Cost-Driven Handover and Routing for 6G Integrated Terrestrial and Non-Terrestrial Aeronautical Networks

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***Abstract*—The connectivity needs of aviation businesses are rapidly evolving, which requires secure and efficient communication for aircraft crews and passengers. Reliable connectivity enables real-time communication for flight safety, navigation, and traffic management. It also supports route planning, fuel management, and maintenance, reducing delays and operational costs. However, future high data rate applications and an increased aircraft fleet may challenge current aeronautical networks such as SATCOM and VDL-2. The Sixth Generation (6G) of mobile networks aims to achieve ubiquitous, resilient, and sustainable connectivity globally. By integrating terrestrial (air-ground links) and non-terrestrial (LEO satellites and High-Altitude Platforms) networks, 6G enhances network capacity and reliability during flights, even in remote areas. Despite high initial investments and operational costs, cost-driven methods are essential for efficient operations. In this work, we propose a handover and route switching framework to support resilient communications in the 6G network that can minimise the costs of network usage while meeting the strict service requirements for safety-critical flight services. We consider the predictive trajectory flight path and the deterministic trajectory of the LEO satellites and High-Altitude Platforms (HAPs) aircraft. We evaluate this method in our simulation framework, where we demonstrate the network performance in a flight served by a set of ATG stations, HAP stations, and a LEO constellation. We analyse the handover frequency, throughput, delay, and final costs of operation comparing our method to the standard handover methods to show the trade-off between cost and network performance.**

***Index Terms*—6G networks, non-terrestrial networks, graph-based handover, cost model**

I. Introduction

The connectivity needs of aviation businesses are rapidly evolving. As a result, aircraft crews and passengers require more secure and efficient communication, no matter where they are. This enhanced communication demands reliable connectivity for aeronautical networks, enabling real-time communication for flight safety, navigation, and traffic management. In addition, seamless and constant connectivity also supports efficient route planning, fuel management, and maintenance, reducing delays and operational costs. However, accommodating future high data rate applications and an increased aircraft fleet may pose challenges for current aeronautical networks, such as SATCOM and VDL-2.

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The Sixth Generation (6G) of mobile networks is proposed to achieve ubiquitous, resilient, and sustainable connectivity throughout the world. For this reason, the 6G technologies can be aligned with the proposal of future aeronautical networks. The global coverage is achieved by integrating the terrestrial networks (air-to-ground links, ATG) and non-terrestrial networks, including LEO satellite links and High-Altitude Platform (HAPS). This enables increased network capacity for reliable and seamless connectivity during flights, even in remote areas. The benefit of integrating different technologies under the same network system relies on intelligent and complex coordination to ensure seamless handover and efficient management of the spectrum, power, and bandwidth across the different systems.

Undoubtedly, the 6G integrated networks will have a high initial investment as deploying the non-terrestrial network will involve significant upfront costs for satellite launches, ground stations, and infrastructure from many different stakeholders. The operational costs of maintaining and operating the new networks, including satellite and HAPS maintenance and fuel, can also be expensive. Therefore, to allow a competitive and sustainable market, cost-driven methods are essential to operate efficiently in integrated terrestrial and non-terrestrial networks.

In this work, we propose a handover and route switching framework to support resilient communications in the 6G aeronautical network that can minimise the costs of network usage while meeting the strict service requirements of safety-critical flight services.

- As we propose a cost-driven method, first we survey the total cost of ownership and operation of each network (i.e., ATG, LEO, HAP networks), including both CAPEX and OPEX, according to the literature.
- We model the average financial cost of utilization time per traffic flow granularity delivery, while estimating the cost of best effort usage.
- Based on this model, we develop an algorithm for handover and routing planning that considers the predictive

trajectory flight path and the deterministic trajectory of the LEO satellites and HAPS aircraft.

- We consider the graph-based handover framework to create a service time-based graph with the vertices representing the gNB instances over a predicted period and the edges' weight are computed according to the costs of communication usage and handover.
- We design the decision about the sequence and timing of handovers by finding the shortest path in the graph. This decision aims to minimise the cost of utilisation subject to the connectivity requirements and network resource constraints.
- We evaluate this method in our simulation framework, where we demonstrate the network performance in a flight served by a set of ATG stations, a set of HAP stations and a LEO constellation.
- Then, we analyse the handover frequency, throughput, delay, and final costs of operation comparing our method to the standard handover methods to show the trade-off between cost and network performance.

