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Simulated Annealing-Based Multilink Selection Algorithm in SDN-Enabled Avionic Networks

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ABSTRACT In this paper, a novel multilink selection framework is developed for different applications with various quality of service (QoS) requirements in avionic systems, based on the multi-attribute decision-making model. Two metaheuristic algorithms are proposed to solve this model while optimizing the multilink selection performances. Multilink configuration and multi-homing capabilities are generally required for aircrafts operating in a heterogeneous wireless network environment. The first algorithm, called Analytic Hierarchy Process and Simulated Annealing (AHP-SA), utilizes a two-phase process. In Phase one, an analytic hierarchy process (AHP) is used to choose the decision weight factors. Then, in Phase two, a simulated annealing process is applied to select suitable networks, for various service requests, based on the weights obtained from first phase. Further, to improve customer satisfaction, Simulated Annealing algorithm for Simultaneous Weights and Network Selection Optimisation (SA-SWNO) is developed, in which a simulated annealing algorithm is applied to dynamically optimize weight factors of objective functions and the request-to-network assignment matrix. Simulation results demonstrate that both proposed algorithms outperform the commonly used price-based or QoS-based network selection scheme with much higher averaged satisfaction degree and lower computational complexity.

INDEX TERMS Avionic, multi-attribute utility, network selection, simulated annealing, multilink and multi-homing.

I. INTRODUCTION

The purpose of network selection in the aeronautical environment is to ensure the always best connection for aircrafts, i.e., to guarantee the aircrafts to access the most suitable, reliable, secure and fast data communication network according to their requirements. A good network selection scheme can not only efficiently improve the degree of satisfaction and quality of experience of aircrafts but also effectively reduce access failures. It is a challenge for these aircrafts to select an optimal access network.

The research of this paper is based on the Cockpit Network Communications Environment Testing (COMET)¹ project under the European Commission's program Clean Sky 2 in partnership with the European aeronautical industry. COMET

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¹<http://www.comet-cs2.eu/>

intended to design, develop, and test novel dual Aircraft Communications Addressing and Reporting System (ACARS) and Internet Protocol Suite (IPS) system for cockpit and ground network infrastructures operating to enable seamless air-to-ground connectivity in support of trajectory-based ATC operations and future airline services.

To select the most suitable link for air-to-ground communications or vice versa, a pre-screen process takes place prior to a multilink selection process. The pre-screen process examines the security policy to discard radio links that are not suitable for safety-critical services. The multilink selection process is then applied to select the most optimal link among the available links. This paper focuses on the multilink selection process. Two simulated annealing (SA) based algorithms are considered: Analytic Hierarchy Process and Simulated Annealing (AHP-SA) and Simultaneous Weights and Network Selection Optimisation (SA-SWNO). Both algorithms take advantage of the benefits of simulated

annealing for global optimisation to select the most optimum link based on multiple network attributes. In AHP-SA, AHP is applied to determine the weights of the different network attributes of the different radio links and SA is used to determine the request-to-assignment matrix through which the scores and ranks of the radio links are obtained. In SA-SWNO, SA is used to optimize the weights of the network attributes of the different radio links and the request-to-assignment matrix simultaneously.

The remaining of this paper is organized as follows: Section II briefly overviews the related work. Section III states the contribution of this paper. Section IV describes the network selection for avionic networks in general. In Section V, the utility function of each network attribute is established, and Section VI demonstrates the aggregate multi-attribute utility function and specific algorithms, including AHP-SA and SA-SWNO algorithms to solve the problem. In Section VII, the performance of both AHP-SA and SA-SWNO is evaluated by simulation results. Finally, Section VIII concludes this paper.

II. RELATED WORK

Many different methods have been proposed for network selection solutions in the literature and can be categorized into four primary techniques:

- *Game theory.* Yan *et al.* [1] proposed a scheme called enhanced congestion game with link failures (E-CGF) to achieve optimal network selection. In congestion games, a set of users compete for a finite set of network resources. The goal of E-CGF is to make a compromise between achieved throughput and transit cost. Yen *et al.* [2] modelled the access point selection games in an IEEE 802.11 access network with the consideration of potential link rate and workload status. Zhang and Peng [3] proposed an algorithm based on game theory for D2D communication relay selection to improve the communication quality and extend the communication coverage. In these methods, the link failure probability is used in a hidden Markov model to improve the connection probability. A user can use more than one radio network simultaneously to improve performances through redundant transmission. This may lead to unnecessary network connection, resulting in non-optimal use of resources at the system level, thereby reducing the system performance.
- *Machine learning.* Wang *et al.* [4] proposed a model-driven framework with a joint offline and online learning to achieve fast and optimal network selection in the ultra-dense heterogeneous networks with multiple radio access technologies (RATs), such as WiFi, UMTS, LTE, and WiMAX. Yan *et al.* [5] proposed a smart aggregated RAT access (SARA) strategy to maximize the long-term network throughput while meeting diverse traffic quality of service (QoS) requirements. Yan *et al.* [5] developed a multiagent reinforcement learning to perform RAT selection in conjunction with resource allocation

for individual user access requests, through sensing dynamic channel states and traffic QoS requirements. Sandoval *et al.* [6] made use of reinforcement learning for the RAT selection problem on the Internet of Thing (IoT) networks. The IoT nodes learned from real-world data to derive optimal RAT selection policies, which are implemented as Artificial Neural Networks (ANN). Luong *et al.* [7] applied deep learning approach to solve multilink selection in the SDN-enabled avionic networks. This method can significantly reduce the running time while still guaranteed a high accuracy of around 98.5-99.2%. Even machine learning has many advantages and is a very hot research topic with many applications, machine learning requires representative and massive data to train a model, and the learning process is time-consuming with the increase of data size.

- *Fuzzy logic with uncertain parameters.* Baldo and Zorzi [8] proposed a distributed cognitive network access scheme by using Fuzzy Logic techniques to process cross-layer communication quality metrics and to estimate the expected transport-layer performance. These estimates and the QoS requirements of the applications are inputs for the Fuzzy Decision-Making techniques to choose the most suitable access opportunity for a user. Bouali *et al.* [9] proposed a novel context-aware user-driven framework for network selection in multi-RAT environments based on fuzzy logic. Although these methods can provide a better solution (selection) from the user perspective, it does not provide a global solution at the system level.
- *Multi-attribute decision-making (MADM).* In this category, it is crucial to determine the weights of different decision factors of the network selection. Different methods can be used to select these weights, for example, Simple Additive Weighting (SAW) [10], Multiplicative Exponential Weighting (MEW) [11], the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [12], Grey Relational Analysis (GRA) [13], and Analytic Hierarchy Process (AHP) [14]. These methods use weigh factors to change a multi-attribute (objective) problem into a single objective optimisation problem and different weight factors lead to different solutions. As a result, the solutions obtained are only optimized with respect to the input weight factors.

Previous works were conducted to investigate the optimal datalink selection problem in the aeronautical communication environment. A Priority Distinction Selection (PDS) algorithm was presented to maximize the number of aircrafts accessing their optimal links [15]. This algorithm starts with the link screening process to determine the number of available networks that can meet users' requirements, then set the user priority accordingly. The aircraft with a smaller number of possible links is assigned with higher priority and is allowed access first. Alam *et al.* [16] proposed an intelligent TRigger-based aUtomatic Subjective weighTing (i-TRUST) method to compute the subjective weights of

different attributes for network selection that reflected the relative importance of user preferences and requirements automatically. However, all these above works are user-centric solutions, in which the network selection decision is taken at the user-side. This user-centric mechanism has significant disadvantages. Since users decide which networks to connect to, there can be a scenario where all the users select the same datalink, which is the best among available links. This behaviour can cause congestion at the specific ground radio station, leading to deterioration of users' quality of experience, and does not optimize the utility of the whole system. In this paper, the Software Defined Networking (SDN) concept has been leveraged to provide a centralized multilink selection that tries to balance the traffic load between various available connections while also satisfying user service requirements. Moreover, in these above approaches, the weight distribution of various factors for network selection and the user-to-network assignment are determined separately. This two-phase process may not guarantee an optimal solution.

III. CONTRIBUTIONS OF THE PAPER

Considering the drawbacks of existing algorithms identified in II for the multi-link selection process, this paper derived two new multilink selection algorithms: AHP-SA and SA-SWNO. The algorithms take advantage of the benefit of SA for global optimisation. In addition, SA is a relatively simple evolutionary algorithm and is less computationally complex. It is suitable for integer programming-based problems such as the multilink selection problem defined in this paper. The main contributions of this paper are summarized as follows:

- An adaptive multilink selection model has been developed based on the aeronautical communication services' requirements and the available network resources.
- An AHP-SA algorithm is proposed as an integer linear programme (ILP) combining the analytic hierarchy process (AHP) with the simulated annealing (SA) approach. In this algorithm, AHP is applied to determine the weights of the network attributes prior to applying the SA algorithm to determine the request-to-network assignment to obtain the most optimum link.
- A SA-SWNO algorithm is developed to simultaneously optimize both the weights of the network attributes and the request-to-network assignment matrix by providing a feedback mechanism from the request-to-assignment matrix to optimize the weights of the network attributes which is then used to optimize the assignment matrix.

