Design and Optimization of Aerial-Aided Multi-Access Edge Computing towards 6G

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Abstract— Ubiquity in network coverage is one of the main features of 5G and is expected to be extended to the computing domain in 6G. In order to provide this holistic approach of ubiquity in communication and computation, an integration of satellite, aerial and terrestrial networks is foreseen. In particular, the rising amount of applications such as In-Flight Entertainment and Connectivity Services (IFECS) and SDN-enabled satellites renders network management more challenging. Moreover, due to the stringent Quality of Service (QoS) requirements edge computing gains in importance for these applications. Here, network performance can be boosted by considering components of the aerial network, like aircrafts, as potential Multi-Access Edge Computing (MEC) nodes. Thus, we propose an Aerial-Aided Multi-Access Edge Computing (AA-MEC) architecture that provides a framework for optimal management of computing resources and internet-based services in the sky. Furthermore, we formulate optimization problems to minimize the network latency for the two use cases of providing IFECS to other aircrafts in the sky and providing services for offloading AI/ML-tasks from satellites. Due to the dynamic nature of the satellite and aerial networks, we propose a re-configurable optimization. For the transforming network we continuously identify the optimal MEC node for each application and the optimal path to the destination MEC node. In summary, our results demonstrate that using AA-MEC improves network latency performance by 10.43% compared to the traditional approach of using only terrestrial MEC nodes for latency-critical applications such as online gaming. Furthermore, we record a benefit of at least 6.7% decrease in flow latency for IFECS and 56.03% decrease for computation offloading.

Index Terms— Aeronautical Communications, MEC, 6G

I. Introduction

Sixth Generation (6G) mobile networks aim to provide global coverage to ensure availability and seamless access [1]. This not only enables communication in sparsely populated and isolated regions but also supports new applications like autonomous mobility, for example, autonomous ships and trains. Terrestrial networks do not satisfy this requirement mainly due to the large amount of surface covered by water bodies and inaccessible locations on land. Moreover, given natural disasters and obstructed terrain, the terrestrial infrastructure cannot cope with the high availability demand. Therefore, satellite networks have been suggested to realize global coverage. However, satellites exhibit limitations due to their physical location. Space radiation requires hardware to be laid out redundantly with larger structural sizes compared to terrestrial hardware. This results in higher energy consumption and lower computing capacity. In addition, upgradability is constrained by the physical access possibilities exacerbating both problems over time. Furthermore, satellite networks exhibit the highest latency compared to other network types. In the best case, LEO satellites record a minimum round trip time of ca. 1 milliseconds due to a theoretical minimum operating altitude of 160 km. For geostationary satellites this increases to ca. 240 milliseconds, as they operate at 36000 km. These latency values fall far behind the 6G-envisioned latency requirements [1].

Deploying Aerial Base Stations (ABSs), i.e. Unmanned Aerial Vehicles (UAVs), drones, balloons, or aircrafts equipped with wireless transceivers providing Aerial Radio Access Networks (ARANs) [2], instead of satellites, overcomes such shortcomings. This is due to a flight altitude of maximum 10-15 km resulting in a latency of ca. 50 µs. At this altitude communication hardware is not affected by radiation anymore. Furthermore, ABSs offer better channel conditions compared to satellite networks, due to the propagation distance and a higher Line of Sight (LoS) probability compared to terrestrial networks. However, coverage area of a single ABS is smaller than that of an satellite increasing the amount of handovers.

Combining the terrestrial, aerial and satellite network allows to harness the benefits and to compensate for the deficits of each network. The overlapping coverage of these networks allows increasing the total available data rate, the user experienced data rate, and the device density. In addition, the redundancy introduced by overlapping coverage results in a more fail-safe and reliable network. This is especially important in cases of natural disasters, wars and other events that usually damage the local terrestrial infrastructure and lower the reliability of
terrestrial networks. Moreover, this Multi-Layer Network (MLN) allows the usage of different layers for different applications. The satellite layer reduces handovers for globally moving nodes, whereas the terrestrial layer exhibits the highest data-rate for local nodes, resulting in a better total Quality of Service (QoS) for every node in the network. Also, cost concerns that previously benefited the deployment of terrestrial networks over other network infrastructures have lost significance as satellite deployment costs have shrunk due to increased subsidies, technological advancements and more competition [3]. Arguments that terrestrial networks are easier to maintain render obsolete, as the physical distance of satellite networks lead to different maintenance costs. Examples for profitable, usable and large-scale satellite networks as of today are Kuiper, Starlink and OneWeb. In addition, previously mentioned new applications make combined network approaches more independent of market demands generated by population density. In summary, an MLN is able to increase the capacity, the user experienced data rate and energy efficiency, and supports a higher node density while decreasing the latency, which is in line with the goals of 6G [1].

The considered MLN also allows for ubiquitous and edge computing, by utilizing aircrafts as potential Multi-Access Edge Computing (MEC)-nodes thereby placing the processing and storage capability throughout the network. This Aerial-Aided Multi-Access Edge Computing (AA-MEC) facilitates the newly envisioned 6G applications as Internet of Things (IoT), Industry 4.0, Smart Cities and new AI/ML-based distributed applications [1]. These applications require that processing tasks are completed with a maximum tolerable delay. Thus, tasks need to be offloaded taking calculation time and latency of the offloading process into account. Therefore, it is necessary to optimize the placement of the edge computing units and the routing of the task to the edge.

