction, the initial conditions are assumed as follows:

$$t_0 = -\infty,\ \ s_0^{\{l\}} = 0,\ \ q_0^{\{l\}} = 0,\ \ \Delta_1^{\{l\}} = \infty,\ \ r_o^{\{l\}} = 0 \tag{12}$$

Given assumption 7, the queuing time is only greater than 0 in case the traffic is generated faster than it can be served by the link:

$$q_i^{\{l\}} = \max\left(t_{i-1} + q_{i-1}^{\{l\}} + s_{i-1}^{\{l\}} - t_i, 0\right) \tag{13}$$

With the assumptions made, the performance model is derived in the next section from the air-ground data link model from Section 3.2 and the traffic characteristics from Chapter 2.

4.3.2. The single-link model

The Single-Link RCP performance model is a set of equations to calculate the availability, integrity, transaction time and continuity parameters of the Expected Communication Technical Performance (ECTP) provided to a transaction by an air-ground data link. Because of the assumptions, the expected integrity using this model is always zero undetected errors per transaction. An undetected error here would be a change in the packets information without the receiver being aware.

The continuity and transaction time are given together in the form of the continuity being a function of the transaction time. The continuity is the probability that the message is correctly delivered at the egress edge of the link, with all the packets received within the transaction time value.

The end system generates a message and transmits it to its destination. If the message is not received within λ seconds, a retransmission is triggered. The messages are identified in the equations with the letter δ, with the first message sent δ=0, the first retransmission being δ=1 and so on. Therefore, the time each message is sent is calculated as $\lambda\cdot\delta$ and the time reference (i.e. the 0 second mark) is set at the time that the first message begins transmitting.

The probability that a message transmission δ with a retransmission timeout λ is received within T is denoted $K^{\{l\}}(T,\lambda,\delta)$; it is calculated as the product of three different probabilities (14). First, the probability that the state x of link l (i.e. $x^{\{l\}}$) at the time that the first packet of message δ, is the Forward state. Note that the in the Air-Ground data link model, the Forward state is represented with a 0, and the Drop state with a 1 (see Section 3.2.3). Second, the probability that all the packets that compose the message are successfully delivered, knowing that the link is at forwarding state at the beginning of the transmission. Finally, the probability that the time it takes to deliver all the packets τ is smaller or equal to T.

$$K^{\{l\}}(T,\lambda,\delta) = \Pr\left(x^{\{l\}}(\delta,\lambda) = 0\right) \cdot \Pr\left(k \mid x^{\{l\}}(\delta,\lambda) = 0\right) \cdot \Pr(\tau_k \leq T - \delta \cdot \lambda) \tag{14}$$

Since the packet order is maintained at the link's egress, the latest packet to arrive is packet k. Thus, the time to deliver a message τ_k (15) is the time between the first packet is received at the link's ingress (t_1) and the time the last packet is delivered at the link's egress ($t_k+L_k^{\{l\}}$). The expression of the latency of a packet is given by (3).

$$\tau_k = L_k^{\{l\}} + t_k - t_1 = q_k^{\{l\}} + s_k^{\{l\}} + c^{\{l\}} + r_k^{\{l\}} + t_k - t_1 \tag{15}$$

Given the assumption that no queueing delay is caused by other traffic, of the contributions to the transaction time (15), only r_i is a random variable. Thus, the probability that a message is delivered within β is:

$$\begin{aligned} \Pr(\tau_k \leq \beta) &= \Pr\left(q_k^{\{l\}} + s_k^{\{l\}} + c^{\{l\}} + r_k^{\{l\}} + t_k - t_1 \leq \beta\right) \\ &= \Pr\left(r_k^{\{l\}} \leq \beta - t_k + t_1 - q_k^{\{l\}} + s_k^{\{l\}} - c^{\{l\}}\right) \\ &= \sum_{y=0}^{\beta - t_k + t_1 - q_k^{\{l\}} - s_k^{\{l\}} - c^{\{l\}}} \left[\Pr\left(r_k^{\{l\}} = y\right)\right] \end{aligned} \tag{16}$$

Combining (16) with (7), and given that since all packets must be received then $h = i$-1:

$$\Pr(\tau_k \leq \beta) = \sum_{y=0}^{\beta - t_k + t_1 - q_k^{\{l\}} - s_k^{\{l\}} - c^{\{l\}}} \left[\sum_{z=0}^{\infty} \left[\Pr\left(\mathrm{X}^{\{l\}}\left(\Delta_k^{\{l\}}, r_{k-1}^{\{l\}} = z\right) = j\right) \cdot \Pr\left(r_{k-1}^{\{l\}} = y\right)\right]\right] \tag{17}$$

The probability of receiving all packets can be calculated as the probability that the link remains in the forward state for all the packets that are sent. If the message is composed of only one message, this is then a certainty:

$$\Pr\left(k \mid x^{\{l\}}(\delta,\lambda) = 0\right) = \begin{cases} 1, & k = 1 \\ \prod_{i=2}^{k} \left[p_{0,0}^{\{l\}}\left(\Delta_i^{\{l\}}\right)\right], & k > 1 \end{cases} \tag{18}$$

If the value of λ is chosen high enough that the probability that the message is still in transit without losses but not yet delivered is low, then it can be assumed that the previous transmission failed because the link entered in the Drop state, leading to the expression (19). This assumption is true when the $\Pr(\tau \leq \lambda - T_{ACK})$ tends to 1, where T_{ACK} is the time needed to transmit the logical acknowledgement.

$$\Pr\left(x^{\{l\}}(\delta,\lambda) = 0\right) \sim \begin{cases} \pi_0^{\{l\}}, & \delta = 0 \\ p_{1,0}^{\{l\}}(\lambda), & \delta > 1 \end{cases} \tag{19}$$

The continuity for transaction time T can be calculated as the probability that any of the messages transmitted arrive within T seconds since the transaction started:

$$C^{\{l\}}(T,\lambda) = 1 - \prod_{\delta=0}^{\lfloor T/\lambda \rfloor}\left[1 - K^{\{l\}}(T,\lambda,\delta)\right] \tag{20}$$

The ECTP availability parameter is directly the value of the link availability of the employed link if the continuity and integrity requirements are met. Otherwise, the availability parameter is 0:

$$A^{\{l\}} = \begin{cases} Av^{\{l\}}, & C^{\{l\}} \geq C_{\mathrm{req}}^{\{l\}} \wedge I^{\{l\}} \leq I_{\mathrm{req}}^{\{l\}} \\ 0, & \text{otherwise} \end{cases} \tag{21}$$

The equations proposed in this section can be used to determine the RCP performance of the air-ground data links. However, applying it requires making an assumption of the retransmission timeout λ as explained in the next section.

4.3.3. Calculating the ECTP with the Single-link RCP model

The Single-Link RCP model can be used to calculate the ECTP of any link for any service. The continuity should be calculated for the required transaction time values of the ATC/C2 service. The traffic characteristics needed in the model are k and b (ATC values in Table 4). In some cases, the application sending the traffic might trigger a retransmission. As defined in Section 2.2.2, after a timeout of λ without receiving a logical acknowledgement, the application retransmits the message as it assumes it to be lost. The value of λ is necessary to calculate the continuity but it has not yet been defined.

The value of λ depends on the service application implementation, so any calculation of the expected performance must be done assuming a numerical value. For every service, it is assumed that the minimum value of λ corresponds to the time it would take for the link to send the message and the logical acknowledgement with a high probability (99%), assuming no losses on the link. The expected transmission is drawn in Figure 20. The logical acknowledgement's absolute minimum size is taken, 48 bytes (40 bytes IPv6 header and 8 bytes UDP header).

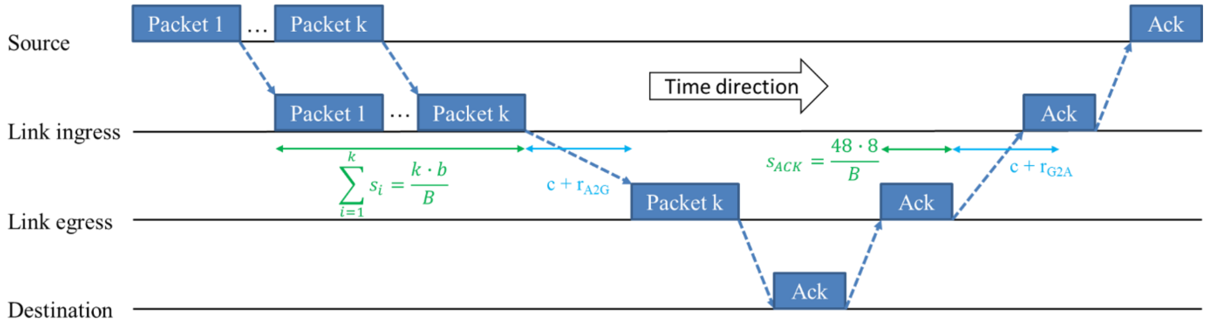

Figure 20: Retransmission time assumption

The minimum value of the retransmission timeout is calculated with (22). The values for the link profiles are given in Table 16.

$$\lambda_{min}(k,b,B,c,r) = \frac{k \cdot b + 48 \cdot 8}{B} + 2c + r_{A2G} + r_{G2A} \bigg| \Pr(r_{A2G} + r_{G2A}) = 0.99 \tag{22}$$

Link profile	$r_{A2G}+r_{G2A}$ (99% prob.) [ms]	λ_{min} [ms]
GEO SatCom	39664	$\frac{k \cdot b + 384}{432} + 40374$
LEO SatCom	7828	$\frac{k \cdot b + 384}{1.2} + 8586$

Link profile	**r_{A2G}+r_{G2A} (99% prob.) [ms]**	**λ_{min} [ms]**
Direct Wireless	111	$\frac{k \cdot b + 384}{220} + 371$

Table 16: Retransmission timeout for the generic link profiles (note: *b* in bits)

Whereas intuition leads to the conclusion that if the objective is to increase the expected continuity, the value of lambda should be the smallest possible, this is not always true. In case that a transmission failed because of a packet loss, increasing the time between retransmissions also increases the probability that the link is back to forwarding state in the following transmission. Thus, it is assumed that the application chooses the value of lambda that provides the best performance possible for the required transaction times. The maximum value of lambda is obtained by adjusting the retransmissions to fit in the biggest required transaction time T_{req}, as shown in Figure 21 and expressed in (23).

$$\lambda_{max} = \frac{\max(T_{req})}{\left\lfloor \max(T_{req}) / \lambda_{min} \right\rfloor} \tag{23}$$

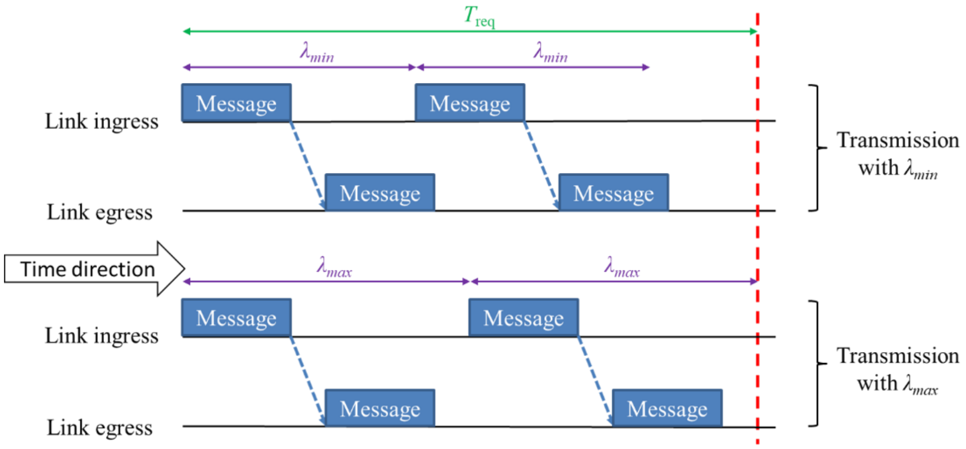

Figure 21: Maximum retransmission timeout assumption

With all the information available to calculate the performance of the air-ground data links, the model could be used for evaluating the performance of the links in-situ, as described in the next section.

4.3.4. Using the performance model for route selection

If the routing decision when transmitting over the air-ground data links is done based on the performance requirements of each service, the RCTP must be compared to the ECTP each of the links provides. When multiple links with higher expected performance than required, the choice could be influenced by multiple factors such as cost, the margin between ECTP and RCTP or the link load. How the decision is made is up to the airline's choice, following any normative of the regulatory bodies.

If the ECTP of a link is calculated using the Single-Link RCP performance model from Section 4.3.2, the link parameters values must be known. Those values are not always available. A long period after the deployment, the links' values are probably known from measurements. Before that, the values are available from an estimation based on initial measurements and simulations. Regardless, the values will usually be given as a confidence interval. If this is the case, the ECTP for all the values in the range must be calculated: if all combinations meet the RCTP, the link supports the service's requirements. If multiple links meet the requirements, another criterion is added to the routing decision, the level of confidence.

When the link parameters values are known as confidence intervals, if any of the values in the range would yield an ECTP that does not meet the RCTP, the link must be considered as non-compliant. If the value of any of the parameters of the link is unknown, the link must also be considered as non-compliant.

In the situation that only non-compliant links are available, which link must be used to route the traffic, if any, is out of scope of this thesis' work. Whether it is better to refrain from using the communications or try using the link with highest performance and hope for the best, ultimately depends on the regulation applicable.

Regardless of whether the performance model is used for route selection or when designing a new link, the results of the model are compared to other performance evaluation tools to verify its results. The next section compares the results of the model with those obtained using an emulator.

4.3.5. Emulation test

The objective of this section is to compare the expected continuity obtained using emulation and the Single-Link RCP performance model from Section 4.3.2. The emulation tests are performed using the testbed created for the European project "Advanced Cockpit for Reduction Of Stress and Workload" (ACROSS). The testbed has been described in detail in [19]. The emulator is implemented in multiple virtual machines, each representing one of the network nodes. It emulates the network, so the results are generated in real time. It features the ATN/IPS protocol stack as described in Section 2.2, multiple links to emulate the future multi-link ATC communications and a new router named Communication Performance Manager (CPM).

The CPM is an evolution of the Integrated Router and Home Agent proposed in [77] as part of the European project "Seamless Aeronautical Networking Through Integration of Data Links, Radios and Antennas" (SANDRA). The CPM implements routing based on the required performance of the traffic and the expected performance of the available links. It implements MPEC for the cases that the expected performance of the available links does not meet the requirements. The erasure coding implementation is based on linear network coding.

A test has been performed with the emulator to compare the expected performance with measurements taken with IPv6 traffic. The emulation test service has the following properties: k=3, b=1000 bytes and the link used has the Direct Wireless parameters' values (see Table 15).

The actual continuity CDF measured with the emulator (ACDF) matches the shape of the expected curve, with small differences (Figure 22). The expected performance is calculated using the Single-Link RCP performance model for the four approximations of the link: optimistic, conservative, continuant and pessimistic (see Section 3.2.4).

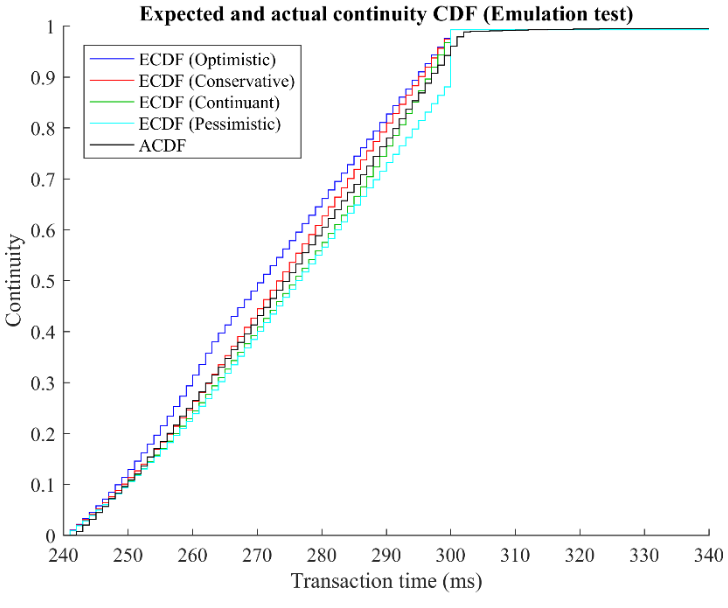

Figure 22: Single link emulation test CDF

Then, the difference between the expected continuity with each approximation and the measured continuity is plotted in Figure 23. Regardless of the approximation, the difference is within 0.08 points. The optimistic and pessimistic approximations differ the most from the actual continuity. Looking at the relative difference (Figure 24), the conservative approximation fits the best, with an error within 5% for all the transaction times, except those with a very small continuity value. All the continuity requirements are always expressed for values higher or equal to 95%, so high relative errors for small continuity values (C<10%) are irrelevant. The relative difference after the continuity stagnation (when the random delay is highest) is below 0.2%.

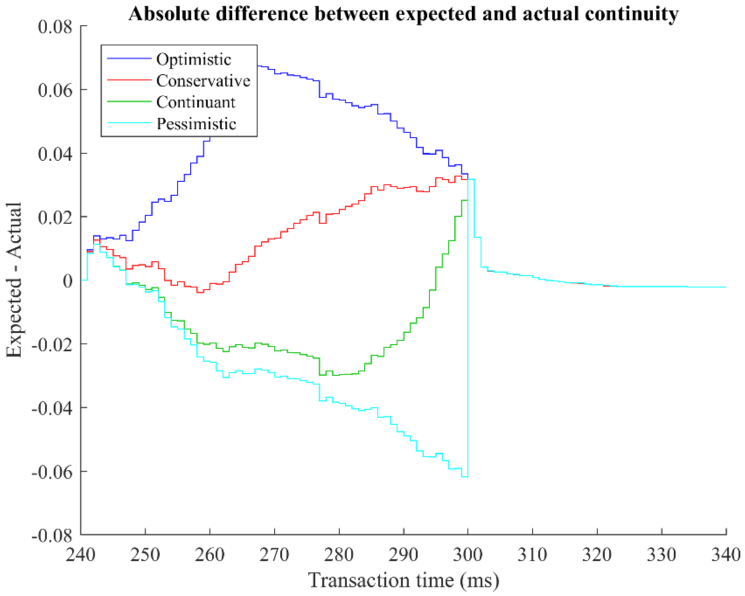

Figure 23: Absolute difference between expected continuity and actual continuity for all approximations (single link)

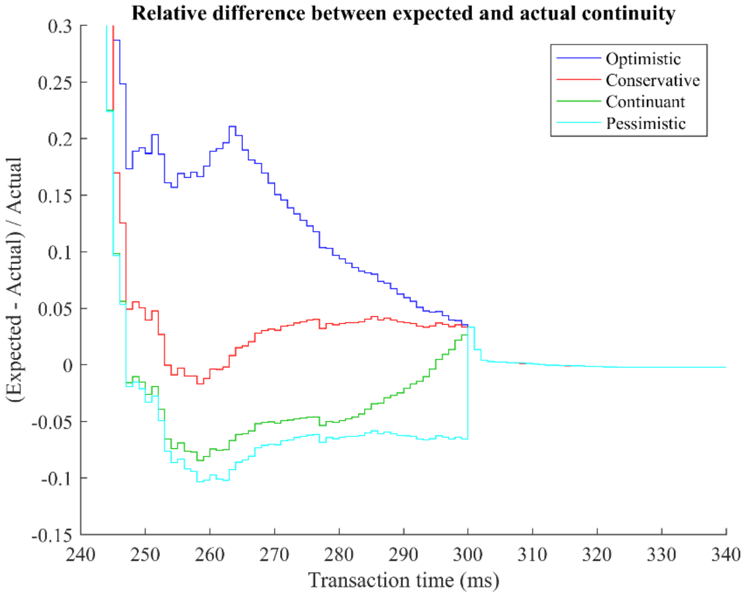

Figure 24: Relative difference between expected continuity and actual continuity for all approximations (single link)

These results indicate that the equations proposed in section 4.3.2 to obtain the expected continuity match closely the actual continuity measured with the emulator. The next section repeats the test but it uses a simulator instead of an emulator.

4.3.6. Simulation test

The objective of this section is to compare the expected continuity obtained using simulation and the Single-Link RCP performance model from Section 4.3.2. The simulation results in this thesis are generated an event-driven simulator created specifically for this work. The simulator is implemented in Java and can be used to simulate a transaction between a single source and a single destination. Between the two nodes, the user can create a network to test single-link and multi-link communications. In the case of multi-link, both Packet Repetition and MPEC encoder and decoder routers are available. The simulator is available under GPL license [68]. It can be used to simulate any scenario and extended to implement new features.

The simulator is based on events, so idle time is not simulated. New events are registered in a scenario controller that triggers them in chronological order. The advantage of this approach is that the results are obtained faster than real time (e.g. the emulator). However, it is still slower than calculation using the Single-Link RCP performance model (Section 4.3) and the MPEC RCP performance model (later in Section 5.4). This is especially relevant when many runs are required for high accuracy (i.e. enough decimals) and high precision (i.e. the results don't depend on the number of runs).

The nodes only simulate the impact of their functionalities. No protocol stack is implemented, instead packets are object instances that are passed on by the nodes. Also, the erasure code isn't implemented, the decoder only counts how many encoded packets have been received to determine if it can forward the original packets.

The test setup is the same as with the emulation test, with *k*=3, *b*=1000 bytes and a Direct Wireless link. However, the results obtained with the simulator depend on the random delay approximation used from Section 3.2.4. Thus, the difference between the two curves is calculated for each approximation.

The results show that the continuity calculated with the Single-Link RCP performance model and the simulated values are very close. The absolute difference is in the 10^{-5} order of magnitude (Figure 25) and the relative difference in the 10^{-4} order (Figure 26). The small differences mean that the model provides results that match closely those obtained with the simulator.

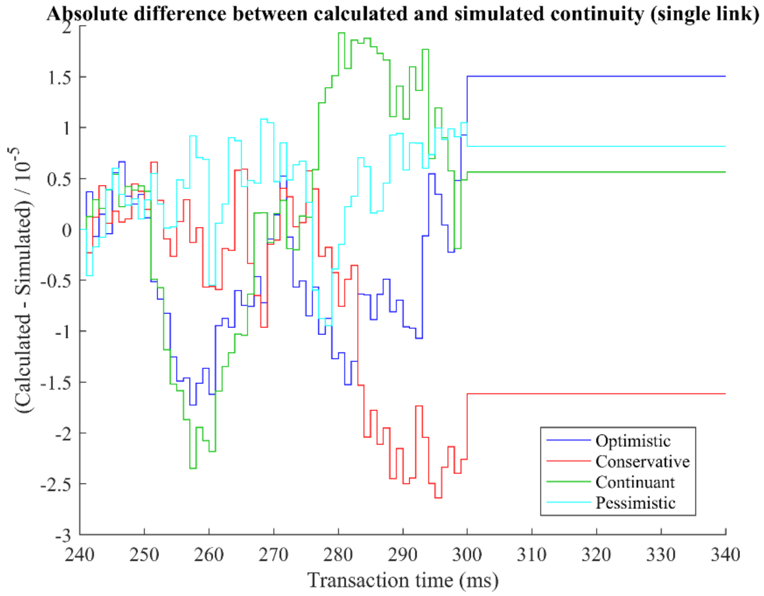

Figure 25: Absolute difference between calculated and simulated continuities with a single link

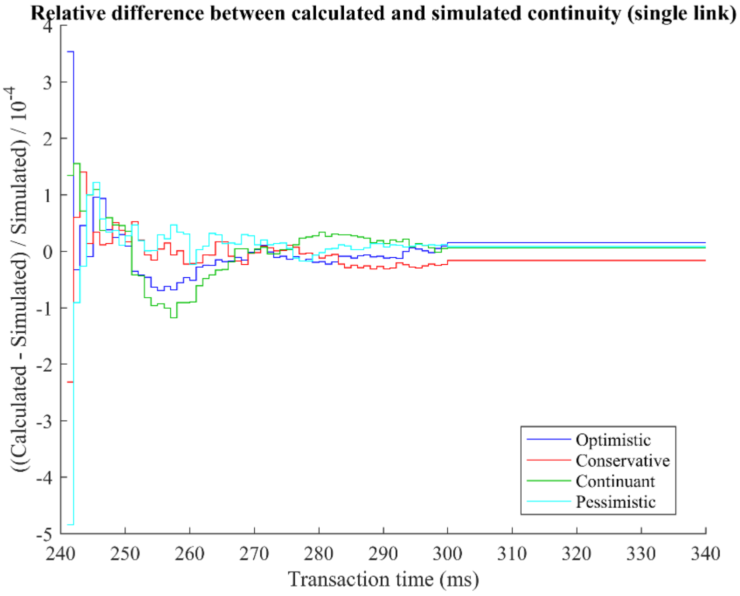

Figure 26: Relative difference between calculated and simulated continuities with a single link

Having validated the Single-Link RCP performance model from Section 4.3, in the next section it is used to evaluate the performance provided by the generic air-ground data links from Section 3.4.

4.4. Generic air-ground data link performance

4.4.1. Expected performance of the ATC services with the generic links

In this section, the ECTP of each of the ATC services (see Section 2.4) when they are transmit over the generic links (see Section 3.4) are discussed. The expected continuity and availability are calculated using the Single-Link RCP model from Section 4.3 for each ATC service over the APT, TMA, ENR and ORP domains. The results can be found in the Annex A.3, in Table 24 for the GEO SatCom link, in Table 25 for the LEO SatCom link and in Table 26 for the Direct Wireless link.

The expected continuity of the GEO SatCom link (Table 24) is lower than the required continuity for all the ATC services and for all the domains. Therefore, the GEO SatCom link is unsuitable to support the future data-centric ATC services described in Section 2.4. In fact, the combination of high losses, high constant delay and high random delay yield values of expected continuity below 95%.

The LEO SatCom link (Table 25) meets the 95% required continuity for a few services in the ORP domain. For each of those services, the highest continuity requirement of each service (T_C columns in Table 25) is not met. The expected continuity values for all other services and domains are below the requirements. Like the GEO SatCom, the LEO SatCom link does not provide the level of performance required for the future data-centric ATC services. Despite having a lower bit rate than the GEO SatCom, some of the services 95% continuity requirement are met because the highest random delay of the LEO SatCom is lower.

The expected continuity calculated for the Direct Wireless link (Table 26) is higher than the required continuity for all the ATC services in the APT, TMA and ENR domains. The expected availability (0.9990) meets all the services' required value except for the "SURV" service (0.9995). The expected availability is directly obtained from the link availability. The link availability of the Direct Wireless link is set in Section 3.4.3 by selecting the certified link availability of existing data links. Given difference of less than one order of magnitude between the requirement and the existing technology's performance, a real link implementation when the ATC data-centric services are in use will likely be higher than the required 99.95%. If that would be the case, all the ATC service requirements would be met for the APT, TMA and ENR domains. The ORP domain isn't considered for this link because the coverage of the Direct Wireless link is restricted to continental airspace.

The SURV service has the strictest requirements of all the ATC services considered. This service is related to keeping aircraft separated at a safe operational distance. If the future air traffic density is higher than expected, the time requirements will be tightened. The inclusion of unmanned aircraft in unsegregated space is one of the possible reasons for the current estimation falling short. Seeing the results in the previous sections, the only generic link that meets the continuity requirements is the Direct Wireless link. Figure 27 shows the expected continuity of SURV service over the Direct Wireless link. The figure also shows the value of one minus the continuity on the right-side y-axis. Together with a logarithmic scale, this helps with the visualization of values very close to one.

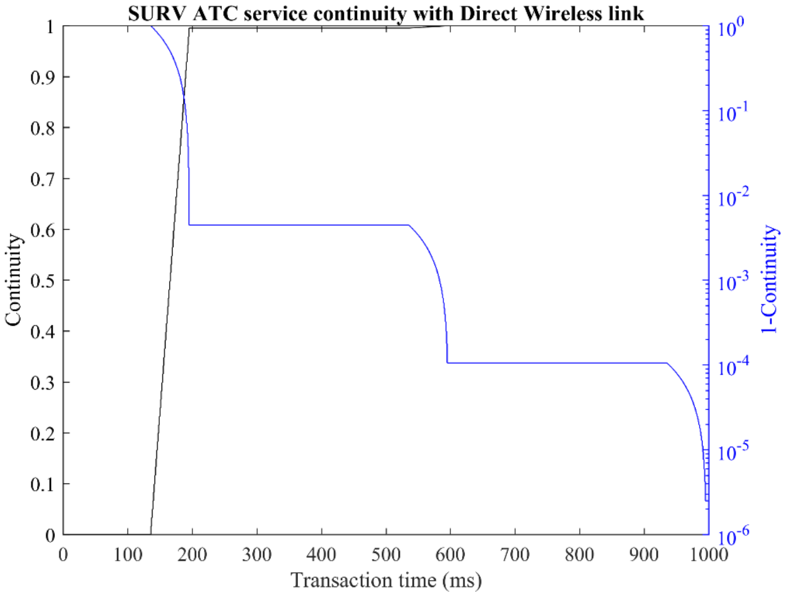

Figure 27: Expected continuity of the SURV service with the Direct Wireless link

The 95% expected continuity is achieved for 193 ms, less than half the required value for the APT domain (400 ms) and less than a sixth for the TMA and ENR domains (1.2 s). The 99.996% expected continuity is achieved for a transaction time of 974 ms, less than one third of the required value for the APT domain (3.2 s) and less than one eight for the TMA and ENR domains (8 s). These transaction time results could be used to re-assess the requirements in aircraft separation and allow higher aircraft density in areas with a link performing like the Direct Wireless available.

In addition to the performance of the ATC services, the performance of unmanned aviation communications will also play an important role in the future data-centric scenario. Thus, the performance of the C2 landing service is calculated in the next section.

4.4.2. Expected performance of the C2 landing service with the generic links

The requirements for the C2 landing service are much stricter as those described in COCRv2 for the ATC services. Considering this fact and the results for the ATC services, the expected performance is calculated only with the Direct Wireless link. The transaction time and continuity are shown in Figure 28. The minimum transaction time achievable with a non-zero probability, is 294 ms; well above the 160 ms required by the requirements. The C2 landing service requirements cannot be fulfilled with any of the generic link profiles. The performance shown in Figure 28 is calculated using the pessimistic approximation (see Section 3.2.4).

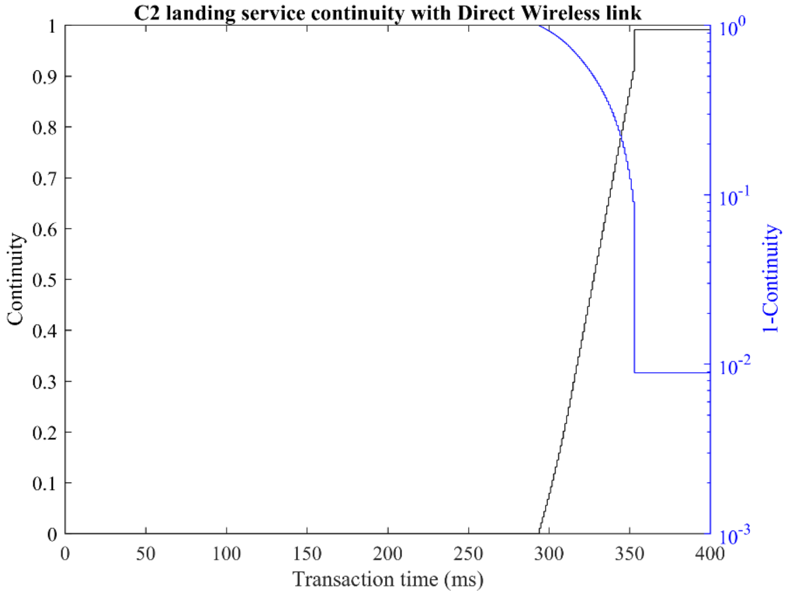

Figure 28: Expected continuity of the C2 landing service with the Direct Wireless link

The expected continuity provided by the generic air-ground data links to the C2 landing service is much lower than the required value. Therefore, new air-ground data links are needed. In the next section, new air-ground data link parameters' values are obtained that meet the requirements of all C2 landing service and ATC services.

4.5. Future air-ground data link requirements

4.5.1. Methodology

When the requirements for a data service are not met by any of the existing or planned air-ground data links, an obvious solution is developing a new link. A first approach to the parameters' values of the link must be made to select the underlying technologies, such as link layer protocols or the physical layer properties.

There is no combination of values for the link that could be called "the right values". Increasing the value of one parameter might allow reducing another one. There are limits to doing a trade-off between parameters because each parameter has a minimum value that must be met. In this section, a set of values that ensure that the RCTP for each domain are met are provided. Then, a for each of the domains (APT, TMA, ENR and the trade-off between delay and loss parameters is calculated. In all cases, the links are assumed to be symmetrical and the requirements for both air-to-ground and ground-to-air met.

The integrity requirement is always met with the current model. The link availability parameter must be at least, equal to the highest requirement of all the data services. The remaining values to be obtained are bit rate B, constant delay c, random delay r and the loss state transition rates μ_0 and μ_1. All these parameters are obtained from the continuity and transaction time requirements.

To obtain the values of latency and loss, the first step is finding the latency parameters the meet the transaction time requirements, with disregard to any continuity requirement. To do that, let's assume a "perfect link" with no losses (μ_0=0 and initial state x=0) and no random delay (r=0). Any link with no losses and with a constant delay plus the highest value possible of the random delay equal or smaller to the constant delay of the perfect link would meet the requirements. The latency parameters are obtained as a relation between the bit rate and constant plus highest random delay, or c+max(r).

For each value of c+max(r), the bit rate value is found by first checking if the RCTP requirements are met with 1 kbps bit rate and if not, it is increased by an additional 1 kbps until the requirements are met.

The overall message latency must be below the requirements. If all the latency would be caused by the c+max(r) contribution, the transmission time would be zero and thus the bit rate required infinite. A margin of 10 ms is reserved for the transmission time in the calculations, so the maximum value of c+max(r) checked is the minimum transaction time requirements minus ten milliseconds.

If the perfect link would exist, the expected continuity would always be one. If losses are added to the perfect link, the expected continuity is lowered. The next step is finding the values of μ_0 and μ_1 that keep the expected continuity above the requirements. If the physical and link layers of the network force an average length of the loss state (fixing μ_1), a maximum μ_0 must be ensured to prevent the losses from lowering the expected continuity below the required value. The range of average duration of loss is chosen between 1 ms and 10 s. The lower end is the accuracy of the results (milliseconds) and the higher end is the order of magnitude of the ATC requirements (tens of seconds). Thus, the values of μ_1 range from 10^{-1} to 10^3 s^{-1}. The maximum μ_0 is obtained considering the minimum bit rate for all the possible values of constant plus maximum random delay obtained in the previous step.

This methodology is applied in the next to two sections to calculate the link parameters values that meet the ATC and C2 landing service requirements.

4.5.2. Future link requirements for the ATC services

The link availability requirement corresponds to the availability requirement of the strictest service, in the case of the ATC services being 99.995% from the SURV service. The strictest transaction time requirement for the APT domain is 400 ms. For the TMA, ENR and ORP domains, it is 1200 ms. Assuming a perfect link, to support all the ATC services relevant on each domain the trade-off between delay and bit rate is shown in Figure 29. The TMA and ENR domains are shown together because the results for both domains are the same. A bit rate of 116 kbps is enough for all the domains if the delay requirements are met.

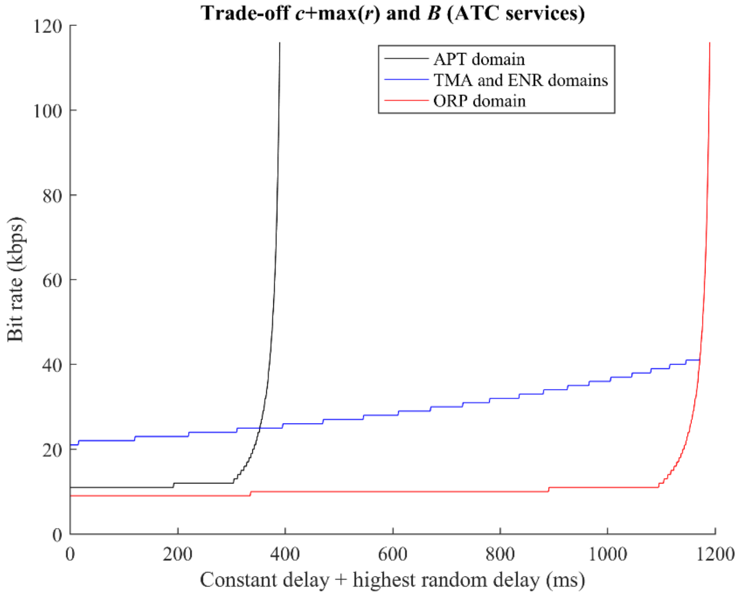

Figure 29: Bit rate, constant and random delay requirements of a link to meet the ATC requirements

The steep increase in bit rate requirement in Figure 29 is caused by the maximum link latency imposed by the ATC requirements. The link latency is conditioned by the strictest transaction time of each domain (400 ms for APT, 1200 ms for TMA, ENR and ORP), all given by the SURV and WAKE services. When the constant delay plus the highest random delay (x-axis in Figure 29) is close to the strictest transaction time, there constant delay plus the highest random delay make up for most of the latency incurred by packets sent over the link. Thus, there is less margin left for the transaction time. In fact, the curve in Figure 29 takes the highest value at B = 116 kbps because that is the minimum value required to transmit a SURV or WAKE message (composed by a single packet of 28 bytes, see Table

4) in 10 ms. The margin of 10 ms is left for the transaction time as explained in the methodology (Section 4.5.1). If no margin was imposed, as the constant plus highest random delay tends to the strictest transaction time, the bit rate requirement would tend to infinity.

