Optimal Datalink Selection for Future Aeronautical Telecommunication Networks

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***Abstract*—Modern aeronautical telecommunication networks (ATN) make use of different simultaneous datalinks to deliver robust, secure and efficient ATN services. This paper proposes a Multiple Attribute Decision Making based optimal datalink selection algorithm which considers different attributes including safety, QoS, costs and user/operator preferences. An intelligent TRigger-based aUtomatic Subjective weighTing (*i*-TRUST) method is also proposed for computing subjective weights necessary to provide user flexibility. Simulation results demonstrate that the proposed algorithm significantly improves the performance of the ATN system.**

***Index Terms*—Aeronautical communications, datalink selection, intelligent algorithm, Multiple Attribute Decision Making.**

I. Introduction

THE capacity demand in aeronautical telecommunication networks (ATN) for air traffic control (ATC) and air traffic management (ATM) systems has grown dramatically over the past years. The rise in the capacity demand is reflected by the growing number of aircraft and passengers, which is expected to double by 2035 [1], as well as the introduction of new high data rate aeronautical communications services, in particular Internet applications. As a result, the need to improve the capacity, safety and efficiency of the global airspace has prompted several global initiatives to modernize ATM systems, most notably the EU Single European Sky ATM Research (SESAR) and the US Next-Generation Air Transportation System (NextGen) programmes, with a major focus on Air Traffic Services (ATS) and Aeronautical Operational Control (AOC) operating concepts and requirements [2].

The ATM modernization requires a paradigm shift from the current analogue voice to digital data communications to handle the increasing amount of and more complex information exchange between controllers and pilots for future ATM operational procedures [3]. ATM applications include both safety-critical, such as AOC and ATS, and non-safety critical services, such as Airline Administration Control (AAC) and Aeronautical Passenger Communications (APC) services. The AOC and APC services are expected to be the major motivation for broadband communications due to the higher transmission rate requirement [4]. In addition, future integration of unmanned air vehicles (UAVs) is expected to add further complexity to the already congested civil air space. Eurocontrol and the American Federal Aviation Administration (FAA) have identified two primary drivers for anticipating the increasing demand of the future aeronautical broadband services: i) an appropriate communication infrastructure to support emerging and future radio technologies, and to cater for future air traffic growth, and ii) a consistent global solution to support a seamless ATM system [3]. Therefore, an integrated ATN solution is becoming imperative for aircraft operators to improve the capacity, efficiency and cost-effectiveness of the ATM system while ensuring a high degree of its flexibility, scalability, modularity and reconfigurability.

The EU project NEWSKY (Networking the Sky) [2] specified a single system based on IP technology with the capability of transmitting data through multiple datalinks, directly to the ground via satellites. Another EU project SANDRA (Seamless Aeronautical Networking through Integration of Data Links, Radios and Antennas) [5], [6] defined an Integrated Modular Radio (IMR) building on sophisticated software-defined radio (SDR) technology. The SANDRA project integrated multiple datalinks directly to the ground networks such as including VHF Digital Link mode 2 (VDL 2) and Aeronautical Mobile Airport Communications System (AeroMACS) and/or via satellites to provide aeronautical communication services. The IMR concept of SANDRA project was further validated in the UK project SINCBAC (Secure Integrated Network Communications for Broadband and ATM Connectivity) to provide secure voice and data connectivity for both ATM and passenger services through a heterogeneous set of radio access technologies (VDL 2, Iridium and Inmarsat BGAN) to connect with the ground ATN infrastructure. Each datalink has its own transmission characteristics providing communication services and is configured to deliver either safety critical or non-safety critical communication services or a combination of both. However, in a heterogeneous radio environment in an aircraft, different applications have different QoS requirements, security requirements and user/operator preferences. The on-board terminal when forwarding the data is required to select the right datalink due to the safety and high demand of the expensive datalinks. Therefore, it is an imperative decision to select the best datalink to transfer data when multiple datalinks are available in order to provide an efficient, reliable, secure and cost-effective communication solution, and none of the previous projects have considered an optimized datalink selection process.

Authors in [7] have discussed the importance of the

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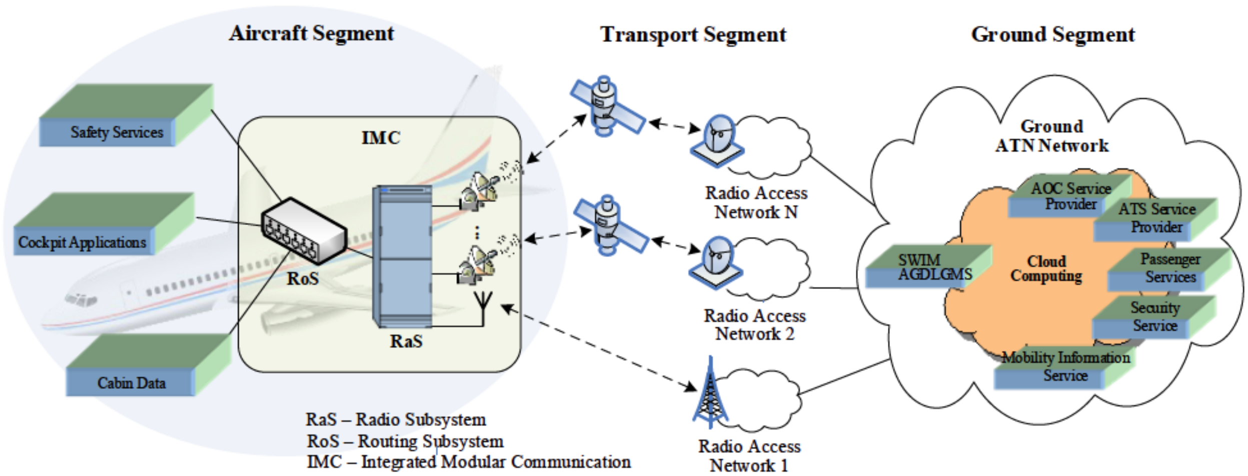

Fig. 1. An integrated modular communication ATM architecture.

optimised datalink selection in this context, but they neither analyzed nor suggested results for it. Currently, link selection in heterogeneous mobile communications environment is usually made based on the reference signal strength [2]. The challenging task is to consider multiple criteria in terms of the datalink characteristics, type of services or applications together with user and aircraft operator preferences [8]. Since it is necessary to consider many attributes simultaneously, a multiple attribute decision making (MADM) approach [9]–[11] is required. MADM based techniques are gaining popularity due to its relatively high precision and capability of adopting user and operator preferences [10], [12]. When multiple attributes are considered, decision makers must compute the weight of each attribute representing their relative importance in order to rank available alternatives. There are two broad categories of determining weights: objective and subjective methods [9]. While the latter is related to user experience, the objective method does not take any user preference into account. Two objective weighting methods such as entropy and variance [8], [10] and three well-known subjective weighting methods such as eigenvector [10], weighted least square [8], [12] and Trigger-based aUtomatic Subjective weighting (TRUST) [8], [11] methods are commonly used. The first two subjective weighting methods do not work well for the datalink selection problem since their pair-wise comparison process is slow and not automatic [8], [9], [11]. The TRUST method [11] has the ability to automatically compute the subjective weights and it is comparatively fast and efficient.