In an MLN most nodes are mobile, e.g. satellites and aircrafts. These nodes exhibit different speeds and trajectories. Fig. 1 visualizes this by showing how the links and MEC destinations of a satellite change while orbiting the earth. This results in continuously varying distances between nodes and dynamic changes in the network topology. This raises new challenges in routing, placement of computing tasks, and the provision of QoS, especially latency guarantees. The dynamicity of the nodes influences the existence of a route and its life span. As trajectories and links change in real time, routes cannot be planned in advance. In this scenario, a static routing approach would result in increasing latency or even breaks in communication links. In computational task offloading applications, a static selection of MEC destinations detracts from its purpose since the computing instances are not always on the edge to the changing network topology. The adaptability results in the need to reconfigure to always maintain optimality in path results in a more complex optimization problem. This results in the need for a new optimization problem description wherein the network must be optimized dynamically.

A. Contribution of this study

The requirements for 6G networks, particularly in terms of latency and the need for seamless integration of the satellite, aerial and terrestrial networks, solutions to reduce delay become imperative. However, the design of such a system given the mobile nature of the envisioned three-dimensional architecture becomes challenging. In this work, to cater for delay reduction, in line with 6G requirements, we propose an AA-MEC architecture, where already existing aircrafts can serve as computing entities for other components in the sky, for instance satellites or other aircrafts.

In this regard, we focus on two use cases. The first provides In-Flight Entertainment and Connectivity Services (IFECSs) to aircrafts during flights. The second enables processing for tasks offloaded from satellites, e.g. tasks related to SDN-enabled or AI-enabled satellite computations. We formulate and solve optimization problems with the goal of minimizing network latency for these two use cases while guaranteeing a maximum packet delay requirement for all the services. Moreover, as part of the optimization, our proposal defines the optimal edge computing destination (aerial or terrestrial) for each aircraft or satellite as well as the optimal path towards the destination. Due to the network dynamicity, we consider a re-configurable allocation of the processing resources to ensure that at each network change, the optimal solution is determined.

B. Article Structure

The remainder of this article is structured as follows. A detailed analysis of the related literature is given in Section II. Further, the technologies used for the different network components are elaborated in Section III. The system model is described in Section IV, whereas the optimization problem formulation is described in Section V. The main findings of this work are illustrated in
Section VI. Finally, the implications of the AA-MEC are discussed in Section VII.

II. Related work

The state of the art that is relevant for our proposed solution comes from three main areas: airborne internet, computational offloading and architectural concepts.

A. Airborne Internet

While many publications consider ground users as the source of service requests in MLN [4] [5], it is important to consider aircrafts as sources because airborne internet has been growing in demand in recent years. This is particularly a challenge due to the high speed of the nodes and the resulting rapid changes in the network topology and channel conditions.

The authors in [6] consider an aerial mesh network that requires airborne internet services. The requested content is transmitted from a satellite gateway on the ground to the nearest aircraft and then routed to the other aircrafts requesting this content, through a multi-hop aerial network. The routing is optimized and this results in reduction of latency since the aircrafts can act as relays for the content from the ground station. Similarly, the focus of [7] is on providing airborne internet for a European Space-Air-Ground-Integrated Network. They also consider that the services are placed on ground, in data centers. The study compares different optimization algorithms focusing on routing, service placement, and service migration.

In contrast to the above-mentioned works, the authors in [8] consider caching the content also on aircrafts and adding communication links between aircrafts. To solve the more complex routing problem they apply a reinforcement learning based algorithm which optimizes for energy efficiency. However, they do not take into account latency requirements for QoS although aircraft passengers can request latency critical applications. Moreover, the dynamicity of the links leading to connection losses and increasing latency are also not considered. This new, more complex optimization is taken into account in our work by continuously optimizing the MEC destinations for service placement while also providing latency guarantees.

B. Computation Offloading

With the emergence of processing intensive applications like AI/ML, the importance of computational offloading increases. For this, various studies investigated offloading schemes in MEC. Reference [9] applies a reinforcement learning approach to minimize latency in Fog networks, a special case of MEC networks. However, the latency constraints of Fog networks limit the placement of task offloading destinations. Furthermore, the dynamicity of the network is not considered and routes are not recalculated, which would be important in a dynamic MLN.

An architecture that deploys MEC nodes in a satellite and terrestrial network is considered in [10]. They describe an offloading algorithm with the goal to optimize energy consumption and reduce latency by assigning computational tasks at minimal cost. For this, they consider special satellites as relay stations. However, they do not consider terrestrial or aerial MEC nodes, which would add complexity to the problem.

The practicality of deploying MEC nodes on satellites is limited due to increased latency and reduced calculation capabilities for hardware deployed in space. In [11], an MLN that consists of a Low Earth Orbiting (LEO) constellation, UAVs and IoT devices is studied. The network uses UAVs as flying MEC servers and proposes a task scheduling mechanism for that architecture. The users have computational tasks to offload to the UAVs carrying MEC servers and the computing resource allocation and task scheduling is optimized for this scenario. This optimization is solved by applying reinforcement learning. However, they do not consider connections between terrestrial gateways and aircrafts. In addition, aerial nodes are just considered to provide computational resources but not act as endpoints for content requests.

Reference [12] proposes an architecture called satellite MEC, which is a MEC service offered via satellite links. This service can be provided in different scenarios wherein the location of the MEC server is either the satellite or the terrestrial station. Terrestrial offloading works similar to regular MEC schemes, since servers are located in close proximity. On the other hand, satellite MEC servers are deployed in LEO satellites in satellite-borne offloading. The limitation of this method is the resulting increased energy consumption of a satellite and the inability to deal with latency-critical applications. The authors of [13] propose a MLN network where the satellite, aircraft and terrestrial layers contain MEC servers and tasks request only originate from the terrestrial layer. For this network architecture they propose a deep imitation learning-driven offloading and a caching algorithm to find the optimal task and cache placement. However they do not consider computational task requests from other layers.