For each value of μ_1, the maximum value of μ_0 is given by the results in Figure 30. The same results are plotted again in Figure 31 with the maximum average packet loss ratio instead of the maximum μ_0. In the best case, the maximum *PLR* is about 1% for the APT, ENR and TMA domains and 0.5% for the ORP domain. The maximum *PLR* is in the 10^{-2} for values of μ_1 higher than 1 s^{-1}. With high values of μ_1 the maximum *PLR* becomes independent of μ_1 because the duration of the link in the loss state is short, thus affecting the retransmissions independently. The smaller the value of μ_1, the longer the link stays in the loss state after a change. For example, for μ_1=0.1 s^{-1} the average duration of the loss state is 10 s. For μ_1<1 s^{-1}, a link in loss state is more likely to affect all the retransmissions within the required transaction time from Table 3. Therefore, for those values of μ_1, a newly designed link has stricter *PLR* requirements than the same link with higher values of μ_1.

The results in Figure 30 and Figure 31 show for every μ_1 the most restrictive μ_0 that meets the requirements of all the services. The value of μ_0 affects the expected continuity for each service differently. The continuity is calculated using (20) and it depends of three probabilities (14) that depend on the values of μ_1 and μ_0. First, the probability of the link being in Forward state when the transaction begins; see (19), (44) and (46). For a given μ_1 and μ_0 this probability is the same for all services. Second, the probability that all the packets of a message are transmitted if the link was in Forward state at the beginning of the transmission; see (18) and (49). For a given μ_1 and μ_0 this probability is lower for services with messages consisting of multiple packets. However, the probability also depends on the packet sizes, so we cannot simply say that the more packets per message, the lower the probability. Finally, the probability that all the forwarded packets are received in time does not depend on the values of μ_1 and μ_0, but on other link parameters. This probability is different for each service, as it depends on the number and size of the packets that compose the messages. Combining all these factors, the most restrictive μ_0 are given by the following services: in the APT domain the SURV and D-OTIS services (Figure 32), in the TMA and ENR domains the SURV, ACL, D-ORIS and D-OTIS services (Figure 33) and in the ORP domain, the SURV and COTRAC services (Figure 34).

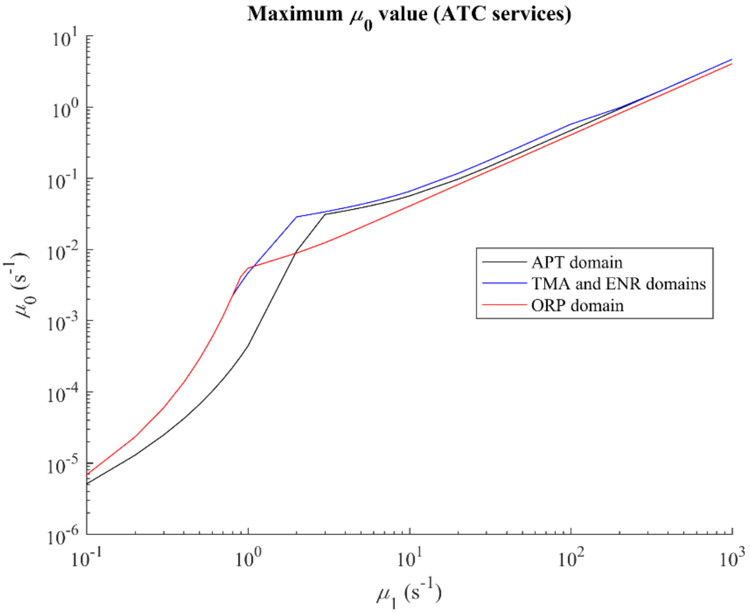

Figure 30: μ_0 vs μ_1 required to meet the ATC requirements

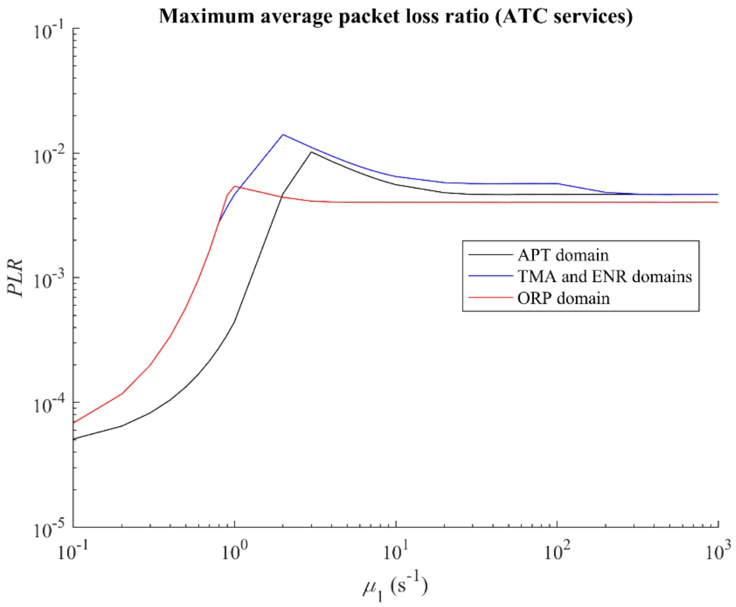

Figure 31: *PLR* vs μ_1 required to meet the ATC requirements

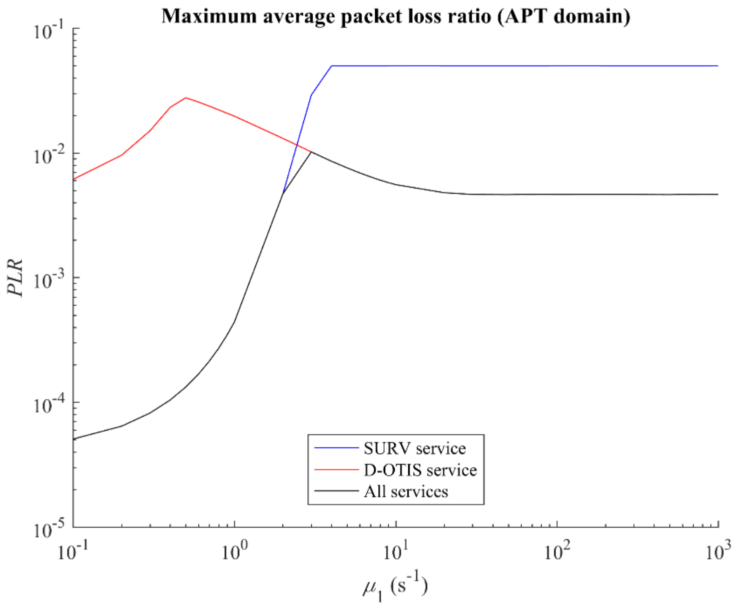

Figure 32: *PLR* vs μ_1 required to meet the ATC requirements in the APT domain and the services that fix the values

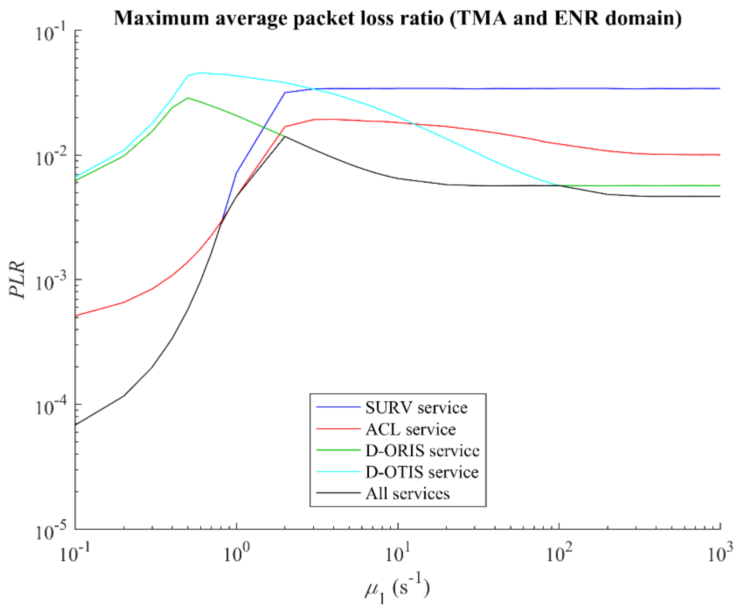

Figure 33: ***PLR*** **vs** μ_1 **required to meet the ATC requirements in the TMA and ENR domains and the services that fix the values**

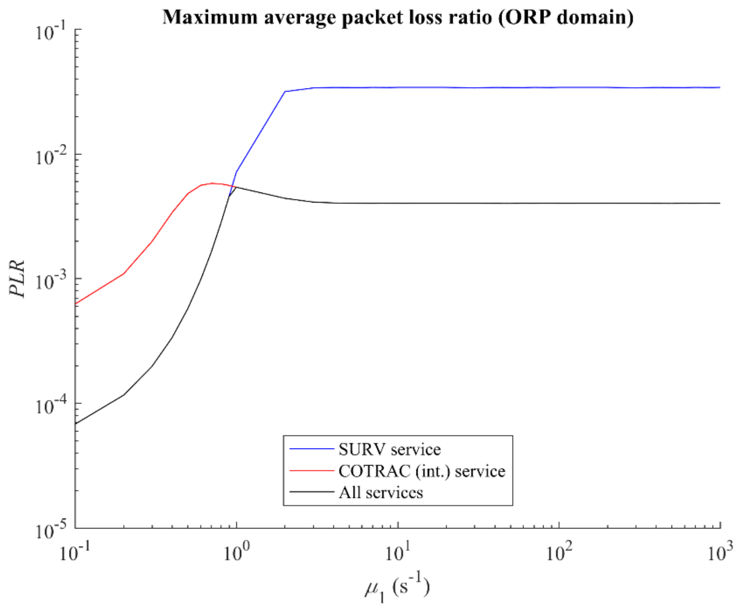

Figure 34: ***PLR*** **vs** μ_1 **required to meet the ATC requirements in the ORP domain and the services that fix the values**

The requirements loss requirements in Figure 30 and Figure 31 are valid for the different combinations of bit rate, constant delay and random delay from Figure 29. If only one set of values is chosen for those parameters, the loss requirements can be obtained for them specifically. The results when fixing the values of c, max(r) and B are better than when the results obtained for all possible values of those parameters because the requirements are only met for a single case. The selection of the values is done based on the difficulty to meet the requirements with the available technology. The maximum value bit rate in Figure 29 (116 kbps) is easily achievable. Thus, Figure 35 and Figure 36 are calculated fixing B = 116 kbps and c+max(r) to the highest value for the APT domain (390 ms), the TMA and ENR domains (1190 ms) and the ORP domain (1190 ms). For those values of bit rate and delay, the maximum average packet loss ratio goes above 1% for some values of μ_1 (see Figure 36).

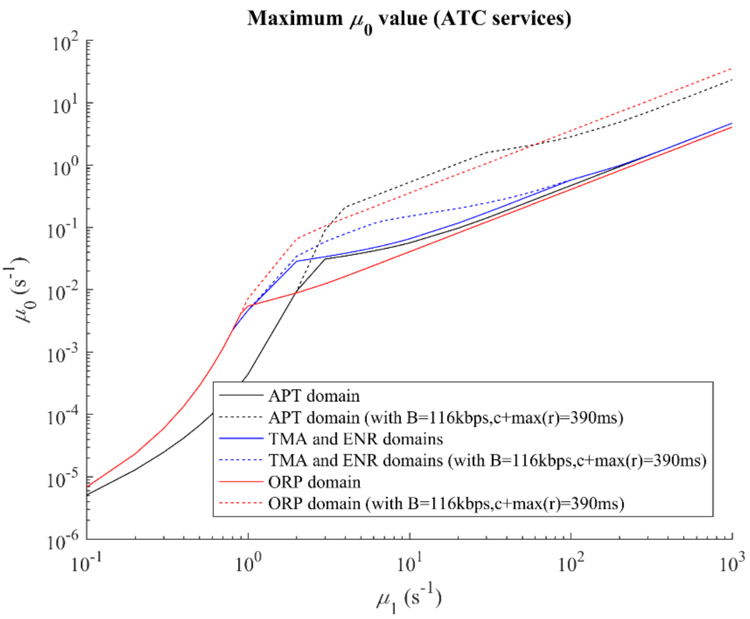

Figure 35: μ_0 **vs** μ_1 **required to meet the ATC requirements with fixed bit rate and delay requirements**

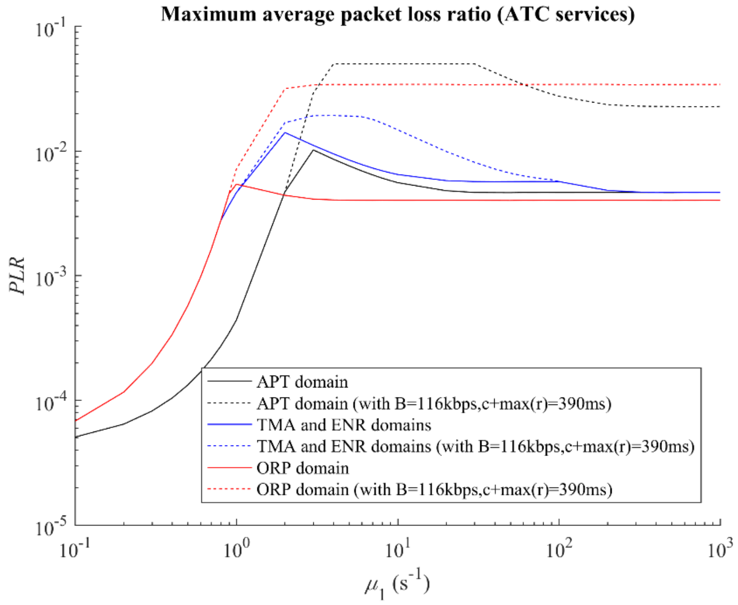

Figure 36: ***PLR*** **vs** μ_1 **required to meet the ATC requirements with fixed bit rate and delay requirements**

The maximum value of μ_0 can be increased at the expense of increasing the latency requirements. If the link transmits the messages faster, the number of times a message can be retransmitted increases. When that happens, the same continuity is achieved with a lower probability of receiving each message. Therefore, the requirement of μ_0 can relaxed (i.e. the maximum value of μ_0 can be increased). Figure 37, Figure 38 and Figure 39 show the trade-off for all domains for a fixed value of μ_1=1. For this value, the maximum μ_0 value can be increased up to one order of magnitude, for the TMA and ENR domains (Figure 38) and for the ORP domain (Figure 39). The value of μ_1=1 is chosen to illustrate the trade-off, but the procedure can be repeated for other values.

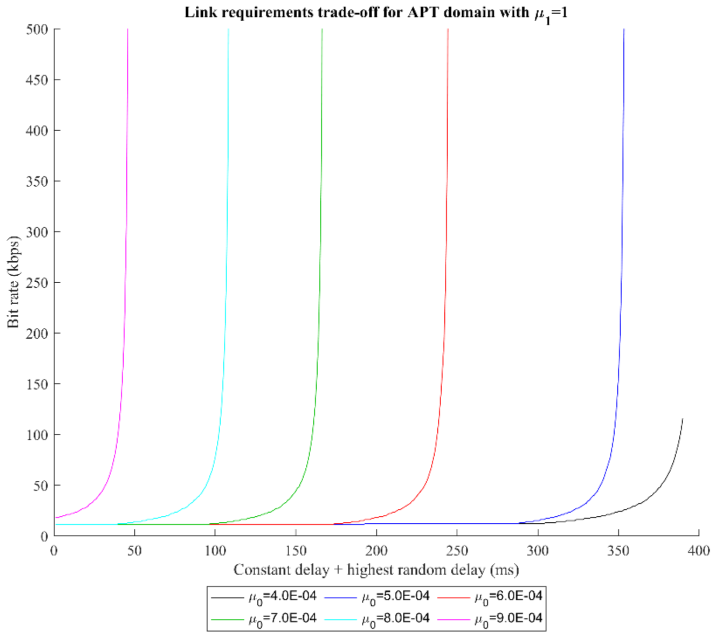

Figure 37: Link requirements trade-off to meet the ATC requirements with μ_1=1 (APT domain)

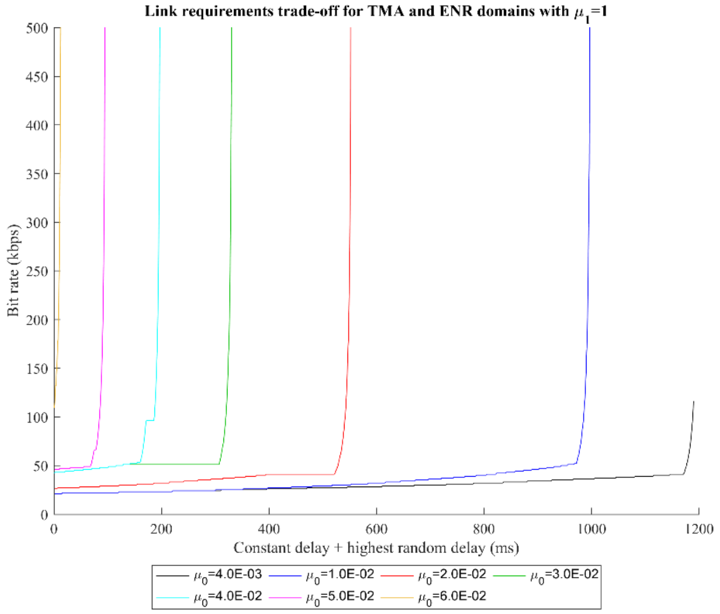

Figure 38: Link requirements trade-off to meet the ATC requirements with μ_1=1 (TMA and ENR domains)

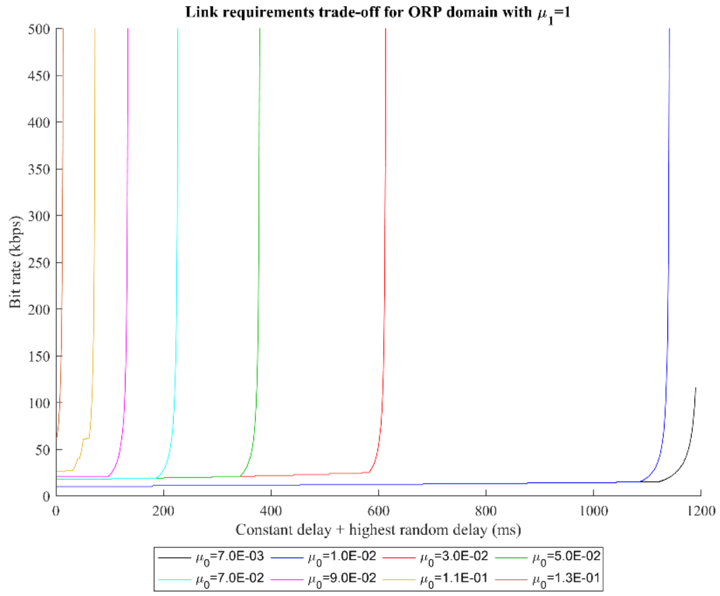

Figure 39: Link requirements trade-off to meet the ATC requirements with μ_1=1 (ORP domain)

The link requirements to support the ATC services are obtained in this section. In the next section the same methodology is applied to obtain the C2 landing service requirements.

4.5.3. Future link requirements for the C2 landing service

The link availability requirement is directly the availability requirement of the C2 landing service, 99.9995%. The transaction time requirement is 160 ms, so the values of c+max(r) to calculate the requirements go from 1 to 150 ms. The trade-off obtained using the perfect link (see Figure 40) show that the minimum bit rate is 228 kbps and the maximum 4432 kbps.

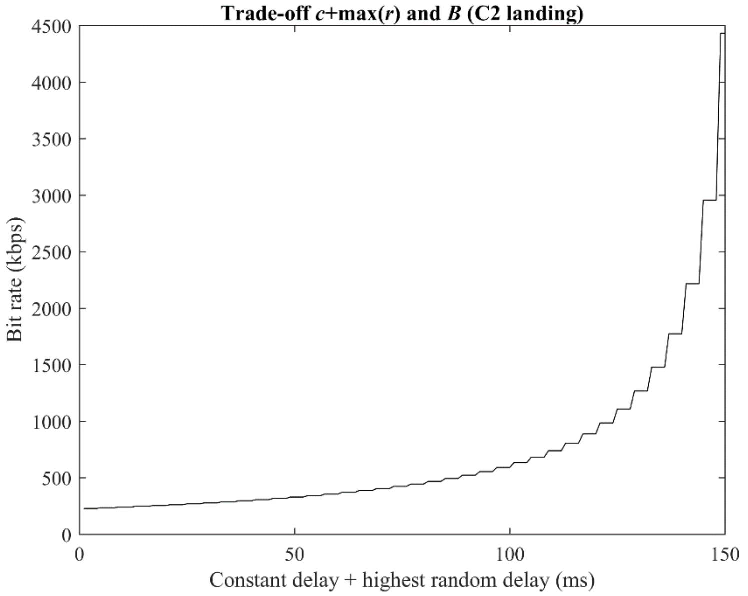

Figure 40: Bit rate, constant and random delay requirements of a link to meet the C2 landing requirements

The maximum value of μ_0 is given for each value of μ_1, in Figure 41. The same results are plotted again in Figure 42 with the maximum average packet loss ratio instead of the maximum μ_0. The results show that the required *PLR* is at best 10^{-11}, an extremely low value compared to today's wireless link typical values.

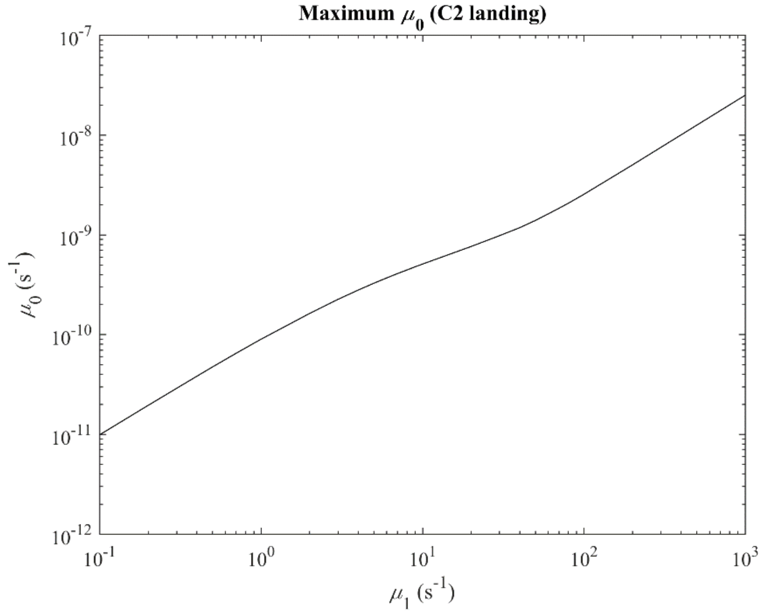

Figure 41: μ_0 **vs** μ_1 **required to meet the C2 landing requirements**

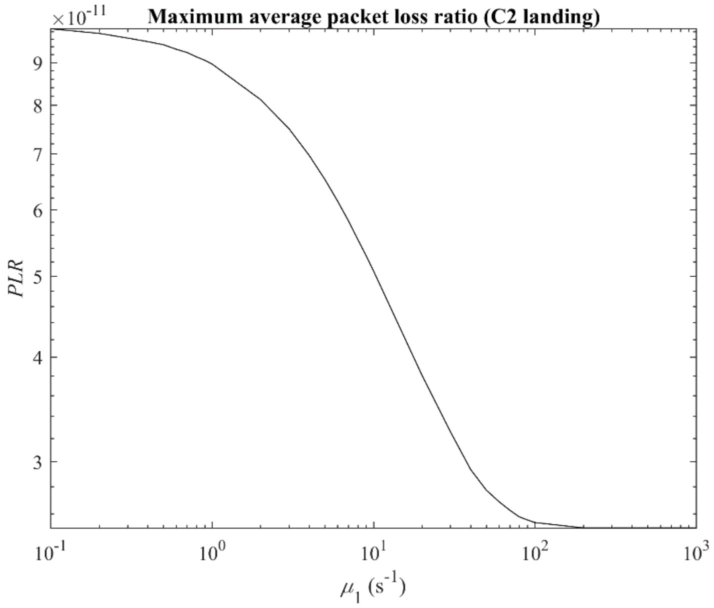

Figure 42: ***PLR*** **vs** μ_1 **required to meet the C2 landing requirements**

The maximum value of μ_0 can be slightly increased at the expense of reducing the maximum constant and random delay and increasing the bit rate, as shown in Figure 43. Note that the curves for $\mu_0=8\cdot10^{-11}$ and $\mu_0=9\cdot10^{-11}$ differ only for low values of the x-axis.

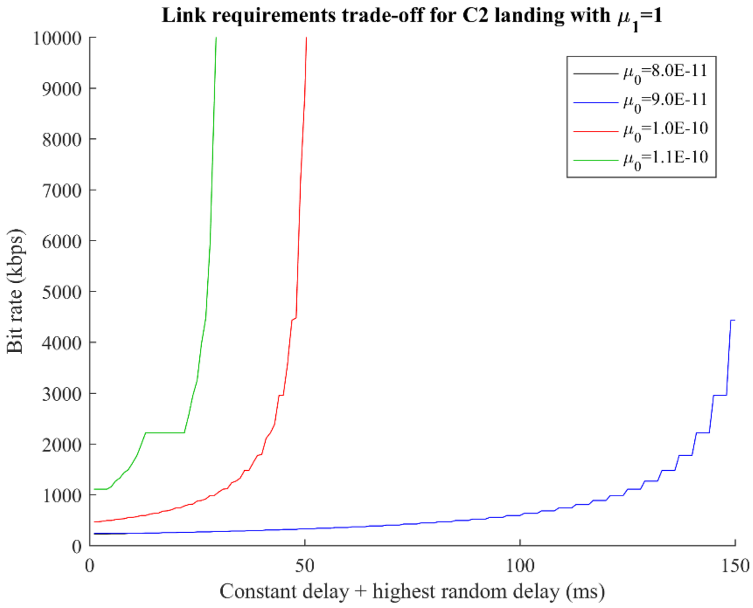

Figure 43: Link requirements trade-off to meet the C2 landing requirements with μ_1=1

With the air-ground data link requirements to support the C2 landing service ends the collection of results. In the next section, all the results of this chapter are analysed.

4.6. Analysis of the results

In this chapter, the Single-Link RCP performance model is proposed. The results calculated using this model are analysed in this section. The results generated with the model are obtained after some assumptions are made (see Sections 4.3.1 and 4.3.3). The traffic is always assumed to be in isolation, so traffic from other sources don't affect the queuing delay at the link ingress (congestion still has an impact in the random delay). Whereas this assumption makes the model much simpler, the results are overestimating the continuity provided by the links. The result is a good approximation for a link with a low load, as it is expected for ATC communications. The assumption that packets from different messages not being mergeable also has an impact on the expected continuity but for applications for which this is not true, it would mean an increase of expected continuity for high transaction times, after retransmissions are triggered. The results provided in this chapter are still a good first approximation that can save time and resources when making decisions before the next step (simulation, emulation or measurements).

The first results obtained are the expected performance of the generic air-ground data link profiles from Section 3.4, are presented in Section 4.4. The continuity of each ATC service is calculated for all the transaction time requirements. The results show that the GEO and LEO SatCom links don't meet the requirements of any of the ATC services, regardless of the flight domain. The expected continuity is lower than 99% in all cases. Thus, the expected performance is a few orders of magnitude short of the requirements. The Direct Wireless link meets the continuity requirements for all the domains where it is available. However, the generic link profile is based on the available information on the LDACS link, and it will only provide continental flight coverage. When and where the LDACS link is available, the APT, TMA and ENR requirements will likely be covered. The future in other locations or for the ORP domain depends on the performance of ESA's Iris programme and Iridium Certus, or new yet unannounced technologies. The expected continuity of the C2 landing service is also calculated, but with the Direct Wireless link the minimum transaction time is 294 ms (with minimum continuity), well above the 160 ms required (with high continuity).

The results in Section 4.5 are the link requirements to meet the data-centric requirements. The results for links to meet the ATC requirements are strict. The availability requirement for all domains is 99.995%, a value well within reach. Existing air-ground data links already certified for ATC communications such as Iridium SBD and Inmarsat are currently advertising figures of 99.99%, one order of magnitude short of the requirements. The bit rate requirement depends on the other contributions to the latency, but with the results obtained in this chapter, 116 kbps suffice regardless of the domain. The bit rate is the easiest requirement to achieve, as new data links provide hundreds of kbps. The constant plus random delay requirements are more complicated to meet. In the APT domain, the sum must not exceed 390 ms, above the expected value for LDACS. In the other domains the requirement is 1190 ms. In the case of a geostationary-orbit-satellite-based link, with a minimum propagation delay of about one quarter of a second, there is still margin. However, the impact of factors such as congestion or link layer retransmissions that can greatly increase the random delay must be controlled to meet the requirement. In the best case, the maximum average packet loss ratio is between 2-5%, depending on the flight domain. For some values combinations of bit rate, constant delay and random delay, the average packet loss ratio is in the 10^{-3} order of magnitude at best. Considering that the Single-Link RCP performance model considers the delay to be bounded and as such, packets exceeding the random delay count towards the packet loss figures, the loss requirements are the hardest to meet.

The average packet loss ratio figures (Figure 31 and Figure 36) show that the maximum value is achieved for certain values of the rate of change of the drop state (μ_1). The inverse of μ_1 is the average time spent in the drop state. If a link has a low value of μ_1, then the probability of changing from the loss state (x=1) is low, thus if the original message is lost, retransmissions are also likely to fail. Links with high values of μ_1 change often their state, so it is more likely that the link changes state to loss between the transmission of all the packets in a message. Therefore, it is recommended to design links in the μ_1 ranges with the highest maximum average packet loss ratio values. To meet the ATC services performance requirements, that means having values of μ_1 higher than one.

The results can be used to determine how much must the GEO and LEO SatCom links improve to meet the ATC services RCTP. The LEO SatCom parameters' values are all much lower than the requirements, meaning that a new link is necessary; Iridium is currently finishing the deployment of their new LEO satellites for Iridium Certus. The GEO SatCom parameters' values are below the requirements but closer than the LEO SatCom. The bit rate requirements are met for all domains. The sum of constant and random delay for the APT domain is only met with 1.6%, but the requirement for the TMA, ENR and ORP domains is met with 79% probability. The value of μ_0 of the GEO SatCom link (0.1361 s^{-1}) is also below the requirements by about one order of magnitude. The GEO SatCom link could potentially meet the requirements if the performance is improved through negotiation of a Service Level Agreement (SLA) with the communication service provider. With an SLA, parameters such as the random delay can be lowered by agreeing higher priority levels that reduce the impact of congestion. Whether the gap between the performance assumed with the generic link profile and the requirements can be covered, depends on the real technology's limits.

The link requirements to fulfil the C2 landing requirements are extreme. For a constant plus random delay of 150 ms, the bit rate requirement is 4432 kbps. This is beyond the expected bit rate of the next generation of air-ground data links. The loss requirements are also unrealistic with 10^{-11} average packet loss ratio requirement at best, being a strict value even for cabled communications.

All the conclusions drawn from this analysis are presented in the next section.

4.7. Conclusions

The link performance for data-centric communications is studied in this chapter. The performance the future air-ground data links will provide the ATC services is calculated. The requirements of the air-ground data links to meet the requirements is also obtained and analysed.

To obtain the expected performance of the air-ground data links, multiple approaches are possible. Provided that in this chapter the future and existing links are analysed, measurements are not possible for all technologies. As presented in the state-of-the-art, emulation and simulation has been done before for ATC communications. In this work, a mathematical model to calculate the ECTP is proposed. The advantage of this approach is it is faster to yield the results. The model is validated with both a simulator and an emulator. The Single-Link RCP performance model is a useful tool to quickly obtain an approximation of the performance expected from a real link but also of links under design. Additionally, the model could be implemented in the routers that have to make the decision over which link to send the packets, for a fast decision that can only be achieved using calculation or pre-established lookup tables.

The performance of the generic air-ground data links shows that the examined satellite links are insufficient to meet the ATC requirements. The performance of the GEO SatCom link falls just short for the ORP requirements and a reduction of the random delay and a decrease of the loss probability could be enough to meet the continuity requirements. For the real link (and not the "generic" approximation), if the ATC requirements are not met with the standard performance provided, an SLA to push the performance to the limits of the technology could suffice. The expected continuity with the Direct Wireless link is higher than any of the ATC service requirements of the APT, TMA and ENR domains. If the LDACS link in which the Direct Wireless is based has similar performance, the deployment of this link will suffice to meet the ATC service requirements over continental airspace within 200 nautical miles of the LDACS ground stations.

The requirements for any link to support the ATC services are calculated and presented in Section 4.5. The figures provide multiple trade-offs between bit rate, constant plus random delay and the loss state change rates. The bit rate requirements are easily achievable by future links but the delay and loss requirements, are harder to meet when combined. The delay must be met with a 100% probability, so any packets exceeding the requirements must be counted as a loss. The required average packet loss ratio is in the order of 10^{-3}, forcing robust link and physical layer protection against errors.

The C2 landing service requirements are not met with any of the generic links. The minimum transaction time possible with the Direct Wireless link is 294 ms, almost twice the 160 ms requirement. To meet the continuity requirements, the link parameters of delay, bit rate and loss must be unattainable. Either the requirements of the C2 landing are lowered by re-assessing the need of such a high continuity value or the link requirements are reduced using performance-improving techniques.

The results of this chapter provide a glance of the expected performance of the generic links, an approximation of existing and future air-ground data links. To evaluate the performance of existing links, the expected continuity must be recalculated with finer link parameters characterization, often not public and only available to the communication service provider. The results for the future direct wireless link, while only an approximation, indicate that the link will comfortably exceed the requirements. The link requirement results provide an indication of the target values for communication service providers to evaluate the suitability of their links and for scientists to develop new technologies that could be implemented in to support the future data-centric communications.

The link requirements for the ATC services are strict. The Direct Wireless meets them, but it approximates a real link, meaning that it is not certain that LDACS will. If it does, one must consider that it has limited coverage and only aircraft equipped with it would meet the continuity requirements, a step that would happen gradually. The availability of the link also still to be determined, as it depends on the real deployment. For the ORP domain, if Iridium Certus does not meet the requirements, an unknown for now, a new satellite link is needed. The link requirements for the C2 landing service are too high. In the next chapter, the expected performance is increased by exploiting the multi-link scenario, thus reducing the individual link's requirements.

5. MULTI-LINK PERFORMANCE

5.1. Introduction

Data-centric aircraft will be equipped with multiple air-ground data links to meet the future communication requirements. This assumption has been made both for commercial aviation in the SESAR programme [78] and for the UAV/RPAV by NASA [79]. Having multiple link technologies available reduces the downtime and allows choosing the performance provided to each service by selecting the appropriate link.

In scenarios other than aeronautical communications, such as streaming and wireless sensor networks, multiple links are often available. Researchers in those fields have proposed techniques to exploit the multi-link availability to improve the performance. In addition to the obvious increase in bandwidth, transmitting in parallel over independent links is a way to achieve spatial diversity and with that, a reduction of the correlation in latency and loss. To reach an efficient result, erasure coding in combination with parallel transmission of packets has been proposed.

The first part of this chapter aims at selecting the technique best suited to exploit the multi-link scenario for the future data-centric ATC and C2 communications. The state-of-the-art of the different techniques and protocols proposed for aeronautical communications and other scenarios is reviewed in Section 5.2. Then, in Section 5.3 a selection process is followed. Two candidates fit the selection criteria, Packet Repetition and an optimal block erasure code over multiple links, and their performance is analysed through simulation. The latter is chosen and named Multi-Path Erasure Coding (MPEC) when applied to meeting the RCP requirements because it provides better performance.

To calculate the performance provided with MPEC a model relating the traffic profile, the link parameters and the MPEC parameters (coding rate and packet distribution over the links) is proposed in Section 5.4. To the best knowledge of the author, this is the first model to calculate the performance in terms of the RCP when using multiple links and optimal block erasure codes. The accuracy of the model is checked with a simulator and an emulator.

The performance of multiple independent links with the values of the profiles described in Section 3.4 is calculated in Section 5.5 using the proposed model. Having multiple satellite links provides enough performance to meet some of the ATC service requirements but not all. This is an improvement over the single-link case, in which none are met.

The link requirements to meet the performance of all the ATC services or the C2 landing service for a single link are very strict, as shown in the previous chapter. Using MPEC, the combined performance of multiple links increases beyond what is provided by any individual link. In Section 5.6, the individual link requirements when deploying multiple independent replicas of the same link are obtained. The results show that the loss requirements can be greatly reduced, with the maximum average packet loss ratio being one to two orders of magnitude higher with just two links. Also, having at least three links reduces the delay requirements obtained for the single-link case.

The results presented in this chapter are analysed in Section 5.7. MPEC provides a substantial improvement in the continuity and transaction time parameters of the RCP at the expense of the issues of having multiple links (extra hardware, higher frequency spectrum needed, etc.) and increasing up to one order of magnitude the availability requirements for five links. The feasibility of MPEC is discussed both in terms of implementation in the aeronautical network and the technology's certification process in Section 5.8. The chapter concludes in Section 5.9 with some thoughts on the results and the work done.

5.2. State-of-the-art

5.2.1. Overview

The objective of this chapter is to improve the performance of the air-ground data links using multiple links. With this approach, the new link requirements can be reduced if instead of a single link, multiple links are used. In this state-of-the-art section, different techniques to improve the performance are reviewed so that one can be chosen in Section 5.3.