Despite the automatic subjective weight computation by the TRUST method, it completely ignores certain attributes that are not important to the users, but they may be important from other perspectives such as the operator, for example, to improve the system efficiency. Consequently, the link selection decision may not be optimal. Another limitation of the TRUST method is that there is no provision for users to prioritize one event over others as in the eigenvector method, which leads to the inaccuracy of obtaining the subjective weights. To alleviate the limitations of the TRUST method and to address the necessity of the automatic weight computation, an intelligent TRUST (*i*-TRUST) method is proposed in this paper. The proposed *i*-TRUST algorithm is intelligent enough to prioritize user requirements according to relative importance and by introducing a parameter, ( ) added to each attribute to reflect the user preference in a precise way. It is worth noting that the contribution in this paper is two-fold: firstly, the derivation and integration of both objective and subjective weights while formulating the datalink selection problem in the future aeronautical telecommunication networks as an MADM based problem for making optimal datalink selection decisions; and secondly, an intelligent algorithm is proposed to automatically compute the subjective weights that reflects the importance of user preferences in order to improve the overall system performance.

The paper is organized as follows: Section II presents an overview of the ATM architecture. Section III explains the datalink selection techniques while the MADM-based datalink selection procedure with the proposed *i*-TRUST method is described in Section IV. Section V describes the comparative analysis and performance of the proposed optimized algorithm followed by conclusion in Section VI.

II. ATM Architecture

The design of ATM architecture adopts an open standard approach utilizing IP, ETSI and IEEE standards for an integrated communications protocol architecture.

A. Architecture Overview

The ATM system architecture is responsible for the control and management of communications and information exchanges required for the operation primarily consists of three distinct activities [13]: ATC, Air Traffic flow Management (ATFM) and Aeronautical Information Services (AIS). In order to perform these activities, there is a

TABLE I
TRAFFIC DOMAIN MAPPING OF COMMUNICATION SERVICES AND APPLICATIONS.

Traffic Domains	ATN Communication Services	Applications
Safety service traffic	ATS (critical)	Radio (voice) ADS-B/ADS-C Trajectory negotiation Meteo CPDLC Air-Air (Freer)
Cabin data traffic	APC (non-critical) AAC (non-critical)	Email Internet Tel-fax-data Multimedia etc.
Cockpit applications traffic	AOC (critical)	Fleet management Engineering activities Maintenance

requirement to have a reliable and efficient communication environment. There are three main elements of communication environment for activities: the ground ATN network, radio link technologies and a terminal node (TN) on-board aircraft. In this paper, the concept of the ATM architecture distinguishes these three elements as ground, transport, and aircraft segments, respectively, as shown in Fig. 1.

The TN on-board the aircraft is referred to as the integrated modular communication (IMC) terminal consisting of a routing subsystem (RoS) and a radio subsystem (RaS) equipped with multiple datalinks. The RoS represents the network layer of the protocol stack and it consists of a secure router. In this architectural design, the segregation between different traffic domains has to be taken into account due to the high security requirements and the secure router in the RoS is responsible for the secure segregation and security aware routing. Different types of ground applications to the corresponding air applications over different air-ground sub-networks can be provided. Table I provides the traffic domain mapping of communication services and applications. On the other hand, the RaS, which represents the datalink and the physical layers of the protocol stack, supports radio resource allocation, radio link establishment, QoS mapping and protocol adaptation. The TN has the possibility to choose a datalink among available datalinks subject to specific requirements. As the communications involve both operational (ATC, AOC, AAC) and non-operational (APC) services and they share network resources, the optimal datalink selection for a specific service can be challenging due to many challenges including safety and security concerns.

B. Datalink Parameters and Preferences

The TN on-board the aircraft collects information about available datalinks and maintains a database of information that is necessary for decision-making in regards to the selection of the optimal datalink selection. Both the user and operator preferences as well as the data link conditions are considered in making the optimal decision. The following are identified as the most important decision parameters in the datalink selection context:

Link quality: The link quality is measured in terms of received signal strength (RSS), which evaluates the availability of datalinks [14].

QoS requirements: In ATM, the satisfaction of the required QoS in terms of bandwidth, delays and packet loss rate is an important measure for safety and security.

Link costs: Different datalinks may have different charging policies. Therefore, it is important to consider the data usage cost in the datalink selection decision. This is especially the case for aeronautical passenger services.

Resource utilization: Since the number of users supported by each datalink for aeronautical communications is restricted, another key decision making parameter is resource utilization to ensure that the link selection algorithm not only improves the data rate and cost, but also the resource utilization.

Security: Safety-related communications require a security concept handling threats and attacks to the system [15], [16]. The IMC security concept supports the segregation of traffic into different security domains in the aircraft segment, which can dictate the datalink selection decision to a given service.

Additionally, it is also important to provide flexibility to both users and aircraft operators in making the datalink selection process. The rationale for providing the flexibility is to allow, for example, the operator to prefer different settings depending upon their flight types such as economic and/or business class flights, thus the user and operator preferences are also required to consider in the datalink selection process. In the following sections, the necessary procedures for the optimal datalink selection process will be described.

III. DATALINK SELECTION TECHNIQUES

Future aeronautical communication systems are expected to support multiple datalinks for air-ground communications. In order to improve the overall network performance, a datalink selection technique is required to select the best link to be used for any connection request. The selection of the most suitable link is subjected to different flight phases and other ATM operational requirements such as security and safety requirements. Therefore, it is important for the system to fulfil those requirements when considering the possible optimization aspects. As such, a baseline and an optimized datalink selection techniques are considered in this section for comparison.