We anticipate that this framework will enhance the economic viability of 6G networks, ensuring they are dependable for future safety-critical aeronautical communications.

II. Related Works

Cost-based algorithms have been proposed for vertical handover (VHO) in heterogeneous networks. Those algorithms prioritize network selection based on weighted metrics such as power consumption, data rate, and service costs, rather than relying solely on signal strength [1]–[3]. For example, the algorithm in [1] triggers handover when the cost of remaining in the current network exceeds switching costs to an alternative network. These papers collectively emphasize that cost-based vertical handover methods use integrated cost functions combining monetary cost, power consumption, signalling overhead, and QoS metrics to optimize handover decisions in heterogeneous wireless networks, ensuring efficient and seamless connectivity while minimizing operational expenses.

While they focus on vertical handovers between Universal Mobile Telecommunication Systems (UMTS) and wireless local area networks (WLANS), there is a lack of studies proposing cost-based approaches on vertical handovers between integrated terrestrial mobile networks and non-terrestrial networks. Besides that, their analyses only infer the implicit effect of other optimization methods on cost minimization, while we explicitly evaluate the operation costs.

III. System Model

A. Integrated Terrestrial and Non-Terrestrial Network

In this paper, we build the proposed methods on top of our communication network architecture introduced in [4]–[6] and illustrated in Figure 1. This is made up of three layers: Network infrastructure data layer (comprised of ATG, HAPS, and LEO satellite nodes), control layer, and application layer. The Network Orchestrator (NO), running within the Management and Orchestration (MANO) application, leverages aircraft position tracking, geographic coordinates information of data plane nodes, and AI-based network link performance metrics analytics to support network and traffic-aware aircraft message routing and handover decisions. The control layer exposes the information and status of the network data plane through the northbound interface to the application layer, which is leveraged by the NO to support the data plane adaptive traffic routing and automated network resources (i.e., ports, network links and paths) management. The applications including the NO apply their algorithm logic to meet the application objectives through the SDN controller. The SDN controller forwards the logic to the data plan by using the OpenFlow southbound interface. Finally, the southbound interface converts the logic into specific rules to network nodes ports or resources management policies.

We assume that the 3D network infrastructure is composed of unified 5G/6G radio access networks (RANs) that are integrated with the SDN-based transport network and the common core network. RAN gNB nodes operate a unified waveform that is agnostic to aircraft frequency transmission, handovers, and switching across the different networks, enabling ubiquitous handover and service continuity. In the transport and core networks, the software-based architecture allows flexible network reconfiguration to accommodate dynamic service demands on the different network capabilities. These technologies enable data-driven decisions for efficient message routing and handover management across the integrated 3D network. A data-driven network orchestrator is fed by multiple data and information sources, including the aircraft (current position, flight trajectory, link availability) and the network (gNB positions, satellite trajectory, remaining network resources, end-to-end communication performance predictions) to define and shape message routing and handover plans.

B. Aircraft Message Routing

On the avionic side, we assume that the airborne router has multiple interfaces simultaneously connected to different gNBs of different networks. A message from air services should be forwarded to one of these interfaces according to the Routing Policy. The optimisation of aircraft message routing policy

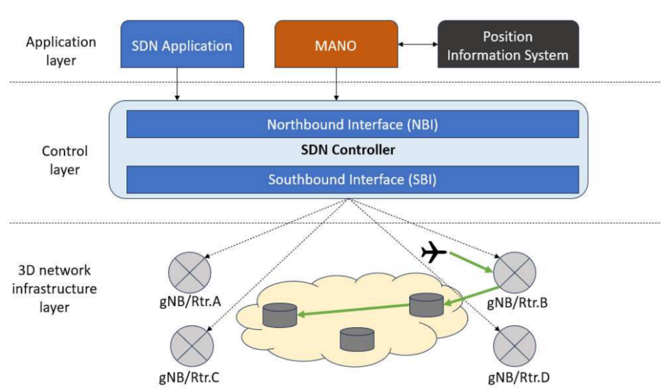


Fig. 1: Integrated 3D network architecture.