First, single-link performance protocols proposed for air-ground data communications are reviewed to see what had been proposed before the multi-link scenario was considered. Latency and erasures are the two main causes of continuity degradation. The impact of latency is reduced when using multiple links because the additional bandwidth reduces the transmission delay and when the different links' latencies are uncorrelated, congestion in one link has a lower impact on the overall message latency. To reduce the impact of erasures, erasure codes are reviewed because they correct erasures, providing an increase in the probability of receiving packets without requiring retransmissions (i.e. an increase in latency), at the expense of additional bit rate consumption. Finally, a review is done of performance improving techniques for aeronautical and other multi-link scenarios. Most of those techniques also use erasure coding.

5.2.2. Single link performance improving protocols

One way to increase the performance of aeronautical data communications is to adapt the protocols used at transport and network layer. Either the end-systems choose to use these protocols to enhance the performance of the communications or the end-to-end path is cut, and the protocols are implemented in a sub-set of the network with Performance Enhancing Proxies (PEP) as shown in Figure 44. In this section, the protocols developed specifically for the aeronautical single-link scenario are reviewed.

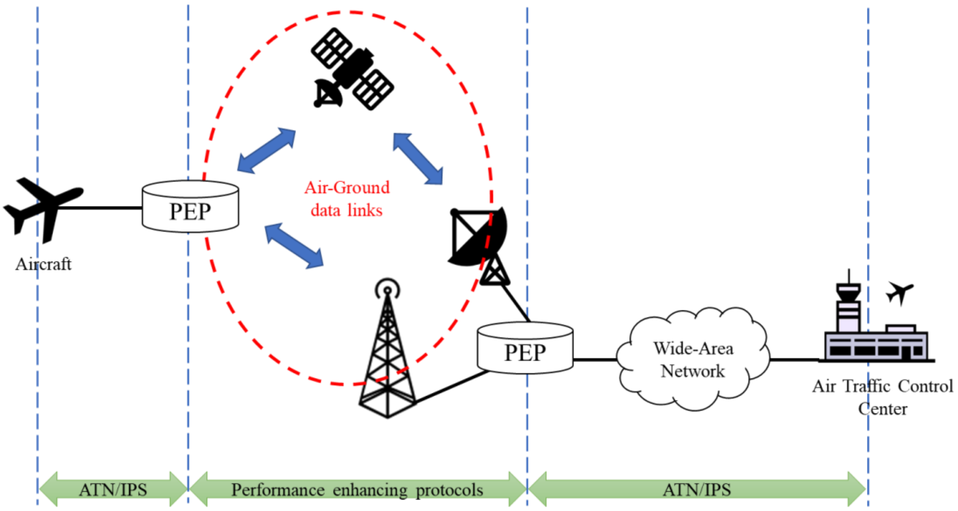

Figure 44: Protocol Enhancing Proxies placement

The two transport protocols adopted in the ATN/IPS for the transport layer are TCP and UDP (see Section 2.2.3). According to [80], a transport protocol for ATC communications must be simple, add little overhead and cope with the specific aeronautical characteristics such as losses and traffic with bursts of data. A new transport protocol has been proposed, Reliable Aeronautical Services Protocol (RASP) in [81]. RASP is a connectionless transport protocol that runs on top of UDP. It adds retransmissions at transport layer by means of a timer and a selective negative acknowledgement mechanism. It avoids the complexity of TCP, but it keeps the assurance of delivery missing in UDP.

The Airborne Network Telemetry Protocol (ANTP) suite [82] has been developed for aircraft telemetry as part of the Integrated Network Enhanced Telemetry program in the U.S.A. Whereas the telemetry scenario presents different challenges than ATC communications (intermittent connectivity and changing networks), both scenarios deal with mobile airborne nodes transmitting over unreliable air-ground data links. The new protocols improve the performance by using cross-layer information and awareness of changes in the network topology. In the ANTP protocol suite, when the transport protocol operates in “unreliable connection” mode it behaves like a UDP-based transport protocol with forward error correction used on the payload. In [82] it is mentioned that the packets can be sent over multiple paths but this part is not further developed in the literature [83] [84].

Even if satellite-specific protocols are not designed only for aeronautical communications, they provide an advantage when those types of air-ground data links are used. Several modifications of TCP exist that are well suited to work over satellite. A survey of the different TCP variants and their use as PEP has been done in [85]. Most versions deal with variations on how the congestion window changes. In satellite link, the long round-trip time is one of the biggest issues. TCP Hybla is a TCP variant that makes the congestion window independent of the round-trip time [86] and its PEP implementation, PEPsal, has been adopted by satellite communication providers [87].

The ANTP protocol suite is oriented at solving issues such as topology-changing networks rather than the performance degradation caused by the latency and erasures modelled in the air-ground data link model from Section 3.1. The other protocols reviewed in this section provide some advantages to the link’s reliability by implementing retransmissions to recover from packet losses. For links with high values of latency like aeronautical links, retransmissions greatly increase the transaction time because at least one round-trip time is required to recover a loss. Techniques to recover from loss that are less dependent on latency are more suitable for the aeronautical scenario. In the following section, erasure codes are explained for adding redundancy, an alternative method to recover from losses that is less affected by the latency. Also, exploiting the multi-link scenario reduces the impact of the high latency of links so multi-link techniques are also reviewed.

5.2.3. Erasure Coding

Erasures are losses of information and together with latency are the main cause for continuity degradation. Thus, when improving the communication performance is important to handle the recovery of erasures. There are two approaches for the recovery: retransmission of the erased information or recovery using redundancy [88].

If the erased information is retransmitted after the erasure is detected, the sender sends the information strictly necessary. In wireless links this might lead to lower throughputs, as the sender might be idle while waiting for an acknowledgement before transmitting more data. It might also cause high latencies as the retransmission is detected only after a round-trip-time. When redundancy is added to the transmission pre-emptively before detecting erasures, the redundancy can be used to correct a limited number of erasures at the receiver without further action from the sender. This technique, called Forward Error Correction (FEC), avoids the possible drawbacks of retransmissions at the expense of an additional bandwidth consumption regardless of the erasures.

Erasure codes can be used to generate the FEC redundancy. The symbols used to generate the redundancy are usually the protocol data units at the layer in which the code is applied. For example, an erasure code applied at network layer would use packets as symbols. The number of redundant symbols generated when using the erasure code is n-k, where n is the number of encoded symbols and k the number of original symbols. The code rate is defined as k/n and it corresponds to the effective throughput relative to the case of not coding.

Rateless or fountain codes do not have a fixed code rate. Thus, the number of encoded symbols n is variable. Rateless codes generate encoded symbols until the transmission is finished and the decoding of the original symbols is successful. This makes them very suitable for streams, as the number of encoded symbols can be adjusted during the stream’s transmission using a feedback channel.

Depending which original symbols are used to generate the encoded symbols, two types of erasure codes are distinguished: block codes and convolutional codes [88]. Block codes generate the encoded symbols from a group of non-overlapping original symbols. Some examples of block erasure codes are Low-Density Parity Check codes [89], Reed-Solomon codes [90] and Linear Network Coding [91].

Convolutional codes slide over a stream of symbols and the encoded symbols are either generated from a finite or infinite number of past symbols, the most famous being Turbo codes [92]. Codes can be systematic and then the original packets are a subset of the encoded packets or non-systematic. With a systematic code if an original packet is received at the decoder, it can be forwarded immediately.

Erasure codes can also be classified based on the number of symbols needed to decode. Optimal codes need k encoded symbols to retrieve the original symbols whereas non-optimal codes require more than k. Therefore, with non-optimal erasure codes the probability of decoding is lower, so more redundancy is needed to achieve the same performance. Non-optimality can provide some advantages like hop-by-hop coding without having to decode at the intermediate nodes (e.g. Random Linear Network Coding [93]) and lower encoding and decoding times.

Using erasure codes with packets as symbols is a way of applying FEC. If the packets in a message are encoded and transmitted, probability of correctly receiving is higher and so is the continuity. Most multi-link techniques use FEC in this manner to improve the performance. The multi-link techniques for aeronautical scenario are reviewed in the next section.

5.2.4. Performance improvement techniques for multiple air-ground data links

Having multiple links available does not necessarily imply that they can be used simultaneously. NASA has started the Hyper-Spectral Communications and Networking Air Traffic Management (HSCNA) project to identify improvement techniques and assess the performance in the multi-link scenario for air transportation and unmanned aviation through simulation [94]. Issues like handover, link selection and load balancing have been listed in [95] and some solutions were identified. For example, spreading the traffic over the available air-ground data links to reduce the risk of congestion (i.e. high correlated latency).

In [96], a new protocol named Aeronautical Multipath Transport Protocol (AeroMTP) has been proposed. AeroMTP generates redundant packets using Raptor codes [97], a rateless erasure code, to recover losses. The encoded packets are distributed over multiple paths according to an estimation of the paths' recent average packet loss ratio and average latency. The distribution is chosen to optimize the overall throughput of data (often called goodput). The transmission over each path is done using a custom congestion control mechanism. To detect congestion, AeroMTP requires all the nodes in the path to respect different treatment to high and low priority packets and all traffic flows to be TCP friendly. Then, it marks packets alternately as high and low priority so that if there is congestion, low priority packets are dropped first. This information is sent back to the sender using an acknowledgement. The congestion control mechanism is further described in the paper.

AeroMTP exploits the availability of the multiple links and adapts its behaviour to the status of each of the links, increasing the goodput. The objective of this work is to reduce the transaction time even if the goodput is lower because the ATC and C2 services are time-sensitive safety communications. This makes AeroMTP an unsuitable candidate. Also, the adoption of the custom protocols of AeroMTP for the future aeronautical communications poses a problem, as the objective of ICAO with the adoption of the ATN/IPS is to use standard network and transport protocols.

Replicating all the packets belonging to the same message over all the available links (a non-optimal block erasure code) and then, discarding all received duplicates has been proposed to increase the continuity and availability in [15]. This technique is hereafter referred to as *Packet Repetition*. An example of Packet Repetition is illustrated in Figure 45.

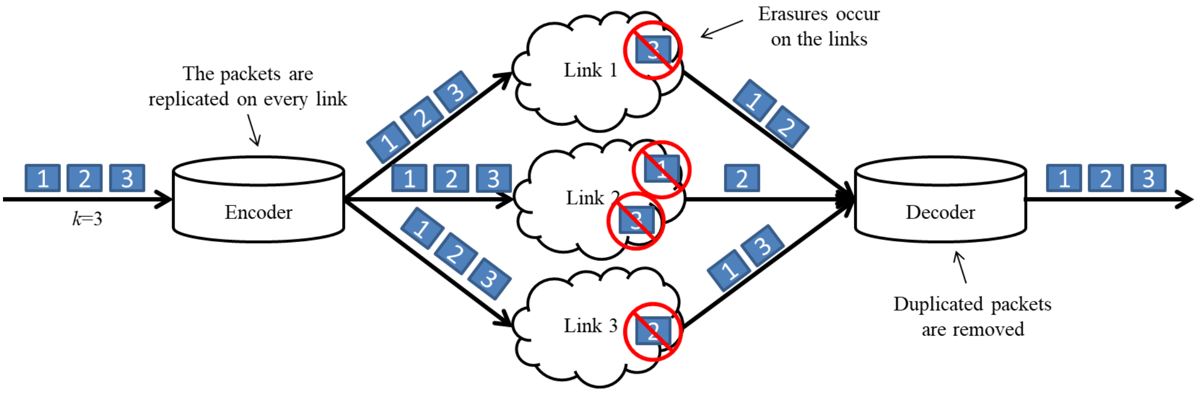

Figure 45: Example of Packet Repetition over three links

By adding redundancy with erasure coding, the probability of receiving all the required packets to recover the message increases. However, if removing any of the links reduces the expected continuity below the required value, all links must be available simultaneously to meet the requirements. In this case, the technique increases the continuity and *decreases* the availability as per (24). L is the set with all the links over which packets are transmitted.

$$A^L(T) = \prod_{\forall l \in L} Av^{\{l\}} \tag{24}$$

In the opposite case, that all the links meet the continuity and availability requirements independently, then active parallel redundancy is achieved. The availability formula (25) is taken from [15] and the continuity and integrity requirements are added.

$$A = 1 - \left[\prod_{\forall l \in L \mid C^{\{l\}} \geq C_{req} \wedge I^{\{l\}} \leq I_{req}} \left[1 - Av^{\{l\}}\right] \right] \tag{25}$$

Another known approach to increase availability is a stand-by parallel redundancy. That is, multiple links are readily available for transmission at any time but only one is used at once. This approach is proposed in [95] albeit it is proposed as a benefit for “reliability” without specifying which parameters are affected. If the handover is done seamlessly after the active link fails, the availability follows the same equation as with active parallel redundancy (25) without additional bit rate consumption. However, the aircraft gateway (for air-to-ground) or the ground gateway (for ground-to-air) require real-time knowledge of the link availability status. If the gateway cannot detect the changes in link availability fast enough, or the redundancy is passive instead of stand-by (the idle links need a start-up time before they are used), packet losses would occur, lowering the actual continuity of the communication.

The aeronautical scenario is not the only one with multiple-links for which performance improving techniques have been developed. The next section reviews those for other scenarios.

5.2.5. Performance improvement techniques in other multi-link scenarios

There are scenarios, other than the aeronautical, in which performance improving techniques have been applied to exploit the availability of multiple links. Having multiple links adds spatial diversity that can be used to reduce the correlation of the losses. When combined with FEC, the result is a highly reliable transmission. For example, redundancy on a per-packet basis and multiple links has been proposed to reduce the end-to-end packet loss in wireless networks in [98]. The novelty of the work was a new load balancing algorithm to maximizing the probability of successfully delivering the original packet subject to a maximum redundancy restriction. Applying erasure coding on a per-packet basis has the drawback that the packet must be fragmented and then encoded, producing an important overhead, an already existing issue in the ATN/IPS (see Section 2.2.5). If the packet is not fragmented, then the only possible coding in a per-packet basis is packet repetition.

Losses when streaming greatly reduce the end user experience. FEC using an optimal erasure code over multiple paths has been proposed for streaming in [16]. In addition to analysing the improvement in the overall average packet loss, that work also considers important quality of service parameters for streaming, the probability of packet loss bursts and the lag-1 autocorrelation. In [99] the same technique has been proposed but the distribution of the encoded packet was done using the time differences between the paths to minimize the average packet loss.

Another scenario in which multiple lossy links are used are wireless sensor networks. A review of different multi-path routing protocols, with a section dedicated to those using coding, was done in [100]. The approach of fragmenting a packet and encoding the fragments has also been proposed for wireless sensor networks in [101]. Erasure coding over multiple paths is also used in energy-efficient protocols like [102].

The performance of the transmission can also be improved in a multi-link scenario by adapting the transport protocol. The Internet Engineering Task Force is working in Multi-Path TCP (MPTCP) to develop mechanisms to send data over multiple paths using TCP [103]. A modification of TCP has been proposed to operate over multiple paths using network coding (a form of erasure coding) named MPTCP/NC [104]. With MPTCP/NC, erasure coding was used to add redundancy against loss to maximize the throughput. The Path-Based Network Coding for MPTCP (PBNC-MPTCP) protocol has been proposed as PEP for satellite networks [105]; it differentiates mainly from MPTCP/NC in the distribution of the redundancy over the paths.

Applying erasure coding on a per-packet basis is either not suitable for the aeronautical scenario (overhead from fragmentation) or it is the same proposal as Packet Repetition. Optimal block erasure codes over multiple links however have been proposed for improving the performance of scenarios sensitive with packet losses. It is a candidate to be applied for the air-ground data links. The multi-path TCP protocol variants are designed to increase the throughput rather than minimize the latency or maximize the probability of delivery, the two main issues that require improvement when trying to improve the continuity. Nevertheless, they are analysed together with all the other candidates in the next section.

5.3. Multi-Link performance-improving proposal

5.3.1. Proposal requirements

The second objective of this work is to reduce the data link requirements while meeting the RCTP of the future data-centric ATC communications (see Table 3) and the C2 communications (see Table 5). If the RCTP requirements remain unchanged, a reduction of the individual link requirements can be achieved by changing the protocols or by exploiting the multi-link diversity and bandwidth increase multiple links provide. In the previous section the state-of-the-art of performance-enhancing techniques for aeronautical and multi-link scenarios are reviewed. In this section, the criteria to select the best candidate for improving the performance in the aeronautical multi-link scenario are presented. The following characteristics will be checked: multi-link capabilities, transport protocol used, block code vs rateless code and optimal vs non-optimal codes. The selection of the characteristics is based on what are the most important features of the proposals. Each characteristic is described in the following paragraphs.

Some techniques are based on modifications of transport protocols. TCP-variants are conceived with optimization of throughput as a goal, that is maximize the data per second transmitted, ignoring the latency of the data. For time-sensitive applications such as ATC services, it is more important that the date arrives promptly than to being bandwidth-efficient. The mechanism used by TCP to recover data loss, retransmissions, causes an increase in the end-to-end latency. When satellite links are the only means of communications for an aircraft, their long round trip times (sometimes exceeding one second) mean that one packet loss increases the transaction time close to some of the ATC requirements (see Table 3). Another issue with TCP and high-latency links is round-trip time required before starting transmitting because of the establishment of the connection. Whereas a TCP could be pre-established and kept alive, this solution requires additional signalling regardless if the data link is used, which increases the bandwidth consumption. The objective of this chapter is to evaluate a technique aimed at reducing the transaction time associated to a value of continuity for transactions based on short messages rather than bulk transmissions. Thus, TCP-based proposals are discarded.

Recovering from losses is approached in most proposals from Section 5.2 by adding redundancy to the transmission using erasure codes. With those codes, the probability that a message composed of multiple packets is recovered in one transmission, even if there are packet losses, increases. For links with high bit-rate, high delay such as future air-ground data links (see Section 3.3) the transmission delay incurred from transmitting the redundancy is small compared to the impact of retransmissions in the latency. For those reasons, techniques using erasure codes to improve the reliability of the transmission are selected.

Two characteristics are looked at when selecting an erasure code: optimality and coding rate. Optimal codes require less bit rate at the cost of higher complexity, that translates into higher coding and decoding delays. The results of PBNC-MPTCP [105] show that the decoding operation for a small number of packets require less than one millisecond, the resolution of the requirements. What is more, these results are obtained using today's computers; calculation speed will have augmented by the time data-centric communications are rolled out. Techniques with optimal codes are preferred over those based on non-optimal codes.

If the encoder already generates enough packets to meet the requirements, like it would be done with a block code, the rateless code loses the advantage of adjusting the coding rate. Additionally, an RCP performance model created to calculate the performance of a technique using a rateless code would require knowledge of the return link's characteristics. For those reasons, the selected technique must implement a block code.

An issue with erasure codes is that the packet losses are correlated. Thus, the probability of the redundant packets being delayed or lost (i.e. link being in "drop" state during the transmission) increases if the original packets were delayed or lost. Using multiple links is a technique that implements spatial diversity. If the links are independent, the losses are uncorrelated. However, without any kind of redundancy all the packets in the message are required, so uncorrelated losses (without redundancy) lower the highest values of continuity. Also, when spreading the packets belonging to the same message over multiple links the bit rate available is the sum of all the links' bit rate. Thus, the message can be delivered faster than with a single link. For this reason, multi-link techniques that combine erasure codes are selected.

5.3.2. Analysis of the candidates

The goal of this section is to review the suitability of the techniques presented in the state-of-the-art (see Section 5.2) for reducing the air-ground link requirements using multiple links and then select the best candidate based on the requirements from the previous section. The performance of the suitable candidates is compared, and the best candidate is chosen and adapted to the aeronautical scenario in Section 5.3.3.

All the techniques are listed in Table 17 with their criteria from the previous section. When in red colour, the criterion is not met. Also, if no erasure code is used, the block code and optimal code columns are not-applicable (N/A). AeroMTP is not TCP-based but it uses the same mechanisms as TCP (congestion control), so the same rationale explained in Section 5.3.1 applies. "Optimal block erasure codes over multiple links" is the name given to the proposals in scenarios other than the aeronautical to use an optimal block erasure code to generate redundant packets and then transmit them over multiple links. Two candidate solutions meet all the criteria: "Packet Repetition" and "Optimal block erasure codes over multiple links". The only difference between both techniques is that Packet Repetition uses a non-optimal code instead of an optimal code.

Candidate technique	**Multi-link**	**TCP-based**	**Erasure code**	**Block code**	**Optimal code**
RASP	No	No	No	N/A	N/A
ANTP	No	No	No	N/A	N/A
TCP variants	No	Yes	No	N/A	N/A
AeroMTP	Yes	Yes	Yes	No	No
Packet Repetition	Yes	No	Yes	Yes	No
Optimal block erasure codes over multiple links	Yes	No	Yes	Yes	Yes
MPTCP	Yes	Yes	No	N/A	N/A
MPTCP/NC	Yes	Yes	Yes	No	No
PBNC-MPTCP	Yes	Yes	Yes	No	No

Table 17: Candidate techniques to improve the performance in the multi-link scenario

The performance difference between Packet Repetition and "optimal block erasure codes over multiple links" is illustrated by comparing the C2 landing service performance over the Direct Wireless link (see Figure 46). To make the comparison with the optimal code, *k* encoded packets are sent over each of the Direct Wireless links available (assumed independent). To further add to the comparison, the cases with a single link with the same coding rate, and a transmitting over a single link with higher bit rate with the same coding rate are simulated. To make it easier to differentiate the values of continuity above 0.99, the results are shown as one minus Continuity (1-*C*) instead of Continuity (*C*). Given the correlated nature of the losses, the impact of erasure coding on continuity with a single link is limited. Therefore, using erasure coding in the single link case provides an edge when no additional links are available. Having the additional bit rate in one link is not as beneficial as using packet repetition or an optimal block erasure coding to achieve higher continuity values (i.e. lower values of 1-*C*). For both multi-link techniques, the continuity increases a few orders of magnitude with respect to the single link case. The more links (and therefore higher coding rate) are added, the more the continuity increases. Regardless of the number of links, the lowest transaction time possible with Packet Repetition remains the same as with the single link. For the same number of links, the continuity for all transaction time values is always higher (i.e. lower 1-*C*) with an optimal block erasure code than with Packet Repetition.

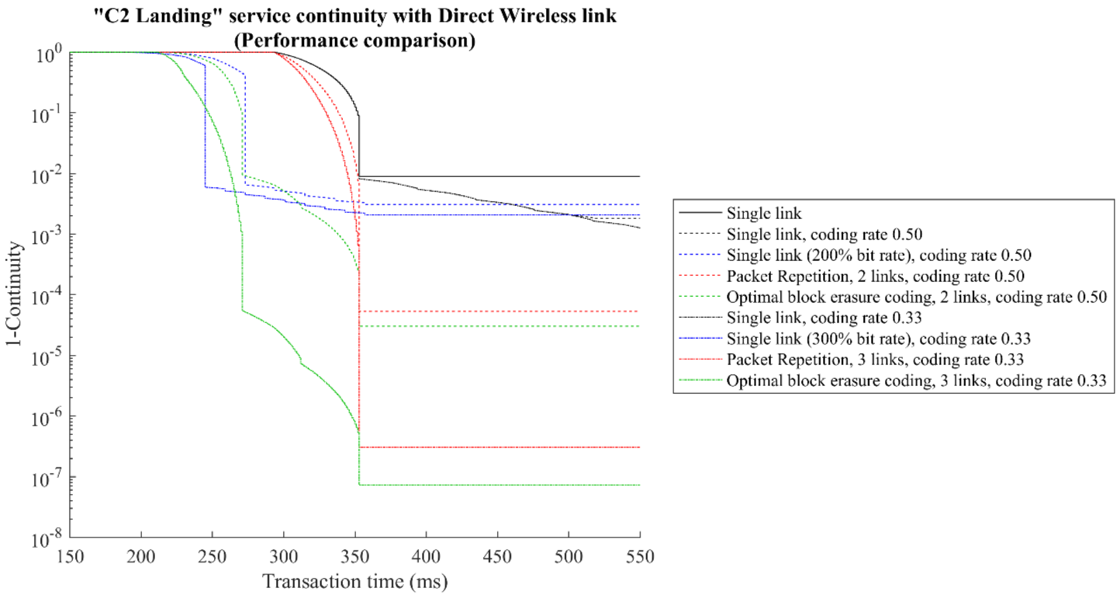

Figure 46: Comparison between the Packet Repetition and using an optimal block erasure code over multiple links

The implementation of the repetition of packets on the edges of the links is simple: the encoder must only replicate the packet and the decoder to remove duplicates. The simplicity in the implementation of the erasure code in Packet Repetition doesn’t translate in substantial latency gains, as seen in Figure 46. Therefore, the optimal code technique “optimal block erasure codes over multiple links” is preferred.

The next section describes in detail how the selected technique “optimal block erasure codes over multiple links” is applied to the air-ground data links. Then, a model is proposed to evaluate the performance of this technique under any link configuration.

5.3.3. Multi-Path Erasure Coding (MPEC)

The technique chosen in the previous section to improve the performance consists in using an optimal block erasure code over multiple links. When used under this context, it is named here Multi-Path Erasure Coding (MPEC).

The choice of the erasure code is discussed in this paragraph. In this scenario systematic codes are neither an advantage nor a disadvantage, as the assumption is that all the packets forming the message must be received to retrieve the message. In fact, if all the packets of a message are coded in the same block using a non-systematic code, the order of the original packets is kept even when sent over multiple links with very different latencies, which could prove an advantage as the application might not be prepared to receive out-of-order packets. No choice is made on this regard, but all diagrams consider a non-systematic code for illustrative purposes. Multiple optimal block erasures codes fit the description given (see Section 5.2.3), but their choice does not change the premises under which this work lays. Therefore, no specific code to generate the encoded packets is selected in the proposal.

Using an optimal block erasure code over multiple links has been proposed before for other applications. However, the objective of applying this technique has always been reducing the average packet loss ratio and increasing the effective throughput. MPEC’s novelty is not being a new technique but rather a new approach when looking at its benefits including its impact on the latency, a major factor in the RCTP metric (the transaction time). MPEC is used to meet the second objective of this work. A model to calculate the performance of MPEC using the RCP metric is provided in Section 5.4. To the best knowledge of the author this is the first model of its kind available. Then, the performance of multiple generic links using MPEC technique is calculated in Section 5.5. The new link requirements, reduced with respect to those in Section 4.5 by using MPEC, are presented in Section 5.6.

With MPEC, the packets belonging to the same message are all coded together. Selecting a block to code with packets from different services or messages could potentially have advantages. However, packets would be held back at the encoder until others arrive, increasing the latency. Evaluating this trade-off would require modelling the traffic generated by the end-systems, which is out-of-scope of this thesis.

Before being routed over the links, the original k packets that form the message are encoded into n encoded packets. The n encoded packets are then transmitted over the links. The set of links over which the packets are distributed is named L, each link l and the number of encoded packets over link l is denoted e_l:

$$\begin{gathered} E = \{e_l \mid e_l \geq 1\} \\ L = \{l \mid e_l \geq 1\} \end{gathered} \tag{26}$$

By definition, n can be expressed as:

$$n \equiv \sum_{\forall e_l \in E} e_l \tag{27}$$

For every packet transmitted over the links, the encoder must choose the links to be used (L) and how many encoded packets are sent over each link E. An example is shown in Figure 47; for a three-packet message, the encoder sends three encoded packets over the first link and two over the third link. The decision of how many encoded packets are generated and transmitted over each link must be made according to the comparison between the expected and the required performance. To do this, the encoder must be aware of the links' availability status and it must recognize which service the packets belong to, for example using the IPv6 source and destination addresses, and the UDP ports.

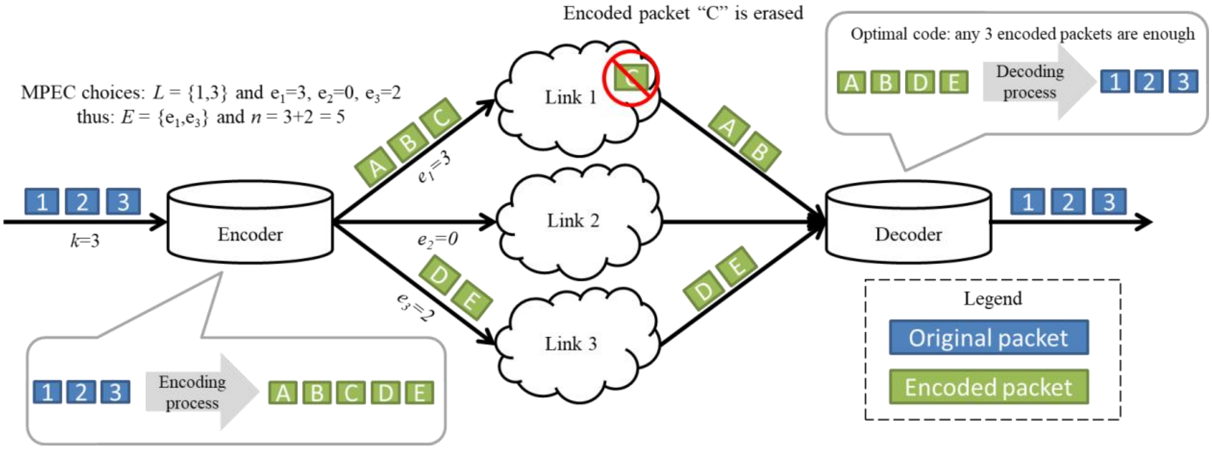

Figure 47: Example of MPEC coding decision

To apply MPEC as just described, the encoder function must be placed at a node where the routing of all the packets is done. Also, the encoder must be aware of the links' availability status. A decoder must be placed in the same node for traffic sent in the opposite direction. Since MPEC would act as a proxy changing how the routing is done, it acts as a network layer PEP and must be placed as shown in Figure 44. The placement in the aircraft is relatively simple, as the aircraft has a local network and an airborne router with access to all the links [77]. Ideally for the ground placement, all air-ground links would have their ground station collocated. However, this is currently not the case and it is highly unlikely to change in the future. Thus, a point in the network where all the traffic goes through in the ground must be chosen. If the MIPv6 protocol is used for ATN/IPS mobility (see Section 2.2.4), this node could be the home agent. The issue that arises with choosing a node away from the ground stations is that the extra delay added to the packets must be counted towards the RCTP allocation of the ground network rather than the air-ground data links. From a practical point of view, this delay should be considered as part of the link's requirements.

This section covers the definition of MPEC and how it is applied to the aeronautical scenario. The next section the first step towards the evaluation of this technique through the development of a new performance model for MPEC.

5.4. MPEC RCP performance model

5.4.1. Assumptions

The following assumptions are made to develop the model:

1. The ATN/IPS protocol stack is used as described in Section 2.2.
2. The air-ground data link can be characterized using the model described in Section 3.2.
3. To receive a message, all the IPv6 packets that compose it must be received.
4. The probability of having an undetected error is null.
5. The retransmission of a message does not invalidate the previously sent message.
6. The IPv6 packets forming a retransmitted message are unrelated to the IPv6 packets of previously sent messages. Thus, it is not possible to merge packets of multiple transmissions to restore a message.
7. Traffic services are considered in isolation.
8. The erasure code is an optimal block erasure code.

Assumptions 1 to 7 are the same as for the single link, see Section 4.3.1. Thus, the initial conditions in (12) and the expression of the queuing time (13) are valid for each of the links used in the multi-link communications. Assumption 8 is in line with the MPEC proposal from Section 5.3.

With the assumptions made, the performance model is derived in the next section from the description of MPEC from Section 5.3, the air-ground data link model from Section 3.2 and the traffic characteristics from Chapter 2.

5.4.2. The MPEC model

The MPEC RCP performance model is a set of equations to calculate the availability, transaction time and continuity parameters of the Expected Communication Technical Performance (ECTP) provided to a transaction by any number of air-ground data links using MPEC as defined in Section 5.3. The expected integrity from this model is always of zero undetected errors per transaction. Packets transmitted over an air-ground data link following the model from Section 3.2 are either dropped or correctly forwarded.

Calculating the continuity parameter works slightly different for MPEC than the calculation for a single link. The end-to-end message is composed of k packets. After erasure coding is applied, n encoded packets are formed, thus generating a redundancy of n-k packets. Given the optimality of the code, only k out of the n encoded packets transmitted over the links must be delivered in time to retrieve the message. In the single link case k packets are transmitted, and all k must be timely delivered.

For any set L of links, the number of encoded packets received within β after being sent over the links with the packets distributed according to the set E is defined using the random variable $\eta^L(\beta, E)$. This random variable depends on the probability of each link l in L to successfully deliver the packets forwarded over the link. For this, the random variable $\Gamma^{\{l\}}(\beta, e_l)$ is defined as the number of packets received over link l, within β seconds, given that e_l encoded packets are transmitted. Thus, $\eta^L(\beta, E)$ is defined as the sum of all $\Gamma^{\{l\}}(\beta, e_l)$ in the set L:

$$\eta^L(\beta, E) \sim \sum_{\forall l \in L} \Gamma^{\{l\}}(\beta, e_p) \tag{28}$$

The probability that $\eta^L(\beta, E)$ takes a certain value is given by (29). It depends on the probability of the combination of received packets.

$$\Pr(\eta^L(\beta,E)=z) = \sum_{\forall\{\gamma_l \mid \sum_{\forall l\in L}[\gamma_l]=z\}} \left[\prod_{\forall l\in L}\left[\Pr\left(\Gamma^{\{l\}}(\beta,e_l)=\gamma_l\right)\right]\right] \tag{29}$$

The probability that a message is correctly received is the probability that $\eta^L(\beta, E)$ takes a value higher or equal to k. To calculate the continuity, the time β depends on the transaction time requirement T, the number of transmissions δ, and the retransmission timeout λ. Thus, the probability that a message is correctly received is denoted as $K^L(T,\lambda,\delta,E)$ and given by (30).

$$K^L(T,\lambda,\delta,E) = \Pr(\eta^L(T-\delta\cdot\lambda,E)\geq k) \tag{30}$$

The continuity for transaction time T, $C^L(T,\lambda,E)$, is calculated in (31) as the probability that any of the messages transmitted arrive within T seconds since the transaction started.

$$C^L(T,\lambda,E) = 1 - \prod_{\delta=0}^{\lfloor T/\lambda \rfloor}\left[1-K^L(T,\lambda,\delta,E)\right] \tag{31}$$

The probability of $\Gamma^{\{l\}}(\beta, e_l)$ to take the value γ_l in (29) is obtained by calculating the probability of each sequence of delivered/undelivered packets. Let's define the finite sequence $\left(\theta_i^{\{l\}}(\beta)\right)_{i=1}^{e_l}$ where each θ_i represents whether the encoded packet i is delivered within β (θ_i=0), or not delivered in time (θ_i=1). Each row in Table 18 shows an example of all the possible finite sequences for e_l=3; packets "delivered" are forwarded with a latency within β.

1st packet	**2nd packet**	**3rd packet**	$\left(\boldsymbol{\theta}_i^{\{l\}}(\boldsymbol{\beta})\right)_{i=1}^{3} = (\boldsymbol{\theta}_1^{\{l\}},\boldsymbol{\theta}_2^{\{l\}},\boldsymbol{\theta}_3^{\{l\}})$	$\boldsymbol{\gamma_l}$
Failed	Failed	Failed	(1,1,1)	0
Failed	Failed	Delivered	(1,1,0)	1
Failed	Delivered	Failed	(1,0,1)	1
Failed	Delivered	Delivered	(1,0,0)	2
Delivered	Failed	Failed	(0,1,1)	1
Delivered	Failed	Delivered	(0,1,0)	2
Delivered	Delivered	Failed	(0,0,1)	2
Delivered	Delivered	Delivered	(0,0,0)	3

Table 18: All combinations of finite sequences for e_l = 3.