Both AHP-SA and SA-SWNO are implemented in MATLAB. Experimental results show that both AHP-SA and SA-SWNO schemes can efficiently handle the selection of multiple datalink networks for aircrafts with various aeronautical communication services access. Under the premise of ensuring QoS guarantee, the average user satisfaction is significantly improved by both AHP-SA and

SA-SWNO when compared with some other well-known network selection schemes.

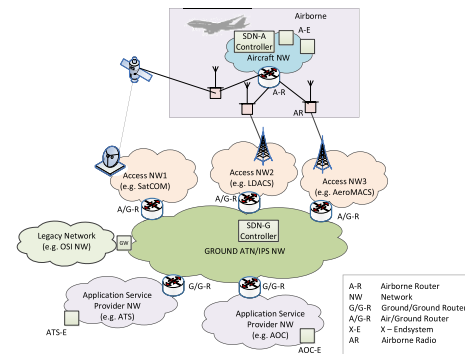


FIGURE 1. SDN-enabled COMET network architecture.

IV. NETWORK SELECTION FOR AVIONIC NETWORKS

A. ARCHITECTURE FOR SDN-ENABLED AVIONIC NETWORK

The overall COMET network architecture, as shown in Fig. 1, is a system consisting of the Air segment and Ground segment that has been adopted from the SESAR Future Communication Infrastructure (FCI). However, the COMET system is SDN-enabled with SDN controllers on both air and ground segments.

The COMET Air segment includes Airborne Router (A-R), Airborne Local Network (Aircraft NW), SDN-Air (SDN-A) controller, Airborne Radios (ARs), and Airborne End System (AES). The A-R is an SDN-enabled router. The ARs are physical radio stations that provide communication with the Ground segment through different Air/Ground (A/G) subsystems. Four different types of A/G datalinks are considered in this paper, including the Inmarsat BGAN for satellite communications, L-band Digital Aeronautical Communications System (LDACS), VHF Datalink - Mode 2 (VDL2) and Aeronautical Mobile Airport Communication System (AeroMACS).

The AES deals with transport and application functions to provide Aeronautical Communication Services (ACSS) for the aircraft system, including Airline Operation Control (AOC), Air Traffic Control (ATC), Aeronautical Administrative Communications (AAC) and Airline Passenger Communications (APC). The SDN-A acts as a network operating system of the air segment and provides the control functionalities, including Policy Repository, QoS Control, Security Control, Session Control, and Mobility and Multilink Control.

The COMET Ground segment includes access sub-networks, Ground Radios – GRs, Air/Ground Routers – A/G-Rs, Ground/Ground Routers (G/G-Rs), SDN-Ground (SDN-G) controllers, and the Ground End System (G-E). The GRs are physical radio stations that provide communication with the Air segment. All the A-G/Rs and G/G-Rs are SDN-enabled routers that connect between the ATN/IPs (Internet Protocol Suite) network and the access sub-networks,

and between ATN/IPS network and Application Service Provider (ASP) networks. The G-E provides Aeronautical Communication Services for the ground system. For the global ATN/IPS network, multiple SDN-G controllers need to be deployed. The placement problem of SDN-G controllers is fundamentally important for the design of such an SDN-enabled aeronautical communication system. This problem was investigated in [17] to dynamically placed SDN-G controllers in optimal positions depending on the dynamics of traffic patterns in the ATN network. Each SDN-G controller acts as a network operating system of the ground sub-segment that manages, and provides the same control functionalities, including Policy Repository, QoS Control, Security Control, Session Control, and Mobility and Multilink Control. In order to simplify the analysis, only one SDN-G controller is considered in the current network model.

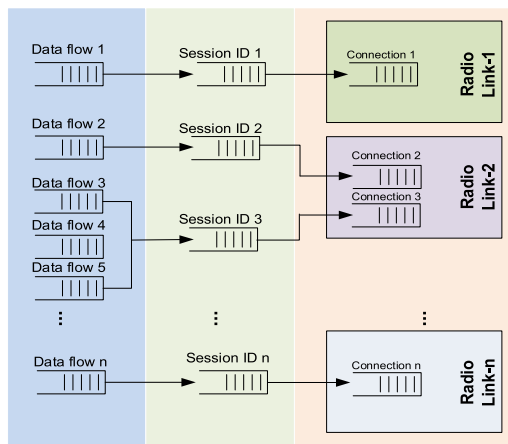


FIGURE 2. COMET session concept.

B. SESSION CONCEPT

The COMET Sessions concept is used for connection management and connection bindings between the aeronautical applications and the radio applications. It provides a very efficient and flexible way to manage the available radio resources of the different radio links by considering the diverse QoS requirements, price constraints and traffic domain security requirements. The main objective of the COMET Session is to set up the mappings between the application data flows and the radio link connections, as shown in Fig. 2.

A data flow, also known as an IP flow, is defined as the flow of IP packets being sent from a source application to a receiving application on the aircraft and on the ground. A data flow is uniquely identified by the following five identifiers: the protocol type, a source address, a destination address, a source port number and the destination port number. A connection is a user plane link in the link layer on radios. Before the establishment of a connection, an association between the radio terminal and the core network is established for a given radio access technology. An association is a logical communication link set up between peer-to-peer communication equipment (radio terminal and core network).

Each COMET session is uniquely identified by a unique identifier, i.e. Session ID, which is used as the mapping information between the data flow(s) and the link connection.

A COMET session defines a set of QoS profile, security profile and routing profile. The QoS profile consists of the required QoS and the offered QoS for a given session. The required QoS for a session is based on the aeronautical application requirements. They are key factors considered during the link selection decision for the given session. These application QoS requirements will be mapped onto the QoS parameters suitable for the selected radio link. The offered QoS represents the QoS which can be provided by the session through a specific radio access technology. It must match or exceed the QoS requirements. The security profile and routing profile will provide the information used for secure routing purposes. The security profile indicates for which traffic domain the session supports. As a session is dedicated to a particular traffic domain, data flows from different traffic domains cannot share the same course. The routing profile provides the associated radio access network information, such as an IP address, which is used when data is sent out.

C. SDN-BASED MULTILINK SELECTION FRAMEWORK

The SESAR ATM Master Plan [18] have introduced the Multilink Operational Concept for future aeronautical telecommunication networks, where multiple datalinks are expected to support air-ground communications. In the COMET system, the aircraft are equipped with different physical radio stations to provide capabilities to use various A/G datalinks for communications between the airborne segment and the ground segment. The COMET system considers a heterogenous set of radio access technologies, including VDL-2, AeroMACS, LDACS, and SATCOM. Each datalink has its own transmission characteristics including data rate, transmission delay, packet loss rate and the money cost. Besides, different Aeronautical Communication Service (ACS) applications have diverse QoS requirements, security requirements, for example, critical and non-critical safety communication services. Last but not least, during different flight phases phases of flight, more than one A/G datalinks could be available at the same time but may not all satisfy both QoS and security requirements. An effective multilink selection solution should take into account all the above considerations.

The COMET multilink selection solution starts with a pre-screen process (PSP), followed by a link selection optimisation process (LSOP) to select the best link for transmission from a list of pre-screened links obtained from the pre-screen phase. The pre-screen process considers the flight phase and eliminates the links that are not suitable and do not fulfill the security requirements. The optimisation process adopts the Multi-Attributes Decision Making (MADM) approach to establish a multi-criteria utility function for the link selection problem of the aircraft regarding the QoS (such as bandwidth, delay, packet loss rate), money cost, and load balancing.

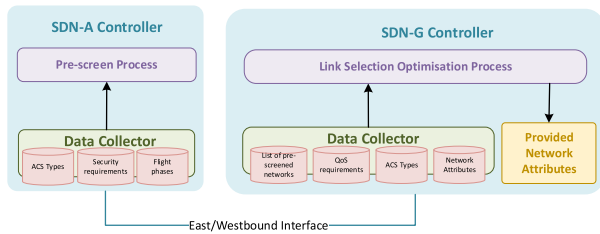


FIGURE 3. SDN-based multilink selection framework.

1) MULTILINK SELECTION FRAMEWORK FUNCTIONAL ARCHITECTURE

Fig. 3 shows the proposed SDN-based multilink selection framework for aeronautical telecommunication networking. The proposed solution considers the objective of both aircraft-side and network-side. It has two sub-modules: an aircraft-side module called Pre-screen module and a network-side module called Link selection optimisation module, which takes input from the SDN-A controller on each aircraft about the list of pre-screened networks. The data collector functionality on the SDN-A and SDN-G controllers consider different information for the pre-screen process (PSP) and the link selection optimisation process (LSOP).