requires input from the service requirements and network conditions, provided by the Network Orchestrator. This allows for meeting service requirements while optimising the network performance. In this work, we apply the message routing and resource optimisation process that we proposed in our previous work [5]. In that method, we follow the objective given by the handover decision (e.g., the visibility time) and only switch to an alternative link if the current conditions do not satisfy the service requirements.

$$\underset{g}{maximize} \quad RP(g), \tag{1}$$

where RP is the aircraft routing priority decided by the handover algorithm. The optimization is subject to the service requirements described below:

$$\text{subject to} \quad g \in G \tag{2}$$
$$P_{RX}(g) > \overline{P_{RX}} \tag{3}$$
$$\sum_{a \in A} L(a) <= C(g) \tag{4}$$
$$R'(a,g) > \overline{R} \tag{5}$$
$$D'(a,g) < \overline{D} \tag{6}$$

- Eq. (2): The associated gNB g belongs to the set G of connected gNBs over multiple links of the aircraft.
- Eq. (3): The received power of the associated gNB $P_{RX}(g)$ shall be higher than the sensitivity threshold $\overline{P_{RX}}$, indicating availability.
- Eq. (4): The sum of the data load $L(a)$ of all aircraft a at the gNB g should be less than the total capacity $C(g)$ of the gNB.
- Eq. (5): The predicted data rate of the associated gNB $R'(a,g)$ shall be higher than the service data rate requirement $\overline{R}$.
- Eq. (6): The predicted end-to-end delay of the associated gNB $D'(a,g)$ shall be less than the service delay requirement $\overline{D}$.

We assume that the aircraft is connected to multiple links. The associated gNB of each link is given by the successful handover decision described in Section III-C. Thus, the Network Orchestrator will assess the Routing Plan Update Decision and steer the traffic among those multiple links according to their conditions and the service requirements.

C. Cost-Driven Handover and gNB Association

In the airborne router, each interface is connected to an independent radio equipment. This equipment should be associated with a gNB in the unified radio access network of the integrated 3D system. We assume that the gNB association follows the traditional Xn intra-RAN handover process, as specified in the 3GPP standard [7].

To support NTN use cases, in Release 16 of the 3GPP standard for 5G/6G mobile communications [8], new handover condition triggers have been introduced to take advantage of the predictable mobility of satellites and other aerial gNBs. In addition to the traditional measurement-based trigger, it is expected that the handover can be triggered by location-based events, elevation angle, and time-based events.

Specifically, in this work, we assume that handovers are triggered by time-based events. These events are generated by a proactive handover scheduler that requires the input from the geographical information (i.e., aircraft flight plan, the deterministic LEO satellite positions in orbit and the HAP and ATG gNB static locations) and network conditions provided by the Network Orchestrator. Given that input, it predicts the visibility time of the neighbouring gNBs (see Fig. 2) and schedules a handover event to be triggered once the link is available. This process is executed periodically within a given time frame.

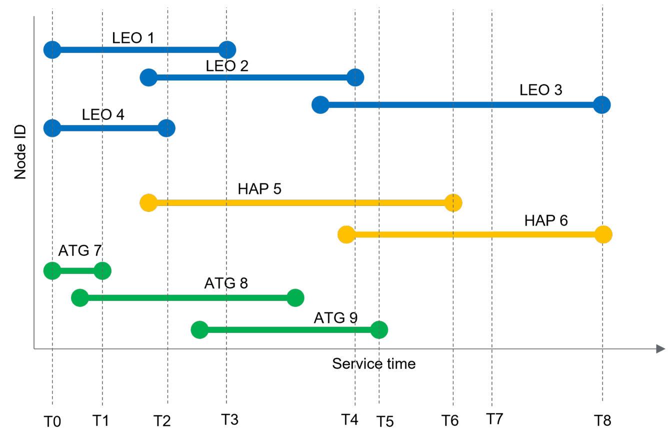


Fig. 2: Predicted service times of visible gNBs to the aircraft.

To generate the schedule of handover decisions, we employ the graph-based algorithm of our previous work [9]. A directed graph is created where the nodes represent potential target gNBs, and directed links represent possible handovers between two gNBs with an overlap in visibility time, as described in [10]. The handover decision is generated by finding the shortest path between the start and end points, as illustrated in Fig. 3.