In both cases, a pre-link selection process illustrated in Fig. 2 takes place to identify candidate datalinks out of the available datalinks that would satisfy a set of pre-defined criteria including the current flight phase, the link characteristics and the QoS requirements before the final selection of a target datalink. The current flight phase information is used to constrain the eligible link alternatives while the QoS requirements give the request's QoS specification as the offered QoS should match the request QoS requirements. The security requirements limit the request that can be used for a

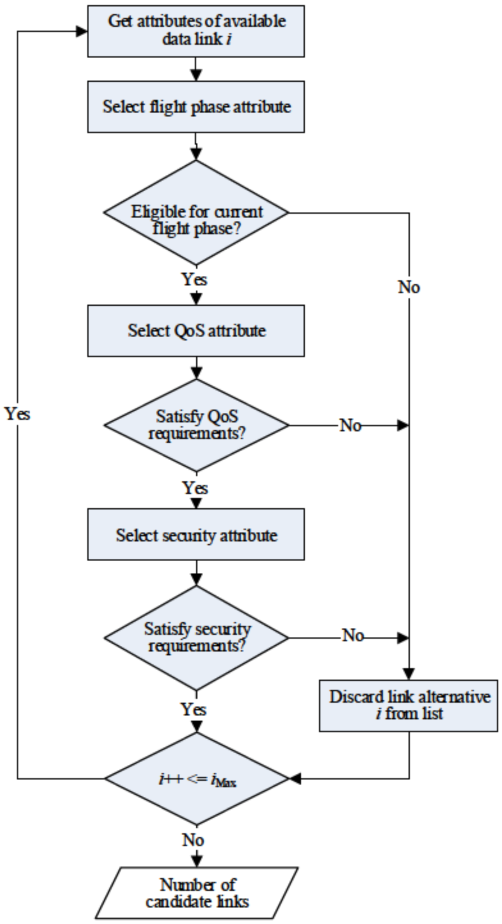

Fig. 2. Pre-link selection flow chart.

particular traffic domain. Whenever an attribute of a link fails to meet those requirements, it is removed from the candidate link list. The rationale of the pre-link selection process is that datalinks that do not fulfil the requirements cannot be selected in order to reduce the complexity.

A. Baseline Datalink Selection

The baseline datalink selection algorithm is a static process that selects the target datalink out of the candidate datalinks by ordering them based on a predefined datalink priority list, $L = \{l_1, l_2, ..., l_n\}$. In this paper, four types of radio links are considered: Inmarsat BGAN (Broadband Global Area Network) Class 4 and Class 6, VDL 2 and Iridium. The two BGAN Classes can be used for both cockpit and passenger voice and data communications, but Class 6 offers higher data rate (432kbps) than that of Class 4 (200kbps). VDL 2 is dedicated for voice and short messages between the pilot and the controller on the ground, while Iridium can be used for both cockpit and passenger voice communications transport. It has to be noted that security measures to segregate cockpit and passengers' communications are outside the scope of this paper, but readers can refer to [17] for more information on risks analysis in relation to this topic. In the baseline algorithm, if a cockpit voice application, for example, is requested, a list of candidate datalinks which satisfy the minimum

TABLE II
Attribute Values for Available Datalinks.

Attributes \ Datalinks	VDL 2	Iridium	BGAN
BR (kbps)	31.5	2.4	Class 4: Up to 200 Class 6: Up to 432
PD (ms)	2000	748	950 (800 to 1100)
BER	$10^{\;5}$	$10^{\;6}$	$10^{\;5}$
RMF	-	-	-
RSS	-	-	-
CST ($/MB[1])	1	7	3

requirements of the requested applications are selected from the pre-selection process. The baseline algorithm will then order the candidate list according to a pre-defined priority factor. If the link usage cost is used as the priority criteria, then an order list can be formed as follows:

1) VDL 2
2) BGAN Class 4 (BGAN1)
3) BGAN Class 6 (BGAN2)
4) Iridium

It implies that VDL 2 is the top choice for the requested applications and Iridium has the lowest priority as the link usage cost is the priority parameter in this case. The relative usage cost of each datalink is shown in Table II, which has been drawn from available packages offered by the corresponding operator. However, the priority can vary depending on the preference. In general, the steps involved in the baseline algorithm are summarized as follows:

***Step 1*:** If there is only one datalink on the candidate link list after the pre-link screening, it will be chosen as the target link to establish connection.

***Step 2*:** If there are more than one candidate datalinks, the candidate datalink list is sorted to form a designated priority link list, L. The algorithm first chooses the datalink with the highest priority from the sorted candidate list as the target link. A connection establishment request is created based on the QoS parameter mapping for the target datalink. In the case of failure for the connection establishment, the second highest priority candidate link is chosen as the target link to establish connection. This process is repeated until a connection is established successfully or all links in the candidate priority list have been tried.

***Step 3*:** If there is no candidate datalink in the list, no connection will be established and the request will be dropped.

The corresponding baseline datalink selection flowchart is illustrated in Fig. 3, where the candidate datalinks are found from the pre-link selection process.

B. Optimised Datalink Selection

The baseline link selection algorithm mainly relies on the pre-defined link priority list based on a single specific attribute and the weakness of the baseline approach is that multiple attributes cannot be used for the link selection process. Thus, the baseline algorithm is not an optimal link selection

[1]These are relative values calculated based available packages for each link.

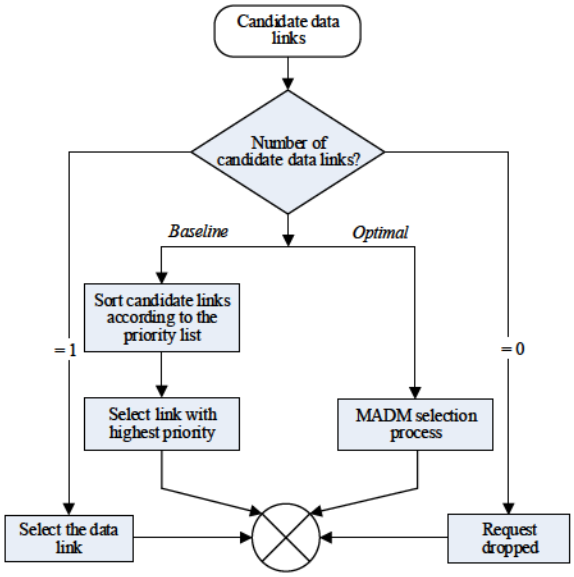

Fig. 3. Baseline and optimal link selection algorithms.