The SDN-A controller on each aircraft collects the information on the flight phase, the Aeronautical Communication Service (ACS) type, and the security requirements. Then, the SDN-A controller will perform the pre-screen process to produce a list of pre-screened links based on flight phase and security requirements. This list of pre-screened networks will be sent over the East/Westbound interface toward the SDN-G controller. The active link between aircraft and the ground will be used for the communication between SDN-A and SDN-G controllers. The SDN-i wrapper application facilitated by the BGP provides mechanism to exchange information between SDN-A and SDN-G controllers. The SDN-G controller has an overview of the network state on the ground segment, such as the current capacity of each sub-network, the number of aircrafts it currently supports and the number of available communication slots. The SDN-G controller also collects the statistical information on the available data rate, delay, and packet loss rate that each sub-network can deliver to the ACS. Based on this information, the LSOP module in the SDN-G controller will map different datalinks to the various ACSs. In case the communication between SDN-A and SDN-G fails then SDN-A would assess the available links considering target parameters for link selection.

2) PRE-SCREEN PROCESS (PSP)

The PSP is an aircraft-side technique that runs on different aircrafts. The aircraft scans the available ground stations within its communication range and generate the list of available networks depending on Received Signal Strength (RSS) of each datalink. The aircraft measures and filters out the datalinks according to flight phase and security requirements.

Considering different flight phases, the aircraft speed changes accordingly, 0-5.5 m/s for parking phase, 0-15 m/s for taxiing phase, 25-150 m/s for take-off and landing phases, and 245-257 m/s for en-route phase [19]. In COMET system, the communication ranges of the A/G datalinks are also different, for example, approximately 400 km for VDL-2 [20], up to 12 km for AeroMACS [21], [22], 200 nautical miles (approximately 370 km) for LDACS [15], and around 550 km for SATCOM. An aircraft in the en-route phase should not consider the AeroMACs network for data transmissions due to the small coverage area. The ACS tries to access the AeroMACs datalink in the en-route step will experience a service interruption or ping-pong effect that deteriorates the quality of experience for the ACS.

Algorithm 1 Pre-Screen Process (PSP)

Input: Aeronautical Communication Service Types, Security requirements, Flight phase, List of available links L_a .
Output: List of pre-screened networks L_{pre}

- 1: Initialize $L_{pre} = L_a$
- 2: **for** each link l in L_{pre} , **do**
- 3: Consider the flight phase
- 4: **if** link l is not suitable **then**
- 5: remove link l from L_{pre} , $L_{pre} = L_{pre} \setminus \{l\}$
- 6: **end if**
- 7: Consider the security requirements and service types
- 8: **if** link l is not satisfy the security requirements **then**
- 9: remove link l from L_{pre} , $L_{pre} = L_{pre} \setminus \{l\}$
- 10: **end if**
- 11: **end for**
- 12: return L_{pre}

The details of the PSP are presented in Algorithm 1. The algorithm initializes the list of pre-screened networks L_{pre} as the list of available links L_a that is built based on the RSS. Then, it goes through each link in L_{pre} . The link that is not suitable considering the flight phase or does not satisfy the security requirements is removed from the list L_{pre} . It should be noted that the PSP reduces computational complexity and processing time as PSP eliminates some of the datalinks. After PSP, the L_{pre} is returned and will be sent over East/Westbound interface to the SDN-G controller for the optimisation process. The optimisation process will have to work only on a small set of available networks.

3) LINK SELECTION OPTIMISATION PROCESS (LSOP)

The LSOP is the network-side technique, which gets inputs from many pre-screen modules run on different aircrafts. The Data Collector functionality in the SDN-G controller collects and provides all the information needed for the LSOP functionality, including ACS type, QoS requirements, network attributes, and list of pre-screened links L_{pre} for each ACS request. The QoS requirements depend on the nature of the data flows and are decided by the ACS type, including bandwidth requirement, delay requirement, and packet loss rate requirement. These attributes include the current load of each sub-network (number of available slots

for communication); statistical information on the available data rate, delay, and packet loss rate that each sub-network can deliver to the ACS request; and the money cost.

The LSOP is implemented as a Multi-Attributes Decision Making (MADM) agent that establishes a multi-criteria utility function from the collected information. The description of how this multi-criteria utility function is built and presented in detail in Section V. The total utility function of the whole system is then calculated concerning the utility value of each ACS request when a datalink is selected for transmission. The MADM then dynamically map the best COMET sessions to be used for forwarding specific ACS requests to maximize the total utility of the whole system. The MADM agent output will be stored in the Provided Network Attributes (PNA). The PNA module provides information on the quality assessment parameters such as utility, cost, delay, bandwidth, packet loss rate that each sub-network can deliver for an ACS request.

The LSOP has different flavours for performance evaluation purpose, including price-based policy, QoS-based policy, SAW, and two proposed schemes AHP-SA, SA-SWNO. The comparison results are detailed in Section VII.

V. UTILITY FUNCTIONS

For the multilink selection procedure, multiple attributes are considered simultaneously such that the aggregated multi-criteria utility function is the combination of different utility functions of various features. The utility function of each decision factor needs to be designed according to the multi-attribute utility theory [23]. It must satisfy the following conditions:

- monotonic (the utility is monotonic if it shows a monotonic increase (or decrease) with an increase in attribute value);
- twice differentiable;
- concave or convex.

In the following sections, the design of each utility function is presented.

A. UTILITY FUNCTION OF BANDWIDTH

The bandwidth is an upward attribute in which the ACS's Quality of Experience (QoE) increases accordingly when the bandwidth increases. When the minimum bandwidth b_{min} required by an ACS request exceeds the available bandwidth of the network b , the ACS request will not be granted. Hence no bandwidth will be utilized under this condition. On the contrary, when $b \geq b_{max}$, where b_{max} is the maximum required bandwidth, the available network bandwidth can be fully used. When $b_{min} < b < b_{max}$, the bandwidth utility increases as the available network bandwidth increases. For b lying within this range, denote b_{thres} as the threshold bandwidth value that separates the QoE into the satisfied and unsatisfied zones, and $u(b_{thres}) = 0.5$. When $b_{min} < b < b_{thres}$, the unsatisfactory user experience may result. When $b_{thres} < b \leq b_{max}$, the satisfactory user experience may result. The utility function for the bandwidth

is adopted from [24] and is defined as follow:

$$u(b) = \begin{cases} 0, & b < b_{min} & (1a) \\ \frac{\left(\frac{b-b_{min}}{b_{thres}-b_{min}}\right)^{\gamma_b}}{1 + \left(\frac{b-b_{min}}{b_{thres}-b_{min}}\right)^{\gamma_b}}, & b_{min} \leq b \leq b_{thres} & (1b) \\ 1 - \frac{\left(\frac{b_{max}-b}{b_{max}-b_{thres}}\right)^{\gamma_b}}{1 + \left(\frac{b_{max}-b}{b_{max}-b_{thres}}\right)^{\gamma_b}}, & b_{thres} < b \leq b_{max} & (1c) \\ 1, & b > b_{max} & (1d) \end{cases}$$

where b denotes the bandwidth of the access network, b_{min} and b_{max} represent the lower and upper bounds of the ACS bandwidth requirements, respectively, $b_{thres} = \frac{b_{min}+b_{max}}{2}$, and $\gamma_b \geq 2$ is the tuned parameter showing the steepness of the function.

B. UTILITY FUNCTION OF DELAY

The delay is a downward attribute that negatively affects the ACS's Quality of Experience (QoE) when the delay increases. When the delay of the access network, d , exceeds the maximum delay requirement, d_{max} required by an ACS request, the session request will not be granted. Hence the delay utility value $u(d) = 0$ under this condition. There is no need for the minimum delay requirement since this will be equal to 0. In contrast to the bandwidth requirement, when $0 < d \leq d_{max}$, the delay utility decreases as the available network delay increases. For d lying within this range, denote d_{thres} as the threshold bandwidth value that separates the QoE into the satisfied and unsatisfied zones, and $u(d_{thres}) = 0.5$. When $0 < d \leq d_{thres}$, the satisfactory user experience may result. When $d_{thres} < d \leq d_{max}$, the unsatisfactory user experience may result. The utility function for the delay is defined as follow:

$$u(d) = \begin{cases} 1, & d = 0 & (2a) \\ \frac{1}{1 + \left(\frac{d}{d_{thres}}\right)^{\gamma_d}}, & 0 \leq d \leq d_{thres} & (2b) \\ \frac{\left(\frac{d_{max}-d}{d_{max}-d_{thres}}\right)^{\gamma_d}}{1 + \left(\frac{d_{max}-d}{d_{max}-d_{thres}}\right)^{\gamma_d}}, & d_{thres} < d \leq d_{max} & (2c) \\ 0, & d > d_{max} & (2d) \end{cases}$$

where d denotes the delay of the access network, d_{max} represents the upper bound of the ACS delay requirements, $d_{thres} = d_{max}/2$, and $\gamma_d \geq 2$ is the tuned parameter showing the steepness of the function.