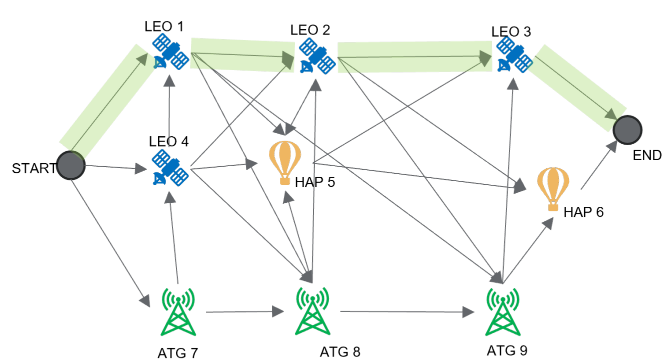


Fig. 3: Directed graph generated from predicted service time, where the main handover decision (highlighted in green) is calculated as the shortest path of the graph.

This framework allows for flexible implementation of multi-

TABLE I: Cost of operation for different gNBs.

gNB type	Duration of operation	Total cost	Per year	Usage cost per second
ATG [11], [12]	n/a	n/a	€168 k	€5.3e-3
HAP [11], [13]	10 years	€5 M	€500 k	€15.9e-3
LEO [14]	10 years	€1.82 M	€182 k	€5.8e-3

factor handover optimisation. We can define different link weights for various objectives, such as minimising the number of handovers while maintaining the required reliability (as we proposed in [9]). In this paper, we propose a cost-driven objective in which we aim to minimise the costs of communication and handover procedures. Thus, we define the graph edge weight W as the rate of consumption in the remaining time:

$$W = \frac{C_C + H_C}{T_{rem}} \quad [\text{€/s}]; \tag{7}$$

$$C_C = U_C \cdot \frac{B_{req}}{B} \cdot \frac{T_{rem}}{T_{interval}} \cdot T_{delay} \cdot n_{hops} \cdot 2, \tag{8}$$

$$H_C = U_C \cdot \frac{B_{ho}}{B} \cdot n_{hoPkts} \cdot T_{hoDelay} \cdot 2, \tag{9}$$

where C_C is the communication cost, H_C is the handover cost, U_C is the usage cost per second, B_{req} is the required bandwidth, B is the total bandwidth, T_{rem} is the remaining visibility time, $T_{interval}$ is the minimum packet interval time, T_{delay} is the maximum packet delay, n_{hops} is the number of hops, n_{hoPkts} is the number of handover control packets, B_{ho} is the required bandwidth for handover, $T_{hoDelay}$ is the handover control packet delay, and all is multiplied by 2 as we consider the usage cost of a gNB on both uplink and downlink.

We assume that the network usage cost is a function of the Total Cost of Ownership (TCO) of a gNB per year. We estimate the yearly TCO of each type of gNB (ATG, HAPS and LEO) according to the literature to derive the usage cost per second (U_C).

- For the ATG gNB, we assume a macro cell gNB for 5G/6G networks, with a total development, operation, and maintenance cost of €168,000 per year for a gNB [11], [12].
- For the HAP gNB, we assume an aerostatic HAPS that can fly for 10 years. The projected cost of deployment, operation, and maintenance is about €500,000 per year [11], [13].
- For the LEO gNB, we assume a small LEO satellite with a weight of 260 kg. The operating costs and launch costs are €7,000/kg [14], resulting in a projected cost of about 182,000 EUR per year operating over 10 years.

Given the yearly TCO above, we summarise the usage costs in Table I. The value of the Usage Cost per second (U_C) is used as a reference to weigh the handover and message routing decisions among the different sub-networks.

The main handover decision is derived from the shortest path in the directed graph, considering the graph edge weights defined in the previous step. The resulting schedule will trigger the handover of the gNB connected to the primary interface on the airborne router. For the cell association in other interfaces, an alternative and orthogonal schedule can be generated. A completely different set of gNBs from the main decision should be scheduled by removing the already scheduled gNBs to generate a new graph, as illustrated in Fig. 4. Hence, the handover decision for the second interface is derived from the shortest path in the new graph. Then, to schedule the handover decisions in the remaining interfaces, the algorithm executes the same process iteratively. At the end of all iterations, each interface will be simultaneously connected to a different gNB, creating alternative paths for aircraft messages and more resilient communication.