Then, $\Pr(\Gamma^{\{l\}}(\beta, e_l)=\gamma_l)$ is calculated as the sum of the probabilities of all the sequences for the given value of γ_l delivered packets (32).

$$\Pr\left(\Gamma^{\{l\}}(\beta,e_l)=\gamma_l\right) = \sum_{\left\{\forall\left(\theta_i^{\{l\}}(\beta)\right)_{i=1}^{e_l} \middle| e_l - \sum_{i=1}^{e_l}\left[\theta_i^{\{l\}}(\beta)\right]=\gamma_l\right\}} \Pr\left(\left(\theta_i^{\{l\}}(\beta)\right)_{i=1}^{e_l}\right) \tag{32}$$

If the last packet of the sequence is timely delivered and given that each link keeps the packet order, it can be concluded that any undelivered packets were dropped. If the last packet isn't delivered in time, then the missing packets can either be lost or be late. Thus, the probability of the finite sequence $\left(\theta_i^{\{l\}}(\beta)\right)_{i=1}^{e_l}$ is calculated in (33) differently depending on the last element of the sequence.

$$\Pr\left(\left(\theta_i^{\{l\}}(\beta)\right)_{i=1}^{e_l}\right) = \begin{cases} \Pr\left(\left(\theta_i^{\{l\}}(\beta)\right)_{i=1}^{e_l} \middle| \theta_{e_l}^{\{l\}}(\beta)=0\right), & \theta_{e_l}^{\{l\}}(\beta)=0 \\ \Pr\left(\left(\theta_i^{\{l\}}(\beta)\right)_{i=1}^{e_l} \middle| \theta_{e_l}^{\{l\}}(\beta)=1\right), & \theta_{e_l}^{\{l\}}(\beta)=1 \end{cases} \tag{33}$$

In case that the last packet is timely delivered, i.e. $\theta_{e_l}^{\{l\}}(\beta) = 0$, the probability of the finite sequence is calculated with (34). The probability of the first packet is assumed to be the stationary probability of the link.

$$\Pr\left(\left(\theta_i^{\{l\}}(\beta)\right)_{i=1}^{e_l} \middle| \theta_{e_l}^{\{l\}}(\beta) = 0\right) = \begin{cases} \pi_{\theta_1}^{\{l\}} \cdot \Pr\left(\tau_{e_l} \leq \beta\right), & e_l = 1 \\ \pi_{\theta_1}^{\{l\}} \cdot \left[\prod_{i=2}^{e_l} \left[p_{\theta_{i-1},\theta_i}^{\{l\}}\left(\Delta_i^{\{l\}}\right)\right]\right] \cdot \Pr\left(\tau_{e_l} \leq \beta\right), & e_l > 1 \end{cases} \tag{34}$$

Thus, the probability that a message is delivered within β from the beginning of the transaction $\Pr\left(\tau_{e_l} \leq \beta\right)$ is obtained with (35), which is the same as the single link equation (16) but considering the sum of encoding and decoding time ε.

$$\begin{aligned} \Pr(\tau_k \leq \beta) = {} & \Pr\left(q_k^{\{l\}} + s_k^{\{l\}} + c^{\{l\}} + r_k^{\{l\}} + \varepsilon + t_k - t_1 \leq \beta\right) \\ = {} & \Pr\left(r_k^{\{l\}} \leq \beta - \varepsilon - t_k + t_1 - q_k^{\{l\}} + s_k^{\{l\}} - c^{\{l\}}\right) \\ = {} & \sum_{j=0}^{\beta-\varepsilon-t_k+t_1-q_k^{\{l\}}-s_k^{\{l\}}-c^{\{l\}}} \left[\Pr\left(r_k^{\{l\}} = j\right)\right] \end{aligned} \tag{35}$$

Developing the random variable $r_k^{\{l\}}$ for the single link is done with (7) considering $h = i\text{-}1$, because all the packets must be received. When calculating the finite sequence in the MPEC case, the same consideration can be used if the random delay of the dropped packets is taken as the same of the last correctly received packet, as expressed with (36).

$$f_X(x, r_{i-1}, \Delta_i \mid \theta_i^{\{l\}}(\beta) = 1) = \begin{cases} 1, & x = max\,(0, r_{i-1} - \Delta_i) \\ 0, & otherwise \end{cases} \tag{36}$$

The probability of delivering a message within β (35) can be developed to (37) using (7) and considering $h = i\text{-}1$ with (36) for undelivered packets.

$$\Pr(\tau_k \leq \beta) = \sum_{j=0}^{\beta-\varepsilon-t_k+t_1-q_k^{\{l\}}-s_k^{\{l\}}-c^{\{l\}}} \left[\sum_{z=0}^{\infty} \left[\Pr\left(\mathrm{X}^{\{l\}}\left(\Delta_k^{\{l\}}, r_h^{\{l\}} = z\right) = j\right) \cdot \Pr\left(r_h^{\{l\}} = z\right)\right]\right] \tag{37}$$

If the last element of the sequence is an undelivered packet ($\theta_{e_p}^{\{l\}}(\beta) = 1$) the expression is more complicated than (33), as the reason that the last packet is undelivered is that either the packet is dropped, or it is late. However, it is possible to simplify the problem. First, for any sequence $\left(\theta_i^{\{l\}}(\beta)\right)_{i=1}^{e_l}$ with the last element being an undelivered packet and at least one packet being delivered, $\Psi\left(\left(\theta_i^{\{p\}}(\beta)\right)_{i=1}^{e_p}\right)$ defines the sum of the probability of all the sequences that share the same combination of delivered and undelivered packets until the last delivered packet:

$$\Psi\left(\left(\theta_i^{\{l\}}(\beta)\right)_{i=1}^{e_l}\right) = \begin{cases} \sum_{\Omega} \Pr\left(\left(\Phi_i^{\{l\}}(\beta)\right)_{i=1}^{e_l}\right), & \theta_{e_l}^{\{l\}}(\beta) = 1 \land \exists \theta_i^{\{l\}}(\beta) = 0 \\ \text{Undefined}, & otherwise \end{cases}$$

$$\text{with } \Omega = \left\{\forall \left(\Phi_i^{\{l\}}(\beta)\right)_{i=1}^{e_l} \middle| \left\{\underbrace{\Phi_i = \theta_i \; \forall i \leq j \land (\exists z | \Phi_z \neq \theta_z)}_{\substack{\text{the sequence of } \Phi \text{ is different than } \theta \\ \text{but the first } j \text{ elements are the same}}} \middle| \underbrace{\theta_j^{\{l\}}(\beta) = 0 \land \theta_z^{\{l\}}(\beta) = 1 \; \forall z \in (j, e_l]}_{j \text{ is the last received packet in the sequence}}\right\}\right\} \tag{38}$$

Then, using the law of total probability, the probability of any sequence with the last packet being undelivered, is calculated with (39). When calculating $\Psi\left(\left(\theta_i^{\{p\}}(\beta)\right)_{i=1}^{e_p}\right)$, some of the sequences $\left(\Phi_i^{\{l\}}(\beta)\right)_{i=1}^{e_l}$ will end with delivery and some with no delivery; the first are calculated with (34) and the latter recursively with (39).

$$\Pr\left(\left(\theta_i^{\{l\}}(\beta)\right)_{i=1}^{e_l} |\theta_{e_p}^{\{l\}}(\beta) = 1\right) = \\ = \begin{cases} 1 - \left[\prod_{\left\{\forall\left(\Phi_i^{\{l\}}(\beta)\right)_{i=1}^{e_l} \middle| \exists z | \Phi_z \neq \theta_z\right\}} \Pr\left(\left(\Phi_i^{\{l\}}(\beta)\right)_{i=1}^{e_l}\right)\right], & \theta_i^{\{l\}}(\beta) = 1 \ \forall i \\ \Pr\left(\left(\theta_i^{\{l\}}(\beta)\right)_{i=1}^{j} \middle| \underbrace{\theta_j^{\{l\}}(\beta) = 0 \wedge \theta_z^{\{l\}}(\beta) = 1 \ \forall z \in (j, e_l]}_{j \text{ is the last received packet in the sequence}}\right) - \Psi\left(\left(\theta_i^{\{l\}}(\beta)\right)_{i=1}^{e_l}\right), & otherwise \end{cases} \tag{39}$$

The expected availability is a function of the link availability of the links in L. If removing any of the links involved in the MPEC transmission would mean that the continuity and integrity requirements are no longer met, the availability can be calculated as (24) as without erasure coding. The general equation to calculate the availability is given by (40). All combinations of the links that independently meet the requirements contribute to increasing the availability.

$$A^L = \sum_{\forall\omega \mid \{\omega:\omega\subseteq L | C^{\omega}(E_{\omega})\geq C_{req} \wedge I^{\omega}(E_{\omega})\leq I_{req}\}} \left[\prod_{\forall z\in\omega} \left[Av^{\{z\}}\right] \prod_{\forall y\in L/\omega} \left[1 - Av^{\{y\}}\right]\right] \tag{40}$$

The MPEC RCP performance model presented in this section resembles the Single-Link RCP performance model from Section 4.3. The reason is that both models are based on the same air-ground data link model, RCP metric and traffic characteristics. When used to evaluate the same scenario, they yield different results though, as some of the assumptions made when developing the model are different. Those differences are explained in the next section.

5.4.3. Comparison between “Single-Link” and “MPEC” RCP performance models

The MPEC RCP performance model can be used to calculate the performance of a single link without any redundancy. In that case, the model is used with one link (L={l_1}) and without redundancy (E={e_1} and e_1=k). Ideally, in this situation the MPEC RCP performance model should yield the same results as the “Single-Link” RCP performance model (see Chapter 4). However, different assumptions are made for each model in the probability that the link is in forward state after a failed transmission. In this section, the differences in the assumptions made on each model and the calculation of expected continuity are discussed.

In the Single Link RCP Performance Model, if a retransmission is triggered, the link must have been in drop state and it is unlikely to have been just for one packet. Therefore, the probability that the link is in forward state for the first packet of a retransmission is approximated to the probability of changing from drop to forward states between transmissions in (19). In the MPEC RCP Performance Model, the state of each link is considered independently. If a retransmission is triggered, some links might have transmitted correctly all the forwarded packets, but overall less than k encoded packets are received at the decoder. Thus, a link can be in forward state and have correctly transmitted all the packets. Considering all the cases for each retransmission would add too much complexity to the model, so the probability is approximated by the steady-state probability in (34). Thus, the results for the continuity are affected if the transaction time requirement allows for retransmissions.

The following comparisons are made to explore the extent of the differences. First, a multiple-packet message service is chosen (C2 landing) and the expected continuity with the Direct Wireless Link is calculated with each model. The link’s random delay is modelled using the pessimistic approximation. This choice does not affect the comparison between models. Figure 48 shows that the difference starts being noticeable from the third transmission with the one minus Continuity results being within one order of magnitude.

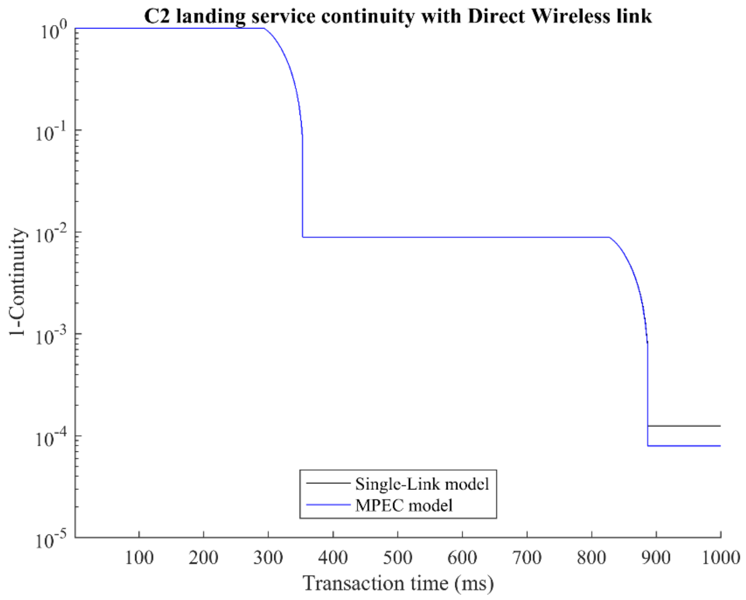

Figure 48: Expected continuity comparison between Single-Link and MPEC RCP performance models.

Then, the impact on the results of the future air-ground data links from Section 4.5 are evaluated. To do so, the results of μ_1 vs μ_0 for the ATC domains are calculated with the MPEC model and overlapped with the Single-Link results (see Figure 49). The difference between the two models is unnoticeable when the probability of changing from drop state to forward state tends to the steady-state probability, as it happens for big values of $\mu_0+\mu_1$ with respect to the retransmission time (i.e. $\mu_0^{\{l\}}+\mu_1^{\{l\}} >> \lambda^{-1}$). The ATC requirements for low values of μ_0 and μ_1 are different depending on the model, but the results are the same for $\mu_1 \geq 3$ in all domains. Future links will likely be in the $\mu_1 \geq 3$ zone, based on the values obtained for the generic link profiles defined in this thesis; the GEO and direct wireless, have μ_1 values of ~2.3 s^{-1} and ~9.8 s^{-1} respectively. The results in the C2 landing service requirements remain the same for the range calculated for the single link.

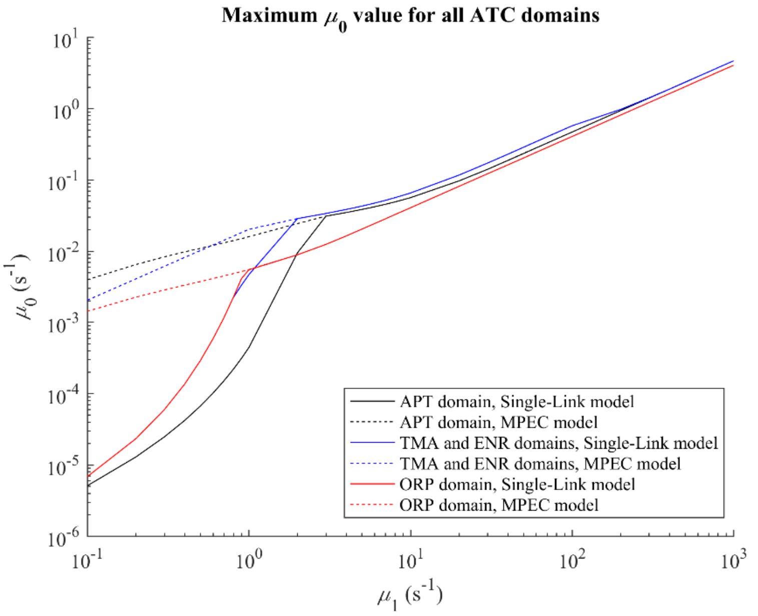

Figure 49: Comparison of the expected maximum μ_0 for the APT domain, calculated with two models

When redundancy is used, only the MPEC model can be used to calculate the expected performance. In that case, the number of encoded packets per link must be chosen. Next section explains how the selection of this parameter is done in this thesis.

5.4.4. Calculating the ECTP with the MPEC RCP model

All the ECTP results in this chapter are calculated using the MPEC model, even in the case of having a single link without redundancy. Adding redundancy to a single link increases the continuity marginally (Figure 50), sending more than *k* encoded packets over a single link is not as efficient as having additional links (Figure 48).

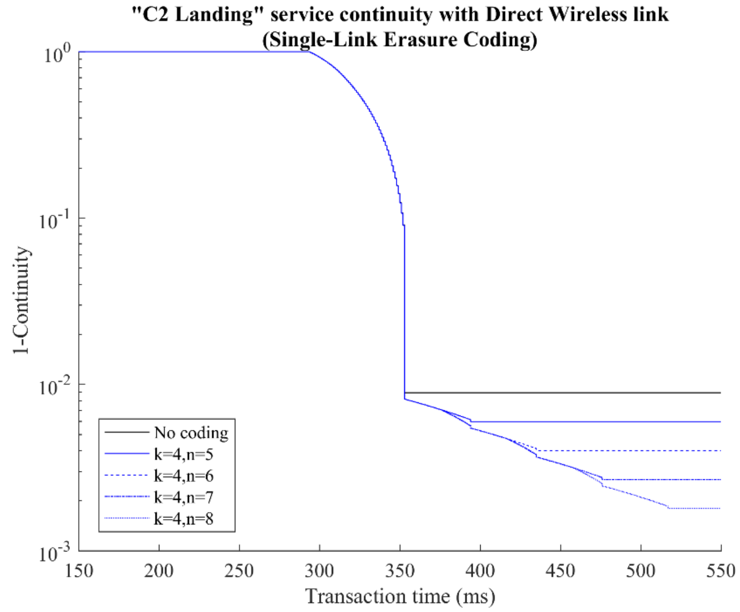

Figure 50: Continuity provided by the direct wireless path to the C2 landing service using erasure coding

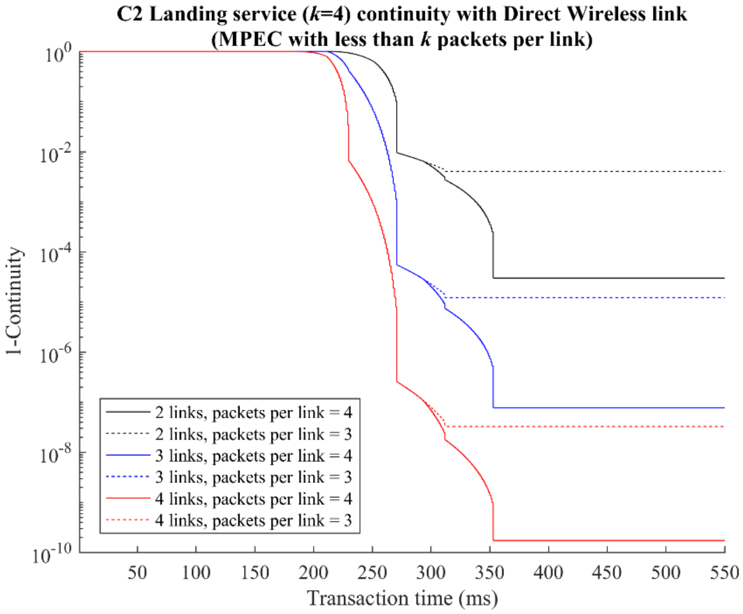

Figure 51: C2 landing MPEC performance with the Direct Wireless link sending less than *k* packets per link

Sending less than *k* packets over every link decreases the continuity, as shown in Figure 51 has an increase of 2-3 orders of magnitude in one minus Continuity. Note that despite sending less than *k* packets per link, the combined number of encoded packets transmitted over the links *n* is bigger than *k*.

The link's random delay to calculate the continuity in Figure 51 is modelled using the pessimistic approximation. This choice does not affect the analysis made in this section.

Thus, when using MPEC to obtain any performance results here forth, if $|L|$ is the number of links, a total of $n=k\cdot|L|$ packets are transmitted, and the coding rate is $|L|^{-1}$. Then, the same rules to determine the retransmission timeout as in the single link case are used (see Section 4.3.3).

The new link requirements for the ATC services obtained using the MPEC model are only calculated for values of $\mu_1 \geq 10$ to be safe and avoid the impact of the model's assumptions as explained in Section 5.4.3. Also, given the expected decoding time being smaller than 1 ms (see Section 5.3.1) and the encoding operation being even simpler, the sum of encoding and decoding time is negligible ($\varepsilon = 0$).

Finally, the decoder must know how the encoding operation is performed to carry out the decoding operation. Given that no choice is made on the code, how this is done cannot be specified. An assumption is made that no additional overhead is required. An example on how to achieve this is using linear network coding with pre-set coefficients. The encoder must tag the packet with the encoding generation number and the number of the encoded packet. The 8-bit DSCP field in the IPv6 header could be used to carry this information.

The results calculating the performance of the model are compared with the results obtained from an emulator in the next section.

5.4.5. Emulation test

The objective of this section is to compare the expected continuity obtained using emulation and the MPEC RCP performance model from Section 5.4.2. A test has been performed with the emulator (see Section 4.3.5) to compare the expected performance with measurements taken with IPv6 traffic, as with the test with the single link. The emulation test service has the following properties: k=3, b=1000 bytes. Two independent Direct Wireless links (see Table 15) are used. Also, two encoded packets are sent over each link, so that $L=\{l_1, l_2\}$ and $E=\{e_1,e_2\}$ with e_1=2 and e_2=2.

The actual continuity's CDF measured in with the emulator is plotted in Figure 52 as "ACDF" with the curves of the expected performance using the different random delay approximations from Section 3.2.4. Visually, all the curves share the same shape with small discrepancies, like the optimistic approximation being separated from the actual continuity for values between 0.4 and 0.9.

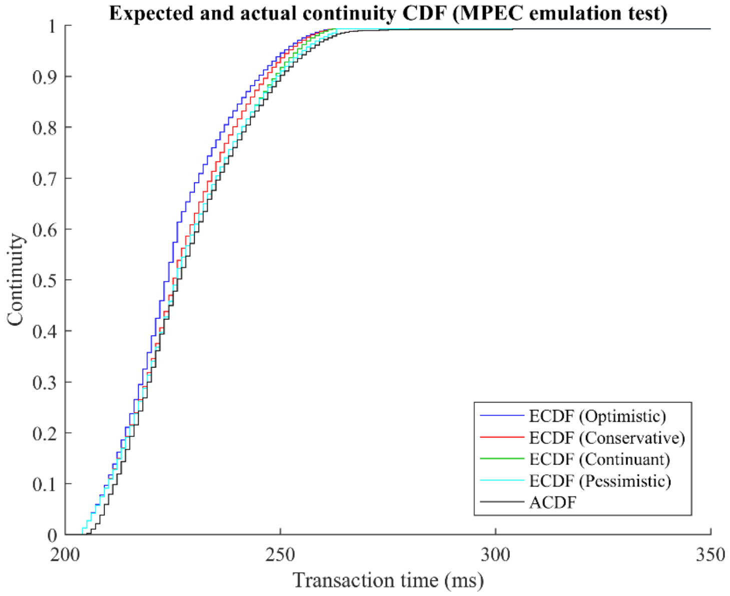

Figure 52: MPEC emulation test CDF

The absolute difference between expected and actual continuity is shown in Figure 53. The optimistic approximation has errors up to ~0.11 points. All other approximations are within ~0.04. The relative difference is show in Figure 54. Values of continuity lower than 0.1 are not shown in the zoom in the relevant part. All the continuity requirements are always expressed for values higher or equal to 0.95, so high relative errors for small continuity values are irrelevant. For high continuity values (≥0.95), the difference falls within 3% for all approximations. The maximum value of continuity before any retransmission of 0.1% for all the approximations.

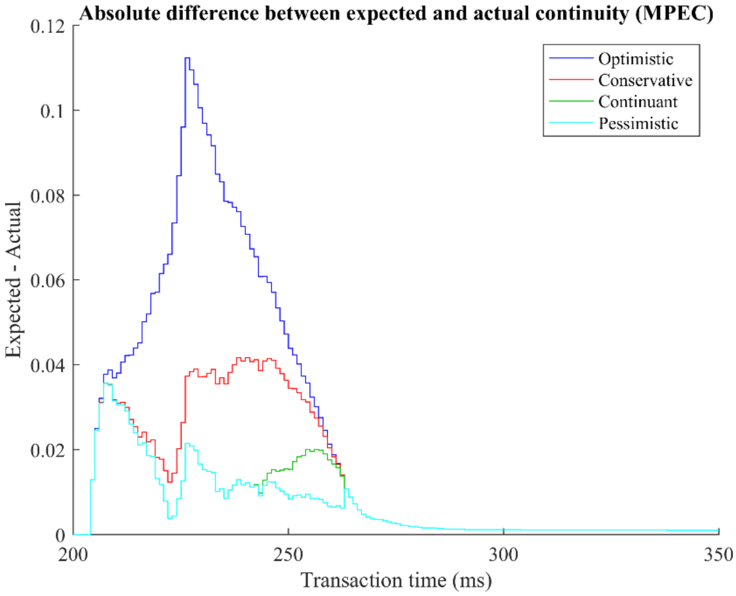

Figure 53: Absolute difference between expected continuity and actual continuity for all approximations (MPEC)

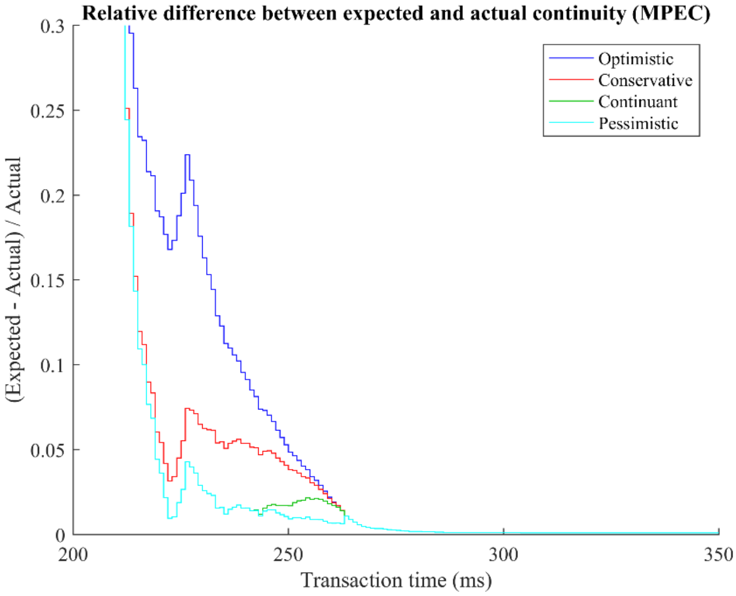

Figure 54: Relative difference between expected continuity and actual continuity for all approximations (MPEC)

These results indicate that MPEC RCP Performance Model proposed in Section 5.4.2 to obtain the expected continuity match closely high continuity values measured with the emulator. However, the results also indicate that the expected continuity is higher than the actual continuity measured with the emulator regardless of the approximation or continuity. The same comparison is repeated in the next section using a simulator instead of an emulator.

5.4.6. Simulation test

The objective of this section is to compare the expected continuity obtained using simulation and the MPEC RCP performance model from Section 5.4.2. The results obtained with the model are compared to those measured using the simulator (see Section 4.3.6) to compare the expected performance obtained with calculation and simulation. This test follows the same setup as the emulation test from Section 5.4.5. The simulation test service has the following properties: k=3, b=1000 bytes. Two independent Direct Wireless links (see Table 15) are used. Two encoded packets are sent over each link, so that $L=\{l_1, l_2\}$ and $E=\{e_1,e_2\}$ with e_1=2 and e_2=2.

The curves for the actual continuity measured with the simulator depend on the approximation used to simulate the air-ground data link (see Section 3.2.4). The results show the difference between the simulation and model results. For all the approximations, the absolute difference in the continuity results is in the 10^{-4} order of magnitude (see Figure 55), which in relative values is ±0.03% (see Figure 56).

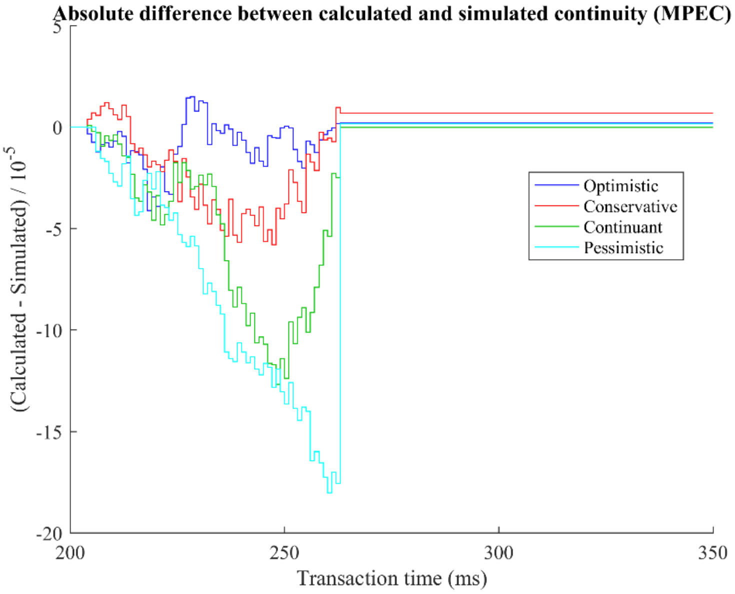

Figure 55: Absolute difference between calculated and simulated continuities with MPEC

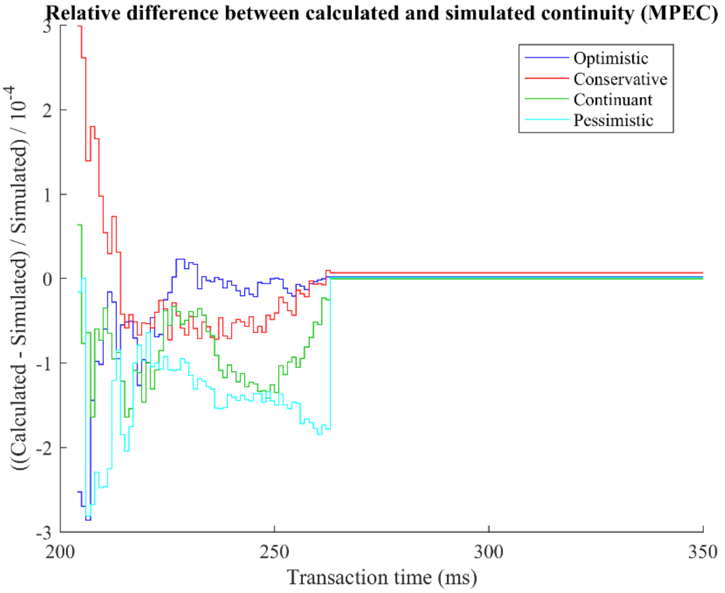

Figure 56: Relative difference between calculated and simulated continuities with MPEC

The difference between the simulated and calculated results is very small, giving confidence in the results calculated with the MPEC RCP model from Section 5.4.2. When comparing the performance of MPEC with other techniques, they must be implemented in a simulation or emulation environment. In the next section, the MPEC model is adapted to be usable to calculate the performance with Packet Repetition.

5.4.7. Using the MPEC RCP model for Packet Repetition

The MPEC RCP model can be easily adapted to calculate the performance of Packet Repetition. The probability of receiving a packet K^L is redefined with (41). All other equations from the model in Section 5.4.2 can be reused.

$$K^L(T,\lambda,\delta,k) \underbrace{=}_{\beta=T-\delta\cdot\lambda} \sum_{\forall\Omega|\Omega=\left\{\left(\theta_i^{\{l\}}(T)\right)_{i=1}^{k}\ \forall l\epsilon L \middle| \forall i\ \exists l|\theta_i^{\{l\}}(T)=0\right\}} \prod_{\forall l\epsilon L} \Pr\left(\left(\theta_i^{\{l\}}(\beta)\right)_{i=1}^{k}\right) \tag{41}$$

The values of one minus continuity for the C2 landing service case from simulating Packet Repetition in Figure 46 are calculated using the model and shown in Figure 57. The model allows for a quick calculation of the results for more links. The results from the calculation show the same increase in continuity and the same minimum transaction single link (294 ms). Note that the steep step in Figure 57 is due to the link’s random delay pessimistic approximation, but the value once the continuity (and thus of 1-C) stagnates is the same regardless of the approximation.

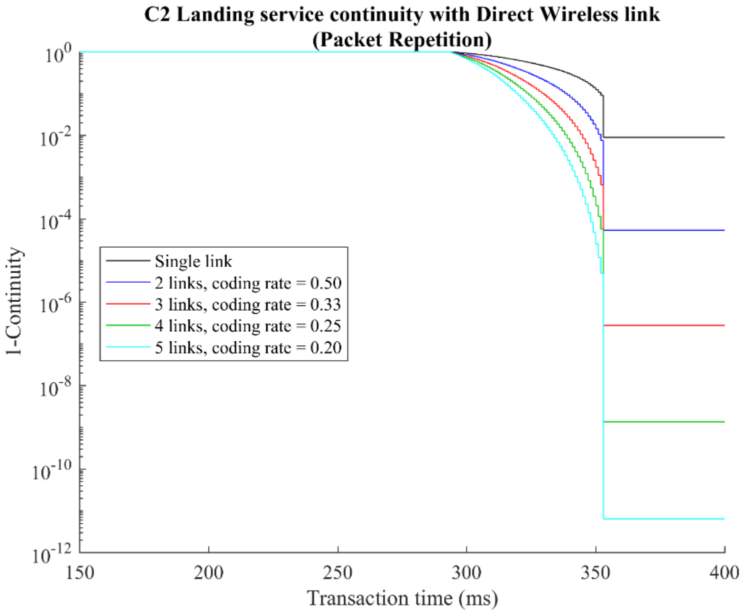

Figure 57: Continuity of the C2 landing service provided by Packet Repetition over multiple Direct Wireless links

With the model well defined, the next step is calculating the performance provided by the air-ground data links. The expected performance of multiple generic links is discussed in the next section.

5.5. MPEC performance with multiple generic links

5.5.1. ATC services requirements

The continuity and transaction time requirements of the ATC services are met with the Direct Wireless link wherever it is available (Section 4.4.1). The performance cannot be met with neither the GEO

SatCom link nor LEO SatCom link (Section 4.4.1). If multiple independent links with the same values for all parameters would be available, the continuity improves.

Assuming multiple independent GEO and LEO SatCom links, the minimum number of links needed to meet the requirements are calculated and given in Table 27 and Table 28 respectively. The results show that it is impossible to meet all the requirements with those links regardless of the number of links. However, the requirements of most services are met with two or three independent links.

5.5.2. C2 landing service

The requirements of the C2 landing service cannot be met with any of the generic links, regardless of their number. Even with the best performing link, the Direct Wireless link, the minimum transaction achievable is 171 ms, above the 160 ms requirement. However, in this section the number of links needed to achieve the continuity requirement is investigated.

Having at least four links, the lowest transaction time value is reduced from 294 ms to 171 ms, that is, the minimum latency of the link when transmitting one packet. The calculated continuity results shown in Figure 58 as one minus Continuity, indicate that the expected continuity with five links is in the required order ($C \geq 0.9999999999$ or $1-C \leq 10^{-10}$) without need of retransmissions. This value is achieved for a transaction time of 308 ms. Should the link have lower latency, the transaction time requirement might be met. The link's random delay to calculate the continuity in Figure 58 is modelled using the pessimistic approximation. The first transaction time to reach $1-C <= 10^{-10}$ with using the optimistic approximation is only 2 ms lower. The minimum transaction time achievable is 171 ms regardless of the approximation.

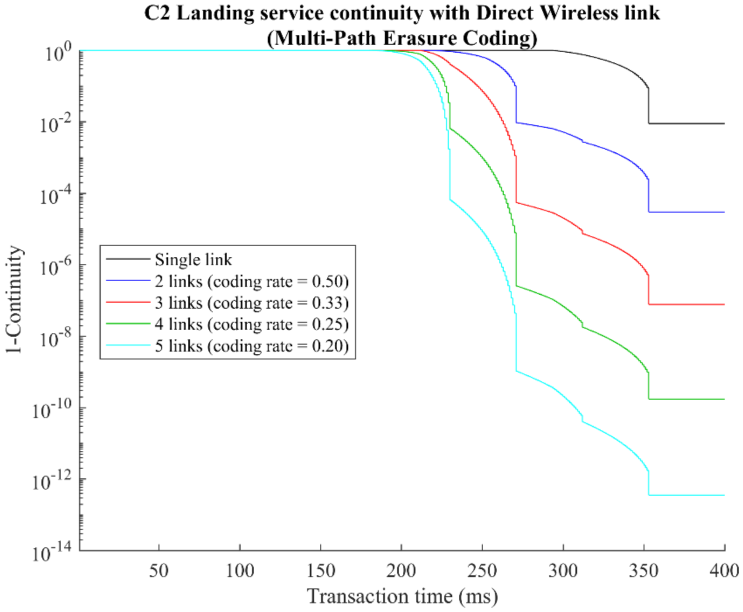

Figure 58: Continuity of the C2 landing service provided by MPEC over multiple Direct Wireless links

If instead of using the generic links, new links are designed, the MPEC model can be used to derive the minimum link parameters' values. The next section presents a method to calculate them and then it is applied for both the ATC and C2 landing services.

5.6. Future air-ground data link requirements with MPEC

5.6.1. Methodology

The objective of the work presented in this section is to reduce the individual link bit rate, delay and loss requirements obtained in the single-link case (see Section 4.5). To achieve the reduction, MPEC is used. Two methods are proposed to reduce the requirements. They are not unique, several other trade-offs are possible, but these two are focused on the strictest values obtained for a single link.

Method one consists in keeping the same bit rate and delay requirements as for the single link and use MPEC to lower the loss requirements. The overall bit rate requirement is increased but it is shared by all the links, leaving the individual link's bit rate requirement the same. The procedure is the same as explained in Section 4.5.1 but the loss requirements are calculated with multiple links.

Method two consists in fixing the bit rate to the highest requirements and relaxing the constant plus random delay requirement. In addition to fixing a higher maximum value, a second value to meet 95% is given. The loss requirements are recalculated using the procedure explained in Section 4.5.1, and given enough links, they are also reduced when compared to the single link case. With 95% cumulative probability, the smallest transaction time requirement in the domain. The maximum value is the smallest transaction time with a continuity requirement higher than 95% (T_C) in the domain. Given the bit rate requirements, 10 ms of margin are left for the packets to be transmitted. These requirements are expressed with the following conditions:

$$\begin{cases} \Pr(c + r \leq \min(T) - 10ms) = 0.95 \\ \Pr(c + r \leq \min(T_C) - 10ms) = 1 \end{cases} \tag{42}$$

Regardless of the method, when multiple links are required to increase the continuity, the availability *A* (RCP parameter) does not correspond to the link availability parameter *Av* of each link. As explained in Section 5.2.4, if all the links are required the availability decreases as per (24). Given that with both methods the multiple links considered have the same values for all parameters, the link availability requirements for the are listed in in Table 19. The requirements are driven from the highest requirement, 99.995% availability for the SURV service.

Number of links	Link Availability requirement (ATC services)	Link Availability requirement (C2 landing)
1	99.99500 %	99.99950 %
2	99.99750 %	99.99975 %
3	99.99833 %	99.99983 %
4	99.99875 %	99.99988 %
5	99.99900 %	99.99990 %
6	99.99917 %	99.99992 %

Table 19: Link availability requirements per link using MPEC

The performance requirements of the links are calculated for up to six independent links. In the foreseeable future it is unlikely that more than three independent links are deployed, but the results are obtained to show the performance improvement if such a link combination would be deployed. To meet the RCP requirements, each link must meet (or exceed) the delay and loss required values obtained in the results. The links do not necessarily have to use the same technology.

In the next section, method one is used to reduce the loss parameter requirements of each link with respect to the results of Section 4.4, when multiple links are used.

5.6.2. Reducing the loss requirements (method one)

The requirements obtained using method one have the same values of bit rate, constant and random delay requirements as the single link. The change is a reduction of the loss requirements. The new values have been calculated for up to six simultaneous independent links. The results show that as for the single link, the TMA and ENR requirements are the same.

The ATC requirements are obtained for the APT domain (Figure 59), the TMA and ENR domains (Figure 60) and the ORP domain (Figure 61). The results show that the average packet loss ratio required is one order of magnitude higher with only one additional link and that it can be as high as 0.5 with five or six links, depending on the domain.