C. UTILITY FUNCTION OF PACKET LOSS RATE (PLR)

The packet loss rate (PLR) has similar properties to network delay and is a downward attribute. When the network PLR p exceeds the maximum PLR requirement p_{max} required by an ACS, the ACS request will not be granted. Similar to the delay requirement, when $0 < p \leq p_{max}$, the ACS's QoE is regarded as i) satisfactory when $0 < p \leq p_{thres}$; ii) unsatisfactory when $p_{thres} < p \leq p_{max}$; and $u(p_{thres}) = 0.5$. The utility function for the PLR is defined as follow:

$$u(p) = \begin{cases} 1, & p = 0 & (3a) \\ \frac{1}{1 + \left(\frac{p}{p_{thres}}\right)^{\gamma_p}}, & 0 \leq p \leq p_{thres} & (3b) \\ \frac{\left(\frac{p_{max}-p}{p_{max}-p_{thres}}\right)^{\gamma_p}}{1 + \left(\frac{p_{max}-p}{p_{max}-p_{thres}}\right)^{\gamma_p}}, & p_{thres} < p \leq p_{max} & (3c) \\ 0, & p > p_{max} & (3d) \end{cases}$$

where p denotes the packet loss rate of the access network, p_{max} represents the upper bound of the ACS request's PLR requirements, $p_{thres} = p_{max}/2$, and $\gamma_p \geq 2$ is the tuned parameter showing the steepness of the function.

D. UTILITY FUNCTION OF COST

The money cost has similar properties to network delay, PLR and is a downward attribute. The utility function for the cost is defined as follows:

$$u(c) = \begin{cases} 1, & c = 0 & (4a) \\ \frac{1}{1 + \left(\frac{c}{c_{thres}}\right)^{\gamma_c}}, & 0 \leq c \leq c_{thres} & (4b) \\ \frac{\left(\frac{c_{max}-c}{c_{max}-c_{thres}}\right)^{\gamma_c}}{1 + \left(\frac{c_{max}-c}{c_{max}-c_{thres}}\right)^{\gamma_c}}, & c_{thres} < c \leq c_{max} & (4c) \\ 0, & c > c_{max} & (4d) \end{cases}$$

where c denotes the packet loss rate of the access network, c_{max} represents the upper bound of the ACS cost requirements, $c_{thres} = c_{max}/2$, and $\gamma_c \geq 2$ is the tuned parameter showing the steepness of the function.

E. UTILITY FUNCTION OF LOAD

The load has similar properties to network delay, PLR, cost and is a downward attribute. It is important to note that the load attribute is dynamically changed during the datalink selection process. Let us consider the scenario where many aircrafts are trying to access the ATN/IPS network through multiple A/G datalinks. For aircraft-side selection approach, since aircrafts decide which networks to connect to, it considers the load attribute from its point of view without concerning the other aircrafts may choose the same datalink, which is the best among available links. Therefore, the load attribute that aircraft-side selection approach uses is not

correct and does not reflect the real traffic load of each sub-network after the connections are established. This problem can lead to the sub-optimal solution and result in congestion at the specific ground radio station. However, in this paper, the SDN-based network-side selection is implemented. The SDN-G controller has an overview of all sub-networks and decides which datalink to be used for each ACS request.

The utility function for the load is defined as follow:

$$u(l) = \begin{cases} 1, & l = 0 & (5a) \\ \frac{1}{1 + \left(\frac{l}{l_{thres}}\right)^{\gamma_l}}, & 0 \leq l \leq l_{thres} & (5b) \\ \frac{\left(\frac{l_{max}-l}{l_{max}-l_{thres}}\right)^{\gamma_l}}{1 + \left(\frac{l_{max}-l}{l_{max}-l_{thres}}\right)^{\gamma_l}}, & l_{thres} < l \leq l_{max} & (5c) \\ 0, & l > l_{max} & (5d) \end{cases}$$

where l denotes the current traffic load of the access network, l_{max} represents the upper bound of the ACS load requirements, $l_{thres} = l_{max}/2$, and $\gamma_l \geq 2$ is the tuned parameter showing the steepness of the function.

VI. MULTI-ATTRIBUTE ACCESS NETWORK SELECTION

In the following, the collective impact of several attributes on the decision-making during network selection is presented. The requirements on an aggregate utility function is introduced. Finally, the multi-attribute aggregated utility function is derived.

A. MULTI-ATTRIBUTE UTILITY FUNCTION

The design of a multi-attribute utility function to include each considering network attribute is a significant task. This multi-attribute utility function needs to reflect the interaction between different characteristics during the aggregation process. Therefore, several properties for this utility function are given as follows:

$$\frac{\partial U(x)}{\partial u_i} \geq 0 \quad (6)$$

$$\text{sign}\left(\frac{\partial U(x)}{\partial u_i}\right) = \text{sign}(u'_i(x_i)) \quad (7)$$

$$\lim_{u_i \rightarrow 0} U(x) = 0 \quad \forall i = 1 \dots n \quad (8)$$

$$\lim_{u_1, \dots, u_n \rightarrow 1} U(x) = 1. \quad (9)$$

Equation (6) ensures the aggregate utility should increase when the utility of each decision attribute increases. According to Equation (7), the aggregate utility should be an increasing function of the upward attribute and a decreasing function of the downward attribute. Equation (8) guarantees the aggregate utility is 0 when the utility of any attribute approaches 0. It helps to eliminate the access networks that have the utility of any decision attribute equal to 0 in the decision-making process. Equation (9) reflects that when all utilities of different attributes are equal to 1, the aggregate utility should also be equal to 1.

Based on the requirements in Equations (6)-(9), the multi-attribute utility function is defined as follows:

$$U(\mathbf{x}) = \prod_{i=1}^n [u_i(x_i)]^{w_i} \quad (10)$$

$$\sum_{i=1}^n w_i = 1 \quad (11)$$

where \mathbf{x} is a network selection attribute vector and \mathbf{w} is an associated preference vector, n is the size of the vector \mathbf{x} , w_i is the weight for the attribute i , and $u_i(x_i)$ is the utility of the attribute i that follows the utility equations (1)-(5).

B. NETWORK SELECTION MODEL

Given the set of ACS requests $V = \{v_1, v_2, \dots, v_N\}$, the set of available access links/networks $L = \{l_1, l_2, \dots, l_M\}$, let $A = [a_{jk}]_{N \times M}$ denote the assignment matrix of the network selection, where a_{jk} is defined as:

$$a_{jk} = \begin{cases} 1, & \text{if ACS request } v_j \\ & \text{is assigned to the link } l_k \\ 0, & \text{otherwise} \end{cases} \quad (12)$$

According to (10), the overall multi-attribute utility of the ACS request v_j when the network l_k is chosen for data transmission can be expressed as:

$$U_{kj}(\mathbf{x}) = \prod_{i=1}^n [u_i^{kj}(x_i)]^{w_i} \quad (13)$$

The total utility of the network selection problem is defined as:

$$U_{total} = \sum_{k=1}^M \sum_{j=1}^N a_{kj} \prod_{i=1}^n [u_i^{kj}(x_i)]^{w_i} \quad (14)$$

Based on the above discussion, the network selection model has been proposed as follows. Given the set of ACS requests V , the set of available access links/networks L , the task is to decide an optimal request-to-network assignment matrix A , to achieve the optimal network selection efficiency by maximising the total utility given in Equation (14).

$$\max \sum_{k=1}^M \sum_{j=1}^N a_{kj} \prod_{i=1}^n [u_i^{kj}(x_i)]^{w_i} \quad (15)$$

$$\forall v_j \in V : \sum_{l_k \in L} a_{kj} = 1 \quad (16)$$

$$\forall v_j \in V, \quad l_k \in L : a_{jk} \in \{0, 1\} \quad (17)$$

$$\sum_{i=1}^n w_i = 1 \quad (18)$$

$$\forall i : 0 < w_i < 1 \quad (19)$$

$$\gamma_b \geq 2 \quad (20)$$

$$\gamma_d \geq 2 \quad (21)$$

$$\gamma_p \geq 2 \quad (22)$$

$$\gamma_c \geq 2 \quad (23)$$

$$\gamma_l \geq 2 \quad (24)$$

Constraint (16) guarantees that each ACS request uses only one link for data transmission at a given time. Equation (17) indicates that the variable a_{jk} is binary. Equations (18) and (19) ensures that the sum of weights for all attributes equals to 1. Equations (20)-(24) demonstrates the condition for the steepness parameter of each single-attribute utility function.