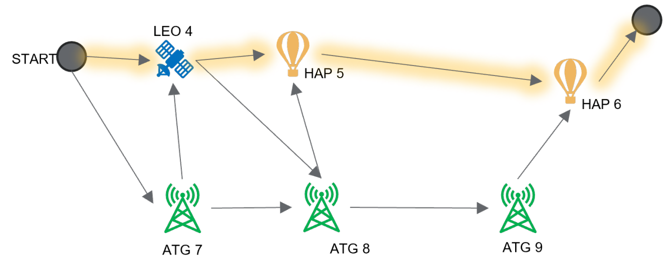


Fig. 4: Directed graph generated by removing the main handover decision. The alternative handover decision (highlighted in yellow) is calculated as the new shortest path of the new graph.

IV. Numerical Results

A. Performance Indicators

To characterise the cost effectiveness of our proposed method, we analyse a combination of key metrics: 99th percentile of delay, average data rate, average network load, and the cost of network usage.

We measure the end-to-end delay considering the transmission, propagation, processing, relay network, and core network delays. We measure the data rate by calculating the Shannon capacity given the SNR of the link. We measure the network load by summing the bandwidth used by each aircraft in each subnetwork.

The cost of network usage represents the accumulated transmission and reception costs of data and control packets throughout the duration of the simulated flight. For each data packet, we measure the delay and bandwidth used and calculate the total communication cost similarly to Eq. 8. For the total handover cost, we measure the number of handovers and multiply by the handover cost in Eq. 9. Depending on which subnetwork the packet was transmitted from or the handover was executed, the usage cost per second (U_C) varies according to Table I. Therefore, the cost of network usage (N_C) is the sum of the total communication cost and total handover cost.

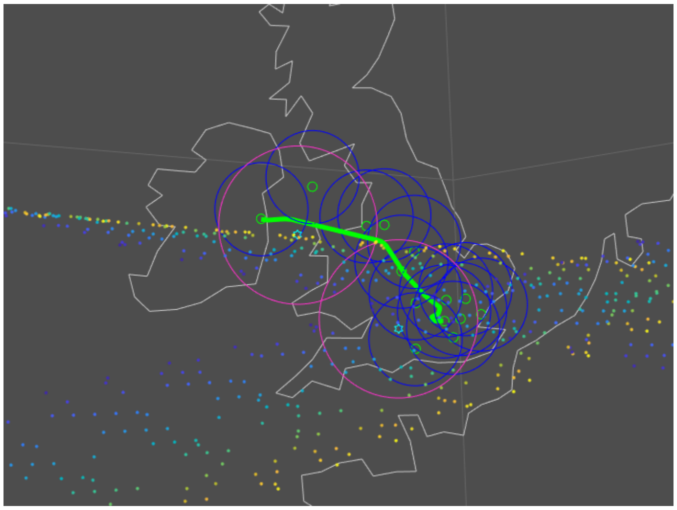


Fig. 5: Regional flight BAW827 from Dublin to London (green line). The pink circles illustrate the HAPS coverage, the blue circles illustrate the ATG coverage, and the yellow-blue dots are the LEO satellites.

B. Simulation Setup

We evaluate the performance of our methods during a flight from Dublin to London, as illustrated in Fig. 5, using our in-house simulation framework [9]. The aircraft mobility data trace is extracted from real flight information available in the Flight Aware tool [15]. To load the network, we simulate 50 aircraft flying. One aircraft follows the real flight trace while the other 49 are randomly placed around the main traced aircraft. These 49 aircraft follow the main one keeping the same distance throughout the flight. We assume that the ATG gNBs are deployed at airports. We consider the deployment of two HAP stations to cover the entire flight length and to ensure redundant links to the ATG and LEO stations. We assume a typical LEO satellite constellation. The specific system parameters are detailed in Table II.