In contrast to the above-mentioned works, firstly we extend the MEC capability to aircrafts, thus bringing computational resources and content services closer to the origin of the requests in the air. Secondly, we also take the dynamicity of the network into account while selecting the destinations for offloading tasks by performing a re-configurable optimization.

C. Architecture

To enable latency-critical applications and provide a comprehensive network that supports 6G requirements and aerial use cases, the design of an optimal MLN architecture is of great importance. Inmarsat ORCHES-
TRA [14] envisions a dynamic multi-layered network architecture consisting of satellite and terrestrial layers to support 5G. They aim to provide global network coverage for mobile nodes and enable new use cases like Smart Ships and connectivity for Urban Air Mobility. However, they only focus on connectivity solutions and ignore the potential of the network elements to act as computing entities. They also do not consider an aerial layer as part of this architecture. Moreover, even in such a 2-layer network providing connectivity solutions, the network can be optimized further for performance metrics such as latency.

The authors in [15] optimize the placement of the terrestrial gateways for SpaceX’s Starlink as the reference constellation in the satellite layer. For this, the three metrics of latency, maximum load on the node, and load balancing among gateways are considered. The placement coordinates are obtained by applying a genetic algorithm. However, such a free optimization is not always feasible since the positioning of gateways is also influenced by political and economic considerations. Networks with constraints on gateway positions and an additional aerial layer containing MEC servers, as in our case, are therefore more difficult to optimize.

An aerial layer is incorporated in [16] resulting in an MLN with an aerial layer consisting of short range UAVs and a terrestrial layer with users and base stations. The users have computational tasks that could be offloaded to the MEC servers on the base stations or UAVs. However, with the increasing applications of AI/ML on satellites resulting in computationally intensive tasks, it becomes imperative to also consider a satellite layer in the design of MLNs. Besides, the authors perform an optimization to reduce the energy consumption in the network and calculate the optimal placement of tasks, trajectory of UAVs and offloading routes. Despite latency being a critical motivator for MEC use cases, the authors do not provide a guarantee for the maximum latency for the offloaded tasks. They also do not consider any tasks arising within the aerial layer which could be served by other nodes in the aerial layer. Taking this factor into account would result in a highly dynamic network topology, thus adding complexity to the optimization problem.

Therefore, in our MLN, we include an aerial layer and a satellite layer that can act as sources for content and task requests, which is necessary given the rise in web services and computationally intensive applications in the sky. This results in a highly dynamic network which we also factor in while performing our re-configurable optimization. Since this dynamic MLN is optimized for latency, we provide guarantees on the maximum delays experienced by the data packets, thus assuring QoS.

A. Satellite Constellation Networks

A satellite constellation consists of multiple satellites that orbit a planet to serve a common purpose. Iridium, Intelsat, Kuiper, OneWeb and StarLink are operational examples with the goal of providing a worldwide communication network coverage. These satellites may orbit at different trajectories and altitudes. One shortcoming of the mentioned satellite constellations is that they only provide a data rate of 25 Mbit/s as long as their user density does not exceed 0.1 user/m² [17]. On the other hand, they are highly mobile and thus, more applicable than terrestrial networks in extreme situations. For instance, satellites have been successfully applied to enable operational networks after heavy damage to terrestrial infrastructures due to military conflicts and natural disasters. Moreover, applying satellites may support terrestrial networks whose access is highly constrained due to environmental factors, e.g. undersea cables. On top of that, technological advancements may provide for additional applications of satellites, e.g. intelligent transportation, remote area monitoring, disaster rescue, and large-scale high-speed mobile internet access [18]. The constellation design not only influences the QoS, measured by communication latency, handover frequency, throughput but also metrics such as manufacturing cost, orbital period, the number of satellites in the constellation and routing complexity.

We focus on LEO satellites with an altitude range of 160 to 2,000 km, as they exhibit the lowest communication latency, the highest relative ground speed resulting in the highest flexibility. This is in line with the current trend to deploy LEO satellite constellations [19], due to the recent technological advances and increasing importance of latency-sensitive applications. However, the benefits of LEO satellites come at the cost of a smaller coverage hence higher handover frequency. In addition, the high amount of satellites allow multiple flows which makes the traffic routing more flexible. This is particularly advantageous for the use as a backbone network. However, this flexibility leads to frequent changes in the network topology and therefore an increased routing complexity.

The specific network we base our results on is the Iridium-Next satellite constellation network [20] with 66 satellites operating at an altitude of 781 km. Satellites are grouped into multiple orbital planes resulting in Inter-Satellite Links (ISLs) spanning intra- and inter-plane communication.

A large proportion of the relevant communication endpoints are located in the terrestrial network. Therefore, it is important to enable non-terrestrial networks to access these via terrestrial gateways. In general, satellites are served by one gateway at a time [15]. As the placement of gateways directly influences the performance of the designed architecture [21], gateways should be placed near heavily used terrestrial nodes, but also throughout the globe, to ensure global coverage, reliability and minimal latency. In case of the Iridium-Next Satellite network, gateways are not distributed evenly around the world, but
can mostly be found in regions of heavy usage like North America and Eurasia. An overview of the gateways is provided in Table I. These satellite gateways can act as MEC nodes for different processing tasks in the network.