It is important to note that for the network selection model (15) - (24), there are different approaches to solve, including price-based policy, QoS-based policy, SAW, and two proposed schemes AHP-SA, SA-SWNO. For the AHP-SA approach (will be described in the following Section IV.C), the weight distribution vector $\mathbf{W} = [w_1, \dots, w_n]$ is given through the AHP process, only the assignment matrix $A = [a_{jk}]_{N \times M}$ is the variable to be optimized. AHP is used to determine decision weights, and these decision weights, in turn, affect the network selection solution. However, it is challenging to assure that the decision weights obtain from AHP are optimized. Therefore, the second algorithm is proposed to optimize both decision weights and network selection solution simultaneously. In SA-SWNO approach (will be described in the following Section IV.D), both the weight distribution vector $\mathbf{W} = [w_1, \dots, w_n]$ and assignment matrix $A = [a_{jk}]_{N \times M}$ are considered as variables to be optimized. The performance these two proposed algorithms in terms of average satisfaction degree, bandwidth, delay, cost, load are compared.

C. A COMBINED ANALYTIC HIERARCHY PROCESS AND SIMULATED ANNEALING ALGORITHM (AHP-SA)

In the AHP-SA, the decision weights matrix \mathbf{W}_{AHP-SA} is determined using the analytic hierarchy process (AHP) [25] while the request-to-network assignment matrix \mathbf{A}_{AHP-SA} is optimized using the simulated annealing algorithm.

As shown in the pseudo-code in Algorithm 2, a randomly selected request-to-network assignment matrix is initiated as the best assignment \mathbf{A}_{AHP-SA} . With the given random matrix \mathbf{A}_{AHP-SA} , the corresponding total system utility U_{max} is computed. Inside the while-loop, in every iteration, a new neighbour of request-to-network assignment matrix \mathbf{A}_{new} is generated, and the corresponding U_{new} is calculated. The value of \mathbf{A}_{AHP-SA} will be replaced by the new neighbour matrix \mathbf{A}_{new} as the optimal solution if it offers better utility than the old one, in this case, when $U_{new} \geq U_{max}$. The AHP-SA algorithm also accepts the worse neighbours with the acceptance rate $p(\Delta) = e^{\Delta/T}$, where $\Delta = U_{new} - U_{max}$ and T denotes the current temperature as defined in SA. This mechanism helps avoid being stuck in the local optima so that AHP-SA can find the global optimum of the request-to-network assignment matrix.

Algorithm 2 A Combined Analytic Hierarchy Process and Simulated Annealing Algorithm (AHP-SA)

Input: List of ACS requests \mathbf{V} , list of available networks \mathbf{L} , network attributes matrix \mathbf{N}_{A1} ACS request requirement matrix \mathbf{D} , matrix of decision factor weights from analytic hierarchy process \mathbf{W}_{AHP-SA}

Output: U_{max} the maximum total utility of the network selection problem, \mathbf{A}_{AHP-SA} the optimal request-to-network assignment matrix.

- 1: Initialize $T = T_0, T_{final}, \alpha$
- 2: Randomly generate initial request-to-network assignment matrix \mathbf{A}_{AHP-SA}
- 3: Compute the correspond U_{max} with respect to \mathbf{A}_{AHP-SA} and \mathbf{W}_{AHP-SA}
- 4: **while** $T > T_{final}$ **do**
- 5: generate a new neighbour request-to-network assignment matrix \mathbf{A}_{new} .
- 6: Compute the new total utility U_{new} with respect to \mathbf{A}_{new} and \mathbf{W}_{AHP-SA}
- 7: $\Delta = U_{new} - U_{max}$
- 8: generate a random number $\delta \in (0,1)$
- 9: calculate $p = e^{\frac{\Delta}{T}}$
- 10: **if** $\Delta \geq 0$ or $p > \delta$ **then**
- 11: $U_{max} = U_{new}$
- 12: $\mathbf{A}_{AHP-SA} = \mathbf{A}_{new}$
- 13: **end if**
- 14: $T = T * \alpha$
- 15: **end while**
- 16: **return** $U_{max}, \mathbf{A}_{AHP-SA}$

D. A SIMULATED ANNEALING BASED ALGORITHM FOR SIMULTANEOUS WEIGHTS AND NETWORK SELECTION OPTIMISATION (SA-SWNO)

To improve the user satisfaction, a simulated annealing-based algorithm, called SA-SWNO is proposed. In this method, both the decision weights matrix \mathbf{W}_{opt} and the request-to-network assignment matrix \mathbf{A}_{opt} are optimized simultaneously using the simulated annealing algorithm.

As shown in the pseudo-code in Algorithm 3, a randomly selected decision weights matrix is initiated as the best weights $\mathbf{W}_{SA-SWNO}$, a randomly chosen request-to-network assignment matrix is started as the best assignment $\mathbf{A}_{SA-SWNO}$. With the given random matrixes $\mathbf{W}_{SA-SWNO}$ and $\mathbf{A}_{SA-SWNO}$, the corresponding total system utility U_{max} is computed. Inside the while-loop, in every iteration, a new neighbour of decision weights matrix \mathbf{W}_{new} is generated, a new neighbour of request-to-network assignment matrix \mathbf{A}_{new} is created, then the corresponding U_{new} is calculated. The values of $\mathbf{W}_{SA-SWNO}$ and $\mathbf{A}_{SA-SWNO}$ will be replaced by the new neighbour matrixes \mathbf{W}_{new} and \mathbf{A}_{new} respectively as the optimal solutions if they offer better overall utility than the old ones, in this case, when $U_{new} \geq U_{max}$. The SA-SWNO algorithm also accepts the worse neighbours with

Algorithm 3 A Simulated Annealing Based Algorithm for Simultaneous Weights and Network Selection Optimization (SA-SWNO)

Input: List of ACS requests \mathbf{V} , list of available networks \mathbf{L} , network attributes matrix \mathbf{N}_A ACS request requirement matrix \mathbf{D} ,

Output: U_{max} the maximum total utility of the network selection problem, $\mathbf{W}_{SA-SWNO}$ the optimal decision weights matrix, $\mathbf{A}_{SA-SWNO}$ the optimal request-to-network assignment matrix.

- 1: Initialize $T = T_0, T_{final}, \alpha$
- 2: Randomly generate initial decision weights matrix $\mathbf{W}_{SA-SWNO}$
- 3: Randomly generate initial request-to-network assignment matrix \mathbf{A}_{AHP-SA}
- 4: Compute the correspond U_{max} with respect to $\mathbf{A}_{SA-SWNO}$ and $\mathbf{W}_{SA-SWNO}$
- 5: **while** $T > T_{final}$ **do**
- 6: generate new decision weight matrix \mathbf{W}_{new}
- 7: generate a new request-to-network; assignment matrix \mathbf{A}_{new}
- 8: compute the new total system utility U_{max} respect to \mathbf{A}_{new} and \mathbf{W}_{new}
- 9: $\Delta = U_{new} - U_{max}$
- 10: generate a random number $\delta \in (0,1)$
- 11: calculate $p = e^{\frac{\Delta}{T}}$
- 12: **if** $\Delta \geq 0$ or $p > \delta$ **then**
- 13: $U_{max} = U_{new}$
- 14: $\mathbf{W}_{SA-SWNO} = \mathbf{W}_{new}$
- 15: $\mathbf{A}_{SA-SWNO} = \mathbf{A}_{new}$
- 16: **end if**
- 17: $T = T * \alpha$
- 18: **end while**
- 19: **return** $U_{max}, \mathbf{W}_{SA-SWNO}, \mathbf{A}_{SA-SWNO}$

the acceptance rate $p(\Delta) = e^{\Delta/T}$, where $\Delta = U_{new} - U_{max}$ and T denotes the current temperature. This mechanism helps to avoid being stuck in the local optima so that SA-SWNO can also simultaneously find the global optimum of both the decision weights and request-to-network assignment matrixes.

VII. SIMULATION RESULTS AND ANALYSIS

This section presents the simulation settings for multilink network selection problem in the ATN environment, including the ACSs requirements and the network attributes of different datalinks. Then a detailed performance comparison of various approaches for solving the problem is illustrated.

A. SIMULATION SETTINGS

All simulations were performed in MATLAB R2018a running on a PC with Intel(R) Core (TM) i7-8700 CPU @ 3.20GHz (12 CPUs), ~3.2GHz, 32.00GB RAM, and Windows 10 OS to compare the performances of the two

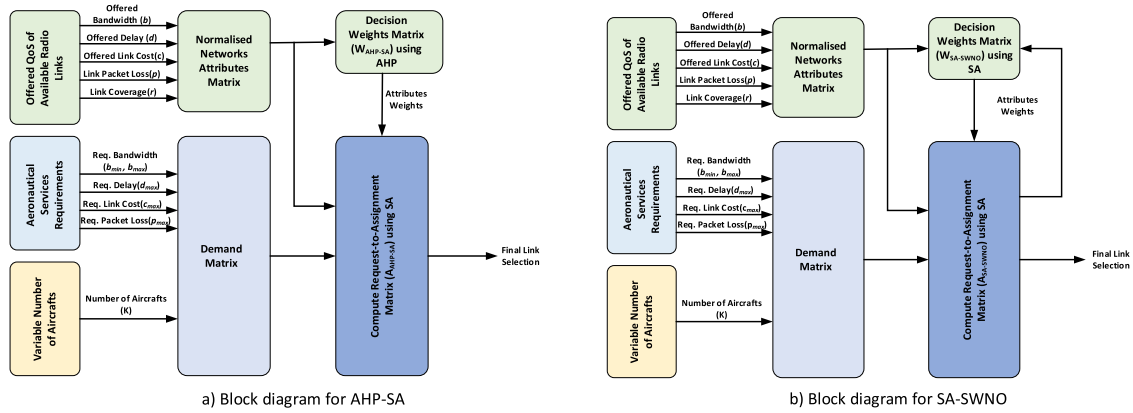


FIGURE 4. Block diagrams for AHP-SA and SA-SWNO simulation.

target algorithms AHP-SA and SA-SWNO along with three baseline algorithms in link selection for multilink scenarios.