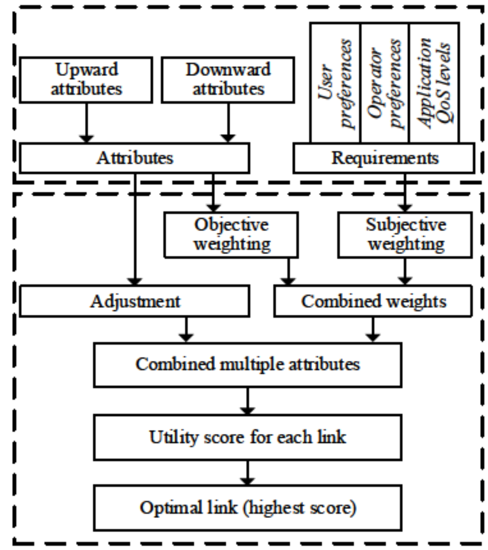

Fig. 4. MADM-based datalink selection process.

algorithm as it only relies on statically configured preferences but not on a wider set of attributes, which are important to consider in making the selection decision.

In the next section, an optimal datalink selection algorithm applying the MADM method integrated with a proposed *i*-TRUST algorithm for subjective weight evaluation to select the most optimum link subject to multiple attributes is derived. This refers to making preferences decision over the candidate datalinks that are characterized by multiple attributes with each datalink having different characteristics and attribute values. The importance of one attribute over another is considered by choosing their weight values. The datalink selection algorithm is presented in Fig. 3 while Fig. 4 illustrates the MADM process, which includes two main steps:

***Initial step*:** This is an information gathering step, where all requirements and information about attributes of every candidate link are collected including user/operator preferences and application requirements.

***MADM step*:** This provides all the necessary steps for the MADM-based datalink selection decision including the adjustment of attribute values through normalization method, computing both objective and subjective weights. The final weight for each attribute is obtained by combining both the objective and subjective weights. In order to make the link selection decision, normalized values of multiple attributes for each candidate link are combined to obtain the utility score for each datalink. Finally, an optimal datalink is determined based on the rank of the utility scores from all candidate datalinks.

The detail analysis of the MADM theory underpinning those steps is explained in the following section.

IV. MADM for Optimal Datalink Selection

A. *Identifying Relevant Attributes*

Adopted attributes are the key to the MADM-based problem and the attributes should be the most important ones deemed relevant to the final decision. A lot of studies have been done in network selection issues using utility functions in terrestrial heterogeneous networks context [9]–[12], [14] and they may not be directly applicable to the aeronautical communications context. This is due to the very different criteria in link selection in aeronautical communications, which must consider the type of aeronautical communications services for the QoS purpose, the policy and rules that may overrule the use of a specific datalink for safety-critical services for safety and security purposes, as well as the airline contract with the aeronautical communication service providers. In addition, a variety of different link technologies may be available for aircraft communications simultaneously and aeronautical communication networks may consider attributes that are different from those considered by terrestrial networks [9]–[12], [14]. Most importantly, the chosen attributes should be measurable in a meaningful and practical way for each of the proposed datalinks. However, the number of adopted attributes, must be restricted for the MADM method to reach a trade-off between computation complexity, requirements and safety services [9]. When considering the attributes for aeronautical communications, one should first think of guaranteeing the required QoS, safety and resource utilisation, which have been discussed in Section II.B. Since the aeronautical communications involve both terrestrial and expensive satellite links, it is therefore important to consider such attributes that have the ability to reflect the link usage cost, link quality, resource utilization, delays as well as to provide flexibility to allow both operators and users to set preferences. Moreover, the performance of each datalink is affected by the received signal strength, which is needed to consider in the decision making.

To determine an optimal link among a diverse set of links, a given set of attributes are considered, which have been carefully identified for the scenario under consideration in this paper, namely: *bit rate* (BR), *packet delay* (PD), *bit error rate* (BER), *relative link costs* (CST), *resource matching factor*

(RMF) and RSS. It is assumed that a playout delay buffer is used to de-jitter the packet voice stream and, hence, jitter is not considered. Security related attribute such as safety or non-safety services has already been taken care of in the pre-link selection. The attributes are classified into *upward* and *downward*. The attributes which have the higher preference relation in favour of the higher values are called upward attributes, *i.e.*, the higher the attribute value the better. On the other hand, downward attributes are in favour of the lower values, *i.e.*, the lower the value the better it is [10]. For example, BR and RSS are upward attributes while PD, BER, CST and RMF are downward attributes. From both operator's and user's point of views, higher values of upward attributes and lower values of downward attributes are preferred. In this regard, an adjustment of the downward attributes into upward attributes is required during normalization process as explained in the following sub-section. The definition and importance of each attribute are described below:

Maximum bit rate (BR): This upward attribute measures the maximum transfer of bits delivered per unit of time and it is the upper limit an application being provided from a datalink.

Packet delay (PD): This downward attribute indicates the maximum delay for delivering packets within the datalink, which is measured in milliseconds.

Bit error rate (BER): This downward attribute is the ratio of the number of error bits to the total number of transmitted bits. It is an important parameter in measuring the performance of datalinks and is used to configure radio interface protocols, algorithms and error detection coding.

Resource matching factor (RMF): It is defined as the difference between the average of the offered bit rate per user and the required bit rate. This indicates how closely fits the required bit rate into the link, i.e., the lower the RMF value the better match. It will provide an improved resource utilization of the system. Therefore, this attribute is considered as a downward attribute and can be defined as:

(1)

where, = average offered bit rate per user in each datalink,
= maximum bit rate in each datalink,
= occupied bit rate in each datalink,
= maximum number of supported users by each datalink,
= current number of user occupied by each datalink.
and, = required bit rate of a request.

Received signal strength (RSS): This upward attribute indicates the link quality and is a measure of power in a received signal in .

Link cost (CST): This downward attribute indicates the average cost of using a datalink, and it can play an important role in the link selection process. The average cost value for each datalink is derived based on the available usage package costs offered in the market.

Table II represents the measures of every attributes for the considered datalinks and the values are chosen based on the specifications [15]. Since the RMF and RSS attributes are dynamic attributes and their values change over time depending upon (1) and the channel condition of the respective datalink, respectively, their corresponding values in the Table II are left blank.

B. Normalization

Different attributes have different measurement units, so normalization is a necessary step in the MADM-based method to avoid anomaly in the decision making process. The normalization method is used to scale different characteristics of different units to a comparable numerical representation. For a given attribute , represents the value of this attribute in the th datalink, and represents its normalized value, where is the normalized function. There are several normalization methods such as Max-Min, Sum, Square-Root and Enhanced Max-Min [10]. However, the first three methods do not consider the difference between upward and downward attributes while the enhanced Max-Min adjusts downward attributes into upward attributes. Therefore, the output of the enhanced Max-Min method are all considered as upward attributes and the enhanced Max-Min method is adopted in this paper as follows:

for upward attributes
for downward attributes
(2)

C. Modelling the Weights

The weighting of an attribute represents its relative importance in regards to other attributes and it determines how different candidate links are ranked. As indicated in previous sections, there are two broad categories of determining weights: objective and subjective methods. The subjective weighting method is related to user experience to obtain subjective weights, while the objective method for obtaining objective weights do not consider user preference.