### B. Multi-Access Edge Computing (MEC)

It can be expected that network nodes vary in processing and storage capabilities. This results in the possibility of computing tasks not being feasibly solved locally. To alleviate this problem, MEC is introduced. MEC is a special case of edge computing proposed by the European Telecommunications Standards Institute (ETSI) [23]. This involves placing real-time or near-real-time processing servers at edge nodes within the Radio Access Network (RAN). Computational tasks can be offloaded to MEC servers, thereby enabling the movement of tasks between network nodes. This introduces a latency due to the propagation time and the execution time of the task. Hence, typically, MEC nodes are located in proximity to end users which is the key factor to decrease serving latency. The MEC concept has become quite popular in recent years with applications like IoT, data caching, video analytics, and autonomous driving [24]. Therefore it is expected to play a key role in 6G communication systems. However, binding MEC servers to gateways, immobilizes them and therefore reduces their usage locations and applications, for example, in sparsely populated or remote areas or military, emergency relief, and disaster response. In cases when a computational task can be executed on multiple MEC nodes within the network, the placement of it emerges as an optimization problem.

### C. Multi-Layer Networks

In this work, the network under study is a Multi-Layer Network comprising a terrestrial, an aerial and a satellite network. Base stations, satellite and Direct Air-to-Ground (DA2G) gateways are nodes found in the terrestrial layer. Aircrafts, low and high-altitude platforms and in general UAVs are found in the aerial layer and satellites are located in the satellite layer. Each layer provides certain resources and displays technological limitations. For instance, inter-satellite communication is often based on optical links which, on one hand, require a LOS channel, but on the other hand, exhibit high bandwidth compared to radio based satellite-gateway links. As another example, aircrafts may provide a high-speed access network with LEO satellites being used as relay stations. The high mobility of the nodes in the aerial and satellite layers results in a dynamic network topology which allows for a more flexible network. An overview of these resources and limitations is given in Table II. The combination of the different types of networks allow each layer to compensate for the weaknesses of the other, resulting in the best use of the 3D space [25]. It is expected that this kind of network will be standardized in 6G [26]. Such 6G networks need data streams to be routed with minimal latency to support the various applications. However, the different communication media combined with the fast moving nodes in the non-terrestrial layers give rise to a new research challenge of how to optimally route data throughout the network.

### IV. System Model and Use Cases

The integration of MEC nodes into the MLN adds the 6G requirement of network flexibility to the MEC concept. We envision that this combined architecture results in an AA-MEC. In this AA-MEC we address two research challenges, the first being the optimal placement of processing tasks across the multiple layers of a dynamically changing network and the second being the optimal routing of the processing tasks to the MEC server.

The AA-MEC architecture designed for this study is illustrated in Fig. 2. The network under study consists of a LEO Iridium-Next satellite, an aerial and a terrestrial layer. Nodes in the satellite layer possess processing capabilities, but this is limited and hence are not suitable recipients for processing tasks from other nodes. Satellites can communicate with terrestrial gateways and aircrafts found in the aerial layer. Aircraft nodes can be further

### Table I

| Gateway Location | Country | Latitude (degrees) | Longitude (degrees) |
|------------------|---------|--------------------|---------------------|
| Beijing          | China   | 39.92              | 116.388             |
| Fairbanks        | USA     | 64.838             | -147.716            |
| Iqaluit          | Canada  | 63.733             | -68.500             |
| Ischewsk         | Russia  | 56.850             | 53.204              |
| Longyearbyen     | Norway  | 79                 | 17.66               |
| Punta Arenas     | Chile   | -53.315            | -71.580             |
| Rome             | Italy   | 41.9               | 12.483              |
| Tempe            | USA     | 33.415             | -111.909            |
| Wahiawa          | USA     | 21.503             | -158.024            |
| Yellowknife      | Canada  | 62.450             | -114.350            |

### Table II

| Layer | Nodes | Advantages | Disadvantages |
|-------|-------|------------|---------------|
| Satellite | GEO, MEO, LEO | large coverage, infrastructure independent | LoS channel, propagation delay |
| Aerial | HAP, LAP, UAV, Aircraft | wide coverage, flexible deployment, low cost | unstable link, high mobility, less capacity |
| Terrestrial | Cellular, WiFi | rich resources, high throughput | limited coverage, infrastructure dependent |
distinguished into passenger and aerial server aircrafts. While passenger aircrafts can function as routing nodes, server aircrafts also possess computing capability. Both aircraft types can communicate with terrestrial gateways over air to ground links. All terrestrial nodes are able to communicate with satellite and aerial nodes. In all cases, MEC servers are modeled as an integrated part of the network nodes of the RAN.

A key requirement in a MEC network is to minimize the user-perceived latency. This study aims to find the effects of the proposed multi-layer architecture on the user-perceived latency for the use cases of airborne internet and computation offloading.

A. Use Cases

1. Airborne Internet

In recent years airborne internet connectivity is growing in demand. This allows critical information, such as weather, flight altitudes and landing conditions to be exchanged. Besides, it enables airplane passengers to receive web services such as messaging services, web-surfing, gaming, Voice over Internet Protocol (VoIP), video and music streaming etc. The main obstacle to airborne connectivity is the lack of communication infrastructure, especially while flying over regions as deserts, the poles and large bodies of water. In such cases, the internet is traditionally provided over satellites resulting in high latency. This is even the case if a LEO constellation is used. Aerial MEC nodes and DA2G can alleviate this problem especially in time-sensitive services. An overview of the service requirements can be found in Table III.