The network simulation environment is set up according to the SDN-enabled COMET network architecture. The Matlab simulation models for AHP-SA and SA-SWNO are depicted Fig. 4.

In the simulation models, four different types of aeronautical communication services are included:

- Controller Pilot Datalink Communications (CPDLC) application [29] is a safety-critical service and provides the pilots with the ability to exchange data messages with the currently responsible ATC centre.
- 4D trajectory-based Operations (4D-TBO) service allows aircraft and ground systems to optimize trajectory in three dimensions (latitude, longitude, and altitude) plus time with periodic exchange of trajectory information update. For example, the flight management system downlinks the Extended Projected Profile (EPP), which consists of up to 128 waypoints in four dimensions, and therefore, provides valuable data to the controllers about the aircraft’s intent (an EPP message size is around 512 octets). This service is implemented using ADS-C and CPDLC extended messages. This ATC service requires much higher bandwidth than standard CPDLC.
- Aeronautical Operational Control (AOC) service is a safety-critical service required for the initiation, continuation, diversion, or termination of flight for safety, regularity and efficiency reasons.
- Aeronautical Passenger Communications (APC) is non-safety-critical service that facilitates the passenger communications and enables passengers to access different services for communication, entertainment, or information during the flight.

Fig. 4 presents the block diagrams for the MATLAB simulation models of AHP-SA and SA-SWNO. Both algorithms are presented with the same set of initial input parameters from the system and the QoS requirements of the aeronautical communication services and the total number of aircrafts:

- Network parameters: coverage (r), offered bandwidth (b), delay(d), cost(c), packet loss ratio (p) from the

four access networks - VDL2, AeroMACS, BGAN and LDACS. These parameters are used to generate the normalized decision matrix.

- ACS QoS requirements: minimum and maximum required bandwidth, (b_{min}, b_{max}), maximum delay (d_{max}), maximum cost (c_{max}) and maximum packet loss rate (p_{max}) along with number of aircrafts (K) to generate the demand matrix.

The Normalized Network Attributes matrix is a $L \times M$ matrix containing the normalized attributes of each radio link, where L is the number of available links or networks and M is the number of network attributes per radio link. In our case, $L = 4$ and $M = 5$.

The Demand Matrix is a $N \times K$ matrix, where N is the number of service parameters per application and K is the number of applications requested by an aircraft. In this paper, four applications and five service parameters per application are considered, i.e. $N = 5$ and $K = 4$. The number of aircrafts ranges from 10 to 100 in the simulation.

In AHP-SA, the weights matrix, W_{AHP-SA} , is determined at the beginning using AHP, whereas in SA-SWNO, the weights matrix $W_{SA-SWNO}$ is updated simultaneously for every iteration of SA-SWNO while constructing the request-to-assignment matrix.

The detailed ACS requirements are presented in Table 1, which includes b_{max} , b_{min} , d_{max} , c_{max} , and p_{max} (see Section V on their definitions). The network parameters including b , d , c , p are presented in Table 2. An addition network parameter, r , the coverage of individual radio links are also included in Table 2. Both b and r are considered positive attributes in the MADM algorithm, i.e. the higher the offered bandwidth the better for the performance of the system. Similarly the larger the coverage, the less frequent the handover. The other radio links parameters such as delay (d), cost (c) and packet loss rate (p) are negative attributes where the lower the values of these parameters are, the better the system performance.

The simulation model also takes into account the number of aircrafts and each aircraft generates random application types. The percentages of traffic generated by each

TABLE 1. Aeronautical communication service requirements [30], [31].

Requirements	Applications			
	CPDLC	AOC	4D-TBO	APC
b_{\min} (Kbps)	4	10	200	500
b_{\max} (Kbps)	31.5	200	1000	10000
d_{\max}	8	2	0.5	2.5
c_{\max}	8	8	5	3
p_{\max}	0.0025	0.0025	0.0025	0.015

TABLE 2. Main simulation parameters.

Network Attributes	Network Types			
	AeroMACS [21]-[22]	LDACS [26]	SATCOM [27]	VDL-2 [28]
Coverage(km), r	12	370	550	400
Bw(Kbps), b	5500	1000	432	31.5
Delay(ms), d	50	100	900	2000
Cost, c	2	3	8	1
PLR, p	0.002	0.002	0.005	0.0025

application type allocated to different access networks are observed. In terms of network selection schemes, the commonly used algorithms such as SAW, QoS-based and price-based selections are also implemented for comparison purposes.

B. SIMULATION RESULTS

In this section, the performance of AHP-SA and SA-SWNO are thoroughly investigated in comparison with the commonly used network selection schemes such as SAW [8], QoS-based and Price-based selection algorithms. The comparison between these five algorithms have been made by considering six different performance parameters: i) The traffic percentage represents the distribution of traffic amongst the available networks. ii) The average user satisfaction degree which provides quantitative value of users' satisfaction when different algorithms are applied. iii) The average delivered delay to analyse the average time required to transmit the data from the aircraft to the ground network using different algorithms. This is an important parameter especially for time-sensitive and safety-critical services. iv) The average delivered bandwidth to compare the throughput of each aircraft when using different algorithms. v) The average cost to analyse how costly will it be for each user to use communication link when using different algorithms for link selection. vi) The average delivered packet loss to assess which algorithms' link selection has the lowest average packet loss. This again is critical when time-sensitive and safety-critical services are considered.

These performance parameters are considered as they can express the impact of link selection decision made by different algorithms in the most suitable way. The information obtained from the results in terms of these performance parameters by applying five different algorithms have been compared and presented in the following subsections.

1) IMPACTS OF THE FLIGHT PHASES

Fig. 5 shows the aircrafts' traffic allocation on different access networks near the airport areas by using five algorithms, including Price-based algorithm, QoS-based algorithm, SAW algorithm, AHP-SA algorithm and SA-SWNO algorithm. In this scenario, all the aircrafts are near the airport areas. They are in the parking, taxiing, or landing phases and have the capability of accessing all four available radio technologies.

Fig. 5(a) shows the traffic percentages allocated to different networks using Price-based algorithm with the increasing numbers of ACS requests. As can be observed from this figure, in all cases with different number of traffic requests, VDL-2 undertakes most of the traffic requests for all the ACS requests. AeroMACS and LDACS take the second and third place in the percentage of traffic requests, respectively, while SATCOM forwards the fewest traffic requests. It is reasonable and understandable for the price-based scheme because VDL-2 and SATCOM have the lowest/highest cost correspondingly, compared to the other two access networks; hence the price-based algorithm always takes the priority to allocate traffic to VDL-2. When the number of traffic requests is small, almost 45% of traffic is assigned to VDL-2, 30% of traffic is given to AeroMACS. When the amount of traffic requests increases, VDL-2 and AeroMACS does not have sufficient network resources to support all the requests, then the percentage of traffic allocated to VDL-2 and AeroMACS decreases, and the portion of traffic allocated to other networks increases.

Fig. 5(b) shows the traffic percentages allocated to different networks using QoS-based algorithm with the increasing numbers of ACS requests. As can be observed from this figure, in all the cases with different number of traffic requests, AeroMACS network seems to be considered as the best choice since it offers the highest bandwidth of 5.5 Mbps, smallest delay of 50 ms and with the lowest packet loss rate of 0.001. From Table 2, LDACS is the second-best in terms of QoS attributes. Even though the price of SATCOM is very high in comparison with the others, it still is the third choice since the QoS-based approach does not consider the cost of the datalink.