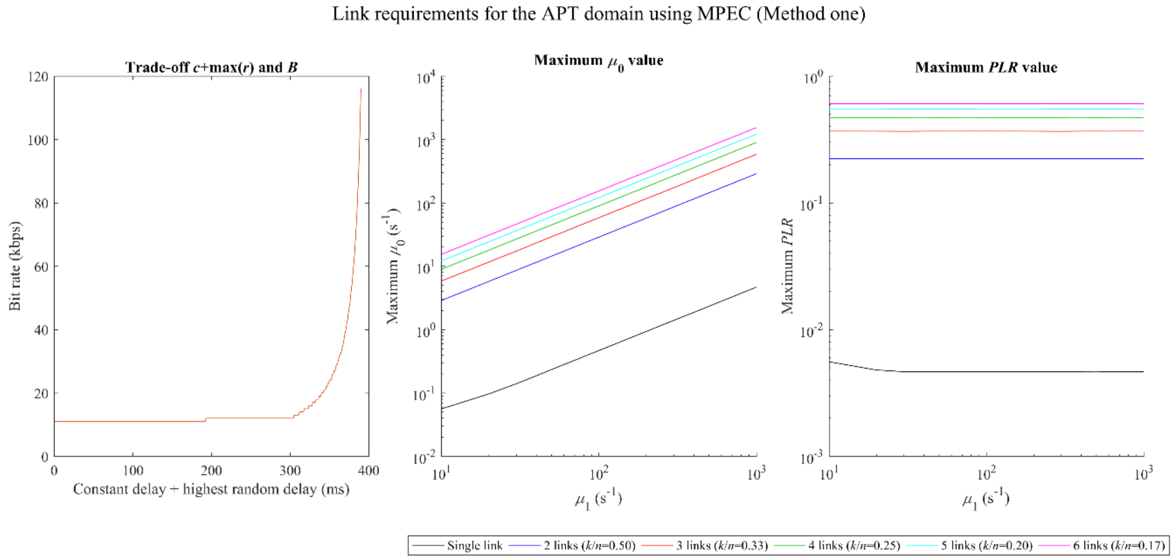

Figure 59: Link requirements for the APT domain ATC requirements using MPEC (method one)

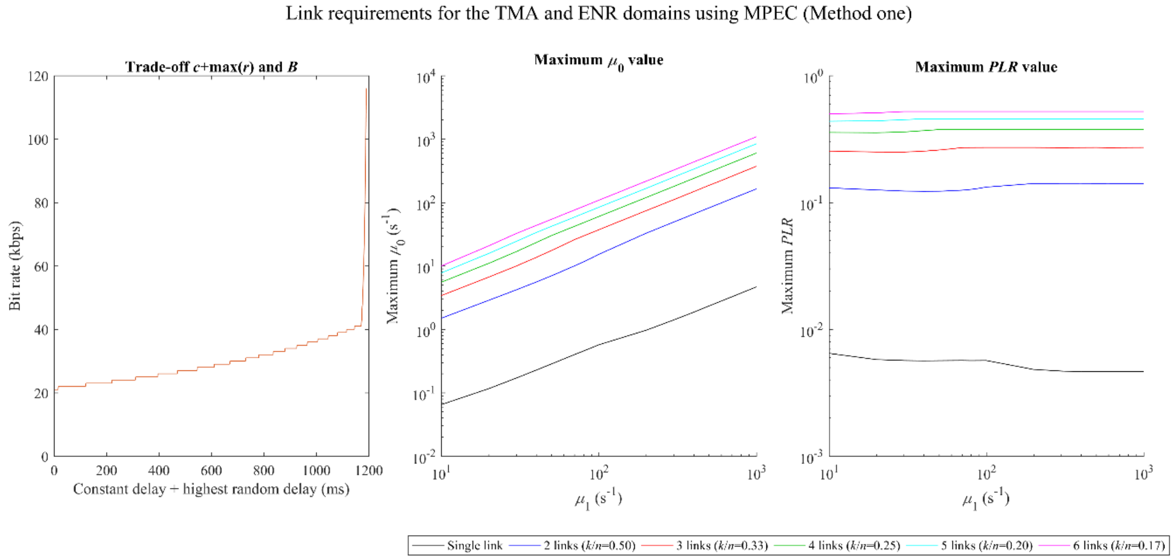

Figure 60: Link requirements for the TMA and ENR domains ATC requirements using MPEC (method one)

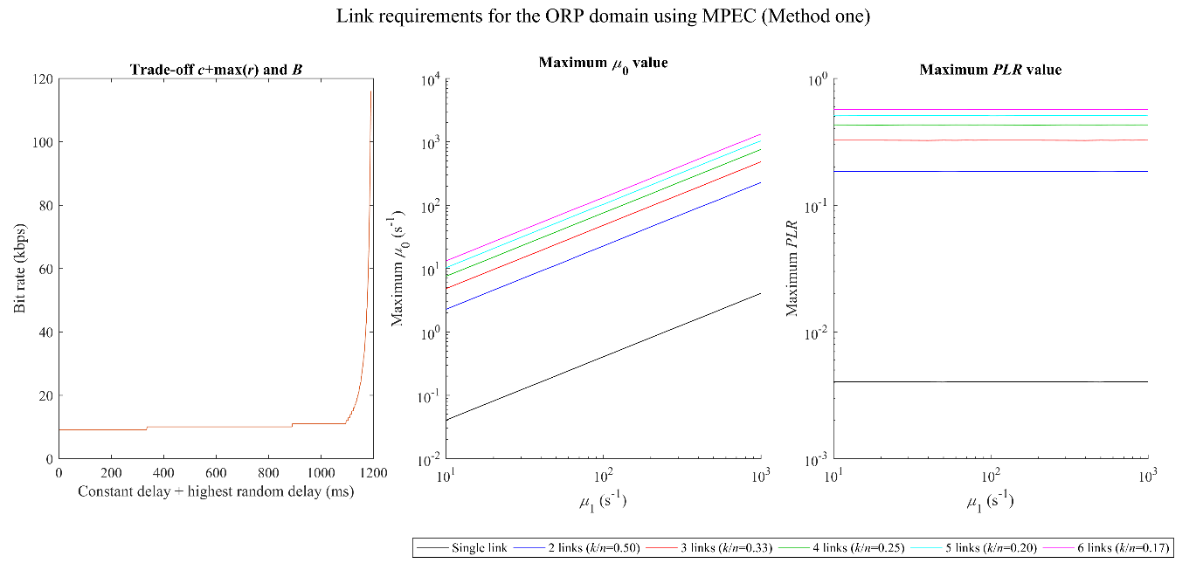

Figure 61: Link requirements for the ORP domain ATC requirements using MPEC (method one)

The C2 landing service requirements results (Figure 62) show a reduction of the loss requirements of several orders of magnitude. Adding one link reduces the *PLR* to the ~10^{-5} order. With five or more links, easily attainable values of *PLR* in the ~10^{-2} order are required.

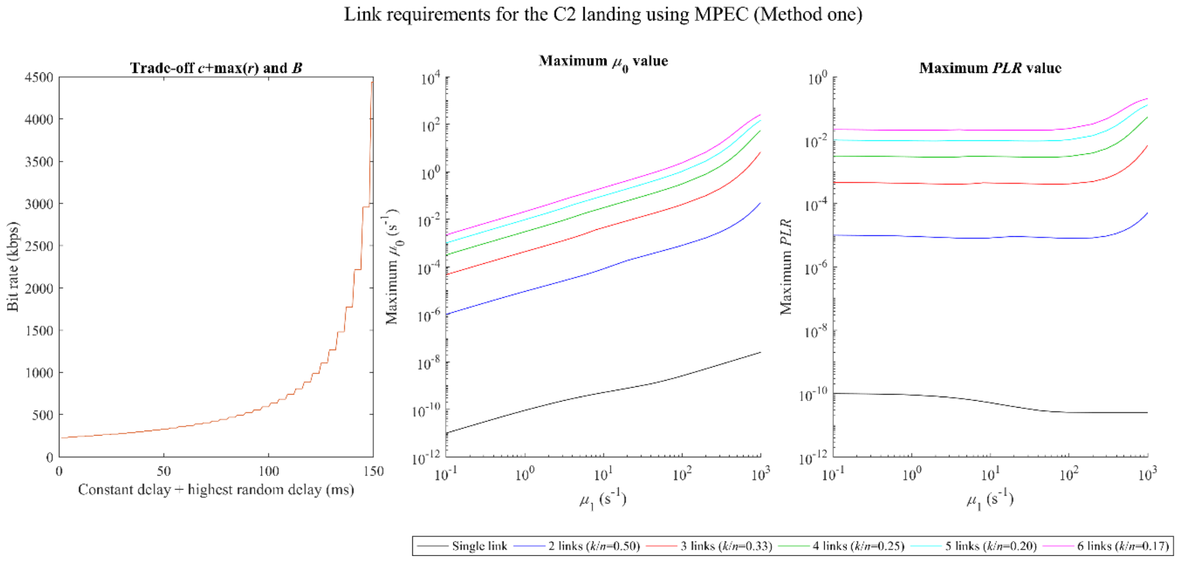

Figure 62: Link requirements for the C2 landing service requirements using MPEC (method one)

The loss parameters values obtained with this method satisfy the requirements for the multiple combinations of *B*, *c* and *r* shown in the trade-off curves of each domain. In Section 4.5.2, it is shown that when fixing the bit rate and delay requirements the loss requirements change as they only apply to that combination. The *PLR* vs μ_1 requirements are recalculated fixing B = 116 kbps and c+max(r) to the highest value for the APT domain (390 ms) in Figure 63, TMA and ENR domains (1190 ms) in Figure 64 and ORP domain (1190 ms) in Figure 65. The same procedure is done for the C2 landing service with B = 4432 kbps and c+max(r) = 150 ms in Figure 66. The figures show that for the given μ_1 range, the values of *PLR* for the ATC services are only affected in the single-link calculations. The C2 landing service calculation of the PLR is also affected for multiple links albeit only slightly, with values changing to the next test value.

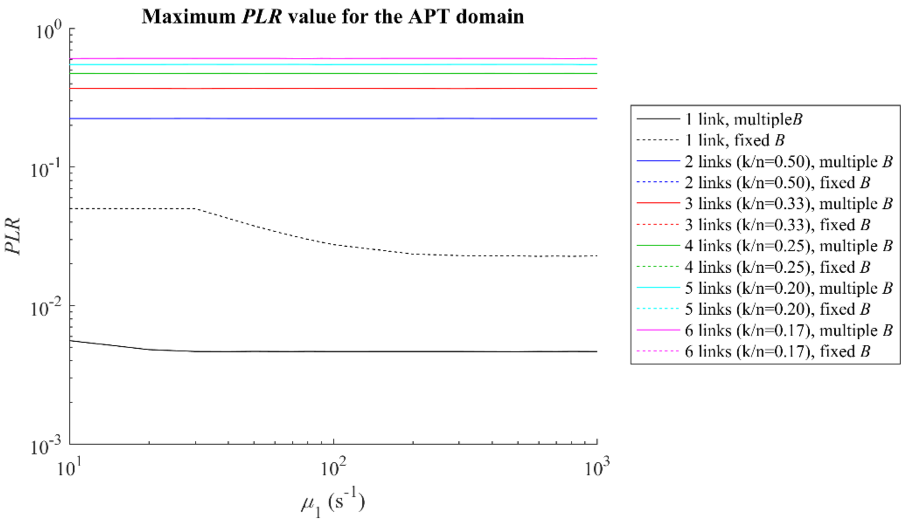

Figure 63: Maximum *PLR* to meet the requirements of APT domain for a range of *B* and for a fixed *B*

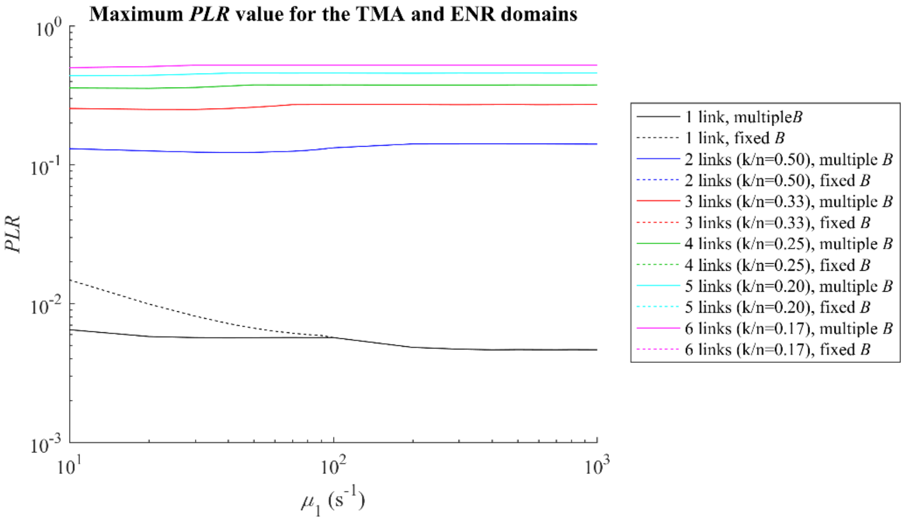

Figure 64: Maximum *PLR* to meet the requirements of TMA and ENR domains for a range of *B* and for a fixed *B*

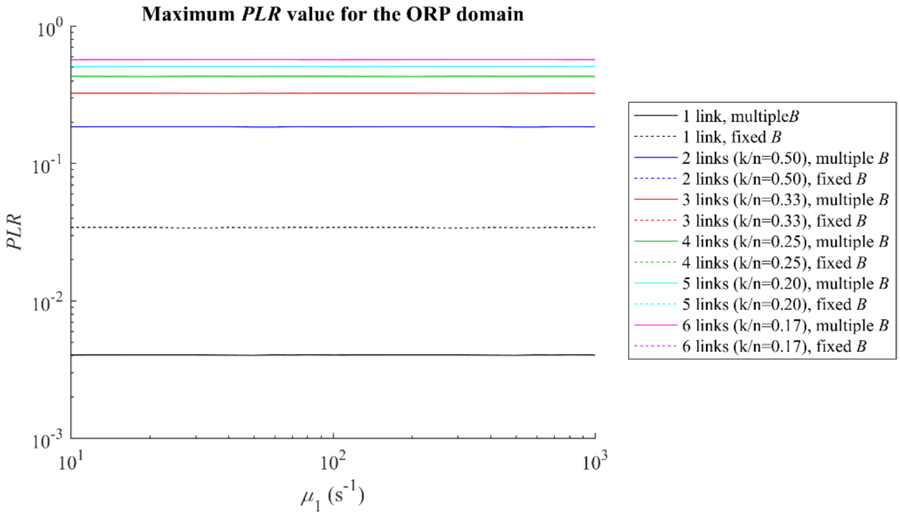

Figure 65: Maximum *PLR* to meet the requirements of ORP domain for a range of *B* and for a fixed *B*

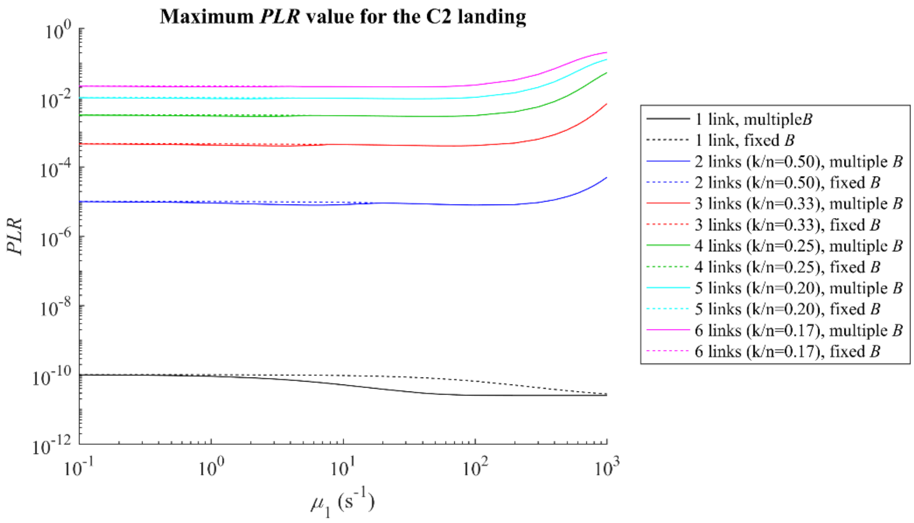

Figure 66: Maximum *PLR* to meet the requirements of C2 landing service for a range of *B* and for a fixed *B*

In the next section, method two is used to reduce the delay and loss parameters requirements of each link with respect to the results of Section 4.4, when multiple links are used. The loss requirements are not reduced as much as with method one.

5.6.3. Reducing the delay and loss requirements (method two)

The requirements using method two are given for the maximum bit rate obtained with the single link, *B*=116 kbps. The requirements for the sum of constant and random delay change as described in the methodology and are collected for each domain in Table 20. The loss requirements also change with this method. Since the requirements of the C2 landing service only state one continuity value, this method is not applied to it. As in the previous analysis, the results show that the TMA and ENR requirements are the same.

Domain	**min($T_{95\%}$)**	**min(T_C)**	**min(T)-10ms** **with Pr($c+r \leq$ min(T)-10ms) = 0.95**	**min(T_C) -10ms** with Pr($c+r \leq$ min(T_C)-10ms) = 1
APT	400 ms	3200 ms	390 ms	3190 ms
TMA	1200 ms	5000 ms	1190 ms	4990 ms
ENR	1200 ms	5000 ms	1190 ms	4990 ms
ORP	1200 ms	8000 ms	1190 ms	7990 ms

Table 20: Values of *c* and *r* multiple domains

The ATC requirements are obtained for the APT domain (Figure 67), the TMA and ENR domains (Figure 68) and the ORP domain (Figure 69). The requirements cannot be met with less than three links. With three links, the packet loss ratio required is above 10^{-2} and the value further decreases as more links are used. Those values are less strict than the single link requirements.

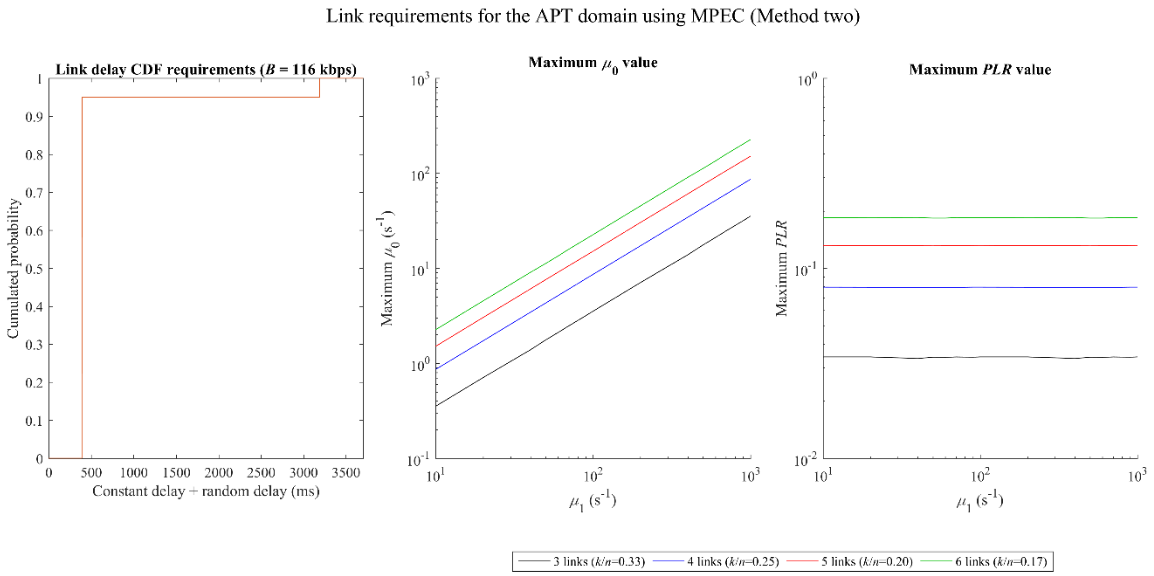

Figure 67: Link requirements for the APT domain ATC requirements using MPEC (method two)

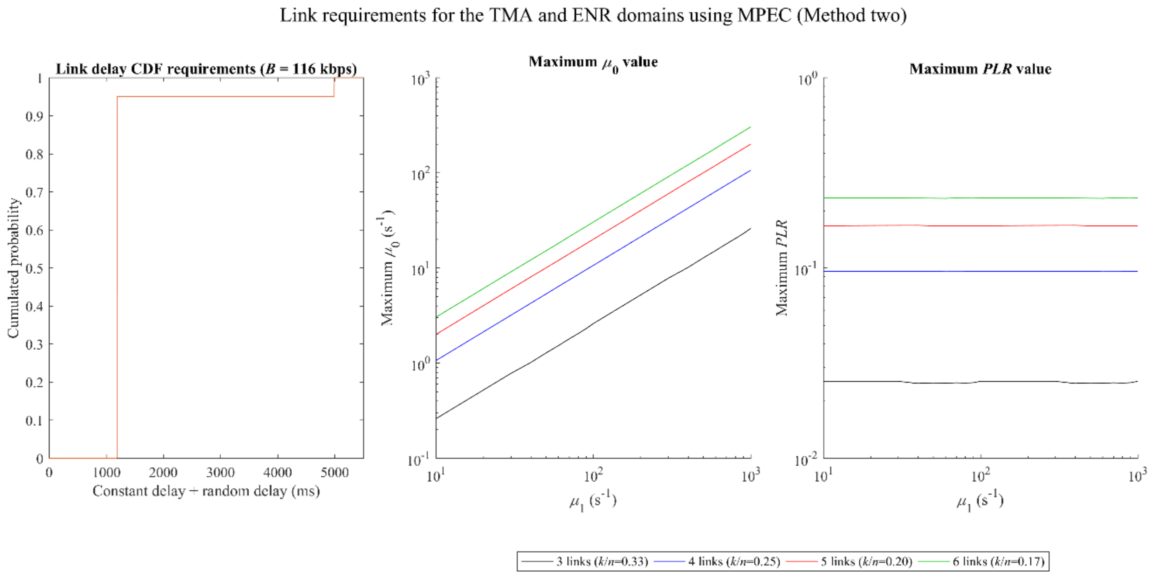

Figure 68: Link requirements for the TMA and ENR domains ATC requirements using MPEC (method two)

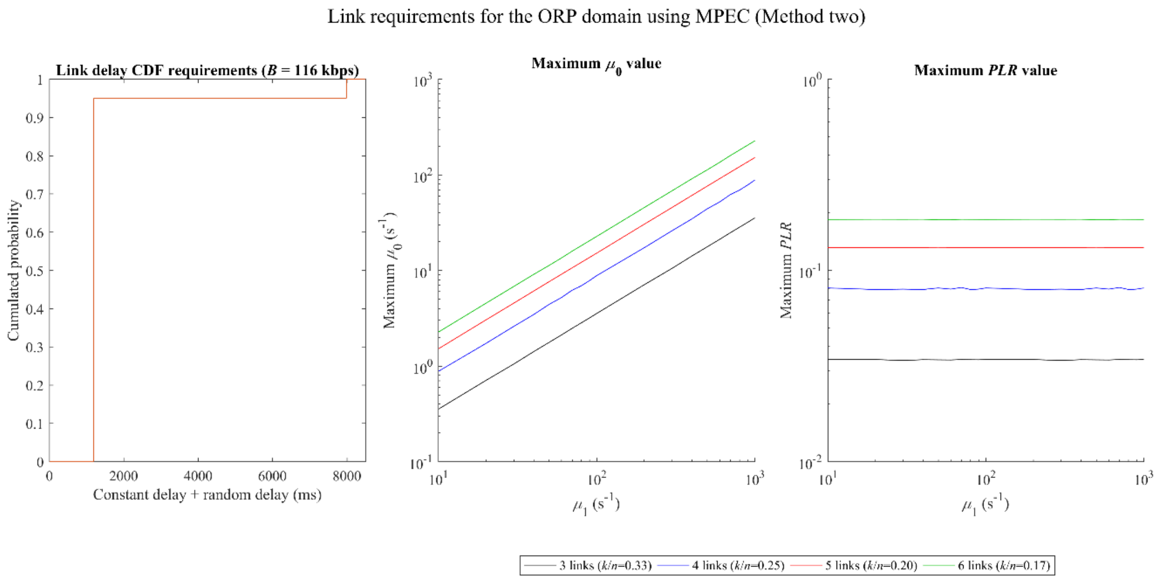

Figure 69: Link requirements for the ORP domain ATC requirements using MPEC (method two)

If air-ground data links with the performance described in this section and the previous (method one) are deployed, the RCP requirements are met. However, not all services require using all links to reach the required performance level. The number of links needed for each service is calculated in the next section.

5.6.4. Number of links required per service

When dimensioning a single link to meet all the requirements, the parameters' values are driven by the strictest services. The same is applicable for the MPEC case, with a small distinction. Even though a given number of links must be available to meet the requirements of all the services, some services don't need to use all of them. Whereas the usage of the links with MPEC depends on the expected performance and this on the link parameters' values, in the Single-Link case all services use the link under the same conditions. Given that it is unfeasible to produce the data for every combination of values of the link characteristics, the number of links required for each service are obtained for some values.

Table 21 shows the minimum number of links needed to meet the requirements of each service for a given set of link parameters' values. The values of bit rate, constant and random delay are chosen from the results in Section 5.6.2. For the loss, three values of *PLR* are chosen: 1%, 5% and 10%. The chosen values are high because the packets incurring a constant plus random delay higher than the value of *c*+*r* provided in the table are considered lost.

ATC service	**APT domain** ***B*=116 kbps** ***c*+*r* = 390 ms** **μ_1=10 s^{-1}**			**TMA domain** ***B*=116 kbps** ***c*+*r* = 1190 ms** **μ_1=10 s^{-1}**			**ENR domain** ***B*=116 kbps** ***c*+*r* = 1190 ms** **μ_1=10 s^{-1}**			**ORP domain** ***B*=116 kbps** ***c*+*r* = 1190 ms** **μ_1=10 s^{-1}**		
PLR →	1%	5%	10%	1%	5%	10%	1%	5%	10%	1%	5%	10%
ACL	1	1	1	1	2	2	1	2	2	1	1	1
ACM	1	1	1	1	2	2	1	2	2	1	1	1
AMC	1	1	1	1	1	1	1	1	1	N/A	N/A	N/A
ARMAND	N/A	N/A	N/A	N/A	N/A	N/A	1	1	1	N/A	N/A	N/A
C&P ACL	N/A	N/A	N/A	1	2	2	1	2	2	1	1	1
COTRAC (int.)	N/A	N/A	N/A	1	2	2	1	2	2	1	1	2
COTRAC (wil.)	N/A	N/A	N/A	1	2	2	1	2	2	1	1	1

ATC service	**APT domain** ***B*=116 kbps** **c+r = 390 ms** **μ_1=10 s^{-1}**			**TMA domain** ***B*=116 kbps** **c+r = 1190 ms** **μ_1=10 s^{-1}**			**ENR domain** ***B*=116 kbps** **c+r = 1190 ms** **μ_1=10 s^{-1}**			**ORP domain** ***B*=116 kbps** **c+r = 1190 ms** **μ_1=10 s^{-1}**		
D-ALERT	1	1	1	1	1	2	1	1	2	1	1	1
D-ATIS (arr)	1	1	1	1	2	2	1	2	2	1	1	1
D-ATIS (dep)	1	1	1	1	2	2	1	2	2	1	1	1
DCL	1	1	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
D-FLUP	1	1	1	1	2	2	1	1	1	1	1	1
DLL	1	1	1	1	1	2	1	1	1	1	1	1
D-ORIS	N/A	N/A	N/A	1	2	2	1	2	2	1	1	1
D-OTIS	1	1	2	1	2	2	1	2	2	1	1	1
D-RVR	1	1	1	1	2	2	1	2	2	1	1	1
DSC	N/A	N/A	N/A	N/A	N/A	N/A	1	1	1	1	1	1
D-SIG	1	1	1	1	1	2	N/A	N/A	N/A	N/A	N/A	N/A
D-SIGMENT	1	1	1	1	2	2	1	2	2	1	1	1
D-TAXI	1	1	1	1	2	2	N/A	N/A	N/A	N/A	N/A	N/A
DYNAV	N/A	N/A	N/A	N/A	N/A	N/A	1	1	1	1	1	1
FLIPCY	1	1	1	1	1	2	1	1	2	1	1	1
FLIPINT	1	1	1	1	2	2	1	2	2	1	1	1
ITP ACL	N/A	N/A	N/A	1	2	2	1	2	2	1	1	1
M&S ACL	N/A	N/A	N/A	1	2	2	1	2	2	1	1	1
PAIRAPP ACL	N/A	N/A	N/A	1	2	2	N/A	N/A	N/A	N/A	N/A	N/A
PPD	1	1	1	1	1	1	1	1	1	1	1	1
SAP (Setup)	N/A	N/A	N/A	1	2	2	1	2	2	N/A	N/A	N/A
SAP (Report)	N/A	N/A	N/A	1	1	2	1	1	2	N/A	N/A	N/A
SURV (ATC)	1	1	2	1	2	2	1	2	2	1	2	2
URCO	1	1	1	1	1	2	1	1	2	1	1	1
WAKE	1	1	2	1	1	2	1	1	2	N/A	N/A	N/A

Table 21: Number of links needed for each ATC service to meet the domain requirements

The same procedure is repeated with the constant and random delay requirements relaxed, as obtained using MPEC with method 2 (see Section 5.6.3). The number of links for each service are listed in Table 22.

ATC service	**APT domain** ***B*=116 kbps** **Pr(c+r = 0.39 s) = 0.95** **Pr(c+r = 3.19 s) = 0.05** **μ_1=10 s^{-1}**			**TMA domain** ***B*=116 kbps** **Pr(c+r = 1.19 s) = 0.95** **Pr(c+r = 4.99 s) = 0.05** **μ_1=10 s^{-1}**			**ENR domain** ***B*=116 kbps** **Pr(c+r = 1.19 s) = 0.95** **Pr(c+r = 4.99 s) = 0.05** **μ_1=10 s^{-1}**			**ORP domain** ***B*=116 kbps** **Pr(c+r = 1.19 s) = 0.95** **Pr(c+r = 7.99 s) = 0.05** **μ_1=10 s^{-1}**		
PLR →	1%	5%	10%	1%	5%	10%	1%	5%	10%	1%	5%	10%
ACL	2	3	4	3	4	4	3	4	4	2	3	4
ACM	2	3	4	3	4	5	3	4	5	2	3	4
AMC	1	2	2	2	2	3	2	2	3	N/A	N/A	N/A
ARMAND	N/A	N/A	N/A	N/A	N/A	N/A	2	2	2	N/A	N/A	N/A
C&P ACL	N/A	N/A	N/A	2	3	4	2	3	4	2	3	4

ATC service	**APT domain** **B=116 kbps** **Pr(c+r = 0.39 s) = 0.95** **Pr(c+r = 3.19 s) = 0.05** **μ_1=10 s^{-1}**			**TMA domain** **B=116 kbps** **Pr(c+r = 1.19 s) = 0.95** **Pr(c+r = 4.99 s) = 0.05** **μ_1=10 s^{-1}**			**ENR domain** **B=116 kbps** **Pr(c+r = 1.19 s) = 0.95** **Pr(c+r = 4.99 s) = 0.05** **μ_1=10 s^{-1}**			**ORP domain** **B=116 kbps** **Pr(c+r = 1.19 s) = 0.95** **Pr(c+r = 7.99 s) = 0.05** **μ_1=10 s^{-1}**		
COTRAC (int.)	N/A	N/A	N/A	2	3	3	2	3	3	2	3	3
COTRAC (wil.)	N/A	N/A	N/A	2	3	4	2	3	4	2	3	4
D-ALERT	2	2	2	2	3	4	2	3	4	2	3	4
D-ATIS (arr)	2	3	3	2	3	3	2	3	3	1	2	2
D-ATIS (dep)	2	2	2	2	2	3	2	2	3	1	2	2
DCL	1	1	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
D-FLUP	2	3	3	2	3	3	2	3	3	1	2	2
DLL	2	2	2	2	3	4	2	2	2	2	2	2
D-ORIS	N/A	N/A	N/A	3	3	3	3	3	3	2	2	2
D-OTIS	3	3	3	3	3	3	3	3	3	2	2	2
D-RVR	2	2	3	3	4	4	2	2	3	1	2	2
DSC	N/A	N/A	N/A	N/A	N/A	N/A	1	2	2	2	2	3
D-SIG	1	2	2	2	3	3	N/A	N/A	N/A	N/A	N/A	N/A
D-SIGMENT	2	2	3	2	2	3	2	2	3	1	2	2
D-TAXI	2	2	3	2	3	4	N/A	N/A	N/A	N/A	N/A	N/A
DYNAV	N/A	N/A	N/A	N/A	N/A	N/A	2	2	2	1	2	2
FLIPCY	2	2	2	2	3	4	2	3	4	2	3	4
FLIPINT	2	2	3	2	3	4	2	3	4	2	3	4
ITP ACL	N/A	N/A	N/A	2	3	4	2	3	4	2	3	4
M&S ACL	N/A	N/A	N/A	2	3	4	2	3	4	2	3	4
PAIRAPP ACL	N/A	N/A	N/A	2	3	4	N/A	N/A	N/A	N/A	N/A	N/A
PPD	1	1	2	2	2	2	2	2	2	1	2	2
SAP (Setup)	N/A	N/A	N/A	2	3	4	2	3	4	N/A	N/A	N/A
SAP (Report)	N/A	N/A	N/A	2	3	4	2	3	4	N/A	N/A	N/A
SURV (ATC)	3	4	5	3	4	5	3	4	5	3	4	5
URCO	2	2	2	2	3	4	2	3	4	2	3	4
WAKE	2	3	4	2	3	4	2	3	4	N/A	N/A	N/A

Table 22: Number of links needed for each ATC service to meet the domain requirements with higher latency links

5.7. Analysis of the results

In this section, the results obtained in this chapter from applying MPEC to increase the continuity are discussed. First, the extent of the drawbacks is revised. Then, the performance results of the generic air-ground data links described in Section 3.4 using MPEC is analysed. To close, the relaxation of link requirements when using MPEC with newly designed links is discussed.

Using MPEC to increase the continuity causes an increase of the link availability requirements. Current air-ground data links certified for ATC communications advertise an availability of 99.99%. The strictest availability requirement for the future ATC data-centric communications is 99.995%, just one order of magnitude away from the current technology. The required availability using MPEC increases but for ATC communications it is within the one order of magnitude (that is, smaller or equal to 99.999%) for five or less links.

The SatCom links does not meet the requirements for any ATC domain. In the ORP domain, where the Direct Wireless link is unavailable, MPEC could be used to meet the requirements for some services but not all. The issue with the GEO SatCom link is the random delay; to being able to use the link even with MPEC, an increase of performance would be required as discussed in the analysis of the single-link results (Section 4.6). The LEO SatCom bit rate is too low to meet the requirements. The next generation of Low-Earth Orbit communication satellites is Iridium Certus and it is expected to be a high-bit rate link. If the requirements are not met straight up, the use of MPEC could be considered.

With the generic link profiles and MPEC, the C2 landing service requirements are unreachable regardless of the number of links. An interesting result is shown in which five independent Direct Wireless links transmitting in parallel with MPEC increase the continuity to the required value (0.9999999999) for a transaction time of 308 ms. Whereas this transaction time is almost twice the required value, the result shows that the continuity value is achievable for low transaction time values.

The requirements for newly designed links proposed in Section 4.5 can be reduced using MPEC, at the cost of having additional links and increasing slightly the availability requirement of each link. The results obtained from applying the MPEC model to calculate the performance of multiple links with an optimal block erasure code show that the continuity can be increased several orders of magnitude with respect to the single-link requirements.

The method one results for new links produce a set of requirements with the same bit rate, constant and random delay requirements as with the single-link. However, the loss requirements are reduced. With two links, the maximum *PLR* requirement for the ATC communications in all domains is above 10%, providing an improvement of one to two orders of magnitude with respect to the single-link case. Having more links further increases the maximum *PLR*. From the number of links needed that meet these requirements (see Table 21), one link with a low *PLR* (1%) would meet the ORP requirements, and with a higher *PLR* (5% or 10%) two would be needed for a few services. Whereas a 10% packet loss is a very achievable target, the requirements are still strict in terms of constant and random delay: 1190 ms does not leave much margin for sources of delay such as congestion. Any GEO satellite transmission is subject to a propagation delay of ~250 ms. The GEO SatCom profile shows that 1190 ms are only met for 79% of the transmissions. If packets with higher delay are counted as lost, the loss requirements are harder to meet. Using MPEC, the *PLR* requirements for the C2 landing service become more attainable at 1% for at least five links.

The constant and random delay requirements obtained with method two allow for higher constant plus random delay values than method one (see the values per domain in Table 20). The method one delay values must be met with a 95% probability and the new values with 5% probability. These are ~8 times the 95% probability delay for the APT domain, ~4 times for the TMA and ENR domains and ~6.5 times for the ORP domain. The drawback of this approach is that the performance is only achievable with three or more links. With this delay requirements and three links, the maximum *PLR* is in the 10^{-2} order of magnitude. With two satellite links meeting the ORP delay requirements and with a 1% *PLR*, the requirements of all ATC services but the SURV service would be met (see Table 22).

The analysis of the results is used to draw the conclusions. Using MPEC is shown to reduce the individual link requirements to meet the continuity requirements in exchange for additional bandwidth requirements and increasing the link availability requirement. Before the conclusions, next section covers the feasibility of the MPEC proposal.