2. Computation Offloading

Different computational tasks arise in satellites. In case the task exceeds the processing capability of the satellite, it can be offloaded to a MEC server. This is defined as computational offloading. This comes at the cost of an additional propagation and transmission latency. However, deploying MEC in aircrafts and satellite gateways brings the computing resources and other services closer to the satellite nodes resulting in reduced propagation and transmission time. As a result, deploying AA-MEC would bring considerable gains to satellite networks. We assume that the satellite and MEC server processors are ARM Cortex-A8 and ARM Cortex-A73 based, respectively. Table IV gives an overview of their processing capabilities.

V. Problem Formulation

The two use cases result in two optimization problems with the goal of minimizing latency in an AA-MEC where gateways and aircrafts act as MEC nodes for A) passenger aircrafts’ IFECS and B) for satellites. All the trajectory simulations of satellites and aircrafts in this work were executed with the help of the Systems Tool Kit (STK) software [31].

The envisioned network topology is defined as a graph $G = (V, E)$, where $V$ are the network nodes (i.e., satellites, gateways and aircrafts). Further, the set $E$ denotes the network edges of the communication links among all entities. The capacity of the links are given in Table V. In the Iridium-Next constellation created with STK, each satellite has two stable ISLs within the same orbit and two stable ISLs to the neighboring orbits. ISLs are part of the edges $E$. However, due to the satellite and aircraft mobility, connections change over time. This is reflected in our work by generating a snapshot $r \in \mathcal{R}$ of the network every 5 minutes. Within a snapshot the network is assumed static [32].
A. Aircrafts as Edge Computing Entities

In the airborne internet use case we consider services provided to passengers within aircrafts that fall into the category of IFECS. All notations used in this use case can be found in Table VI. In an aircraft \( a \in \mathcal{V}_A \) with \( N_a \) passengers, only \( \rho_a = 0.2 \) [7] utilize IFECS. Depending on the aircraft, \( N_a \) ranges from 132 up to 853 passengers with the mode at 180. We distinguish four different services \( m \in \mathcal{M} \), where \( U_m \) denotes the utilization ratio of a service and \( B_m \) the corresponding bandwidth requirement per passenger. An overview of the different services and their requirements is given in Table III.

In our scenario, each service within each aircraft is considered as network flow denoted as \( f_a \). We can then write the total flow demand of a service as

\[
D_{f_a} = B_m \cdot U_m \cdot N_a \cdot \rho_a.  \tag{1}
\]

The total latency of a flow is the aggregation of propagation and flow transmission latencies. The flow transmission latency is defined as the time taken to transmit the whole flow demand \( D_{f_a} \) in one second from the source to the destination and is expressed as

\[
L'_{f_a,i,j,r} = \frac{D_{f_a}}{B_{i,j,r}},  \tag{2}
\]

where \( B_{i,j,r} \) is the bandwidth of the link that connects node \( i \) with node \( j \) at a given snapshot \( r \). The transmission latency for a single packet within a flow \( f \) can be written as

\[
L'_{f,a,i,j,r} = \frac{D_{f_a}}{B_{i,j,r}} \cdot P_{f_a} \cdot \frac{R_{f_a}}{B_{i,j,r}},  \tag{3}
\]

where \( P_{f_a} \) is the size of a packet. Note that we assume that every packet of a flow \( f \in \mathcal{F} \) has the same size. The propagation latency is defined as

\[
L_c_{i,j,r} = \frac{d_{i,j,r}}{c},  \tag{4}
\]

where \( d_{i,j,r} \) is the physical distance from node \( i \) to node \( j \) at snapshot \( r \) and \( c \) is speed of light. Hence, the total latency for a flow and a packet are provided as

\[
L_{f,a,i,j,r} = L'_{f,a,i,j,r} + 2L_c_{i,j,r},  \tag{5}
\]

\[
L_{p,a,i,j,r} = L'_{f,a,i,j,r} + 2L_c_{i,j,r}.  \tag{6}
\]

Since our goal is to provide QoS for IFECSs, we aim to minimize the total flow latency for all flows \( f \in \mathcal{F} \) in the network, in all snapshots \( r \in \mathcal{R} \), while guaranteeing a maximum delay for each packet within a flow \( f \). To achieve this, the optimization problem focuses on two main aspects. The first concerns obtaining the optimal destination for each aircraft \( a \in \mathcal{V}_A \). This destination node can be either an aircraft or gateway denoted by \( d \in \mathcal{V}_A \cup \mathcal{V}_G \). The second aspect is to identify the shortest path to this destination. The overall formulation is given by

\[
\min u_{f_a,i,j}, x_{f_a} \sum_{r \in \mathcal{R}} \sum_{(i,j) \in \mathcal{E}_r, f \in \mathcal{F}} L_{f,a,i,j,r} \cdot u_{f_a,i,j},  \tag{7}
\]

subject to

\[
\sum_{d \in \mathcal{V}_A \cup \mathcal{V}_G} x_{f,a} = 1, \quad \forall f \in \mathcal{F},  \tag{8}
\]

\[
\sum_{(i,k) \in \mathcal{E}_r} u_{f,a,i,k} - \sum_{(k,j) \in \mathcal{E}_r} u_{f,a,k,j} = \begin{cases} 
-1 & \text{if } k = src_{f,a}, \\
0 & \text{otherwise}.
\end{cases}  \tag{9}
\]

\[
\sum_{(i,j) \in \mathcal{E}_r} L_{f,a,i,j} \cdot u_{f,a,i,j} \leq \tau_{f,a}, \quad \forall f \in \mathcal{F},  \tag{10}
\]

\[
\sum_{f \in \mathcal{F}} D_{f,a} \cdot u_{f,a,i,j} \leq B_{i,j,r}, \forall (i,j) \in \mathcal{E}_r,  \tag{11}
\]

\[
\sum_{i \in \mathcal{V}_G} q_{i,j} \leq 1, \quad \forall j \in \mathcal{V}_G,  \tag{12}
\]

\[
\sum_{f \in \mathcal{F}} u_{f,a,i,j} = q_{i,j} \sum_{f \in \mathcal{F}} x_{f,a}, (i,j) \in \mathcal{E}_r \times \mathcal{V}_G.  \tag{13}
\]