The objective weights are calculated directly based on the relative difference between attributes, given by for attribute . There are two common methods for objective weighting such as entropy-based and variance-based [10]. The entropy-based method is not suitable for datalink selection problem because it gives higher weights to the attributes that have similar values among all links and lower weights to those attributes with values varying across different links [9]. The optimal datalink selection needs to give high weights to the attributes that can distinguish one link from others. Therefore, the variance-based method is adopted, where if one attribute has exactly the same value in every link, its weight is set to . The variance-based objective weighting is given by [10]:

(3)

where:

(4)

is the number of attributes,
and is the total number of datalinks.

On the contrary, subjective weights are usually calculated based on the subjective feelings of the decision maker taking into account some subjective information such as customer preferences, operator policies and so on as direct inputs [11]. Assuming the subjective weight vector, can be obtained based on that information using a subjective weighting method, and the vector, can be represented as:

(5)

The subjective weight , where can be obtained by using the widely used pair-wise comparison matrix **B** containing all the comparison values between the th and the th attributes. Since its pair-wise comparison is a slow process and not automatic, the TRUST method [11] is proposed to calculate the subjective weights. The motivating part of the TRUST method is its automatic computation of subjective weights in a comparatively fast and efficient way. However, it has some limitations explained in *Section I*. To compensate the limitation of the TRUST method, a new *i*-TRUST method is proposed, which takes advantage of the automatic subjective weighting from TRUST and captures the subjective preferences by users/operators. In the *i*-TRUST, the particular requirements from a user with their relative importance are given by the following vector:

(6)

where is the number of requirements. The values is in the range between and , where . If , the corresponding th requirement is demanded with its importance level between and , while if , there is no demand for the corresponding requirement. Moreover, indicates the highest important whereas indicates the least important requirement while intermediate values indicate mid-level importance between the highest and the lowest. A binary vector is now defined from where for non-zero elements in . A diagonal matrix is then generated from as:

$$\vdots \quad \ddots \quad \vdots \tag{7}$$

where and . A requirement-to-attribute correspondence matrix, is defined based on the pre-defined relationship between requirements and attributes defined in Table III (in Section V) as:

$$\vdots \quad \ddots \quad \vdots \tag{8}$$

where indicates the effect of the th requirement on the th attribute, *i.e.*, either , or . Before considering the subjective preference, a base or local weight vector is used as:

(9)

where is the base weight of the th requirement and these are manually set in advance by the operator or the algorithm designer with possibly using eigenvector method plus analytic hierarchy process (AHP). Table III represents the relationship between trigger events with such base subjective weight vector and this is stored in the aircraft terminal (*i.e.*, TN). In order to reflect the relative importance of the requirements by the user, a new base subjective weighting vector is obtained by using (6), (7), (8) and (9) as:

(10)

where is the element-wise multiplicative operator. Moreover, in order to avoid the undesirable situation of undermining certain attributes in the TRUST method, a scalar value is added to turning all zero elements into non-zeros denoted by . The final subjective weighting vector can be obtained as:

(11)

where is the normalization function and the weight of the th attribute is obtained as:

(12)

The objective and subjective weights are then combined into a single weight, of the th attribute using (4) and (12) as:

(13)

These combined weights are then used to rank the candidate links to obtain the target datalink as described below.

D. Ranking - Obtaining the Optimal Datalink

MADM algorithms can be of two categories: *compensatory* and *non-compensatory* algorithms. Compensatory algorithm combines multiple attributes to find the best alternative whereas the non-compensatory algorithm is used to find acceptable alternatives, which satisfy the minimum requirements, but may not be the optimal one [18]. Compensatory MADM algorithms are more widely used and these include algorithms like simple additive weighting (SAW), multiplicative exponential weighting (MEW), gray rational analysis (GRA) and Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) [18]. Amongst them the SAW method is commonly used for the network selection problem due to its simplicity [19] and hence is adopted in this paper. The utility score of the th datalink by employing the SAW method is given by:

(14)

where is the weight vector of attributes, , and . Clearly, an important step of the SAW operator is to compute the weights of all the given attribute values, which can be obtained by (13), and then aggregate these weighed attributes by addition. Finally, the best link configuration is obtained by ranking them and selecting the one that has the highest utility score, and this is generally obtained by:

(15)

where is the selected and the best datalink for a given request at any instant.

V. Performance Evaluation and Discussion

A. Simulation Scenarios and Parameters

To evaluate the performance of the proposed optimal datalink selection algorithm for aeronautical communications, a scenario is defined where an aircraft is equipped with the IMC terminal with multiple datalinks and users, who make requests, are allowed to provide preferences. The BR, PD, BER, and RSS attributes are affected by the user choice of the quality preference while the user cost preference affects the CST attribute according to Table III. Both real-time (RT) and non-RT (NRT) applications as well as safety and non-safety services are considered. The safety and non-safety services are categorized depending upon the domain of the requested session from different traffic domains such as cockpit, cabin and passengers. In this simulation, a random number of application requests with different requirements is generated and the data rate requirements are uniformly distributed with the minimum and maximum values of 1.5 kbps and 256 kbps, respectively, while the datalink selection is performed for each request. The session arrival rate refers to the number of new applications requested per unit time. For each arrival rate, the simulation is run for 100 times and the average of the results generated from each simulation is taken as the final result for the simulation. It is worth mentioning that the algorithm also provides the flexibility to the operator to tune the base weight, in Table III to set priority depending upon the flight class in selecting the datalink.

A unified scenario considering a combination of possible application requirements, user and operator preferences shown in Table IV is considered to help explain the proposed link selection algorithm for its performance evaluation. On the datalink side, three types of datalinks, *i.e.*, VDL 2, Iridium and BGAN and six attributes have been considered as illustrated in TABLE II. One VDL 2, one Iridium and two BGAN datalinks (explained in Section II.A and denoted by BGAN1 and BGAN2) are used. Two different applications (RT and NRT) with different data rate requirements are assumed. Ten session requests with a combination of different user preferences, such as money first and quality first, and safety or non-safety services are considered, as shown in TABLE IV. Based on the above studies in *Section IV.C* for selecting the optimal datalink, the enhanced Max-Min method is used for normalization. The variance based method is used for objective weighting while the *i*-TRUST method is used for subjective weighting. In the baseline algorithm, the predefined link list defined in *Section III.A* has been used to select the target datalink for a given request without considering any preferences. The values of attributes for each datalink defined in TABLE II are used for numerical analysis. The receiver sensitivity of -98 dBm (VDL 2), -125 dBm (BGAN), -115 dBm (Iridium - voice) and -112 dBm (Iridium - data) are considered according to the corresponding specifications [20]–[22].