5.8. Feasibility of MPEC

From an economic perspective, using MPEC is costlier than any solution that retransmits only the data that has been lost in the communication, such as TCP. However, for those services with strict time requirements that cannot afford the delay added by retransmissions, forward error correction could be the only way to achieve the required performance to support a service. Also, for UDP-based communications with more relaxed time constrains, increasing the probability of receiving a message can lower the number of retransmissions, lowering the bandwidth consumed and thus the money spent with metered links, making it a cost-effective proposal.

Development and deployment of new radio technologies to meet the requirements when the available links cannot meet the RCTP is a costly and time-consuming solution. MPEC extends the life-cycle of the existing infrastructure as the combination of multiple links provides higher performance than those links could do individually. Although additional bandwidth is consumed, the overall cost is likely to be lower.

A very important aspect of any technology developed for aeronautics is certification. No matter how good a technology is, it must be safe for flying. For that reason, the author of this thesis discussed MPEC for aeronautical data communications with a group of expert regulators from the European Aviation Safety Agency in an informal meeting in May 2016.

From a regulator's perspective, any new technology that doesn't degrade the system's performance below the state before its installation has a much higher chance of being certifiable. In the case of MPEC, the redundancy increases the probability of receiving the message. Another regulatory issue is changing the current state in a way that can be perceived as a degradation. With congested aircraft, the extra queuing delay or lack of bandwidth for the least important services could be considered a degradation; perhaps a worthy one, but nonetheless a degradation. Given enough losses, with a non-systematic code a partial loss of data results in a total loss of data. Thus, to keep the current state of communications in which some applications can work with partial data, a systematic code would be preferred. From a regulators' point of view all these points are not blockers for certification but rather aspects of the technology that should be discussed when a clear proposal is submitted for certification.

Improving the performance of data communications for critical communications is still ahead of current regulation. Communication between cockpit and ground is done through voice with some low-critical services over data. The data-centric scenario in which data communications will be the primary means of communication with voice being relegated to a back-up function, as proposed in COCRv2, is still a vision for the future. There is no regulation yet for the future data-centric operations, neither for the commercial aviation nor for the UAVs. From the regulation's side, it is expected that difficulty in the certification would come in proving that MPEC is an improvement over single-link-communications. The work of this thesis provides the tools to calculate the performance provided by a single link but also using MPEC over any set of links, a necessary first step towards certification.

The best approach towards achieving certification is to gain trust of the process "step by step". The first step would be starting by showing the advantage for non-critical applications like non-critical operations in a situation with reduced communications capabilities. Once it could be shown that a communication system with MPEC provided an advantage for non-critical communications it would be easier to propose it for critical communications such as the "C2 landing" service described in Section 2.5. Another key aspect of the process would be showing the security of the system. However, that part is out of scope of this work.

A common issue with certification of cockpit systems is randomness: systems must be deterministic. The randomness of packet losses and latency for data communications are slightly different from voice, in which degradation usually means lower signal-to-noise ratio and thus quality. However, the accepted delay was already a parameter to measure performance for voice communications. There is no issue with the regulation when working with statistical information. Determining the expected performance using the MPEC RCP model provided in this thesis is a deterministic process: for a given an input (traffic, link and coding parameters), the same output is always obtained. The issue would in fact be if the output could vary every time the model was run, like when simulation tools are used.

After showing the results of applying MPEC, this section covers the feasibility of such technique. To provide an increase in the performance, further steps can be taken towards its certification. The final conclusions follow in the next section.

5.9. Conclusions

The performance improvement in the performance of the future data-centric ATC and C2 communications using multiple available air-ground data links is studied in this chapter. Having multiple links provide the advantage of spatial diversity that can be exploited to increase the performance.

In the state-of-the-art review the different techniques that could increase the continuity provided by the links are presented. All the techniques involve changes at the network or transport layer. The TCP-based techniques analysed are optimized towards throughput maximization, at the expense of increased latency caused by retransmissions. The most promising techniques for high-continuity low-transaction time communications use erasure coding at network layer, to perform forward error correction. Unlike when using retransmissions, erasure correction is independent of the latency of the link, making it possible to achieve low transaction times with high continuity. Another promising feature is routing the packets over the multiple available links to benefit from the mentioned diversity. Of all the candidates, Packet Repetition and an optimal block erasure code over multiple links are compared. Using a simulation tool, it is shown that the optimal code provides a performance advantage over Packet Repetition. Using an optimal block erasure code over multiple links to increase the continuity provided by the links is named Multi-Path Erasure Coding (MPEC). MPEC is not a new technique, as it has been proposed for other scenarios such as streaming and wireless sensor networks. However, it had not been applied to increase the probability of successfully delivering a message within a given time (i.e. continuity).

To analyse the continuity improvement with MPEC, a model to obtain the continuity from the link parameters, the traffic characteristics and the MPEC parameter choices (coding rate and packet distribution over the links) is proposed. The MPEC RCP model's results are compared with both emulation and simulation techniques yielding close results, providing confidence in the validity of the model results. With this model, the performance can be calculated quickly for any scenario in the process of evaluating the expected performance of a system or when designing a new one. The proposed model is the first to provides the means for calculation of the continuity provided by any set of links using erasure coding. To the best knowledge of the author, no other model is publicly available.

The performance of multiple air-ground data link with parameters like those in the profiles proposed in Section 3.4 and when using MPEC are calculated using the RCP model. The Direct Wireless link can meet the ATC continuity requirements when available without need of MPEC (see Section 4.4.1). Even with MPEC, the C2 landing service requirements are unmeetable with that link. As opposed to the single-link case where no ATC service continuity requirements are met, the continuity of the GEO and LEO SatCom links using MPEC is increased to the point that with multiple links most are ATC service requirements are met, but not all.

The new link requirements are easier to achieve with MPEC than with a single-link. The results show that using MPEC, the maximum packet loss ratio can be one to two orders of magnitude higher than with the single-link, and that the maximum delay requirements can be increased four to eight times for 5% of the packets. The drawback is the requirement to deploy multiple independent links, meaning additional hardware, spectrum allocation, etc.

Even if the performance of the Direct Wireless link is expected to be enough to meet the future ATC requirements over continental airspace, the figures provided in this chapter are useful as benchmark for new direct wireless link technology developments. Also, the Direct Wireless link is an estimation of a future not-yet existing link, so the performance of the real technology once the link is deployed could be insufficient to meet the ATC requirements. The ORP domain requirements are expected to be met by the new satellite links. The requirements obtained with the first method are a bit constricting with the delay (1190 ms for the constant plus random delay) but using method two, the requirement is relaxed to a maximum delay of 7990 ms. The relaxation of requirements comes at the cost of having to deploy at least three independent links.

Meeting the C2 landing service requirements will most likely require new dedicated links that have not yet been planned. The C2 landing RCP are a true challenge, with the continuity being a few orders of magnitude stricter than any of the contemplated ATC requirements. Most likely, short-range links will be deployed locally at the landing sites. The expected continuity with five Direct Wireless links is met for a transaction time of 308 ms, up from 160 ms required. That value might be acceptable for trained pilots; it is important to note that the requirements used here for the C2 are not standardized even if they are obtained following the same procedure as the ATC communications. Alternatively, if or when the technology used to land the RPAV/UAV autonomously in case of lost link is mature enough, the safety impact of a lost link would be less hazardous thus reducing the continuity requirements.

Overall, the results obtained in this chapter show that MPEC can be used to combine multiple links to increase the continuity performance in a transaction. By doing so, the delay and loss requirements of the future air-ground data links can be reduced if multiple links with slightly higher link availability can be deployed.

One of the underlaying assumptions that enabled the calculations in this chapter was that all the packets were equally sized. The next chapter analyses how MPEC can be applied when this assumption is no longer valid.

6. PACKET BUNDLING FOR THE FUTURE ATC SERVICES

6.1. Introduction

The average size and number of packets for each transaction supporting an ATC service have been listed in the COCRv2 document [1]. Those values are recalculated for the ATN/IPS protocol stack in Table 4 of this work. Two problems arise from using the average values instead of the statistical distributions: one, the expected performance and link requirements could change if calculated with values other than the average and two, the encoding process of the proposed erasure codes require all the packets to be equally sized. Since the packet size distribution is unknown, nothing can be done with the first problem.

The problem of unequal packet sizes when encoding has been reviewed in literature [106] [107] [108]. One of the solutions consists in concatenating all the packets and fragmenting the resulting data into equally sized packets. The new number of packets to encode can be reduced with respect to the original number by making large fragments. That is a way of aggregating traffic, an approach used in some scenarios like for example when using the ATN/OSI VDL2 link (see Section 3.3.5), as it increases the communication performance. In this chapter, concatenating the packets that compose a message and fragmenting them to reduce the number of packets to the minimum is named packet bundling. Its impact on the expected performance using the Single-Link RCP performance model and the MPEC RCP performance model is investigated.

The state-of-the-art of techniques that allow encoding when the original packets have different sizes is reviewed in Section 6.2. The simplest solution, adopted by most implementations, is to add padding to the shorter packets. However, more advanced techniques have been proposed, including concatenating the packets and fragmenting them.

In Section 6.3, how packet bundling could be applied to the ATC services traffic is explained. The fragment sizes are limited by the Maximum Transmission Unit (MTU) of the network protocol. The new number of packets and packet sizes of the ATC services traffic is listed.

The performance of the ATC services in the single-link case is studied in Section 6.4 and for multiple links in Section 6.5. Packet bundling provides a performance improvement to those services with a high number of packets. The new link requirements obtained in Chapters 4 and 5 are less strict when the requirements are driven by services for which packet bundling reduces the number of packets.

The results for a single link and for multiple links are analysed in Section 6.6. and the conclusions drawn in Section 6.7. Overall, the advantage of packet bundling outweighs the overhead. When implemented together with MPEC, the fragmentation and reconstruction of the packets can be easily placed at the encoder and decoder nodes.

6.2. State-of-the-art

Different sized packets in a transaction are a problem when applying MPEC. The optimal block erasure codes proposed in Section 5.2.3 require all packets to be of the same size. This state-of-the-art section reviews solutions to this issue. A solution to this issue is padding all the packets to the longest size. However, this solution while simple, produces overhead that can be higher than 100% the original data size, as shown in the internet and video traffic analysis in [106].

Alternative approaches to padding have been reviewed in [107]. The most promising technique reviewed is named “chain and fragmentation”. It consists in merging all the packets to be encoded and then fragment the resulting block into equally-sized fragments, finalizing with encoding the fragments. Whereas this solution reduces the padding greatly, it comes at the cost of additional signalling and overhead. The encoded fragments must be encapsulated in new packets and the information to restore the packets from the packets must also be sent. In [108] a new and totally different approach has been proposed to encode different-sized packets. The encoding operation is done for subsets of the packet, named “macro-symbols”. With this approach, the size of the encoded packets is not constant and fixed to the longest original packet as done with padding. Instead, the encoded packets generated in the same encoding operation might have different sizes, with some being smaller than the longest original packet. The advantage of this approach is that it reduces the padding required.

The impact of diverse packet sizes in a transaction and the techniques that would allow MPEC to be used depends on the packet size distribution. That information for the ATC services is not available in COCRv2 [1]. However, before the "chain and fragmentation" technique was proposed for solving the unequal size of packets issue with erasure coding, it has been proposed as means to reduce the number of packets and increase the performance. Aggregating several packets together provides advantages in certain scenarios. For example, when using voice-over-IP in cellular networks, time slots that would otherwise be left partially unfilled are used more efficiently [109]. Also, if the link layer protocol adds a substantial amount of overhead, reducing the number of packets could be beneficial [110]. On the other hand, reducing the number of packets by aggregating packets together could increase the probability of erasure of the packet. This approach is named "Packet bundling" and it is presented in the next section.

6.3. Packet bundling proposal

The objective of this section is to present how the traffic is aggregated to reduce the number of packets (packet bundling). Therefore, the reduction in the number of packets applies to all services both when used over a single-link and with MPEC. The impact on the expected performance is analysed in the following sections. Since the gain for different packet sizes depends on the distribution of sizes, for the analysis the average values from Table 4 are used.

Packet bundling in this work consists in concatenating all the packets in the same transaction and then fragmenting the resulting data into the minimum number of segments allowed by the MTU. The MTU is assumed to be the minimum required by the Internet Protocol version 6 (IPv6), 1280 bytes (see Section 2.2.4). The ATC services with only one packet per message are unaffected by packet bundling because the number of packets cannot be further reduced. When erasure coding is used for those services, the encoded packets are repetitions of the original packet. The C2 landing service is also unaffected because the number of packets cannot be reduced without exceeding the MTU, given that their current size (1108 bytes) is already set to maximize the message data (3965 bytes) in each of the four packets (see Table 5).

Given the air-ground data link model from Section 3.2, packet bundling has the advantage that if the number of packets is reduced, it is more likely to receive all the packets in a message. However, this can be a drawback when using MPEC, as more data is lost when a link erases an encoded packet, making it harder to meet the decoding conditions. Also, the coding rate (*k*/*n*) granularity decreases, as the number of original packets (now original fragments) k decreases. In fact, if all the packets in a transaction are coded together into one, the only possible code is repeating the packet.

After packet bundling, the new number of packets k_{PB} and size of packets b_{PB} is calculated for those services that have more than one packet. Each new bundled packet is given a new IPv6 header (40 bytes), UDP header (8 bytes) and a "fragmentation header" (8 bytes are assumed to be enough). The value of k_{PB} is set to the minimum k_{PB} for which b_{PB} is within the threshold to the path MTU (1280 bytes). A graphical example of the packets construction when bundling is shown in Figure 70. The relative overhead is defined as with (43).

$$O = \frac{k_{\mathrm{PB}} \cdot b_{\mathrm{PB}}}{k \cdot b} - 1 \tag{43}$$

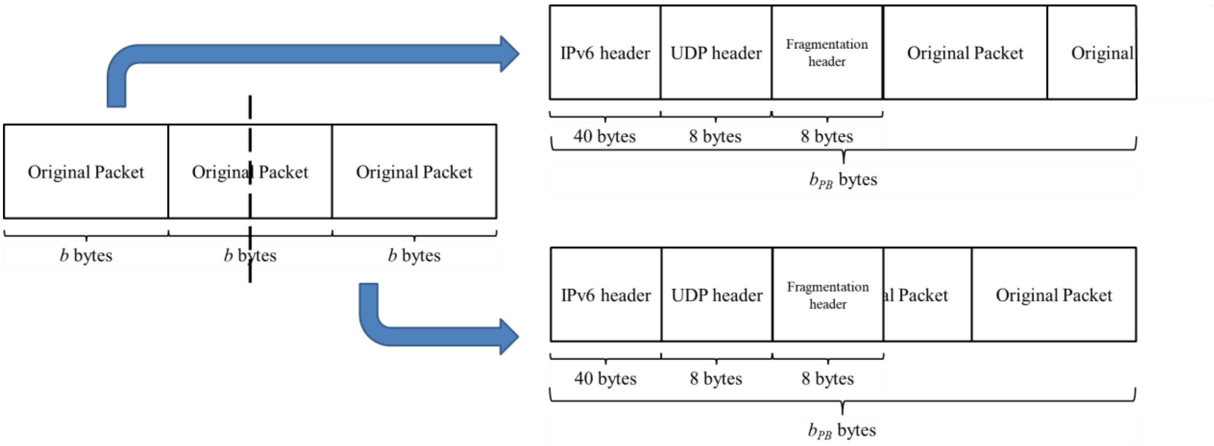

Figure 70: Example of packet bundling process with k=3 and k_{PB}=3

The new values are given in Table 23; those services that remain unchanged are coloured in red. Note that because the packets must be restored to their original sizes, the original IPv6 and UDP headers cannot be removed.

Service	A2G k	A2G b	A2G k_{PB}	A2G b_{PB}	A2G O	G2A k	G2A b	G2A k_{PB}	G2A b_{PB}	G2A O
ACL	2	132	1	320	21.2%	2	132	1	320	21.2%
ACM	1	128	N/A	N/A	N/A	1	164	N/A	N/A	N/A
AMC	0	0	N/A	N/A	N/A	1	128	N/A	N/A	N/A
ARMAND	1	128	N/A	N/A	N/A	1	300	N/A	N/A	N/A
C&P ACL	2	132	1	320	21.2%	2	132	1	320	21.2%
COTRAC (int.)	5	1160	N/A	N/A	N/A	5	1252	N/A	N/A	N/A
COTRAC (wil.)	3	984	N/A	N/A	N/A	3	1140	N/A	N/A	N/A
D-ALERT	1	1040	N/A	N/A	N/A	1	128	N/A	N/A	N/A
D-ATIS (arr)	3	132	1	452	14.1%	5	140	1	756	8.0%
D-ATIS (dep)	2	136	1	328	20.6%	3	140	1	476	13.3%
DCL	2	128	1	312	21.9%	1	156	N/A	N/A	N/A
D-FLUP	3	168	1	560	11.1%	5	228	1	1196	4.9%
DLL	1	260	N/A	N/A	N/A	1	532	N/A	N/A	N/A
D-ORIS	3	132	1	452	14.1%	9	516	4	1217	4.8%
D-OTIS	3	144	1	488	13.0%	11	232	3	907	6.6%
D-RVR	3	160	1	536	11.7%	4	156	1	680	9.0%
DSC	4	124	1	552	11.3%	3	136	1	464	13.7%
D-SIG	3	168	1	560	11.1%	5	1128	N/A	N/A	N/A
D-SIGMENT	3	168	1	560	11.1%	4	168	1	728	8.3%
D-TAXI	1	136	N/A	N/A	N/A	2	172	1	400	16.3%
DYNAV	1	120	N/A	N/A	N/A	1	552	N/A	N/A	N/A
FLIPCY	1	212	N/A	N/A	N/A	1	144	N/A	N/A	N/A
FLIPINT	3	1012	N/A	N/A	N/A	1	180	N/A	N/A	N/A
ITP ACL	2	132	1	320	21.2%	2	132	1	320	21.2%
M&S ACL	2	132	1	320	21.2%	2	132	1	320	21.2%

Service	**A2G** k	**A2G** b	**A2G** k_{PB}	**A2G** b_{PB}	**A2G** O	**G2A** k	**G2A** b	**G2A** k_{PB}	**G2A** b_{PB}	**G2A** O
PAIRAPP ACL	2	132	1	320	21.2%	2	132	1	320	21.2%
PPD	1	316	N/A	N/A	N/A	1	144	N/A	N/A	N/A
SAP (Setup)	2	140	1	336	20.0%	2	132	1	320	21.2%
SAP (Report)	1	144	N/A	N/A	N/A	0	0	N/A	N/A	N/A
SURV (ATC)	1	144	N/A	N/A	N/A	0	0	N/A	N/A	N/A
URCO	1	120	N/A	N/A	N/A	1	136	N/A	N/A	N/A
WAKE	1	144	N/A	N/A	N/A	0	0	N/A	N/A	N/A

Table 23: Number and size of packets per ATC service transaction with packet bundling

The COTRAC and FLIPINT services are the only services that have more than one packet per message and this number cannot be reduced. For the other ATC services, the overhead incurred when using packet bundling ranges from 4.8% to 21.9%. The D-OTIS service in the ground-to-air direction has the highest reduction in number of packets from 11 to 3.

To calculate the expected performance of the services, both the Single-Link RCP performance model and the MPEC RCP performance model are used. The difference with the calculations done in previous chapters is the number of packets per transaction and their size. The next section analyses the performance impact of packet bundling with the Single-Link RCP performance model.

6.4. Packet bundling in the Single-Link case

6.4.1. Overview

Using packet bundling with the generic links to re-calculate the results of Section 4.4 does not change the fact that the generic satellite links cannot meet the performance requirements. The expected performance for the one-packet transactions is below the requirements and it does not change with packet bundling. However, packet bundling has an improving effect on the continuity of services with more than one packet. Given the extra headers, the total transmission delay increases the minimum transaction time.

In the following section the impact of packet bundling is analysed for the service with the highest relative overhead (DCL service in air-to-ground direction) and then in the next one, the service with the highest reduction in number of packets (D-OTIS service in ground-to-air direction). The calculation for both services is done using the pessimistic approximation. Finally, the link requirements to meet the COCRv2 ATC services requirements obtained in Section 4.5 are recalculated with packet bundling.

6.4.2. Highest relative overhead

The DCL service in the air-to-ground direction has the highest relative overhead of all the services when using packet bundling (21.9%). The performance of this service over the GEO SatCom and LEO SatCom links is calculated.

A clear improvement is observed using packet bundling over the GEO SatCom link (Figure 71). Over the LEO SatCom link (Figure 72), an improvement is also observed for some transaction time values. The continuity for some transaction time values is lower with packet bundling because given the low bit rate of the link, the increased transmission delay added by the overhead is very high.

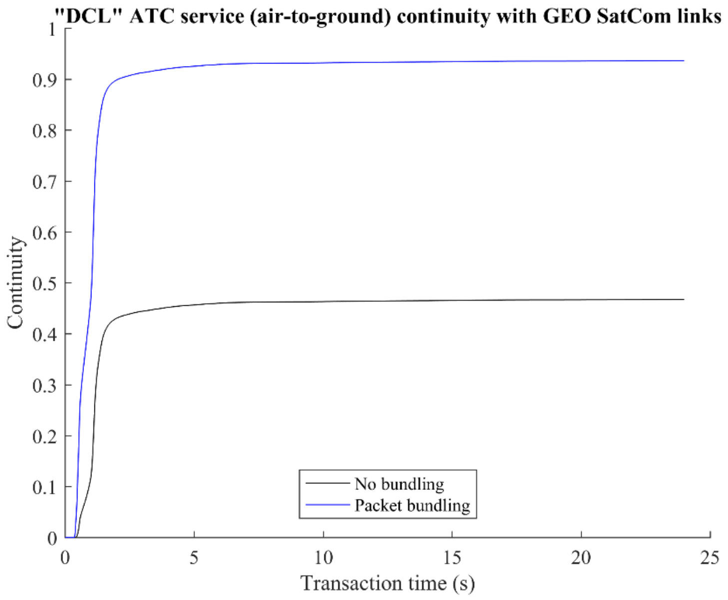

Figure 71: Expected continuity of the DCL ATC service comparison with packet bundling over the GEO SatCom link

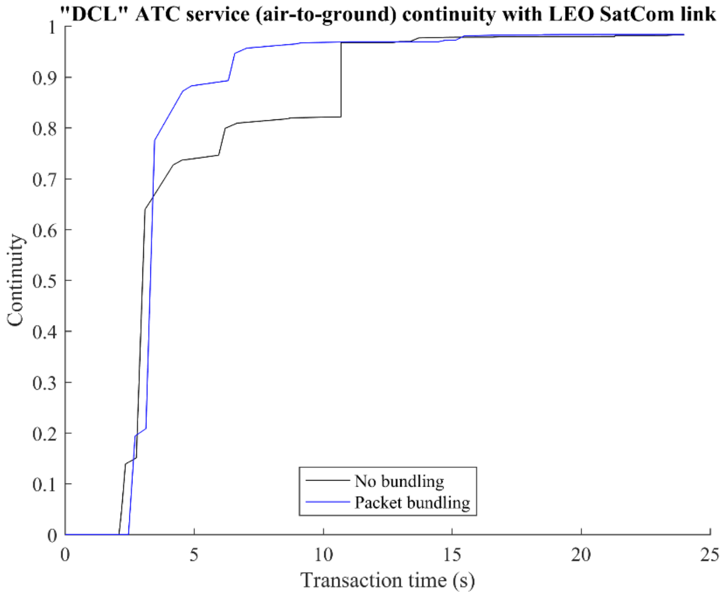

Figure 72: Expected continuity of the DCL ATC service comparison with packet bundling over the LEO SatCom link

Packet bundling is a technique used to reduce the number of packets in a message. Thus, it makes sense to analyse the service most affected by this reduction, as done in the next section.

6.4.3. Highest reduction of number of packets

The D-OTIS service in the ground-to-air direction has the highest reduction in number of packets of all the services when using packet bundling. Without packet bundling over the GEO SatCom link (Figure 73), the continuity is zero; with packet bundling, the continuity is low but not zero. Over the LEO SatCom link (Figure 74), an improvement is also observed for some transaction time values. While the continuity is also lower for some transaction times with the LEO SatCom link like for the DCL service, there is an improvement for higher transaction time values.

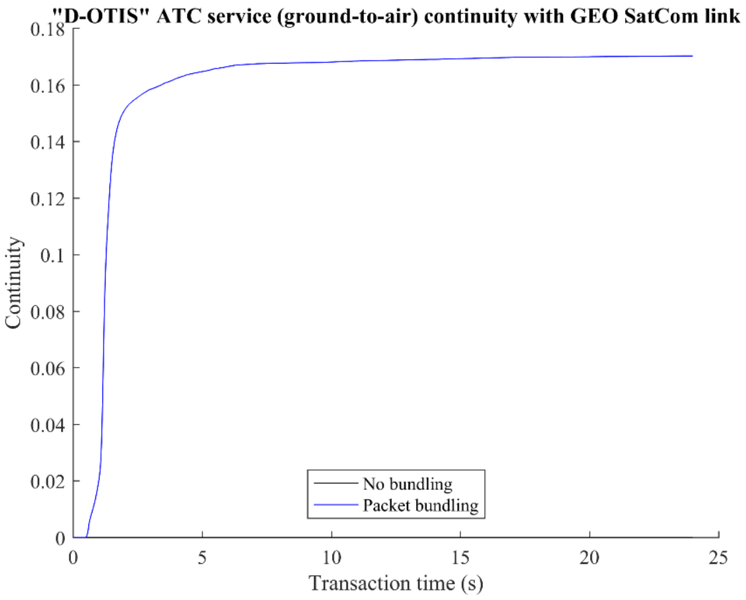

Figure 73: Expected continuity of the D-OTIS ATC service comparison with packet bundling over the GEO SatCom link

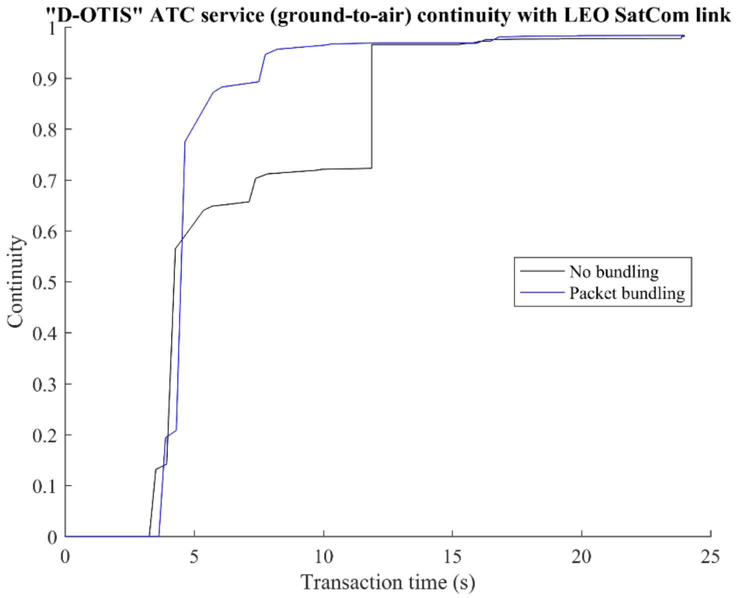

Figure 74: Expected continuity of the D-OTIS ATC service comparison with packet bundling over the LEO SatCom link

In addition to affecting the performance of the individual ATC services, packet bundling can be used to reduce the link parameters' value requirements that meet all the ATC services requirements. The results of this analysis are presented in the next section.

6.4.4. Future link requirements for the ATC services using packet bundling

The link requirements to meet the ATC service performance requirements obtained in Section 4.5.2 are recalculated here using packet bundling. The requirements trade-off between the bit rate and the sum of constant and random delay in Figure 29 remains unchanged by packet bundling, as those requirements are driven by the SURV service, a one-packet per message service.

The maximum *PLR* achievable remains the same with packet bundling. However, the maximum values of μ_0 (Figure 75) and *PLR* (Figure 76) increase for $\mu_1 \geq 3$ s^{-1} (APT domain) and $\mu_1 \geq 0.9$ s^{-1} (TMA and

ENR domains). For high values of μ_0 and μ_1, the duration in the loss states (represented with the Continuous Time Markov Chain from Figure 14) are small and changes happen fast. With packet bundling, having less packets in a message reduces the impact of changes in state, as it is less likely that a change occurs during the transmission of the packets that form a message. For low values of μ_1, link state changes rarely happen in consecutive transmitted packets belonging to the same message, so packet bundling doesn't provide a significant gain.

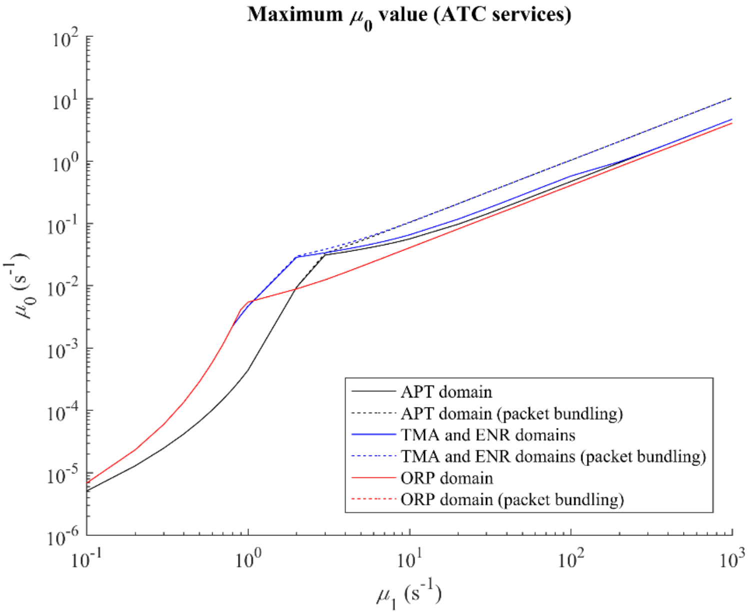

Figure 75: μ_0 vs μ_1 required to meet the ATC requirements using packet bundling

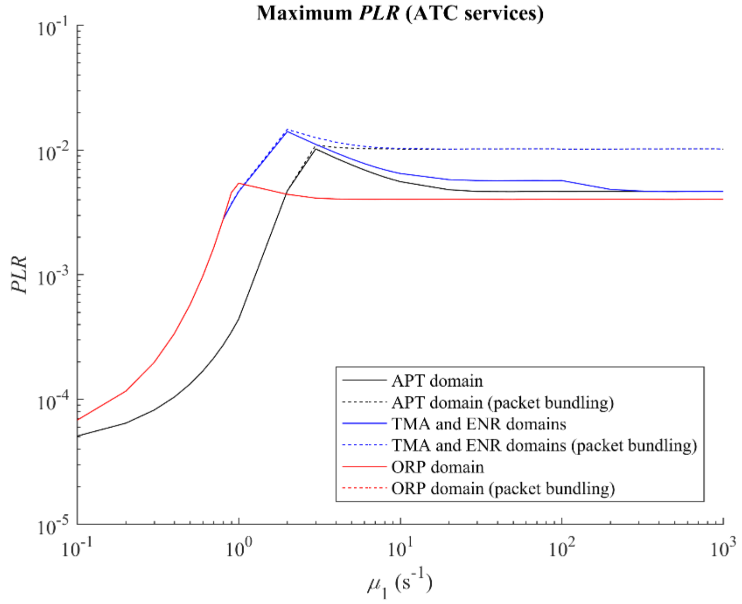

Figure 76: *PLR* vs μ_1 required to meet the ATC requirements using packet bundling

The μ_0 and *PLR* requirements don't improve for all values of μ_1. For each value of μ_1, the strictest μ_0 (Figure 75) and *PLR* (Figure 76) requirement of all the ATC services is selected. If the strictest requirement is given by a service that remains unchanged when using packet bundling, no improvement happens. In the APT domain the SURV and D-OTIS services set the requirements (Figure 32). In the TMA and ENR domains the SURV, ACL, D-ORIS and D-OTIS services drive the requirements (Figure 33). In the ORP domain, it is the SURV and COTRAC services (Figure 34). Of all those services, the ones that remain unchanged with packet bundling are the SURV service, since it has only one packet per message, and the COTRAC service, since the number of packets cannot be reduced because of the packet size and the MTU value.

The loss requirements with a fixed bit rate of 116 kbps and constant plus random delay of 390 ms (APT domain) and 1190 (TMA, ENR and ORP domains) are also recalculated using packet bundling. Like in the case in which the bit rate and delay values are not fixed, the maximum *PLR* achievable does not increase. The maximum μ_0 and *PLR* increase for $\mu_1 \geq 30$ s^{-1} in the APT domain and $\mu_1 \geq 10$ s^{-1} in the TMA and ENR domains.

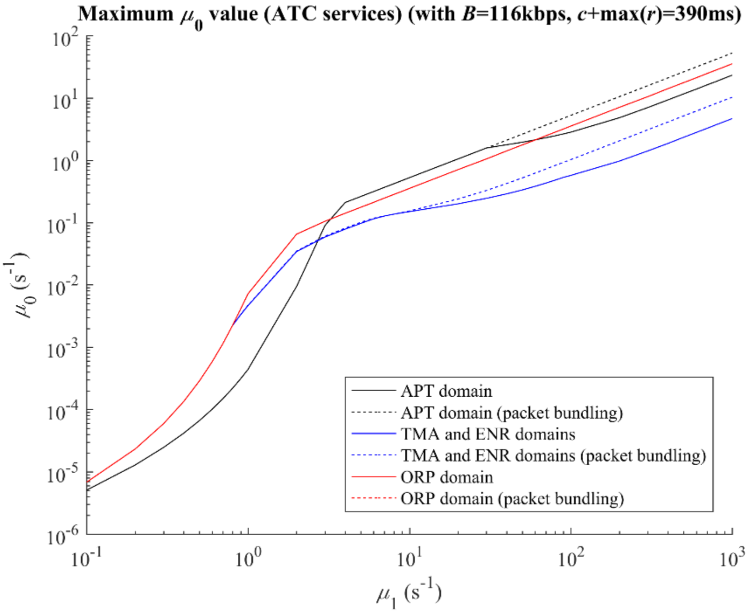

Figure 77: μ_0 vs μ_1 required to meet the ATC requirements using packet bundling with fixed bit rate and delay requirements

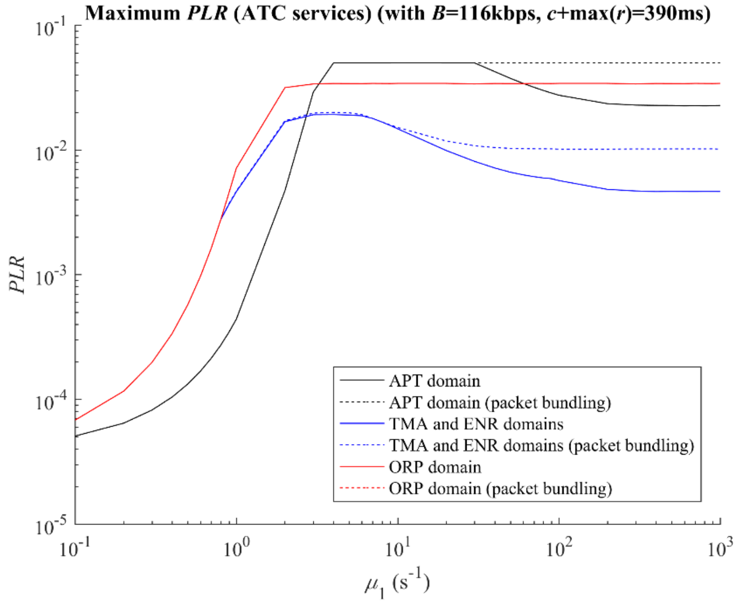

Figure 78: *PLR* vs μ_1 required to meet the ATC requirements using packet bundling with fixed bit rate and delay requirements

Packet bundling provides an increase in performance for the single-link scenario even if it was proposed as a solution for the multi-link scenario using MPEC. The impact of using packet bundling with MPEC is studied in the next section.

6.5. Using packet bundling with MPEC

Packet bundling can be used as a solution to unequal packet sizes when using MPEC. However, if the only objective is to enable the encoding operation, depending on the sizes distribution other techniques proposed in the state-of-the-art (Section 6.2) could be more efficient.

In addition to equalizing the packet sizes, packet bundling reduces the number of packets for some transactions (see Table 23). In the previous section, reducing the number of packets is shown to be beneficial for the single-link case. With MPEC, the same advantages apply. However, when an encoded packet is erased, more information is lost.

The comparison between using and not using packet bundling is calculated with the *PLR* requirements obtained using MPEC and method one (Section 5.6.2). The results show that the link requirements for the APT and ORP domains remain unchanged. The link requirements for the TMA and ENR domains change slightly as shown in Figure 79. The more links are used, the less improvement is observed with packet bundling. This is because with many links, the probability that a message is interrupted during its transmission is less relevant than the probability that at least one link is successful in transmitting all the encoded packets.