Equation (7) expresses the minimization problem formulation given the constraints (8) - (13). Here, the binary variable \( u_{f,a,i,j} \) is equal to 1 if link \( (i,j) \) is used for a flow \( f \) of service \( m \) and aircraft \( a \) and 0 otherwise. Equation (8) ensures that each flows assigned to one server or destination, where \( x_{f,a} \) is a binary variable that takes the value 1 if a flow \( f \in \mathcal{F} \) is matched to its destination, else it remains 0. Equation (9) describes the flow conservation constraint for a generic node \( k \in \mathcal{V}_r \), where the number of flows arriving to and leaving from a node must be equal unless \( k \) is a source or destination.
node of flow \( f \in F \). Equation (10) guarantees that the packet delay of each flow remains below the maximum allowed value \( \tau_L^m \). Equation (11) maintains the link bandwidth constraint. Further, (12) allows at most one single satellite to be connected with a gateway \( g \in V_G^r \), where \( q_{i,j} \) is a binary variable that takes value of 1 if a satellite is selected to have a connection with a gateway and 0 otherwise. Finally, (13) ensures that flows from a satellite go to its connected gateway.

### B. Edge Computing for Satellites

In the case of satellite task offloading, we assume that each satellite \( s \in V_S^r \) needs to process a specific amount of computational tasks. If the computational tasks surpass the processing capabilities of the satellite, the tasks will be offloaded to a MEC node on a gateway \( g \in V_G^r \) or on an aircraft \( a \in V_A^r \). An overview of the additional notations used in this use case can be found in Table VII.

The amount of tasks \( J_s \) a satellite needs to process during a snapshot \( r \) is modeled as a random variable following a Poisson distribution

\[
Pr(J_s = k) = \frac{\lambda_s^k e^{-\lambda_s}}{k!},
\]

where, \( k \) is the number of arriving tasks and \( \lambda_s \) is the average task rate for satellite \( s \). The processing capacity of each satellite \( s \) is defined as the number of instructions its processor is able to handle in a second. The unit is given in Million Instructions per Second (MIPS) and calculated by

\[
C = \text{Freq} \cdot \text{IPC} \cdot n_{\text{cores}}.
\]

Here, \( \text{Freq} \), \( \text{IPC} \) and \( n_{\text{cores}} \) correspond to the CPU frequency in cycles per second, instructions per cycle per core, and number of CPU cores, respectively. \( C_s \) and \( C^{MEC}_r \) are the processing capacity of a satellite \( s \) and a MEC server. A computational task consists of \( I = 25 \cdot 10^6 \) instructions, processes \( D_T = 0.2 \) MB of data and should be completed in no longer than the delay requirement of \( \tau_s = 1000 \) ms [30], [33].

The number of tasks offloaded by a satellite is calculated by

\[
O_s = J_s - C_s.
\]

The lower bound of the bandwidth needed to transmit the offloaded tasks of the satellite is given by

\[
O_s^{B} = \frac{D_T \cdot O_s}{\tau_s}.
\]

The satellite flow transmission latency is given as

\[
L_{s,i,j} = L'_{s,i,j} + 2L_c^{i,j},
\]

where \( L'_{s,i,j} \) denotes the task transmission latency over a link \( (i,j) \in V_r \times V_r \) and \( L_c^{i,j} \) the corresponding propagation latency. The time a MEC server requires to process the offloaded task is given by the computation latency as

\[
L^{MEC}_s = \frac{I \cdot O_s}{C^{MEC}_r}.
\]

The QoS for the satellite computation offloading scenario is defined by the service latency which is the elapsed time from the request to the completion of the task [34]. This is the aggregation of the round trip propagation latencies, transmission latency and computation latency introduced by the MEC server.

To enable satellite task offloading, we aim to minimize the task completion time over all snapshots \( r \in R \) for every satellite \( s \in V_S^r \). The optimization problem identifies the optimal MEC destination node for every satellite \( s \in V_S^r \) and the shortest path to that node. The problem is formulated as

\[
\min_{u_{s,i,j}, x_s^d} \sum_{r \in R} \sum_{(i,j) \in E_r} \sum_{s \in V_S^r} L_{s,i,j,r} \cdot u_{s,i,j},
\]

\[
\text{s.t.} \quad \sum_{d \in V_r} x_s^d = 1, \quad \forall \ s \in V_S^r,
\]

\[
\sum_{(i,k) \in E_r} u_{s,i,k} - \sum_{(k,j) \in E_r} u_{s,k,j} = \begin{cases} -1 & \text{if } k = src_s, \\ x_s^{f_{src}} & \text{if } k \neq src_s, \end{cases}
\]

\[
\sum_{(i,j) \in E_r} L_{s,i,j} \cdot u_{s,i,j} + L^{MEC}_s \leq \tau_s, \quad \forall s \in V_S^r,
\]

\[
\sum_{e \in V_S^r} O_s^B \cdot u_{s,i,j} \leq B_{i,j}, \forall (i,j) \in E_r,
\]

\[
\sum_{e \in V_S^r} q_{i,j} \leq 1, \quad \forall j \in V_G^r.
\]