Fig. 5(c), (d), (e) shows the traffic percentages of different networks using SAW, AHP-SA and SA-SWNO network selection algorithms with increasing number of ACS requests, respectively. All three algorithms try to balance the network allocation between AeroMACS, LDACS and VDL-2 which considers that VDL-2 is the cheapest but with the longest delay and smallest bandwidth available; AeroMACS and LDACS is a little bit more expensive but with much lower delay and higher bandwidth. The results obtained from AHP-SA is rather similar to those obtained from SA-SWNO. By comparing the operations of the AHP-SA and SA-SWNO algorithms, the latter has a slightly more computation time than the AHP-SA algorithm since it has to compute the weight vector which includes five elements (for instance, the weights of cost, PLR, delay, bandwidth, load)

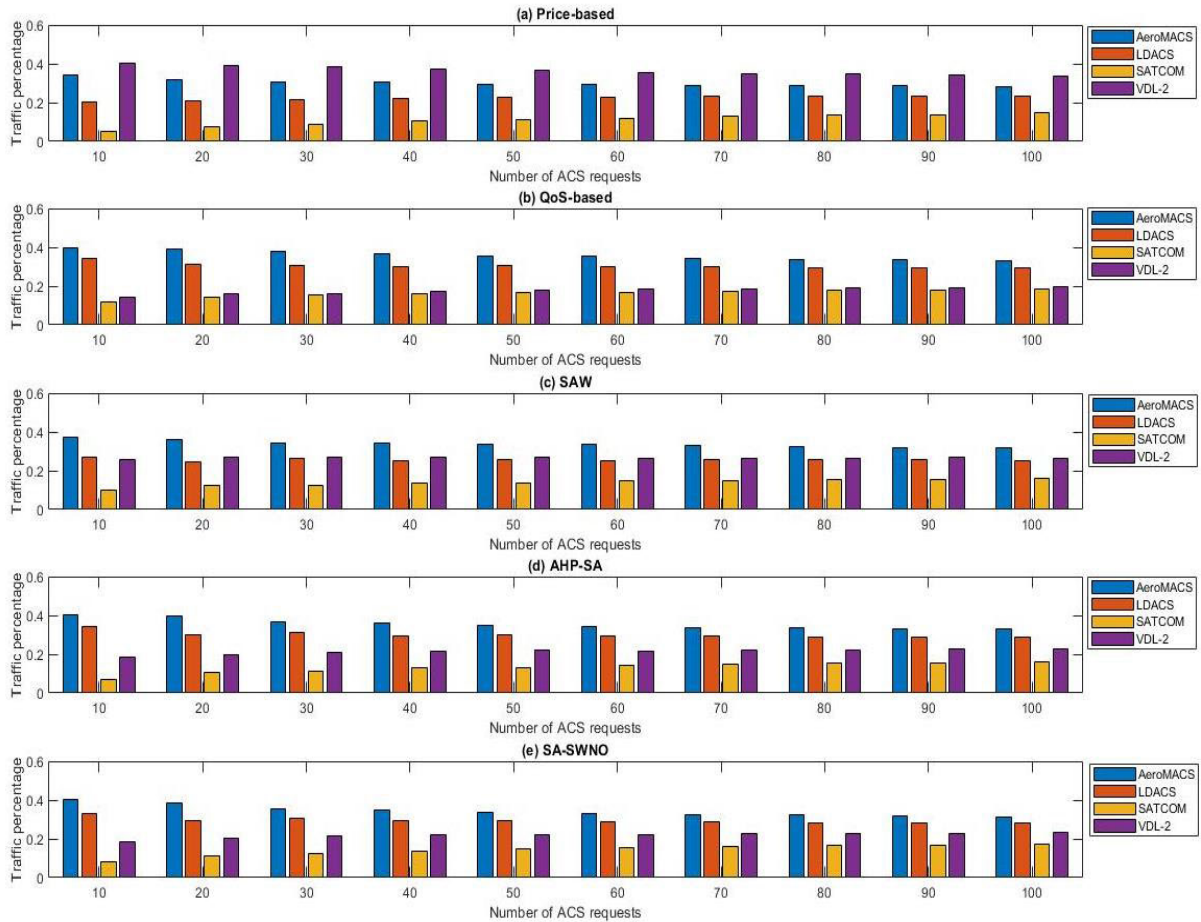


FIGURE 5. The traffic percentage in different networks near airport areas under five algorithms.

to the search space. However, when the number of aircrafts increases, this difference is negligible. For example, when the number of aircrafts is 35, then the number of variables need to be optimized for the AHP-SA algorithm in the network selection model (15)-(24) is 35 in comparison with 40 for the SA-SWNO algorithm.

Fig. 6 shows the aircrafts’ traffic allocation on different access networks over the continental areas under five algorithms. In this scenario, all the aircrafts are in the en-route phase and have access to all three available radio technologies, including LDACS, Satellite, and VDL-2. The behaviour of the five algorithms is similar as in Fig. 5, except the fact that AeroMACS network is not available for selection.

2) AVERAGE SATISFACTION DEGREE

In this section, the performances of two proposed schemes (AHP-SA and SA-SWNO) are compared with the implementation of the SAW scheme, price-based scheme, and QoS-based scheme in terms of average user satisfaction. Fig. 7 plots the aircrafts’ satisfaction degree per request using the five algorithms as a function of gradually increasing numbers of aircrafts with different service types. The average

satisfaction degree is calculated as followed:

$$s = \frac{U_{total}}{N} = \frac{\sum_{k=1}^N \sum_{j=1}^M a_{kj} \prod_{i=1}^n [u_i^{kj}(x_i)]^{w_i}}{N} \quad (25)$$

As can be seen from Fig. 7, the two proposed SA-SWNO and AHP-SA schemes have the best and the second average user satisfaction degree, respectively, in comparison with the other three approaches. When the number of ACS requests increases, the satisfaction degree of the five algorithms gradually decreases. This is because when the number of ACS demands increases, the necessary network resource to fulfill all the ACS requests requirements also rises. However, the available resource is the same in all cases; hence the satisfaction degree decreases. In all the circumstances, both proposed algorithms always have better performance.

The price-based algorithm takes the priority to allocate the traffic requests to the cheapest networks as can be seen in Fig. 5(a), then results in the worst satisfaction degree. The QoS-based algorithm tries to fulfill the QoS requirements of different application types and completely ignores the cost attribute of the network; consequently, the QoS-based link

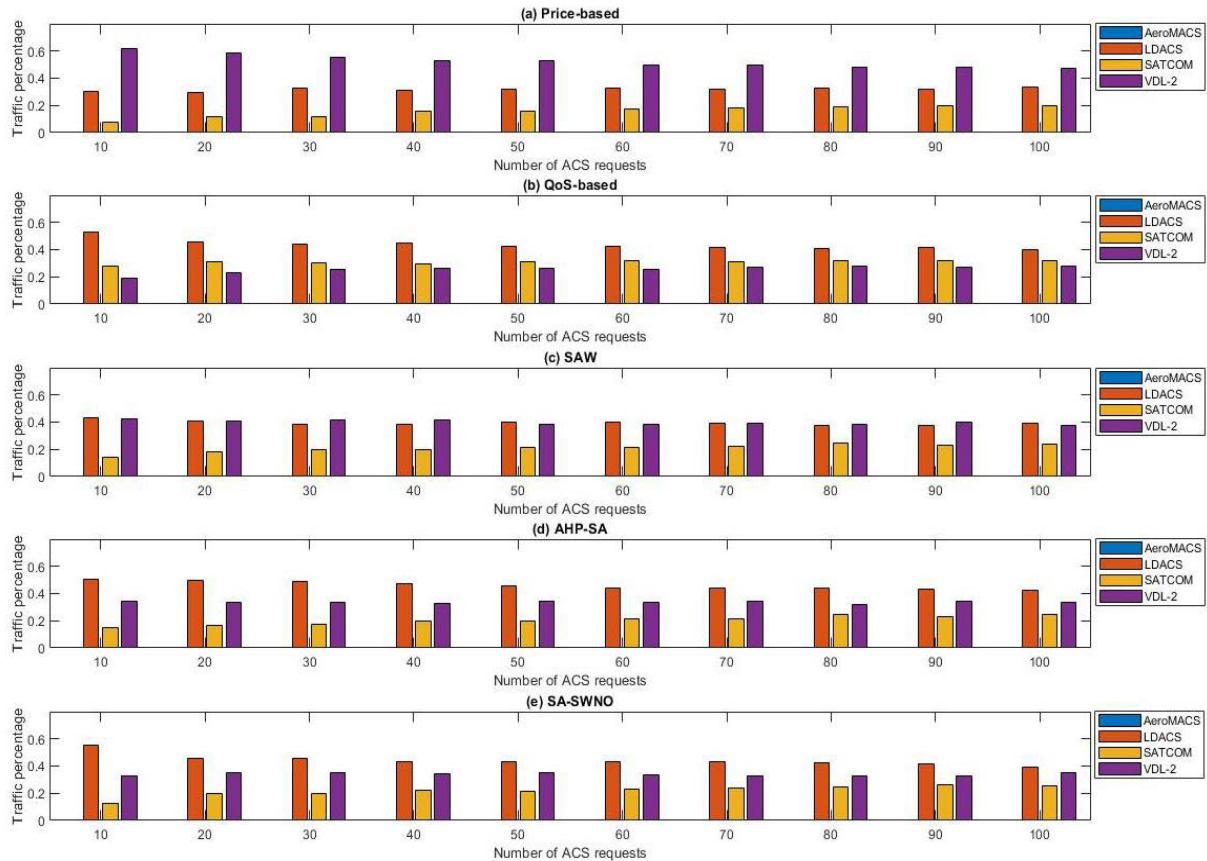


FIGURE 6. The traffic percentage in different networks over continental areas under five algorithms.

selection decision is not optimal. Therefore, decision-makers must assign suitable weight distribution to ensure the goodness of the aggregate utility function. The AHP-SA algorithm uses the analytic hierarchy process (AHP) to determine the appropriate weights for different attributes. The AHP performs the pairwise comparison for all characteristics to achieve the relative importance of each parameter and obtain the weight matrix. The AHP-SA algorithm has experienced better performance than price-based, QoS-based, and SAW algorithms since it considers the relative importance of each parameter when deciding the weight distribution. However, all these four algorithms choose the weights and the request-to-network assignment separately. It may not guarantee the optimal solution.