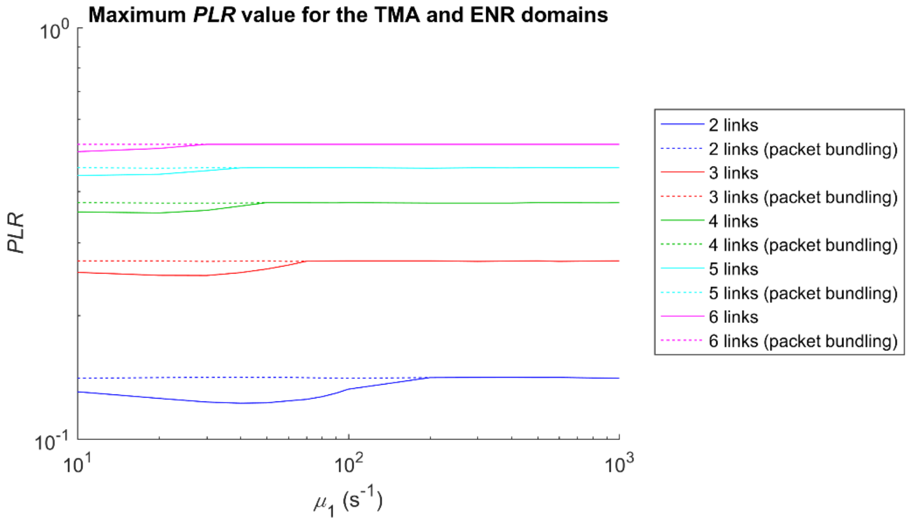

Figure 79: ***PLR*** **vs** μ_1 **required to meet the TMA and ENR domain requirements using packet bundling and MPEC**

Despite not providing any advantage to some domains, packet bundling (or chain and fragmentation) enable the use of MPEC in the case that the packets are not equally sized. The results of applying packet bundling are analysed in the next section.

6.6. Analysis of the results

Packet bundling improves the performance for single-link communications at the expense of additional complexity and overhead (see Table 23). Since the technique is applied only to the packets belonging to the same message, it can only be applied to those transactions with more than one packet per message. Therefore, the GEO and LEO SatCom links cannot meet the RCTP for all ATC services even if packet bundling is used. As shown in Figure 71 and Figure 73, low performing links in terms of loss and delay but with a high bit rate like the GEO SatCom greatly benefit from packet bundling. The continuity is doubled for the DCL ATC service and it reaches 18% from 0% for the D-OTIS ATC service. All this, with an extra transmission delay negligible as opposed to other links such as the LEO SatCom. The link requirements are less strict when $\mu_1 \geq 3$ s^{-1} (APT domain) $\mu_1 \geq 0.9$ s^{-1} (TMA and ENR domains). In that range, the maximum PLR increases (less than one order of magnitude) because having less packets in a message, it is less likely that the frequent link state changes affect the message transmission. The additional transmission delay caused by the overhead is compensated by the increase of continuity. The ORP domain requirements remain the same as the requirement driving services are unaffected by packet bundling.

Using packet bundling with MPEC provides only a small increase in the maximum PLR value for certain values of μ_1 and only for the TMA and ENR domains. The reason for not providing any benefit for the APT and ORP domains is the same as the single-link: the services driving the requirements don't change with packet bundling. As more links are added, the impact of packet bundling is reduced. This is because whereas the probability of successfully transmitting all the encoded packets sent over each link increases with packet bundling, with MPEC it is not as important if one of the links does a partially successful transmission if in total at least k (or k_{PB} with packet bundling) are received.

6.7. Conclusions

In this chapter, packet bundling is proposed to improve the expected performance of ATC service communications. Packet bundling consists in concatenating all the packets in a transaction and then fragmenting the resulting data into packets as big as the MTU allows. Doing that, the number of packets for some ATC services decreases, reducing the negative impact in the continuity that having multiple packets has when transmitted over an air-ground data link characterized with the model from Section 3.2.

When packet bundling is applied for single-link communications, the expected continuity increases in some cases. High bit rate lossy links like the GEO SatCom link see the expected continuity of services with multiple packets per message significantly increased. When designing new links with a value of $\mu_1 \geq 3$ s^{-1} (APT domain) and $\mu_1 \geq 0.9$ s^{-1} (TMA and ENR domains) the transmission of a message is less likely to be interrupted by a link change with packet bundling, resulting in an increase in the maximum PLR required. For lower values of μ_1 or for the ORP domain, packet bundling does not reduce the number of packets of the services driving the requirements, so the PLR requirements remain unchanged. The drawbacks of using packet bundling in the single-link case are the overhead and that it requires the original packets to be reconstructed from the bundle, a capability that requires modifying either the destination node or a router in the path between the air-ground data link and that node.

Using packet bundling reduces the link requirements in a few cases. However, the most important gain from using packet bundling with MPEC is that the encoding operation can be performed regardless of unequal packet sizes. Implementing packet bundling with MPEC is easy as there is no need to modify more nodes; the bundling operation can be implemented with the encoder and the reconstruction with the decoder.

Overall, packet bundling is worth considering when deploying the communications infrastructure. In the specific cases described in this chapter, this technique improves the expected continuity and reduces the link loss requirements. In case it is deployed with MPEC, it also equalizes the packet sizes making the encoding operation possible.

7. CONCLUSIONS

The modernization of Air Traffic Management (ATM) operations has led to a change from voice-centric aeronautical Air Traffic Control (ATC) communications to data-centric. To support the new operations, stricter performance requirements on data communications are planned. Whereas the requirements for the data-centric ATC were established in 2007 in COCRv2, the deployment of the new ATM operations and technologies is not expected until the mid-2020s. An increasing interest in civilian use of unmanned aviation in the same airspace as commercial aviation has also triggered the need for new communication performance requirements. In both cases, the performance requirements are measured using the Required Communication Performance (RCP) metric.

The expected performance of existing and future air-ground data links in the RCP metric is calculated in this thesis. The results show that the satellite links available today[1] are likely incapable of supporting the data-centric ATC communications[2]. There is not enough publicly available information to know whether the next generation of satellite links will. The available information leads to the conclusion that the expected performance of the next generation of direct wireless link[1] will meet the data-centric ATC performance requirements[2] when aircraft flying over continental airspace.

To determine whether the new links meet the requirements when their parameters values are known, or for designing new links, the link parameters value requirements to meet the data-centric ATC performance requirements[2] are calculated for each flight domains. The required bit rate is exceeded by the expected value of any of the future air-ground data links. However, the delay and loss requirements are not straightforwardly met. The required latency incurred by a packet in the APT domain is at most 400 ms and in the TMA, ENR and ORP domains, 1200 ms. The maximum average packet loss ratio in the best case is 5%, but for most combinations of bit rate and delay the requirement is in the 10^{-3} order of magnitude. Meeting all the link requirements can be difficult for the next generation of air-ground data links, especially for satellite links. The results obtained in this thesis can be used by the designers of new links as target for their technologies.

The future data-centric aircraft are expected to be equipped with multiple links. The performance of each of the available links could be insufficient to meet the RCP. For those cases, the techniques that exploit the spatial diversity provided by the available links are reviewed and one selected as candidate to improve the performance. The Multi-Path Erasure Coding (MPEC) technique consists in transmitting packets generated with an optimal block erasure code for forward error correction over the multiple available links. The technique has already been proposed for scenarios other than aeronautical communications, but not to meet latency and loss requirements such as the RCP continuity and transaction time parameters. The MPEC technique provides a substantial improvement in the expected continuity and transaction time with respect to single-link communications, but also with respect to other techniques proposed to improve the ATC continuity performance such as packet repetition.

The link parameters value requirements to meet the data-centric ATC performance requirements[2] when multiple independent links are available are calculated. The link requirements with respect to the single-link requirements are reduced at the expense of additional bandwidth consumption and a slight increase in the link availability requirement. With two links using MPEC, the maximum average packet loss ratio required is above 10%, an easy target even for a wireless link. With three or more links and MPEC, the latency requirements with respect to the single-link requirements must be met with only 95% probability, and the maximum packet latency is 3.2 s (APT domain), 5.0 s (TMA and ENR domains) and 8.0 s (ORP domain). The values obtained as link requirements with MPEC can be used to evaluate the suitability of combining less performing independent links. In addition to reducing the individual

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[1] The conclusions of existing and future air-ground data link technologies are based on a characterization of the links in Section 3.4, made with the information available to the author and making assumptions. Therefore, the conclusions could change if the actual link parameters' values differ enough from the values assumed in this thesis.

[2] Requirements obtained from COCRv2 [1] and listed in Table 3.

link requirements for new designs, MPEC can also be used to improve the performance of the future with air-ground data links designed to meet the future data-centric requirements, if stricter requirements are defined beyond the years 2020s. By doing so, the need to deploy a new generation of links could be delayed.

The future unmanned aviation requirements haven’t been produced yet. In this thesis the RCP requirements for the air-ground data link when remotely landing an aircraft are obtained using a safety analysis procedure like the one used for the ATC requirements in COCRv2. The requirements are several orders of magnitude stricter than the ATC requirements, as it is considered that failure in communications could lead to a significant reduction of the safety margin and possibly a major damage to people. The link’s average packet loss ratio required to meet the RCP is unattainable with wireless communications. Using the MPEC technique with five links the required value is about 1%, a realistic value achievable by current technology. Even with MPEC, the implementation is still challenging as the required bit rate is above 4 Mbps and the constant plus random delay is 150 ms at most.

With the erasure codes proposed for MPEC, all the packets must have the same size. If that is not the case, multiple solutions are available. One of them has been used before to improve the communication performance and it is analysed in this work. With packet bundling, the packets are concatenated to reduce the number of packets per message and equalize the packet size. Using this technique, the expected continuity of the ATC services with reduced number of packets after bundling, improves. The link average packet loss ratio requirement for the single-link and multi-link improve for some flight domains less than one order of magnitude. The gain of packet bundling is maximized when the messages are composed of multiple small packets.

The results obtained in this thesis are calculated using two proposed mathematical models, one for single-link and one for MPEC. The advantage of using the proposed models over other techniques such as simulation, emulation or measurement is the speed at which results are obtained; it is the fastest of all. The main drawback is that with the assumptions made, the results are approximated. When evaluating a technology, the results calculated with the proposed models give an indication whether the expected performance is well below or above the requirements. If the expected performance is very close to the requirements, using the other techniques could be necessary to determine the performance more precisely. When designing new link technologies, the link requirements calculated with the models provide a first performance target for definition and selection of underlying technologies such as physical layer modulations and link layer protocols.

The work presented in this thesis report provides useful tools for the future design, implementation and evaluation of air-ground data links for aviation. The Single-Link RCP performance model and the MPEC RCP performance model can be used to calculate the performance for any scenario with one or more links, with and without MPEC. The link requirements are obtained to meet the COCRv2 requirements and when new RCP are defined, the two models can be used to re-calculate the new link requirements.

A possible next step that would add value to this work would be analysing the impact of the traffic generated by other sources. Adding the additional queuing delay caused by the presence of other traffic would provide better estimates of the air-ground data links performance. These new models require a good characterization of the traffic generated by the future aeronautical services that would use the same air-ground data links as the ATC and C2 services. Another interesting addition to the presented models would be modelling the physical and link layers, making them technology specific but also providing better estimates.

BIBLIOGRAPHY

Publications by the author

[18] D. Gómez Depoorter and O. Lücke, "Required Communication Technical Performance, the application layer QoS metric for aeronautical data communications," in *21st Ka and Broadband Communications Conference*, Bologna, 2015.

[19] D. Gómez Depoorter, O. Raissouni, E. Temprado Garriga and O. Lücke, "The ACROSS Testbed for the Future Aeronauitcal Data Communications," in *ICNS*, Herndon, 2016.

[20] D. Gómez Depoorter and W. Kellerer, "Designing the Air-Ground Data Links for Future Air Traffic Control Communications," *IEEE Transactions on Aerospace and Electronic Systems,* vol. 55, no. 1, pp. 135-146, 2018.

[21] D. Gómez Depoorter and W. Kellerer, "Multiple-Path Erasure Coding for Future Air Traffic Control Communications," *Journal of Air Transportation,* vol. 27, no. 3, pp. 109-120, 2019.

All publications

[1] Eurocontrol and FAA, *Communications operating concept and requirements for the future radio system*, 2nd ed., 2007.

[2] ICAO, *Manual on Required Communication Performance (RCP),* 1st ed., Montréal, 2008.

[3] Eurocontrol, "Challenges of Growth 2008, Summary Report," 2008.

[4] Eurocontrol, "Challenges of Growth 2013, Summary Report," 2013.

[5] "Data Communications (Data Comm)," Federal Aviation Administration, [Online]. Available: https://www.faa.gov/nextgen/programs/datacomm. [Accessed 31 January 2017].

[6] SESAR Joint Undertaking, "European ATM Master Plan," Publications Office of the European Union, Luxembourg, 2015.

[7] ICAO, *Manual on Technical Specifications for fhe ATN using ISO/OSI Standards and Protocols,* 2nd ed., Montréal, 2016.

[8] ICAO, *Manual for the Aeronautical Telecommunication Network (ATN) using Internet Protocol Suite (IPS) Standards and Protocols,* 1st ed., Montréal, 2010.

[9] S. Plass, "Seamless networking for aeronautical communications: One major aspect of the SANDRA concept," *IEEE Aerospace and Electronic Systems Magazine,* vol. 27, no. 9, pp. 21-27, 2012.

[10] G. T. Saccone, M. L. Olive, M. E. Matyas and D. C. Smith, "Safety Services Using the Internet Protocol Suite Benefits, Progress and Challenges," in *Digital Avionics Systems Conference (DASC),* Prague, 2015.

[11] ICAO, "Unmanned Aircraft Systems (UAS)," Montréal, 2011.

[12] ICAO, *Manual on Remotely Piloted Aircraft Systems (RPAS),* 1st ed., Montréal, 2015.

[13] ICAO, *Global Operational Data Link Document (GOLD),* 2nd ed., Montréal, 2013.

[14] European Space Agency, "Satellite Communication For Air Traffic Management (IRIS)," [Online]. Available: http://www.esa.int/Our_Activities/Telecommunications_Integrated_Applications/Satellite_Communication_for_Air_Traffic_Management_Iris. [Accessed 4 November 2016].

[15] D. Zeng and J. C. Gonda, "Performance based network concept for advanced air traffic services," in *Integrated Communications Navigation and Surveillance (ICNS),* Herndon, 2016.

[16] L. Golubchik, J. Lui, T. Tung, A. Chow, W.-J. Lee, G. Franceschinis and C. Anglano, “Multi-path continuous media streaming: what are the benefits?,” *Performance Evaluation,* vol. 49, no. 1-4, pp. 429-449, 2002.

[17] P. Torres Compta, F. H. P. Fitzek and D. E. Lucani, “Network coding is the 5G Key Enabling Technology: effects and strategies to manage heterogeneous packet lengths,” *Transactions on Emerging Telecommunications Technologies,* vol. 26, no. 1, pp. 46-55, 2014.

[18] D. Gómez Depoorter and O. Lücke, “Required Communication Technical Performance, the application layer QoS metric for aeronautical data communications,” in *21st Ka and Broadband Communications Conference,* Bologna, 2015.

[19] D. Gómez Depoorter, O. Raissouni, E. Temprado Garriga and O. Lücke, “The ACROSS Testbed for the Future Aeronauitcal Data Communications,” in *ICNS,* Herndon, 2016.

[20] D. Gómez Depoorter and W. Kellerer, “Designing the Air-Ground Data Links for Future Air Traffic Control Communications,” *IEEE Transactions on Aerospace and Electronic Systems,* vol. 55, no. 1, pp. 135-146, 2019.

[21] D. Gómez Depoorter and W. Kellerer, “Multiple-Path Erasure Coding for Future Air Traffic Control Communications,” *Journal of Air Transportation,* vol. 27, no. 3, pp. 109-120, 2019.

[22] B. Kamali, “An Overview of VHF Civil Radio Network and the Resolution of Spectrum Depletion,” in *Integrated Communications Navigation and Surveillance Conference (ICNS),* Herndon, 2010.

[23] L. Crouzard, G. Gawinowski, O. Robert and P. Smith, “IPv6 and Internet Technology for the Aeronautical Telecommunication Network. A New Networking Approach,” in *Proceedings of the USA/FAA Air Traffic Management R&D Seminar 2000,* Naples, 2000.

[24] V. Devarapalli, R. Wakikawa, A. Petrescu and P. Thubert, “RFC3963. Network Mobility (NEMO) Basic Support Protocol,” 2005.

[25] S. Plass, R. Hermenier, O. Lücke, D. Gómez Depoorter, T. Tordjman, M. Chatterton, M. Amirfeiz, S. Scotti, Y. Cheng, P. Pillai, T. Gräupl, F. Durand, K. Murphy, A. Marriott and A. Zaytsev, “Flight trial demonstration of seamless aeronautical networking,” *IEEE Communications Magazine,* vol. 52, no. 5, pp. 119-128, 2014.

[26] D. Johnson, C. Perkins and J. Arkko, “RFC 3775. Mobility Support in IPv6,” 2004.

[27] S. Kent and K. Seo, “RFC 4301. Security Architecture for the Internet Protocol,” 2005.

[28] S. Kent, “RFC 4303. IP Encapsulating Security Payload (ESP),” 2005.

[29] S. Kelly and S. Frankel, “RFC 4868. Using HMAC-SHA-256, HMAC-SHA-384, and HMAC-SHA-512 with IPsec,” 2007.

[30] C. Kaufman, P. Hoffman, Y. Nir, P. Eronen and T. Kivinen, “RFC7296. Internet Key Exchange Protocol Version 2 (IKEv2),” 2014.

[31] S. Deering and R. Hinden, “RFC 2460. Internet Protocol, Version 6 (IPv6) Specification,” 1998.

[32] M. Ehammer, T. Gräupl and C.-H. Rokitansky, “On the Economic Feasibility of the IPS over Aeronautical Communication Links,” in *Integrated Communications Navigation and Surveillance Conference (ICNS),* Herndon, 2010.

[33] K. Sandlund, G. Pelletier and L.-E. Jonsson, *RFC 5795. The RObust Header Compression (ROHC) Framework,* 2010.

[34] R. Hermenier and C. Kissling, “Optimization of Robust Header Compression for Aeronautical Communication,” in *Integrated Communications, Navigation and Surveillance Conference (ICNS),* Herndon, 2013.

[35] T. Tordjman and O. Lücke, “Evaluation of RObust Header Compression for Aeronautical Operational Data,” in *Advanced Satellite Multimedia Systems Conference (ASMS),* Baiona, 2012.

[36] JARUS WG 5, “Required C2 Performance (RLP) concept,” 2016.

[37] European Aviation Safety Agency, “Technical issues in the implementation of Regulation (EC) in the implementation of Regulation (EC) No. 29/2009 (Data Link),” 2014.

[38] “Project Number 15.02.04. D01 - Final Project Report,” SESAR Joint Undertaking, Brussels, 2016.

[39] “Project Number 15.02.06. D124 - Final Project Report,” SESAR Joint Undertaking, Brussels, 2016.

[40] SESAR Joint Undertaking, “SESAR Joint Undertaking | European collaboration demonstrates use of existing satellite communication systems for enhanced air traffic management,” 2016. [Online]. Available: http://www.sesarju.eu/newsroom/all-news/european-collaboration-demonstrates-use-existing-satellite-communication-systems. [Accessed 6 January 2018].

[41] D. Gómez Depoorter, O. Lücke, O. Raissouni, E. Temprado, G. Wedzinga and A. McKay, “D7.4-2 Report on Communicate assessment platform,” 2015.

[42] S. Henriksen, “Unmanned Aircraft System Control and ATC Communications Bandwidth Requirements,” National Aeronautics and Space Administration, Cleveland, 2008.

[43] NATO Standardization Agency, *STANAG 4586 (EDITION 3) - Standard Interfaces of UAV Control System (UCS) for NATO UAV Interoperability,* 3rd ed., Brussels, 2012.

[44] S. Xu, M. Pérez Pérez, K. Yang and J. Hubert, “Determination of the latency effects on surgical performance and the acceptable latency levels in telesurgery using the dV-Trainer (R) simulator,” *Surgical Endoscopy,* vol. 28, no. 9, p. 2569–2576, 2014.

[45] R. Smith and S. Chauhan, “Using Simulators to Measure Communication Latency Effects in Robotic Telesurgery,” in *Interservice/Industry Training, Simulation, and Education Conference (I/ITSEC),* 2012.

[46] “The air force men who fly drones in Afghanistan by remote control,” *The Telegraph,* 24 September 2012.

[47] Y. Shang and M. Hadjitheodosiou, “TCP splitting protocol for broadband aeronautical satellite network,” in *The 23rd Digital Avionics Systems Conference,* 2004.

[48] P. Reinecke and K. Wolter, “On Stochastic Fault-Injection for IP-Packet Loss Emulation,” in *Computer Performance Engineering - 8th European Performance Engineering Workshop,* Borrowdale, 2011.

[49] A. Roy, “National Air Space (NAS) Data Exchange Environment Through 2060,” National Aeronautics and Space Administration, Cleveland, 2015.

[50] E. Gilbert, “Capacity of a burst-noise channel,” *The Bell System Technical Journal,* vol. 39, no. 5, pp. 1253-1265, 1960.

[51] Iridium Communications Inc., “Iridium Declares Victory; $3 Billion Satellite Constellation Upgrade Complete - Feb 9, 2019,” 6 Februay 2019. [Online]. Available: http://investor.iridium.com/2019-02-06-Iridium-Declares-Victory-3-Billion-Satellite-Constellation-Upgrade-Complete. [Accessed 21 March 2019].

[52] Aviation Week Network, “Iridium Eyes Mid-2019 for Certus Connectivity | Connected Aerospace content from Aviation Week,” 17 October 2018. [Online]. Available: http://aviationweek.com/connected-aerospace/iridium-eyes-mid-2019-certus-connectivity. [Accessed 15 December 2018].

[53] F. O'Connor and F. Durand, "ATN/OSI over sandra mobile IP network: A way to allow existing ATM solutions to leverage any broadband aircraft-ground link technologies," in *Integrated Communications, Navigation and Surveillance Conference (ICNS)*, Herndon, 2013.

[54] EUROCONTROL, "General Terrestrial Data Link - LDACS," [Online]. Available: https://www.eurocontrol.int/articles/general-terrestrial-data-link-ldacs. [Accessed 4 November 2016].

[55] J. Budinger and E. Hall, "Aeronautical Mobile Airport Communications System (AeroMACS)," in *Future Aeronautical Communications*, Rijeka, InTech, 2011, pp. 235-262.

[56] P. Pulini, S. Plass, L. Taponecco, M. Morelli and L. Sanguinetti, "AeroMACS Evolution - Analysis during Landing, Takeoff, and Approach Phases," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 50, no. 3, pp. 1899-1912, 2014.

[57] Inmarsat, "Inmarsat SwiftBroadband coverage," October 2013. [Online]. Available: https://www.inmarsat.com/wp-content/uploads/2013/10/Inmarsat_SwiftBroadband_Coverage_Map.pdf. [Accessed 13 December 2017].

[58] P. Lemme, "SatCom 101 "Operational and Safety Services"," [Online]. Available: https://www.nbaa.org/events/amc/2012/news/presentations/1030-Tue/NBAA2012-1030-SatCom101-Safety-Services.pdf. [Accessed 4 November 2016].

[59] Performance-based Operations Aviation Rulemaking Committee Communications Working Group, "FANS 1/A over Iridium and Performance-Based Concept Recommendations," 2010.

[60] K. O'Keefe and M. Meza, "Report on the Validation of the Requirements in the AMS(R)S SARPs for Iridium," ICAO, 2007.

[61] M. M. McMahon and R. Rathburn, "Measuring Latency in Iridium Satellite Constellation Data Services," in *10th International Command and Control Research and Technology Symposium*, 2005.

[62] NAL Research Corporation, "NAL - Network Reference - SBD," 2013. [Online]. Available: http://www.nalresearch.com/NetRef_SBD.html. [Accessed 4 November 2016].

[63] N. Witt and I. Herail, "Generic Requirements for an ATN/VDL Mode 2 Air/Ground Communications Service Provider," EUROCONTROL, 2013.

[64] J. Kitaori, "Results of LDACS PHY BER performances with GNU Radio," ICAO WG-M, Montréal, 2013.

[65] M. Sajatovic, B. Haindl, M. Ehammer, T. Gräupl, M. Scnell, U. Epple and S. Brandes, "L-DACS1 System Proposal: Deliverable D2," EUROCONTROL, Brussels, 2009.

[66] T. Gräupl and M. Mayr, "Method to emulate the L-band digital aeronautical communication system for SESAR evaluation and verification," in *Digital Avionics Systems Conference (DASC)*, Prague, 2015.

[67] "L-DACS2 System Proposal: Deliverable D2," EUROCONTROL, Brussels, 2009.

[68] D. Gómez Depoorter, "TUM (default) RCP Performance Simulator," 20 April 2019. [Online]. Available: http://doi.org/10.14459/2019mp1485087.

[69] Performance-based Operations Aviation Rulemaking Committee Communications Working Group, "FANS 1/A over Inmarsat-4 Classic Aero (FOICA) Recommendations," 2012.

[70] T. Brewer, "FANS 1/A over SwiftBroadband Performance Analysis," 2016. [Online]. Available: https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/systemops/ato_intl/documents/ipacg/ipacg42/ipacg42fit29_ip03_fans1a_over_sbb_faa.pdf. [Accessed 9 February 2018].

[71] R. Zaruba, “Air/Ground Data Communication Radios for Future ATM,” in *Digital Avionics Systems Conference (DASC),* Prague, 2015.

[72] P. Radford, “Post Implementation Monitoring,” [Online]. Available: https://www.icao.int/APAC/Meetings/2013_FIT_Asia2_RASMAG18/5.%20Performance%20 Monitoring.pdf. [Accessed 9 February 2018].

[73] J. Gonda, D. Zeng, J. Goh, M. Bernock and K. Salisbury, “Mitre data communication laboratory initiative for Departure Clearance (DCL),” in *Integrated Communications, Navigation and Surveillance Conference (ICNS),* Herndon, 2013.

[74] D. Zeng and J. Gonda III, “Verifying Required Communication Performance in Air Traffic Management,” *Journal of Air Transportation,* vol. 24, no. 1, pp. 9-17, 2016.

[75] D. Fernández, M. Admella, L. Albiol and J. M. Cebrián, “Satellite Communications Data Link Solutions for Long Term Air Traffic Management,” in *Fourth SESAR innovation days*, Madrid, 2014.

[76] G. Cosenza, A. Mura, A. Righetto, F. De Piccoli, D. Rapisardi and L. Anselmi, “DeSIRE 2: Satcom Modeling and Simulation a Powerful Tool to Enable Cost Effective and Safe Approach to RPAS Operational Deployment,” *Lecture Notes in Computer Science,* vol. 9991, pp. 309-336, 2016.

[77] O. Lücke, D. Gómez Depoorter, T. Tordjman and F. Kühndel, “The SANDRA Testbed for the Future Aeronautical Communication Network,” in *Integrated Communications Navigation and Surveillance (ICNS),* Herndon, 2013.

[78] N. Fistas, “Future Aeronautical Communications: The Data Link Component,” in *Future Aeronautical Communications,* Rijeka, InTech, 2011, pp. 227-234.

[79] F. L. Templin, R. Jain and Sheffield, “Requirements for an integrated UAS CNS architecture,” in *Integrated Communications, Navigation and Surveillance Conference (ICNS),* Herndon, 2017.

[80] M. Muhammad and M. Berioli, “Transport Protocol for Future Aeronautics,” in *Future Aeronautical Communications*, Rijeka, InTech, 2011, pp. 83-100.

[81] M. Muhammad, T. d. Cola, C. Kissling and M. Berioli, “Reliable Aeronautical Services Protocol: Motivation, Design, and Performance,” in *Global Communications Conference*, Atlanta, 2013.

[82] J. P. Rohrer, A. Jabbar, E. Perrins and J. P. Sterbenz, "Cross-Layer Architectural Framework for Highly-Mobile Multihop Airborne Telemetry Networks," in *Military Communications Conference,* San Diego, 2008.

[83] J. P. Rohrer, “End-to-End Disruption-Tolerant Transport Protocol Issues and Design for Airborne Telemetry Networks,” in *44th International Telemetering Conference,* San Diego, 2008.

[84] “Implementation of the AeroTP Transport Protocol in Python,” in *48th International Telemetering Conference*, San Diego, 2012.

[85] A. Pirovano and F. Garcia, “A New Survey on Improving TCP Performances over Geostationary Satellite Link,” *Network and Communication Technologies,* vol. 2, no. 1, pp. 1-18, 2013.

[86] C. Caini and R. Firrincieli, “TCP Hybla: a TCP enhancement for heterogeneous networks,” *International Journal of Satellite Communications and Networking,* vol. 22, no. 5, pp. 547-566, 2004.

[87] C. Caini, R. Firrincieli and D. Lacamera, “PEPsal: a Performance Enhancing Proxy designed for TCP,” in *Vehicular Technology Conference*, Melbourne, 2006.

[88] H. Liu, H. Ma, M. El Zarki and S. Gupta, “Error control schemes for networks: An overview,” *Mobile Networks and Applications,* vol. 2, no. 2, pp. 167-182, 1997.

[89] R. Gallager, “Low-density parity-check codes,” *IRE Transactions on Information Theory,* vol. 8, no. 1, pp. 21-28, 1962.

[90] I. S. Reed and G. Solomon, “Polynomial Codes Over Certain Finite,” *Journal of the Society for Industrial and Applied Mathematics,* vol. 8, no. 2, pp. 300-304, 1960.

[91] S.-Y. R. Li, R. W. Yeung and N. Cai, “Linear Network Coding,” *IEEE Transactions on Information Theory,* vol. 49, no. 2, pp. 371-381, 2003.

[92] C. Berrou, A. Glavieux and P. Thitimajshima, “Near Shannon limit error-correcting coding and decoding: Turbo-codes,” in *International Conference on Communications*, Geneva, 1993.

[93] D. S. Lun, M. Médard and R. E. M. Koetter, “On Coding for Reliable Communications Over Packet Networks,” *Physical Communication,* vol. 1, no. 1, pp. 3-20, 2008.

[94] P. Davis and B. Boisvert, “Hyper-Spectral Networking Concept of Operations and Future Air Traffic Management Simulations,” in *Digital Avionics Systems Conference*, St. Petersburg, 2017.

[95] B. Kubera and M. Ehammer, “A Survey of Multilink Concepts for Aeronautical Data Link Communications,” in *Integrated Communications, Navigation and Surveillance Conference (ICNS),* Herndon, 2013.

[96] L. Jie, G. Erling, S. Zhiqiang, L. Wei and X. Hongwei, “AeroMTP: A fountain code-based multipath transport protocol for airborne networks,” *Chinese Journal of Aeronautics,* vol. 28, no. 4, pp. 1147-1162, 2015.

[97] A. Shokrollahi, "Raptor codes," *IEEE Transactions on Information Theory,* vol. 52, no. 6, pp. 2551-2567, 2006.

[98] P. Djukic and S. Valaee, “Reliable Packet Transmissions in Multipath Routed Wireless Networks,” *IEEE Transactions on Mobile Computing,* vol. 5, no. 5, pp. 548-559, 2006.

[99] M. Kurant, “Exploiting the Path Propagation Time Differences in Multipath Transmission with FEC,” *IEEE Journal on Selected Areas in Communications*, vol. 29, no. 5, pp. 1021-1031, 2011.

[100] K. Sha, J. Gehlot and R. Greve, “Multipath Routing Techniques in Wireless Sensor Networks: A Survey,” *Wireless Personal Communications,* vol. 70, no. 2, pp. 807-829, 2013.

[101] S. Dulman, T. Nieberg, J. Wu and P. Havinga, “Trade-Off between Traffic Overhead and Reliability in Multipath Routing for Wireless Sensor Networks,” in *Wireless Communications and Networking,* New Orleans, 2003.

[102] J. Ben-Othman and B. Yahya, “Energy efficient and QoS based routing protocol for wireless sensor networks,” *Journal of Parallel and Distributed Computing,* vol. 70, no. 8, pp. 849-857, 2010.

[103] “Multipath TCP (mptcp) - documents,” Internet Engineering Task Force, [Online]. Available: https://datatracker.ietf.org/wg/mptcp/documents/. [Accessed 17 January 2018].

[104] J. Cloud, F. d. P. Calmon, W. Zeng, G. Pau, L. M. Zeger and M. Médard, “Multi-Path TCP with Network Coding for Mobile Devices in Heterogeneous Networks,” in *Vehicular Technology Conference,* Las Vegas, 2013.

[105] G. Giambene, D. K. Luong, V. A. Le and M. Muhammad, “Network Coding and MPTCP in Satellite Networks,” in *Advanced Satellite Multimedia Systems Conference,* Palma de Mallorca, 2016.

[106] M. Taghouti, D. E. Lucani, M. V. Pedersen and A. Bouallegue, “On the impact of Zero-Padding in Network Coding Efficiency with Internet Traffic and Video Traces,” in *European Wireless 2016*, 2016.

[107] P. Torres Compta, F. H.P. Fitzek and D. E. Lucani, “Network coding is the 5G Key Enabling Technology: effects and strategies to manage heterogeneous packet lengths,” *Transactions on Emerging Telecommunications Technologies,* vol. 26, no. 1, pp. 46-55, 2015.

[108] M. Taghouti, D. E. Lucani, M. V. Pedersen and A. Bouallegue, “Random Linear Network Coding for Streams with Unequally Sized Packets Overhead Reduction without Zero-Padded Schemes,” in *23rd International Conference on Telecommunications (ICT)*, Thessaloniki, 2016.

[109] B.-Y. Choi, J. H. Kim and C. Beard, “QoS and Channel-Aware Packet Bundling for Capacity Improvement in Cellular Networks,” *IEEE Transactions on Vehicular Technology*, vol. 59, no. 8, pp. 3886-3901, 2010.

[110] A. Jain, M. Gruteser, M. Neufeld and D. Grunwald, “Benefits of Packet Aggregation in Ad-Hoc Wireless Network. Technical Report CU-CS-960-03,” University of Colorado, Boulder, 2003.

[111] M. Ehammer, T. Gräupl and C.-H. Rokitansky, “TCP/IP over aeronautical communication systems — Effects on bandwidth consumption,” in *Digital Avionics Systems Conference*, Orlando, 2009.

A. ANNEX

A.1. CTMC relations

A two-state Continuous-Time Markov Chain (CTMC) is used to represent the loss-related states of the link (see Figure 14). In the forward state (state 0) the packets are correctly transmitted over the link without any bit errors. However, while in drop state (state 1), no packets are transmitted over the link and any tries result in the packets being lost or erased. The CTMC is modelled using two parameters: the rate of change of the forward state μ_0 and the rate of change of the drop state μ_1. The inverse of those parameters is the average time spent in the state.

The stationary probability of being in the state *x* is denoted π_x and the probability of being in state *z* after *t* seconds, while originally being in state *y* is denoted $p_{y,z}(t)$. These relations, for link *l* are calculated using the following equations (taken from [16]):

$$\pi_0^{\{l\}} = \frac{\mu_1^{\{l\}}}{\mu_0^{\{l\}} + \mu_1^{\{l\}}} \tag{44}$$

$$\pi_1^{\{l\}} = \frac{\mu_0^{\{l\}}}{\mu_0^{\{l\}} + \mu_1^{\{l\}}} \tag{45}$$

$$p_{1,0}^{\{l\}}(\tau) = \pi_0^{\{l\}} \cdot \left[1 - \mathrm{e}^{-\left[\mu_0^{\{l\}} + \mu_1^{\{l\}}\right]\tau}\right] \tag{46}$$

$$p_{0,1}^{\{l\}}(\tau) = \pi_1^{\{l\}} \cdot \left[1 - \mathrm{e}^{-\left[\mu_0^{\{l\}} + \mu_1^{\{l\}}\right]\tau}\right] \tag{47}$$

$$p_{1,1}^{\{l\}}(\tau) = \pi_1^{\{l\}} + \pi_0^{\{l\}} \cdot \mathrm{e}^{-\left[\mu_0^{\{l\}} + \mu_1^{\{l\}}\right]\tau} \tag{48}$$

$$p_{0,0}^{\{l\}}(\tau) = \pi_0^{\{l\}} + \pi_1^{\{l\}} \cdot \mathrm{e}^{-\left[\mu_0^{\{l\}} + \mu_1^{\{l\}}\right]\tau} \tag{49}$$

The average packet loss ratio *PLR* is equal to the stationary probability of the drop state, π_1.

A.2. CTMC estimation

In those cases where absolutely no information is available regarding the correlation of losses, the following process has been used to obtain the CTMC values. First, it is assumed that the average duration of the drop state (μ_1^{-1}) is equal to the time required to transmit 5 packets of size 560 bytes. The number of packets is suggested in [34]. The packet length is approximately the average packet size of COCRv2 messages according to [111], that considers 70% of packets of almost 200 bytes and 30% of 1400 bytes. Thus:

$$\mu_1 = \left(\frac{5 \cdot 560 \cdot 8}{B}\right)^{-1} = \frac{B}{22400} \tag{50}$$

To obtain the average duration of the forward state, the average packet loss ratio is used:

$$\mu_0 = \frac{PLR \cdot \mu_1}{(1 - PLR)} \tag{51}$$

If only the *BER* is available, then:

$$\mu_0 = \frac{\left(1-(1-BER)^{(560\cdot 8)}\right)\cdot \mu_1}{(1-BER)^{(560\cdot 8)}} \tag{52}$$

A.3. Generic air-ground data link performance results

This section of the annex contains the performance of the generic air-ground data links from Section 3.4 calculated with the Single-Link RCP model from Section 4.3. The results are analysed in Section 4.4.1. The performance results for the ATC services using the generic GEO SatCom link profile from Section 3.4.1 are provided in Table 24, those using the generic LEO SatCom profile from Section 3.4.2 in Table 25 and those using the generic Direct Wireless link from Section 3.4.3 in Table 26.