Equation (20) gives the objective function to minimize task completion time, where \( u_{s,i,j} \) is a binary variable that is equal to 1 if link \( (i,j) \) is used by satellite \( s \). Equation (21) ensures that each satellite \( s \) is assigned to one destination, where \( x_s^d \) is a binary variable that takes value of 1 if a satellite \( s \) is matched to a MEC server.
node. Equation (22) represents the flow conservation constraint. Equation (23) guarantees that offloaded tasks are completed within $\tau_s$. Further, (24) guarantees that the sum of bandwidths for all tasks passing through a link $(i,j)$ does not exceed its limit. Finally, (25) ensures that a gateway is connected to at most one satellite and (26) ensures that flows from a satellite go to its connected gateway.

VI. Performance Evaluation

Extensive evaluations of our AA-MEC model and optimization problem are based on the performance metric of flow latency (see (5)). For this we consider different MEC server deployment ratios throughout the aerial network. Specifically we examine network configurations with no aerial nodes containing a MEC server, 20% containing one or 40%. Alternatively, all satellite gateways deploy a MEC server in all configurations. To obtain the coordinates and trajectories of the nodes in the network we run the STK simulator taking a snapshot of the network every 5 minutes on the 18th of August 2021 from 12:00 to 16:00 UTC. This data is then passed to our optimizer, which solves the problem using Gurobi [35]. Results in the airborne internet use case are based on at least 147000 flows per MEC deployment ratio and in the satellite case on ca. 30000 flows per satellite task arrival rate.

A. Static vs. Dynamic Approaches

We start our analysis by quantifying the difference between a static and a dynamic approach for both the airborne internet and satellite offloading use case. While in the dynamic setup, we find the optimal MEC destination for every network snapshot and the optimal path in the network to reach that destination, in a static scenario the MEC destination is optimally chosen only for the first snapshot and then remains static. Nonetheless, the optimal path to the destination is recalculated at every snapshot. This is necessary in case the path is lost due to the mobility of the nodes and in order to provide a fair comparison among the two approaches.

Fig. 3a demonstrates this difference for four applications for the case of airborne internet, considering that 20% of the nodes deploy a MEC server. As can be seen from the figure, the dynamic approach outperforms the static for all applications in terms of flow latency. In web service, online gaming, VoIP and video streaming a 12.82%, 16.3%, 12.56% and 6.7% improvement can be seen, respectively. This is especially significant in gaming services where latency is a deciding factor for the outcome of the game and in VoIP applications where latency highly influences the Quality of Experience (QoE). Fig. 3b demonstrates the same trend for different task arrival rates $\lambda$ for the case of satellite task offloading. While the flow latency decreases by 59.44% when $\lambda = 72$, the decreases become 58.71% and 56.03% for $\lambda = 76$ and $\lambda = 72$, respectively. Satellites benefit more from the dynamic approach as their higher relative ground speed results in larger increase in the distance to their MEC node over time. The continuous optimization of the MEC destinations mitigates this problem. These results, substantiate the need to update selection of the MEC destinations regularly.

B. Airborne Internet

Looking further into the implications of the optimization in the use case of the airborne internet we demonstrate the benefits of the AA-MEC for aircrafts. Table VIII shows that the utilization of satellite gateway MECs decreases with an increase in aerial MEC deployment ratio. This shows the benefit of the AA-MEC which places MEC nodes closer to the sources of services. For example, introducing 20% of aerial MEC nodes reduces the number of application flows ending in satellite gateway MECs by 32%. However, this effect begins to saturate for a higher number of aerial MEC nodes, since the additional utilization drop is just 13%.

Fig. 4 shows the flow latency for selected flights and MEC ratios over different applications. As the MEC deployment ratio increases the flow latency decreases for all selected aircrafts. However, the performance gains differ highly between flights. This is due to various reasons like the changing number of passengers in aircrafts and the geographical location of the aircraft. Its location defines the
TABLE VIII
MEC utilization for different aerial MEC deployment ratios

| MEC Type | MEC\textsubscript{NO} | MEC\textsubscript{20\%} | MEC\textsubscript{40\%} |
|----------|---------------------|---------------------|---------------------|
| Gateway  | 100\% | 68\% | 55\% |
| Aircraft | 0\% | 32\% | 45\% |

Due to uneven gateway distribution around the world, as shown in Table I, some gateways need to cover a larger area and number of aircrafts, resulting in a higher latency for services to be routed to that gateway. Therefore, the network greatly benefits from deploying aerial MECs around these gateways. This is the case for Bogota-Istanbul aircraft, which is reflected in the largest decrease in latency.

Fig. 5 shows the system flow latency over all aircrafts for different MEC deployment ratios. Here, the spread of latencies decreases with increasing MEC deployment ratio. The lower spread benefits QoS guarantees for the different applications. On average, gaming benefits the most with 10.43\% and 16.01\% decrease in flow latency as the MEC deployment ratio increases from 0 to 0.2 and from 0 to 0.4, respectively. In VoIP, those decreases are 6.08\% and 8.32\%. In web services, the decreases are 5.38\% and 7.11\%. In video streaming, the decreases are 0.96\% and 0.41\%. These stated average percentage gains are heavily influenced by aircrafts that barely exhibit a latency reduction. The individual latency improvement for an aircraft can be considerably higher as Fig. 4 shows. Since video streaming accounts for 67.5\% of the traffic in an aircraft, it has the highest flow size among the services and it becomes beneficial to optimize multiple smaller flows arising from the other services. Consequently, the decrease in flow latency is much smaller for video streaming. This is in accordance with our expectation from the services, since video streaming, in comparison to the other services, contains its own buffer and its QoS is less sensitive to latency.