B. Results and Discussion

Firstly, the proposed *i*-TRUST method for computing subjective weights has been validated and compared with the existing TRUST method using Matlab simulation. Since the eigenvector method [23] is commonly used for computing subjective weights because of its accuracy, but a slow process due to its use of pairwise comparisons, the idea here is to find which method produces the weight values closest to those computed by the eigenvector method. The subjective weight vector, employing the eigenvector method is obtained by using pair-wise comparison plus AHP. Depending on the individual request, both TRUST and *i*-TRUST methods use Table III for triggering the corresponding attributes according to the preferred events marked by crosses (x) that allow to form the matrix and evaluates all procedures in *Section IV.C*. The subjective weights can then be computed by (11). In order to see the comparison between these two methods, Fig. 5 shows the correlation of the computed subjective weighs by both TRUST and *i*-TRUST methods and it is clearly evident that *i*-TRUST provides more accurate weights than TRUST. This is due to the fact that the *i*-TRUST has taken the user priority in consideration while computing the weights. For the rest of the results in this paper, the *i*-TRUST will be used for computing the subjective weights.

The detailed procedure to obtain the optimal datalink using the proposed method for all the considered unified scenarios (Table IV) is described and compared with the baseline algorithm. The summary of all ten session requests with the selected link for each session by employing both the optimal and baseline algorithms is shown in Table V. The selected datalink for each request by the proposed optimal algorithm is different from that by the baseline algorithm and these are the best selection.

The detailed optimal link selection process for five selected session requests (RID#1, 4, 5, 6 and 10) will be discussed and is illustrated in TABLE VI. The link characteristics shown in the table are based on Table II, equation (1) and the instantaneous received signal strength of the associated link. For RID#1, only BGAN links (BGAN1 and BGAN2) are treated as candidate links during the pre-link selection process. Both VDL2 and Iridium were not considered as candidate links because Iridium does not satisfy the data rate requirement and VDL2 only provides non-safety services. Since all attributes except the RSS have the same values for both links, the optimal algorithm gave higher weight on the RSS attribute, *i.e.*, 0.50793. Finally, the algorithm computes the utility scores for both links and selects the BGAN2, which has the highest utility score and this is due to the better RSS value of the BGAN2 link, *i.e.*, -82 dBm higher than that of BGAN1 (-116dBm). For RID#4, the user preferred the cheapest link

TABLE III
RELATIONSHIP BETWEEN TRIGGER EVENTS AND SUBJECTIVE WEIGHTS OF ATTRIBUTES.

Events and Weights			**Attributes**					
Level 1	Level 2	Base weights,	BR	PD	BER	RMF	RSS	CST
Applications	Real-time (RT)	0.25	x	x				
	Non-RT	0.20			x			
Customer preferences	Low price	0.30						x
Operator preferences	Load condition	0.15				x		
Dynamic attributes	Signal strength	0.10					x	

TABLE IV
UNIFIED SCENARIOS FOR 10 SESSION REQUESTS.

Request ID (RID)	**Data rate requirements (kbps)**	**Applications**		**Users**		**Operators**
		Real-time (RT)	**Non-RT**	**Quality first**	**Money first**	**Safety first**
1	20					
2	15					
3	1.5					
4	12					
5	2					
6	64					
7	32					
8	256					
9	128					
10	256					

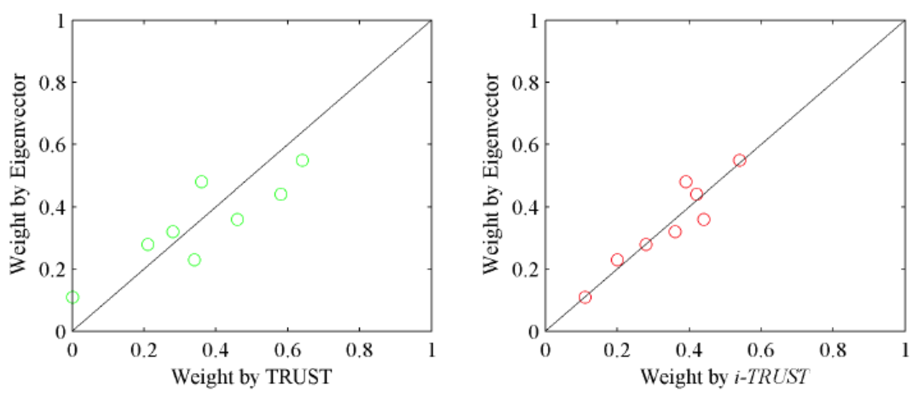

Fig. 5. Comparison results (correlation of weights) between eigenvector, TRUST and *i*-TRUST methods.

TABLE V
OPTIMAL LINK SELECTION BY EMPLOYING THE PROPOSED MADM-BASED ALGORITHM WITH USING THE I-TRUST SUBJECTIVE WEIGHTING METHOD.

Request ID	**Application type**	**Safety/ Non-safety**	**Data rate req. (kbps)**	**Quality importance**	**Price importance**	**Optimal**		**Baseline**	
						RSS (dBm)	**Target link**	**RSS (dBm)**	**Target link**
1	RT	Safety	20	9	1	-82	BGAN2	-100	BGAN1
2	RT	Non-safety	15	9	1	-94	BGAN1	-98	VDL2
3	RT	Safety	1.5	1	9	-80	BGAN2	-80	BGAN2
4	RT	Non-safety	12	1	9	-84	VDL2	-123	BGAN1
5	NRT	Safety	2	9	1	-89	IRIDI	-113	BGAN2
6	NRT	Non-safety	64	9	1	-83	BGAN1	-83	BGAN1
7	NRT	Safety	32	1	9	-82	BGAN2	-82	BGAN2
8	NRT	Non-safety	256	1	9	-93	BGAN1	-93	BGAN1
9	RT	Safety	128	9	1	-76	BGAN2	-76	BGAN2
10	NRT	Non-safety	256	1	9	-	Dropped!	-	Dropped!

TABLE VI
DETAILED OPTIMAL LINK SELECTION PROCESS FOR FIVE SELECTED REQUESTS.