C. Performance Evaluation

We evaluate the cost of network usage by comparing the standard measurement-based handover method with our previously proposed visibility-based method and our cost-based method. In Fig. 6, we present the average network load for each subnetwork, assuming that the 50 aircraft use 1 MHz bandwidth each during the Dublin-London flight. In Fig. 7, we show the respective average cost of network usage per aircraft. We observe that in the measurement-based method the network load is distributed according to the link quality as some aircraft are covered by ATG stations while others are only covered by LEO or HAP stations. The average cost per aircraft is higher than the other methods as it uses the LEO network with long packet delays, which multiplies the cost of usage. The long delays, as seen in Fig. 8, are caused by the fact that the measurement-based handover is triggered when the signal power falls under a threshold of -120 dBm, which can be very low to have a successful reception without many

TABLE II: System Parameters

PHY transmit parameters			
LEO satellite		**HAP station**	
Altitude	550 km	Altitude	20 km
Satellites/orbit	22	Bandwidth	20 MHz
Long. shift/orbit	5°	Carrier frequency	2 GHz
Orbit inclination	54°	Transmit power	16 dBW
EIRP/MHz	14 dBW/MHz	Antenna	Phased array
Bandwidth	400 MHz	Beamwidth	173.5 degrees
Carrier frequency	20 GHz	**ATG station**	
Antenna (data)	Circular	Bandwidth	20 MHz
Aperture	0.5 m	Carrier frequency	3.5 GHz
Max gain	38.5 dBi	Antenna	Phased array
Antenna (control)	Phased array	Beamwidth	166.5°
Beamwidth	45°	Transmit power	16 dBW
PHY receive parameters			
Aircraft – LEO receiver		**Aircraft – HAP receiver**	
Antenna (data)	Circular	Antenna	Phased array
Aperture	0.6 m	Beamwidth	180°
Max gain	39.7 dBi	**Aircraft – ATG receiver**	
Antenna (control)	Phased array	Antenna	Phased array
Beamwidth	180°	Beamwidth	180°
Aircraft - common			
PHY sensitivity	-120 dBm	Noise power	-107.013 dBm
Cable loss	6 dB		
Handover parameters			
Measurement-trigger		**Time-trigger**	
RSSI threshold	-120 dBm	Prediction period	5 min
Sampling period	30 s		

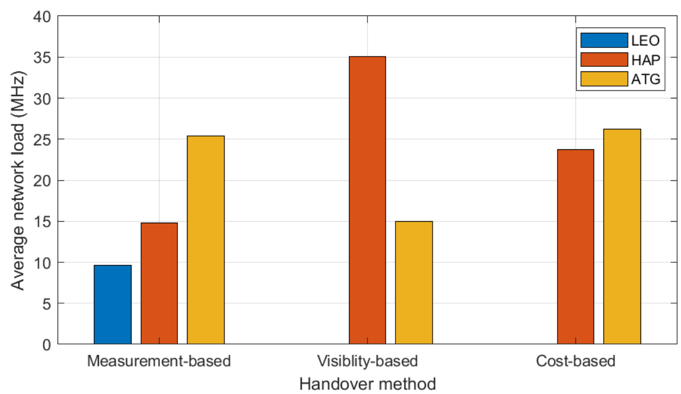


Fig. 6: Average network load distribution among the different subnetworks for each handover method.

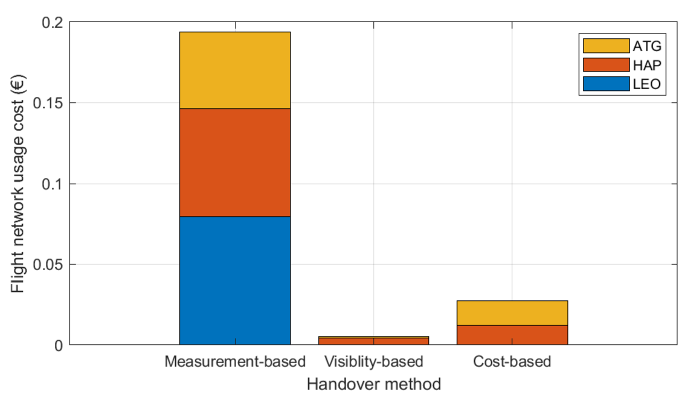
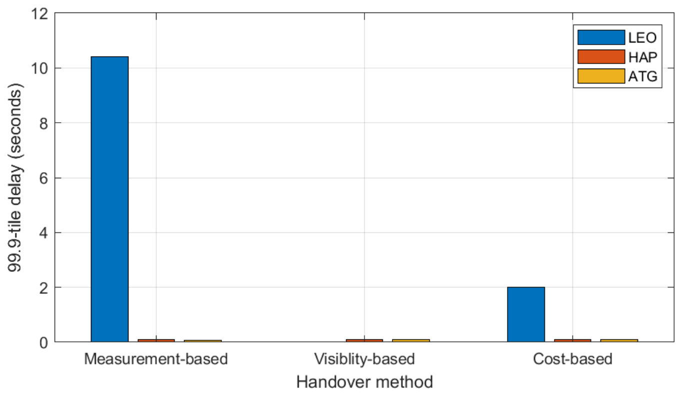
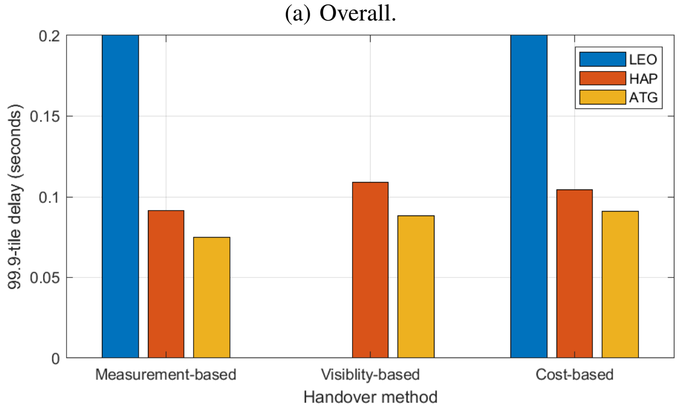