C. Satellite Offloading
Looking further into the implications of the optimization in the use case of satellite task offloading, we demonstrate the benefits of the AA-MEC for satellites. Fig. 6 shows the flow latencies for three exemplary satellites for different aerial MEC deployment ratios for varying task arrival rates $\lambda$. Similar to the airborne scenario, the average latency and the latency spread decrease with increasing MEC deployment ratio. However, the performance gains vary less over the deployment ratios compared to the airborne scenario. This is due to the even distribution of satellites around the globe compared to aircrafts. Further, Fig. 7 shows the overall system flow latency for varying task arrival rates $\lambda$. As expected, with increasing task arrival rate the flow latency increases. This can be counteracted by deploying more aerial MEC nodes. In case of $\lambda=72$, the decreases in flow latencies are 14.47\% and 21.64\% as the MEC deployment ratio
Table IX
Flow distribution over different MEC locations for varying aerial MEC deployments for \( \lambda = 80 \)

| MEC Location | MEC\(_{\text{NO}}\) | MEC\(_{\text{20\%}}\) | MEC\(_{\text{40\%}}\) |
|--------------|-----------------|-----------------|-----------------|
| Beijing      | 15\%            | 8\%             | 6\%             |
| Fairbanks    | 6\%             | 4\%             | 4\%             |
| Iqaluit      | 8\%             | 4\%             | 4\%             |
| Izhevsk      | 8\%             | 4\%             | 4\%             |
| Longyearbyen | 6\%             | 4\%             | 4\%             |
| PuntaArenas  | 27\%            | 19\%            | 16\%            |
| Rome         | 9\%             | 6\%             | 6\%             |
| Tempe        | 7\%             | 4\%             | 3\%             |
| Wahiawa      | 11\%            | 9\%             | 8\%             |
| Yellowknife  | 5\%             | 3\%             | 3\%             |
| Aerial       | 0\%             | 34\%            | 44\%            |

Optimizing for latency also influences the bandwidth requirement as shown in Table X. With increasing deployment of aerial MEC nodes the utilized bandwidth of the network is reduced for any task arrival rate \( \lambda \). However, the ratio between bandwidth reduction and MEC deployment becomes nearly linear as soon as we saturate the local computing capabilities \( \lambda = 80 \) and satellites are forced to offload.

Table X
Bandwidth reduction compared to MEC\(_{\text{NO}}\)

| \( \lambda \) | MEC\(_{\text{20\%}}\) | MEC\(_{\text{40\%}}\) |
|---------------|-----------------|-----------------|
| 72            | 11.93\%         | 17.63\%         |
| 76            | 13.03\%         | 19.19\%         |
| 80            | 6.57\%          | 11.38\%         |

VII. Conclusion and Discussion

In Multi-Layer Networks, different layers support each other to provide better service in terms of coverage, latency and capacity. Moreover, Multi-Layer Networks reduce the reliance on infrastructure by providing redundancy. Introducing Multi-Access Edge Computing on different layers allows for ubiquitous computing. Therefore, we propose the network architecture of Aerial-Aided Multi-Access Edge Computing to boost network performance by bringing computing closer to the sources.

This flexible architecture accounts for the dynamicity introduced by deploying aerial MEC. In order to validate our approach, we implemented a three layer network consisting of a satellite layer with the Iridium-Next constellation, an aerial layer including various flights, and a terrestrial layer consisting of satellite gateways. In this network, the use case of airborne internet with different
In-Flight Entertainment and Connectivity Service and the use case of computational offloading from satellites are investigated. For these use cases we calculate the optimal MEC destinations for task flows and the optimal route to these destinations.

In the use case of computational offloading for satellites, we can improve the flow latency by at least 56.03% when comparing static networks with our dynamically optimized AA-MEC network. Deploying aerial MECs in addition to the terrestrial gateway MECs reduces the flow latency by at least 13.09%. Additionally, our AA-MEC network brings forth at least 6.57% decrease in occupied network bandwidth which results in less energy required for data transmission, increasing the network energy efficiency. Further, the flow latency for IFECs improve by 6.7% from a static network to our AA-MEC. The additional deployment of aerial MECs on average results in a latency reduction of at least 5.71%. Specifically, for gaming applications, the 10.43% decrease in latency can be a deciding factor for the outcome of the game. Our proposed latency minimization problem formulation is especially suited for latency-critical applications with smaller capacity. This can easily be adapted for other configurations of services, for example a latency-critical service with a large bandwidth, by weighting each flow’s latency in the objective function accordingly.

The improvements in latency demonstrated by our AA-MEC can be further boosted by optimizing the selection of aircrafts that will deploy the MEC server. Aircrafts requiring longer links to access the Iridium-Next gateways, like aircrafts flying over Africa, Australia or Oceania, greatly benefit from deploying MEC servers on other aircrafts flying nearby. In scenarios where this is infeasible, considering the High-Altitude Platforms in the aerial layer as MEC nodes would prove beneficial. Furthermore, considering other satellite constellations would bring additional gateways into the picture, thereby influencing the distribution of MEC nodes around the globe.

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