Request requirements (RID:1):

Data rate	:	20
Application	:	Real-Time (RT)
Safety/Non-safety	:	Safety
Quality importance	:	9
Price importance	:	1

Link characteristics:

	BR	PD	BER	RMF	RSS	CST
BGAN1	32.0	950.0	10^{5}	24.73	-100	3.0
BGAN2	32.0	95.0	10^{5}	24.73	-82	3.0

Weights:

	BR	PD	BER	RMF	RSS	CST
W=	0.12577	0.12580	0.02510	0.10040	0.50793	0.11500

Utility scores: 0.246038(BGAN1) 0.753962 (BGAN2)
Optimal link: BGAN2

Request requirements (RID:5):

Data rate	:	2.0
Application	:	Non-Real-Time (NRT)
Safety/Non-safety	:	Safety
Quality importance	:	9
Price importance	:	1

Link characteristics:

	BR	PD	BER	RMF	RSS	CST
IRIDI	2.10	750.0	10^{6}	0.40	-89	7.0
BGAN2	32.0	950.0	10^{5}	24.73	-113	3.0

Weights:

	BR	PD	BER	RMF	RSS	CST
W=	0.01257	0.01260	0.50730	0.05030	0.35969	0.05760

Utility scores: 0.929833 (IRIDI) 0.070167 (BGAN2)
Optimal link: IRIDI

Request requirements (RID:4):

Data rate	:	12
Application	:	Real-Time (RT)
Safety/Non-safety	:	Non-safety
Quality importance	:	1
Price importance	:	9

Link characteristics:

	BR	PD	BER	RMF	RSS	CST
VDL 2	31.5	1200	10^{5}	19.5	-84	1.0
BGAN1	32.0	950	10^{5}	30.8	-123	3.0

Weights:

	BR	PD	BER	RMF	RSS	CST
W=	0.086	0.0861	0.0239	0.0675	0.05594	0.6808

Utility scores: 0.81607 (VDL 2) 0.18393 (BGAN1)
Optimal links: VDL 2

Request requirements (RID:6):

Data rate	:	64
Application	:	Non-Real-Time (NRT)
Safety/Non-safety	:	Non-safety
Quality importance	:	9
Price importance	:	1

Link characteristics:

	BR	PD	BER	RMF	RSS	CST
BGAN1	64	950	10^{5}	2102	-83	3.0

Weights:

	BR	PD	BER	RMF	RSS	CST
W=	0.01257	0.0126	0.5073	0.0503	0.35969	0.0576

Utility scores: 1.0 (BGAN1)
Optimal link: BGAN1

Request requirements (RID: 10):

Data rate	:	256
Application	:	Non-Real-Time (NRT)
Safety/Non-safety	:	Non-safety
Quality importance	:	1
Price importance	:	9

REQUEST DROPPED!

without caring about the link quality. In this case, the optimal algorithm gave more weight to the cost (CST) attribute than others and finally, it selects the VDL2 link which has the highest utility score. Two datalinks (Iridium and BGAN2) were pre-screened as candidate links for the fifth request (RID#5). The BER and RMF attributes were given the higher weight values than others due to the request requirements, *i.e.*, the NRT application, which mainly affect the BER attribute and the RMF attribute is for the operator's choice of interest to enhance the overall system utilization. For RID#6, the algorithm found only one candidate link during the pre-link selection process, so this has been selected as the optimal link. The requested session, RID#10 has been dropped due to the unavailable bandwidth of the links in both cases.

The call dropping probability is defined as the probability that certain session requests (or call requests) are blocked due to lack of resources (*i.e.*, if there are not available datalinks for serving those sessions) and this is usually calculated using Erlang-B formula. Fig. 6 shows the call dropping probability with respect to different arrival rate, λ in order to validate the simulation and theoretical results. It is seen that the call dropping probability increased with λ as expected. However,

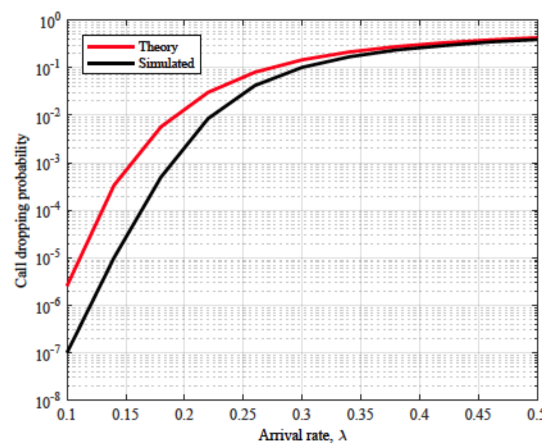

Fig. 6. Call dropping probability for different arrival rates.

there is a minor variation for lower arrival rates between the simulated and theoretical results. This is attributed to the introduction of the RMF attribute in the proposed method, which offers better datalink utilization efficiency, resulting in

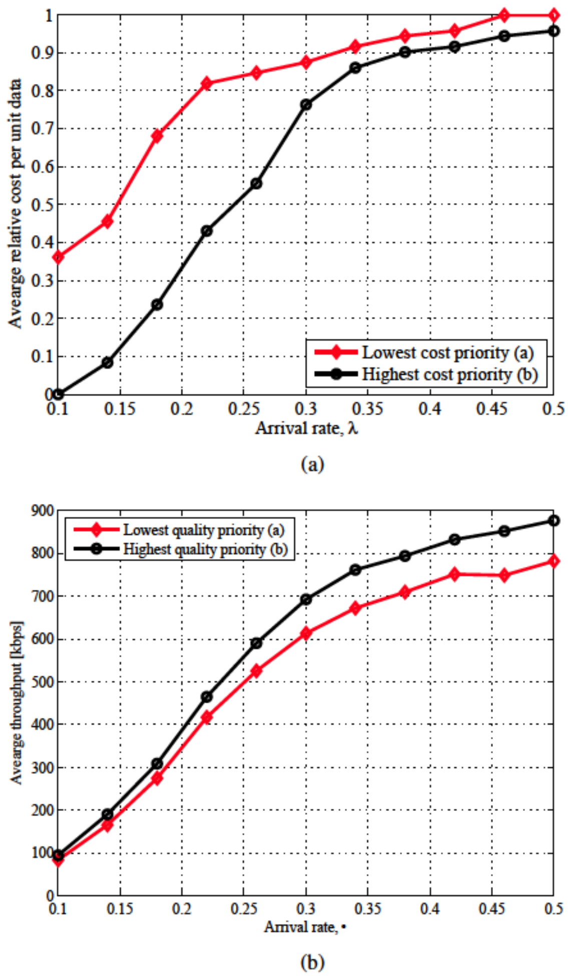

Fig. 7. Illustrating the user preference for improving (a) the service cost and (b) the quality performance.