The results in Table 24, Table 25 and Table 26 are organized with two rows for each ATC service described in Section 2.4, one for the air-to-ground direction (A2G) and another for the ground-to-air direction (G2A). The results on each cell are the expected continuity for the transaction time required by each service with 95% continuity or $T_{95\%}$ (see Table 3) and the expected continuity for the transaction time with required continuity C or T_C (see Table 3). Whenever the expected continuity (value in Table 24, Table 25 and Table 26) is smaller than the required continuity (value in Table 3), the expected continuity value is coloured in red. All the results are given for the four airspace domains defined in Section 2.4. Some services are not used in all domains. The cells corresponding to the continuity of a service for a domain in which it is not defined is filled with a "not applicable" or N/A. Also, the ORP columns of the Direct Wireless link are filled with N/A because that link provides no coverage outside continental airspace; the N/A is red if the ATC service has requirements for the ORP domain. The "*A*" column corresponds to the availability parameter of the RCP metric.

For example, the C&P ACL service in the air-to-ground direction is defined only for the TMA, ENR and ORP domains. Thus, the "$T_{95\%}$ (APT)" and "T_C (APT)" columns are filled with a "N/A". The transaction time requirements with 95% continuity (see Table 3) are 2.4 s (TMA and ENR) and 5.9 s (ORP). The expected continuity with the GEO SatCom (Table 24) for 2.4 s is 0.43762 and for 5.9 s is 0.45987. Given that these values are below the 0.95000 requirement, they are coloured in red. Then, the transaction time requirements with C continuity are 7.8 s (TMA and ENR) and 16.0 s (ORP). The expected continuity with the GEO SatCom (Table 24) for 7.8 s is 0. 46226 and for 16.0 s is 0.46589. Since these values are below the C requirement of 0.9996 from Table 3, the expected continuity is coloured in red.

The expected continuity for the two SatCom links (Table 24 and Table 25) is calculated using the optimistic approximation defined in Section 3.2.4. This approximation provides the highest expected continuity of all approximations and it is higher than above the actual continuity provided by the link. Despite using the optimistic approximation, the results show that the expected continuity is below the required continuity. The expected continuity obtained for the Direct Wireless link (Table 26) exceed the required continuity. The results shown in Table 26 are the same regardless of the approximation, since all results are either 1.00000 (so they are rounded to 1 with the given the number of significant figures) or correspond to services with one packet per message (no approximation is needed for those).

Service	**Dir.**	**$T_{95\%}$ (APT)**	**$T_{95\%}$ (TMA)**	**$T_{95\%}$ (ENR)**	**$T_{95\%}$ (ORP)**	**T_C (APT)**	**T_C (TMA)**	**T_C (ENR)**	**T_C (ORP)**	**A**
ACL	A2G	0.37787	0.37787	0.37787	0.45987	0.45658	0.45658	0.45658	0.46589	0.9999
ACL	G2A	0.37787	0.37787	0.37787	0.45987	0.45658	0.45658	0.45658	0.46589	0.9999
ACM	A2G	0.84235	0.84235	0.84235	0.92874	0.92538	0.92538	0.92538	0.93483	0.9999
ACM	G2A	0.84212	0.84212	0.84212	0.92874	0.92538	0.92538	0.92538	0.93483	0.9999
AMC	A2G	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
AMC	G2A	0.91906	0.91906	0.91906	N/A	0.93121	0.93121	0.93121	N/A	0.9999
ARMAND	A2G	N/A	N/A	0.92434	N/A	N/A	N/A	0.93380	N/A	0.9999

Service	**Dir.**	$T_{95\%}$ **(APT)**	$T_{95\%}$ **(TMA)**	$T_{95\%}$ **(ENR)**	$T_{95\%}$ **(ORP)**	T_C **(APT)**	T_C **(TMA)**	T_C **(ENR)**	T_C **(ORP)**	**A**
ARMAND	G2A	N/A	N/A	0.92434	N/A	N/A	N/A	0.93380	N/A	0.9999
C&P ACL	A2G	N/A	0.43762	0.43762	0.45987	N/A	0.46226	0.46226	0.46589	0.9999
C&P ACL	G2A	N/A	0.43762	0.43762	0.45987	N/A	0.46226	0.46226	0.46589	0.9999
COTRAC (int.)	A2G	N/A	0.01024	0.01024	0.01141	N/A	0.01155	0.01155	0.01175	0.9999
COTRAC (int.)	G2A	N/A	0.01065	0.01065	0.01185	N/A	0.01201	0.01201	0.01220	0.9999
COTRAC (wil.)	A2G	N/A	0.15680	0.15680	0.16825	N/A	0.16959	0.16959	0.17144	0.9999
COTRAC (wil.)	G2A	N/A	0.15963	0.15963	0.17118	N/A	0.17255	0.17255	0.17441	0.9999
D-ALERT	A2G	0.90553	0.90553	0.90553	0.92870	0.93116	0.93116	0.93116	0.93483	0.9999
D-ALERT	G2A	0.90585	0.90585	0.90585	0.92874	0.93116	0.93116	0.93116	0.93483	0.9999
D-ATIS (arr)	A2G	0.14204	0.14204	0.14204	0.15435	0.15414	0.15414	0.15414	0.15665	0.9999
D-ATIS (arr)	G2A	0.00689	0.00689	0.00689	0.00791	0.00789	0.00789	0.00789	0.00810	0.9999
D-ATIS (dep)	A2G	0.43762	0.43762	0.43762	0.46267	0.46226	0.46226	0.46226	0.46730	0.9999
D-ATIS (dep)	G2A	0.14204	0.14204	0.14204	0.15435	0.15414	0.15414	0.15414	0.15665	0.9999
DCL	A2G	0.46267	N/A	N/A	N/A	0.46730	N/A	N/A	N/A	0.9999
DCL	G2A	0.93158	N/A	N/A	N/A	0.93626	N/A	N/A	N/A	0.9999
D-FLUP	A2G	0.14293	0.14293	0.15174	0.15529	0.15509	0.15509	0.15638	0.15760	0.9999
D-FLUP	G2A	0.00720	0.00720	0.00793	0.00824	0.00822	0.00822	0.00833	0.00844	0.9999
DLL	A2G	0.84183	0.90583	0.92434	0.93158	0.93116	0.93116	0.93380	0.93626	0.9999
DLL	G2A	0.84001	0.90569	0.92429	0.93158	0.93116	0.93116	0.93378	0.93626	0.9999
D-ORIS	A2G	N/A	0.14204	0.14204	0.15435	N/A	0.15414	0.15414	0.15665	0.9999
D-ORIS	G2A	N/A	0.00000	0.00000	0.00001	N/A	0.00001	0.00001	0.00001	0.9999
D-OTIS	A2G	0.14204	0.14204	0.14204	0.15435	0.15414	0.15414	0.15414	0.15665	0.9999
D-OTIS	G2A	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.9999
D-RVR	A2G	0.11380	0.11380	0.14204	0.15435	0.15133	0.15133	0.15414	0.15665	0.9999
D-RVR	G2A	0.02591	0.02591	0.03485	0.03891	0.03790	0.03790	0.03884	0.03968	0.9999
DSC	A2G	N/A	N/A	0.03891	0.03944	N/A	N/A	0.03968	0.03964	0.9999
DSC	G2A	N/A	N/A	0.15435	0.15595	N/A	N/A	0.15665	0.15654	0.9999
D-SIG	A2G	0.15174	0.15174	N/A	N/A	0.15638	0.15638	N/A	N/A	0.9999
D-SIG	G2A	0.01097	0.01097	N/A	N/A	0.01147	0.01147	N/A	N/A	0.9999
D-SIGMENT	A2G	0.14293	0.14293	0.14293	0.15529	0.15509	0.15509	0.15509	0.15760	0.9999
D-SIGMENT	G2A	0.03529	0.03529	0.03529	0.03939	0.03932	0.03932	0.03932	0.04017	0.9999
D-TAXI	A2G	0.90585	0.90585	N/A	N/A	0.93116	0.93116	N/A	N/A	0.9999
D-TAXI	G2A	0.43850	0.43850	N/A	N/A	0.46319	0.46319	N/A	N/A	0.9999
DYNAV	A2G	N/A	N/A	0.92434	0.93158	N/A	N/A	0.93380	0.93626	0.9999
DYNAV	G2A	N/A	N/A	0.92429	0.93158	N/A	N/A	0.93378	0.93626	0.9999
FLIPCY	A2G	0.90584	0.90584	0.90584	0.92874	0.93116	0.93116	0.93116	0.93483	0.9999
FLIPCY	G2A	0.90585	0.90585	0.90585	0.92874	0.93116	0.93116	0.93116	0.93483	0.9999
FLIPINT	A2G	0.15680	0.15680	0.15680	0.16825	0.16959	0.16959	0.16959	0.17144	0.9999
FLIPINT	G2A	0.90584	0.90584	0.90584	0.92874	0.93116	0.93116	0.93116	0.93483	0.9999
ITP ACL	A2G	N/A	0.43762	0.43762	0.45987	N/A	0.46226	0.46226	0.46589	0.9999

Service	**Dir.**	$T_{95\%}$ **(APT)**	$T_{95\%}$ **(TMA)**	$T_{95\%}$ **(ENR)**	$T_{95\%}$ **(ORP)**	T_C **(APT)**	T_C **(TMA)**	T_C **(ENR)**	T_C **(ORP)**	**A**
ITP ACL	G2A	N/A	0.43762	0.43762	0.45987	N/A	0.46226	0.46226	0.46589	0.9999
M&S ACL	A2G	N/A	0.43762	0.43762	0.45987	N/A	0.46226	0.46226	0.46589	0.9999
M&S ACL	G2A	N/A	0.43762	0.43762	0.45987	N/A	0.46226	0.46226	0.46589	0.9999
PAIRAPP ACL	A2G	N/A	0.43762	N/A	N/A	N/A	0.46226	N/A	N/A	0.9999
PAIRAPP ACL	G2A	N/A	0.43762	N/A	N/A	N/A	0.46226	N/A	N/A	0.9999
PPD	A2G	0.92434	0.92434	0.92434	0.93158	0.93380	0.93380	0.93380	0.93626	0.9999
PPD	G2A	0.92434	0.92434	0.92434	0.93158	0.93380	0.93380	0.93380	0.93626	0.9999
SAP (Setup)	A2G	N/A	0.43762	0.43762	N/A	N/A	0.46226	0.46226	N/A	0.9999
SAP (Setup)	G2A	N/A	0.43762	0.43762	N/A	N/A	0.46226	0.46226	N/A	0.9999
SAP (Report)	A2G	N/A	0.90585	0.90585	N/A	N/A	0.93116	0.93116	N/A	0.9999
SAP (Report)	G2A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
SURV (ATC)	A2G	0.02137	0.75178	0.75178	0.75178	0.91428	0.93121	0.93121	0.93121	0.9999
SURV (ATC)	G2A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
URCO	A2G	0.90585	0.90585	0.90585	0.92874	0.93116	0.93116	0.93116	0.93483	0.9999
URCO	G2A	0.90585	0.90585	0.90585	0.92874	0.93116	0.93116	0.93116	0.93483	0.9999
WAKE	A2G	0.02137	0.75178	0.75178	N/A	0.91428	0.93121	0.93121	N/A	0.9999
WAKE	G2A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 24: ECTP of the ATC services with the GEO SatCom link (optimistic approximation)

Service	**Dir.**	$T_{95\%}$ **(APT)**	$T_{95\%}$ **(TMA)**	$T_{95\%}$ **(ENR)**	$T_{95\%}$ **(ORP)**	T_C **(APT)**	T_C **(TMA)**	T_C **(ENR)**	T_C **(ORP)**	**A**
ACL	A2G	0.00000	0.00000	0.00000	0.75216	0.74587	0.74587	0.74587	0.88555	0.9999
ACL	G2A	0.00000	0.00000	0.00000	0.75216	0.74587	0.74587	0.74587	0.88555	0.9999
ACM	A2G	0.12915	0.12915	0.12915	0.95724	0.89227	0.89227	0.89227	0.98156	0.9999
ACM	G2A	0.00000	0.00000	0.00000	0.95346	0.89053	0.89053	0.89053	0.98174	0.9999
AMC	A2G	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
AMC	G2A	0.88356	0.88356	0.88356	N/A	0.96732	0.96732	0.96732	N/A	0.9999
ARMAND	A2G	N/A	N/A	0.89009	N/A	N/A	N/A	0.98060	N/A	0.9999
ARMAND	G2A	N/A	N/A	0.87907	N/A	N/A	N/A	0.97200	N/A	0.9999
C&P ACL	A2G	N/A	0.14425	0.14425	0.75216	N/A	0.82065	0.82065	0.88555	0.9999
C&P ACL	G2A	N/A	0.14425	0.14425	0.75216	N/A	0.82065	0.82065	0.88555	0.9999
COTRAC (int.)	A2G	N/A	0.00000	0.00000	0.00000	N/A	0.00000	0.00000	0.00000	0.9999
COTRAC (int.)	G2A	N/A	0.00000	0.00000	0.00000	N/A	0.00000	0.00000	0.00000	0.9999
COTRAC (wil.)	A2G	N/A	0.00000	0.00000	0.00000	N/A	0.00000	0.00000	0.00000	0.9999
COTRAC (wil.)	G2A	N/A	0.00000	0.00000	0.00000	N/A	0.00000	0.00000	0.00000	0.9999
D-ALERT	A2G	0.00000	0.00000	0.00000	0.00000	0.20191	0.20191	0.20191	0.96927	0.9999
D-ALERT	G2A	0.78944	0.78944	0.78944	0.95724	0.96608	0.96608	0.96608	0.98156	0.9999
D-ATIS (arr)	A2G	0.00000	0.00000	0.00000	0.68998	0.68481	0.68481	0.68481	0.79750	0.9999
D-ATIS (arr)	G2A	0.00000	0.00000	0.00000	0.50394	0.46546	0.46546	0.46546	0.64800	0.9999
D-ATIS (dep)	A2G	0.12070	0.12070	0.12070	0.83260	0.82638	0.82638	0.82638	0.90317	0.9999

Service	**Dir.**	$T_{95\%}$ **(APT)**	$T_{95\%}$ **(TMA)**	$T_{95\%}$ **(ENR)**	$T_{95\%}$ **(ORP)**	T_C **(APT)**	T_C **(TMA)**	T_C **(ENR)**	T_C **(ORP)**	**A**
D-ATIS (dep)	G2A	0.00000	0.00000	0.00000	0.70997	0.70473	0.70473	0.70473	0.81405	0.9999
DCL	A2G	0.82013	N/A	N/A	N/A	0.89534	N/A	N/A	N/A	0.9999
DCL	G2A	0.96839	N/A	N/A	N/A	0.98865	N/A	N/A	N/A	0.9999
D-FLUP	A2G	0.00000	0.00000	0.52355	0.74018	0.71727	0.71727	0.74773	0.84056	0.9999
D-FLUP	G2A	0.00000	0.00000	0.00000	0.50890	0.00000	0.00000	0.62335	0.62904	0.9999
DLL	A2G	0.00000	0.19505	0.88371	0.96766	0.96168	0.96168	0.97613	0.98412	0.9999
DLL	G2A	0.00000	0.00000	0.37877	0.95989	0.89469	0.89469	0.96927	0.98408	0.9999
D-ORIS	A2G	N/A	0.00000	0.00000	0.68998	N/A	0.68481	0.68481	0.79750	0.9999
D-ORIS	G2A	N/A	0.00000	0.00000	0.00000	N/A	0.00000	0.00000	0.00000	0.9999
D-OTIS	A2G	0.00000	0.00000	0.00000	0.71717	0.71130	0.71130	0.71130	0.81997	0.9999
D-OTIS	G2A	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.32633	0.9999
D-RVR	A2G	0.00000	0.00000	0.00000	0.73366	0.60944	0.60944	0.72275	0.83430	0.9999
D-RVR	G2A	0.00000	0.00000	0.00000	0.62827	0.12193	0.12193	0.57683	0.75566	0.9999
DSC	A2G	N/A	N/A	0.54050	0.55262	N/A	N/A	0.66785	0.66718	0.9999
DSC	G2A	N/A	N/A	0.70083	0.78503	N/A	N/A	0.80427	0.80413	0.9999
D-SIG	A2G	0.52355	0.52355	N/A	N/A	0.74773	0.74773	N/A	N/A	0.9999
D-SIG	G2A	0.00000	0.00000	N/A	N/A	0.00000	0.00000	N/A	N/A	0.9999
D-SIGMENT	A2G	0.00000	0.00000	0.00000	0.74018	0.71727	0.71727	0.71727	0.84056	0.9999
D-SIGMENT	G2A	0.00000	0.00000	0.00000	0.63845	0.58881	0.58881	0.58881	0.76967	0.9999
D-TAXI	A2G	0.78474	0.78474	N/A	N/A	0.96554	0.96554	N/A	N/A	0.9999
D-TAXI	G2A	0.00000	0.00000	N/A	N/A	0.84832	0.84832	N/A	N/A	0.9999
DYNAV	A2G	N/A	N/A	0.89048	0.96864	N/A	N/A	0.98056	0.98842	0.9999
DYNAV	G2A	N/A	N/A	0.20720	0.95931	N/A	N/A	0.96927	0.98418	0.9999
FLIPCY	A2G	0.20603	0.20603	0.20603	0.94425	0.96308	0.96308	0.96308	0.98126	0.9999
FLIPCY	G2A	0.78003	0.78003	0.78003	0.95644	0.96506	0.96506	0.96506	0.98165	0.9999
FLIPINT	A2G	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.9999
FLIPINT	G2A	0.45810	0.45810	0.45810	0.95110	0.96401	0.96401	0.96401	0.98178	0.9999
ITP ACL	A2G	N/A	0.14425	0.14425	0.75216	N/A	0.82065	0.82065	0.88555	0.9999
ITP ACL	G2A	N/A	0.14425	0.14425	0.75216	N/A	0.82065	0.82065	0.88555	0.9999
M&S ACL	A2G	N/A	0.14425	0.14425	0.75216	N/A	0.82065	0.82065	0.88555	0.9999
M&S ACL	G2A	N/A	0.14425	0.14425	0.75216	N/A	0.82065	0.82065	0.88555	0.9999
PAIRAPP ACL	A2G	N/A	0.14425	N/A	N/A	N/A	0.82065	N/A	N/A	0.9999
PAIRAPP ACL	G2A	N/A	0.14425	N/A	N/A	N/A	0.82065	N/A	N/A	0.9999
PPD	A2G	0.87580	0.87580	0.87580	0.96727	0.97037	0.97037	0.97037	0.98285	0.9999
PPD	G2A	0.88932	0.88932	0.88932	0.96848	0.98066	0.98066	0.98066	0.98858	0.9999
SAP (Setup)	A2G	N/A	0.09093	0.09093	N/A	N/A	0.83119	0.83119	N/A	0.9999
SAP (Setup)	G2A	N/A	0.14425	0.14425	N/A	N/A	0.82065	0.82065	N/A	0.9999
SAP (Report)	A2G	N/A	0.78003	0.78003	N/A	N/A	0.96506	0.96506	N/A	0.9999
SAP (Report)	G2A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
SURV (ATC)	A2G	0.00000	0.00000	0.00000	0.00000	0.85104	0.96703	0.96703	0.96703	0.9999

Service	**Dir.**	$T_{95\%}$ **(APT)**	$T_{95\%}$ **(TMA)**	$T_{95\%}$ **(ENR)**	$T_{95\%}$ **(ORP)**	T_C **(APT)**	T_C **(TMA)**	T_C **(ENR)**	T_C **(ORP)**	**A**
SURV (ATC)	G2A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
URCO	A2G	0.79423	0.79423	0.79423	0.95748	0.96662	0.96662	0.96662	0.98151	0.9999
URCO	G2A	0.78474	0.78474	0.78474	0.95701	0.96554	0.96554	0.96554	0.98160	0.9999
WAKE	A2G	0.00000	0.00000	0.00000	N/A	0.85104	0.96703	0.96703	N/A	0.9999
WAKE	G2A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 25: ECTP of the ATC services with the LEO SatCom link (optimistic approximation)

Service	**Dir.**	$T_{95\%}$ **(APT)**	$T_{95\%}$ **(TMA)**	$T_{95\%}$ **(ENR)**	$T_{95\%}$ **(ORP)**	T_C **(APT)**	T_C **(TMA)**	T_C **(ENR)**	T_C **(ORP)**	**A**
ACL	A2G	1.00000	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
ACL	G2A	1.00000	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
ACM	A2G	1.00000	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
ACM	G2A	1.00000	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
AMC	A2G	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
AMC	G2A	1.00000	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
ARMAND	A2G	N/A	N/A	1.00000	N/A	N/A	N/A	1.00000	N/A	0.9999
ARMAND	G2A	N/A	N/A	1.00000	N/A	N/A	N/A	1.00000	N/A	0.9999
C&P ACL	A2G	N/A	1.00000	1.00000	N/A	N/A	1.00000	1.00000	N/A	0.9999
C&P ACL	G2A	N/A	1.00000	1.00000	N/A	N/A	1.00000	1.00000	N/A	0.9999
COTRAC (int.)	A2G	N/A	1.00000	1.00000	N/A	N/A	1.00000	1.00000	N/A	0.9999
COTRAC (int.)	G2A	N/A	1.00000	1.00000	N/A	N/A	1.00000	1.00000	N/A	0.9999
COTRAC (wil.)	A2G	N/A	1.00000	1.00000	N/A	N/A	1.00000	1.00000	N/A	0.9999
COTRAC (wil.)	G2A	N/A	1.00000	1.00000	N/A	N/A	1.00000	1.00000	N/A	0.9999
D-ALERT	A2G	1.00000	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
D-ALERT	G2A	1.00000	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
D-ATIS (arr)	A2G	1.00000	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
D-ATIS (arr)	G2A	1.00000	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
D-ATIS (dep)	A2G	1.00000	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
D-ATIS (dep)	G2A	1.00000	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
DCL	A2G	1.00000	N/A	N/A	N/A	1.00000	N/A	N/A	N/A	0.9999
DCL	G2A	1.00000	N/A	N/A	N/A	1.00000	N/A	N/A	N/A	0.9999
D-FLUP	A2G	1.00000	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
D-FLUP	G2A	1.00000	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
DLL	A2G	1.00000	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
DLL	G2A	1.00000	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
D-ORIS	A2G	N/A	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
D-ORIS	G2A	N/A	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
D-OTIS	A2G	1.00000	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
D-OTIS	G2A	1.00000	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
D-RVR	A2G	1.00000	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999

Service	**Dir.**	**$T_{95\%}$ (APT)**	**$T_{95\%}$ (TMA)**	**$T_{95\%}$ (ENR)**	**$T_{95\%}$ (ORP)**	**T_C (APT)**	**T_C (TMA)**	**T_C (ENR)**	**T_C (ORP)**	**A**
D-RVR	G2A	1.00000	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
DSC	A2G	N/A	N/A	1.00000	N/A	N/A	N/A	1.00000	N/A	0.9999
DSC	G2A	N/A	N/A	1.00000	N/A	N/A	N/A	1.00000	N/A	0.9999
D-SIG	A2G	1.00000	1.00000	N/A	N/A	1.00000	1.00000	N/A	N/A	0.9999
D-SIG	G2A	1.00000	1.00000	N/A	N/A	1.00000	1.00000	N/A	N/A	0.9999
D-SIGMENT	A2G	1.00000	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
D-SIGMENT	G2A	1.00000	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
D-TAXI	A2G	1.00000	1.00000	N/A	N/A	1.00000	1.00000	N/A	N/A	0.9999
D-TAXI	G2A	1.00000	1.00000	N/A	N/A	1.00000	1.00000	N/A	N/A	0.9999
DYNAV	A2G	N/A	N/A	1.00000	N/A	N/A	N/A	1.00000	N/A	0.9999
DYNAV	G2A	N/A	N/A	1.00000	N/A	N/A	N/A	1.00000	N/A	0.9999
FLIPCY	A2G	1.00000	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
FLIPCY	G2A	1.00000	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
FLIPINT	A2G	1.00000	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
FLIPINT	G2A	1.00000	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
ITP ACL	A2G	N/A	1.00000	1.00000	N/A	N/A	1.00000	1.00000	N/A	0.9999
ITP ACL	G2A	N/A	1.00000	1.00000	N/A	N/A	1.00000	1.00000	N/A	0.9999
M&S ACL	A2G	N/A	1.00000	1.00000	N/A	N/A	1.00000	1.00000	N/A	0.9999
M&S ACL	G2A	N/A	1.00000	1.00000	N/A	N/A	1.00000	1.00000	N/A	0.9999
PAIRAPP ACL	A2G	N/A	1.00000	N/A	N/A	N/A	1.00000	N/A	N/A	0.9999
PAIRAPP ACL	G2A	N/A	1.00000	N/A	N/A	N/A	1.00000	N/A	N/A	0.9999
PPD	A2G	1.00000	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
PPD	G2A	1.00000	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
SAP (Setup)	A2G	N/A	1.00000	1.00000	N/A	N/A	1.00000	1.00000	N/A	0.9999
SAP (Setup)	G2A	N/A	1.00000	1.00000	N/A	N/A	1.00000	1.00000	N/A	0.9999
SAP (Report)	A2G	N/A	1.00000	1.00000	N/A	N/A	1.00000	1.00000	N/A	0.9999
SAP (Report)	G2A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
SURV (ATC)	A2G	0.99553	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
SURV (ATC)	G2A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
URCO	A2G	1.00000	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
URCO	G2A	1.00000	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
WAKE	A2G	0.99555	1.00000	1.00000	N/A	1.00000	1.00000	1.00000	N/A	0.9999
WAKE	G2A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 26: ECTP of the ATC services with the Direct Wireless link

A.4. Generic multiple air-ground data link performance results

This section of the annex contains the minimum number of links needed to meet the requirements of the ATC services using multiple generic air-ground data links from Section 3.4. The results for multiple generic GEO SatCom link profiles (see Section 3.4.1) are provided in Table 27 and for multiple generic LEO SatCom profiles (see Section 3.4.2) are provided in Table 28. The performance is calculated for multiple generic links with the same characteristics but independent from each other and using the MPEC RCP model from Section 5.4. The results are analysed in Section 5.5.1.

The expected performance is compared to the transaction time required by each service with 95% continuity or $T_{95\%}$ (see Table 3) and the expected continuity for the transaction time with required continuity C or T_C (see Table 3), both for each domain (APT, TMA, ENR and ORP). The process is repeated increasing the number of links until a number that meets the requirements is found. The minimum number of links is checked for up to seven links; the number of links available on an aircraft is likely much lower than this though. Also, when the minimum latency of one packet is higher than the required transaction time, the requirements cannot be met regardless of the number of links (marked as "NP"). In both cases, the text is coloured in red. When no requirements are defined, the cell is marked with a not-applicable or N/A.

Service	**Dir.**	$T_{95\%}$ **(APT)**	$T_{95\%}$ **(TMA)**	$T_{95\%}$ **(ENR)**	$T_{95\%}$ **(ORP)**	T_C **(APT)**	T_C **(TMA)**	T_C **(ENR)**	T_C **(ORP)**
ACL	A2G	3	3	3	3	5	5	5	5
ACL	G2A	3	3	3	3	5	5	5	5
ACM	A2G	2	2	2	2	4	4	4	3
ACM	G2A	2	2	2	2	4	4	4	3
AMC	A2G	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
AMC	G2A	2	2	2	N/A	3	3	3	N/A
ARMAND	A2G	N/A	N/A	2	N/A	N/A	N/A	3	N/A
ARMAND	G2A	N/A	N/A	2	N/A	N/A	N/A	3	N/A
C&P ACL	A2G	N/A	3	3	3	N/A	5	5	5
C&P ACL	G2A	N/A	3	3	3	N/A	5	5	5
COTRAC (int.)	A2G	N/A	5	5	5	N/A	> 7	> 7	> 7
COTRAC (int.)	G2A	N/A	5	5	5	N/A	> 7	> 7	> 7
COTRAC (wil.)	A2G	N/A	4	4	4	N/A	6	6	6
COTRAC (wil.)	G2A	N/A	4	4	4	N/A	6	6	6
D-ALERT	A2G	2	2	2	2	3	3	3	3
D-ALERT	G2A	2	2	2	2	3	3	3	3
D-ATIS (arr)	A2G	4	4	4	4	5	5	5	5
D-ATIS (arr)	G2A	6	6	6	6	7	7	7	7
D-ATIS (dep)	A2G	3	3	3	3	4	4	4	4
D-ATIS (dep)	G2A	4	4	4	4	5	5	5	5
DCL	A2G	3	N/A	N/A	N/A	5	N/A	N/A	N/A
DCL	G2A	2	N/A	N/A	N/A	3	N/A	N/A	N/A
D-FLUP	A2G	4	4	4	4	5	5	5	5
D-FLUP	G2A	6	6	5	5	7	7	7	7
DLL	A2G	2	2	2	2	3	3	3	3
DLL	G2A	2	2	2	2	3	3	3	3
D-ORIS	A2G	N/A	4	4	4	N/A	5	5	5
D-ORIS	G2A	N/A	> 7	> 7	> 7	N/A	> 7	> 7	> 7
D-OTIS	A2G	4	4	4	4	5	5	5	5
D-OTIS	G2A	> 7	> 7	> 7	> 7	> 7	> 7	> 7	> 7
D-RVR	A2G	4	4	4	4	5	5	5	5
D-RVR	G2A	5	5	5	4	6	6	6	6
DSC	A2G	N/A	N/A	4	4	N/A	N/A	7	7

Service	**Dir.**	**$T_{95\%}$ (APT)**	**$T_{95\%}$ (TMA)**	**$T_{95\%}$ (ENR)**	**$T_{95\%}$ (ORP)**	**T_C (APT)**	**T_C (TMA)**	**T_C (ENR)**	**T_C (ORP)**
DSC	G2A	N/A	N/A	4	4	N/A	N/A	6	6
D-SIG	A2G	4	4	N/A	N/A	5	5	N/A	N/A
D-SIG	G2A	4	4	N/A	N/A	6	6	N/A	N/A
D-SIGMENT	A2G	4	4	4	4	5	5	5	5
D-SIGMENT	G2A	5	5	5	4	6	6	6	6
D-TAXI	A2G	2	2	N/A	N/A	3	3	N/A	N/A
D-TAXI	G2A	3	3	N/A	N/A	5	5	N/A	N/A
DYNAV	A2G	N/A	N/A	2	2	N/A	N/A	3	3
DYNAV	G2A	N/A	N/A	2	2	N/A	N/A	3	3
FLIPCY	A2G	2	2	2	2	3	3	3	3
FLIPCY	G2A	2	2	2	2	3	3	3	3
FLIPINT	A2G	4	4	4	4	6	6	6	6
FLIPINT	G2A	2	2	2	2	3	3	3	3
ITP ACL	A2G	N/A	3	3	3	N/A	5	5	5
ITP ACL	G2A	N/A	3	3	3	N/A	5	5	5
M&S ACL	A2G	N/A	3	3	3	N/A	5	5	5
M&S ACL	G2A	N/A	3	3	3	N/A	5	5	5
PAIRAPP ACL	A2G	N/A	3	N/A	N/A	N/A	5	N/A	N/A
PAIRAPP ACL	G2A	N/A	3	N/A	N/A	N/A	5	N/A	N/A
PPD	A2G	2	2	2	2	3	3	3	3
PPD	G2A	2	2	2	2	3	3	3	3
SAP (Setup)	A2G	N/A	3	3	N/A	N/A	5	5	N/A
SAP (Setup)	G2A	N/A	3	3	N/A	N/A	5	5	N/A
SAP (Report)	A2G	N/A	2	2	N/A	N/A	3	3	N/A
SAP (Report)	G2A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
SURV (ATC)	A2G	> 7	3	3	3	5	4	4	4
SURV (ATC)	G2A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
URCO	A2G	2	2	2	2	3	3	3	3
URCO	G2A	2	2	2	2	3	3	3	3
WAKE	A2G	> 7	3	3	N/A	4	4	3	N/A
WAKE	G2A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 27: Minimum number GEO SatCom links required to meet the ATC service continuity requirements

Service	**Dir.**	**$T_{95\%}$ (APT)**	**$T_{95\%}$ (TMA)**	**$T_{95\%}$ (ENR)**	**$T_{95\%}$ (ORP)**	**T_C (APT)**	**T_C (TMA)**	**T_C (ENR)**	**T_C (ORP)**
ACL	A2G	> 7	> 7	> 7	2	4	4	4	2
ACL	G2A	> 7	> 7	> 7	2	4	4	4	2
ACM	A2G	> 7	> 7	> 7	1	3	3	3	2
ACM	G2A	> 7	> 7	> 7	1	4	4	4	2
AMC	A2G	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
AMC	G2A	2	2	2	N/A	2	2	2	N/A
ARMAND	A2G	N/A	N/A	2	N/A	N/A	N/A	1	N/A

Service	Dir.	$T_{95\%}$ (APT)	$T_{95\%}$ (TMA)	$T_{95\%}$ (ENR)	$T_{95\%}$ (ORP)	T_C (APT)	T_C (TMA)	T_C (ENR)	T_C (ORP)
ARMAND	G2A	N/A	N/A	2	N/A	N/A	N/A	2	N/A
C&P ACL	A2G	N/A	3	3	2	N/A	4	4	2
C&P ACL	G2A	N/A	3	3	2	N/A	4	4	2
COTRAC (int.)	A2G	N/A	NP	NP	NP	N/A	> 7	> 7	6
COTRAC (int.)	G2A	N/A	NP	NP	NP	N/A	NP	NP	8
COTRAC (wil.)	A2G	N/A	NP	NP	NP	N/A	> 7	> 7	4
COTRAC (wil.)	G2A	N/A	NP	NP	NP	N/A	> 7	> 7	4
D-ALERT	A2G	NP	NP	NP	NP	> 7	> 7	> 7	3
D-ALERT	G2A	2	2	2	1	3	3	3	2
D-ATIS (arr)	A2G	4	4	4	3	4	4	4	1
D-ATIS (arr)	G2A	6	6	6	4	5	5	5	1
D-ATIS (dep)	A2G	3	3	3	2	3	3	3	1
D-ATIS (dep)	G2A	4	4	4	3	4	4	4	1
DCL	A2G	2	N/A	N/A	N/A	2	N/A	N/A	N/A
DCL	G2A	1	N/A	N/A	N/A	1	N/A	N/A	N/A
D-FLUP	A2G	5	5	3	3	4	4	2	1
D-FLUP	G2A	> 7	> 7	4	3	4	4	3	2
DLL	A2G	NP	> 7	2	1	3	3	2	1
DLL	G2A	NP	NP	2	1	3	3	3	2
D-ORIS	A2G	N/A	4	4	3	N/A	4	4	1
D-ORIS	G2A	N/A	NP	NP	7	N/A	> 7	> 7	3
D-OTIS	A2G	4	4	4	3	4	4	4	1
D-OTIS	G2A	> 7	> 7	> 7	5	6	6	6	2
D-RVR	A2G	> 7	> 7	5	3	4	4	4	1
D-RVR	G2A	> 7	> 7	6	4	4	4	4	1
DSC	A2G	N/A	N/A	3	1	N/A	N/A	2	2
DSC	G2A	N/A	N/A	3	1	N/A	N/A	2	2
D-SIG	A2G	3	3	N/A	N/A	2	2	N/A	N/A
D-SIG	G2A	NP	NP	N/A	N/A	7	7	N/A	N/A
D-SIGMENT	A2G	5	5	5	3	4	4	4	1
D-SIGMENT	G2A	7	7	7	3	4	4	4	1
D-TAXI	A2G	2	2	N/A	N/A	3	3	N/A	N/A
D-TAXI	G2A	4	4	N/A	N/A	4	4	N/A	N/A
DYNAV	A2G	N/A	N/A	2	1	N/A	N/A	1	1
DYNAV	G2A	N/A	N/A	2	1	N/A	N/A	2	1
FLIPCY	A2G	2	2	2	1	3	3	3	2
FLIPCY	G2A	2	2	2	1	3	3	3	2
FLIPINT	A2G	NP	NP	NP	NP	> 7	> 7	> 7	4
FLIPINT	G2A	2	2	2	1	3	3	3	2
ITP ACL	A2G	N/A	3	3	2	N/A	4	4	2

Service	**Dir.**	$T_{95\%}$ **(APT)**	$T_{95\%}$ **(TMA)**	$T_{95\%}$ **(ENR)**	$T_{95\%}$ **(ORP)**	T_C **(APT)**	T_C **(TMA)**	T_C **(ENR)**	T_C **(ORP)**
ITP ACL	G2A	N/A	3	3	2	N/A	4	4	2
M&S ACL	A2G	N/A	3	3	2	N/A	4	4	2
M&S ACL	G2A	N/A	3	3	2	N/A	4	4	2
PAIRAPP ACL	A2G	N/A	3	N/A	N/A	N/A	4	N/A	N/A
PAIRAPP ACL	G2A	N/A	3	N/A	N/A	N/A	4	N/A	N/A
PPD	A2G	2	2	2	1	2	2	2	1
PPD	G2A	2	2	2	1	1	1	1	1
SAP (Setup)	A2G	N/A	3	3	N/A	N/A	4	4	N/A
SAP (Setup)	G2A	N/A	3	3	N/A	N/A	4	4	N/A
SAP (Report)	A2G	N/A	2	2	N/A	N/A	3	3	N/A
SAP (Report)	G2A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
SURV (ATC)	A2G	NP	> 7	> 7	> 7	5	3	3	3
SURV (ATC)	G2A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
URCO	A2G	2	2	2	1	3	3	3	2
URCO	G2A	2	2	2	1	3	3	3	2
WAKE	A2G	NP	> 7	> 7	N/A	4	3	3	N/A
WAKE	G2A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 28: Minimum number of LEO SatCom links required to meet the ATC service continuity requirements