Fig. 7: Cost of network usage per flight for each handover method.



(a) Overall.



(b) Zoom in.

Fig. 8: 99th percentile of delay over the flight for each handover method.

retransmission attempts. Furthermore, the measurement-based method does not minimise the number of handovers as the other methods do. Consequentially, the increased number of handovers contributes to a higher cost using this method.

In the visibility-based method, more aircraft are assigned to the HAP network since its cells have bigger coverage than the ATG cells, compared to the cost-based. Consequentially, there are fewer handovers in the HAP network due to the longer visibility time compared to the ATG or LEO network, leading to a smaller cost.

The cost of network usage of the cost-based method as low as that of the visibility method, indicating that minimising the number of handovers contributes to the cost reduction. This method mainly assigns the aircraft to the ATG network where the usage cost is cheaper while assigning the few aircraft that are out of the ATG coverage to the LEO network, in order to maintain the connectivity, meeting performance requirements, as depicted in Figs. 8 and 9.

V. Conclusion

In this paper, we explored cost-driven methods for network management within the context of future 6G aeronautical networks. The 6G integrated network may have high initial investments for deploying the non-terrestrial network and additional terrestrial ground stations, and the operational and

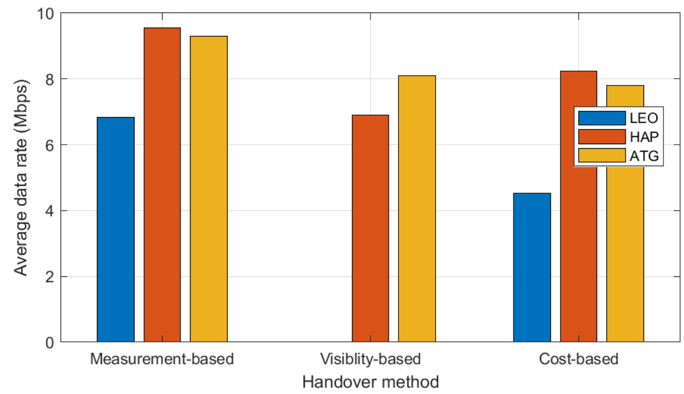


Fig. 9: Average data rate over the flight for each handover method.

maintenance costs can also be expensive. This creates the need for cost-driven methods to keep the network services competitive and sustainable. Therefore, we proposed a handover method that considers the costs of transmitting in a gNB and creates a schedule of handover decisions that minimises the overall costs. This method is built on top of a graph-based framework where the service time of the gNBs is predicted, so the method can proactively schedule a handover when the gNB becomes visible with a good link quality. In our simulation framework, we evaluated our method comparing to the standard 5G measurement-based method and to our previous non-cost-driven method. The results demonstrate that our method can achieve cost-effective operations while meeting service performance requirements. In future works, we will explore different flight cases and more realistic channel occupation models to evaluate our methods and analyse their benefits in more comprehensive scenarios.

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