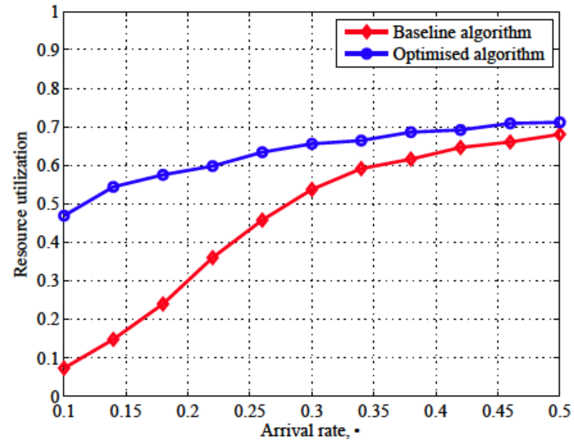

Fig. 8. Resource utilization for different arrival rates.

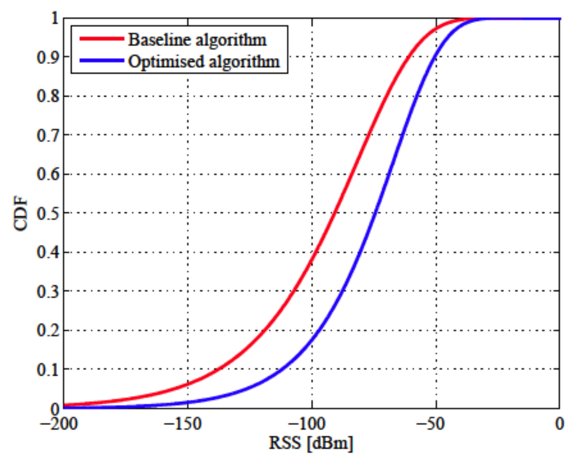

Fig. 9. Cumulative distribution function of the received signal strength.

less calls being dropped. At higher λ, the impact of the RMF attribute becomes less and hence, the simulation result is closer to the theory.

*1) **Cost and throughput analysis:*** Fig. 7(a) shows the cost performance of the proposed algorithm from the user's point of view, *i.e.*, how the user preference affects the performance. The results show the average relative costs per unit data usage for different arrival rates while setting the highest and the lowest cost priority by the user. It is seen that when the user gave the highest priority to the cost parameter (CST), the user was able to save noteworthy data usage costs. For example, over 36% of saving can be achieved by setting the highest cost priority compared to that by setting the lowest cost priority at lower λ. However, the relative saving decreased with the increase of λ due to the lower availability of the cheapest datalink at the higher λ. Similarly, the user preference for the quality attributes shows the similar results in terms of an improved average throughput (up to 12%) as shown in Fig. 7(b), where the users prefer either the highest or lowest priority for the quality attributes while the cost priority was chosen randomly.

*2) **Resource utilization analysis:*** Fig. 8 illustrates the performance of resource utilization of both baseline and proposed optimal algorithms. In the optimal algorithm, the RMF attribute has been considered in order to improve the overall system resource utilization. The results demonstrate that the resource utilization increased with λ in both cases and the optimised algorithm always performed better. When the arrival rate is low, an improvement of up to 81% in the utilization can be achieved with the proposed algorithms compared to the baseline. This is due to the fact that the RMF attribute plays a role to improve the resource utilization by fitting the requested bit rate requirements with the link bandwidth. There were fast increase in the resource utilization of the baseline case as λ increases. It is important to mention that the resource utilization of the baseline approached to that of the optimised one when the arrival rate increased.

*3) **User experience:*** To demonstrate the comparative user experience by using the proposed optimal algorithm, the cumulative distribution function (CDF) of the received signal strength and the average packet delay experienced by each user are shown in Fig. 9 and Fig. 10, respectively. The requested sessions have been generated randomly and the same base weight as in TABLE III are used for computing subjective weights. It can be seen from Fig. 9 (the CDF of RSS) that the higher number of users experiences higher received signal strength with the optimised algorithm than that with the baseline algorithm. For example, the median, *i.e.*, 0.5 on the y-axis for both algorithms shows that 50% of the

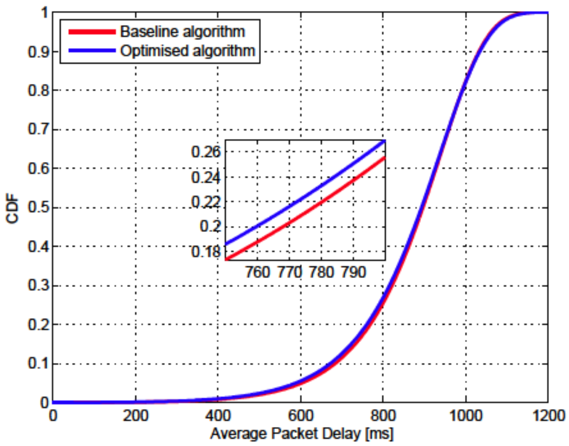

Fig. 10. Cumulative distribution function of the average packet delays.

requested sessions experiences the signal strength of -95 dBm or higher and -75 dBm or higher when employing the baseline and optimal algorithms, respectively. The improvement is derived from the intelligent decision making process of the optimised algorithm based on multiple attribute values, where the proposed *i*-TRUST subjective weighting method in the MADM-based scheme further ensures that the selected datalink is able to offer the good quality signal even if all other link characteristics are the same. On the other hand, the baseline algorithm only considers a pre-defined list. Similarly, the CDF of the average packet delay for the same settings (Fig. 10) also confirms that the optimised algorithm performs better than the baseline algorithm (an improvement of 2%).

VI. Conclusion

In this paper, an integrated modular communication system for an aircraft terminal equipped with an optimal datalink selection algorithm is proposed. In order to select an optimal datalink from a multi-radio terminal, an MADM-based datalink selection algorithm with an intelligent subjective weighting method (*i*-TRUST) is proposed. The algorithm provides greater flexibility to both users and operator in terms of setting their preferences with the capacity of automatic decision making. Results demonstrate that the proposed *i*-TRUST method provides subjective weight values as close as the eigenvector method, which validated the accuracy of computing subjective weights as compared to the existing TRUST method. Finally, the detailed analysis of the proposed MADM-based method has been discussed numerically through regorous simulation analysis, which shows the improvement of the system performance in terms of cost (over 36%), throughput (up to 12%) and resource utilization (up to 81%). The user experience of using high quality datalink is also improved without compromising with the link cost. It is expected that the proposed MADM-based algorithm together the proposed *i*-TRUST subjective weighting method can be employed in other ubiquitous networks.

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