The SA-SWNO algorithm takes the advantages of the simulated annealing approach and the way the network selection has been modelled as a mixed-integer linear programming (MILP) to simultaneously optimize both the weight distribution vector and the assignment matrix. Therefore, the SA-SWNO approach always guarantees the best performance. As described in the network selection model (15)-(24) in Section V.B and further in algorithm 2, both the weight distribution vector $[w_1, \dots, w_n]$ and the assignment matrix $A = [a_{jk}]_{N \times M}$ are considered as the variables to be optimized simultaneously. This mechanism

of SA-SWNO helps to enlarge the search space to include both the weights and the assignment matrix instead of finding only the optimal assignment matrix. In contrast, the weights are given through arbitrary settings as in price-based, QoS-based schemes or through AHP process as in AHP-SA scheme. Accordingly, as indicated in Fig. 7, when the number of aircrafts is changing, SA-SWNO always achieves the highest average satisfaction degree. Compared to SA-SWNO, AHP-SA exhibits a lower average satisfaction degree. Fig. 7 demonstrates that SA-SWNO can effectively choose a suitable access network to meet the aircrafts' requirements and preferences, and it can also provide aircrafts with a higher quality of experience.

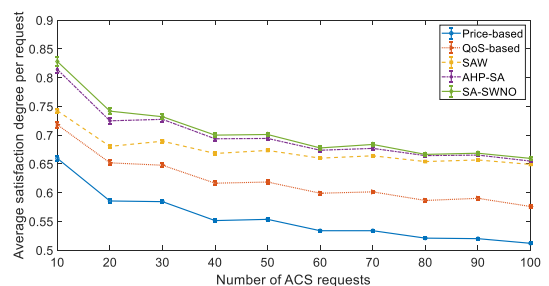


FIGURE 7. The average aircraft satisfaction degree per request with different ACS types under five algorithms.

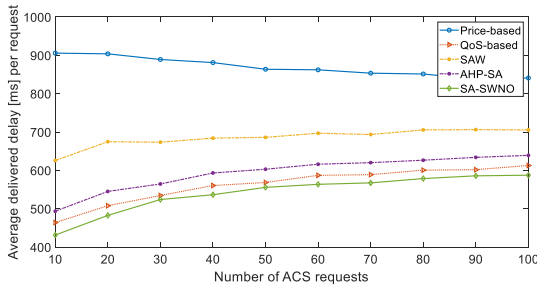


FIGURE 8. The averaged delivered delay with different ACS types under five algorithms.

3) AVERAGE DELIVERED DELAY

Fig. 8 plots the averaged delivered delay using the five algorithms as a function of gradually increasing numbers of ACS requests. Here, the average provided delay per request denotes the average delay experienced by all ACS requests after each ACS request selects the network under the constraints of meeting traffic request demands. Each algorithm is run 500 times to avoid the effects of outliers and obtain the average assigned delay. As can be seen from this figure, the average delay of the price-based algorithm is decreasing when the number of ACS requests increases. The reason for this behaviour is that from Fig. 5(a), when the number of ACS demands increases, the traffic percentage for using the VDL-2 network, which has enormous delay is decreasing. The SA-SWNO and QoS-based algorithms guarantee the best performance with the smallest delay.

4) AVERAGE DELIVERED BANDWIDTH

Fig. 9 plots the average delivered bandwidth of the five algorithms with gradually increasing the number of ACS requests. The average delivered bandwidth denotes the average bandwidth per request obtained by all ACS request after each ACS request selects the suitable network. The delivered bandwidth of the five algorithms gradually decreases with the increasing number of ACS requests because the necessary network resources to fulfill all the ACS requests requirements also rises. As a result, each ACS request is necessarily assigned less network bandwidth. The delivered average bandwidth of Price-based is smallest since VDL-2 also has the lowest bandwidth available. The SAW algorithm provides the second-lowest average bandwidth. However, it suffers from massive delays as in Fig. 8. The SA-SWNO algorithm has the third-lowest average bandwidth, which illustrates that SA-SWNO can effectively select the appropriate access network while utilising the bandwidth resources necessary compared to the QoS-based and AHP-SA algorithms. The QoS-based algorithm has the highest average bandwidth, which does not try to minimize the sufficient bandwidth allocation to fulfill the requirements.

5) AVERAGE DELIVERED COST

Fig. 10 plots the averaged delivered cost using the five algorithms as a function of gradually increasing numbers of

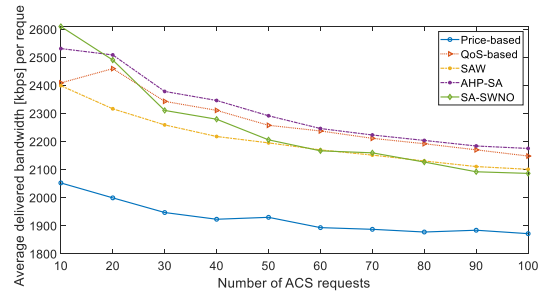


FIGURE 9. The average delivered bandwidth with different ACS types under five algorithms.

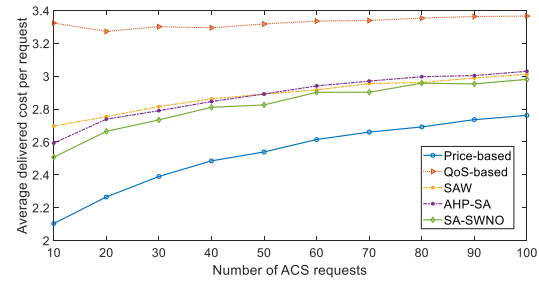


FIGURE 10. The averaged delivered cost with different ACS types under five algorithms.

ACS requests. The average delivered cost denotes the average cost per request obtained by all ACS request after each ACS request selects the suitable network. The price-based algorithm has the lowest price per network. The SA-SWNO and AHP-SA algorithms guarantee the second and third lowest price per network, respectively, which illustrates that both SA-SWNO and AHP-SA can effectively choose the suitable network with reasonable price, while still guarantee QoS requirements. The QoS-based algorithm has the highest price per network since it neglects the cost attributes in the link selection process.

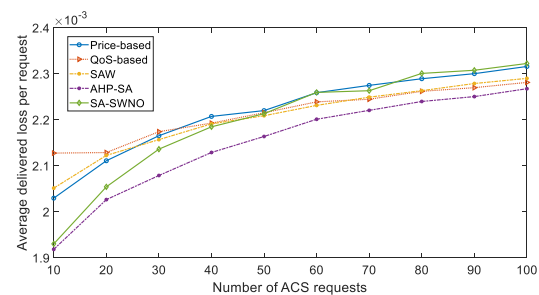


FIGURE 11. The average assigned loss with random application types under five different algorithms.

6) AVERAGE DELIVERED LOSS

Fig. 11 shows the average delivered loss using the five algorithms as a function of gradually increasing numbers of ACS requests. The average delivered loss denotes the average loss per request obtained by all ACS requests after each ACS request selects the suitable network. Both the SA-SWNO and AHP-SA algorithms provide the best performance with the lowest average packet loss rate per network.

VIII. CONCLUSION

In this paper, the SDN-based multilink selection framework for aeronautical telecommunication networking has been proposed by simulating multiple scenarios, where each scenario considers various quality of service (QoS) requirements.

Two simulated annealing-based algorithms, AHP-SA, and SA-SWNO have been presented for solving the multilink selection problem in the avionic network environment. SA is used to determine the weight factors of the objective functions in both algorithms in order to improve the selection performances and user satisfaction.

The proposed algorithms have been compared with existing techniques using six different performance parameters. Simulation results show that both algorithms outperform other well-known link selection algorithms including SAW, price-base, QoS-based algorithms in terms of average satisfaction degree. The proposed SA-SWNO set the weight factors and selections to be decision variables. The results also show that SA-SWNO can improve user satisfaction.

Further works involving the use of machine learning techniques, for example deep reinforcement learning, to learn from both AHP-SA and SA-SWNO, could further reduce the algorithms execution time, and further optimize the weight factors calculation's while taking into account additional features.

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