Floating Fog: extending fog computing to vast waters for aerial users

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Abstract
There are thousands of flights carrying millions of passengers each day, having three or more Internet-connected devices with them on average. Usually, onboard devices remain idle for most of the journey (which can be of several hours), therefore, we can tap on their underutilized potential. Although these devices are generally becoming more and more resourceful, for complex services (such as related to machine learning, augmented/virtual reality, smart healthcare, and so on) those devices do not suffice standalone. This makes a case for multi-device resource aggregation such as through femto-cloud. As our first contribution, we present the utility of femto-cloud for aerial users. But for that sake, a reliable and faster Internet is required (to access online services or cloud resources), which is currently not the case with satellite-based Internet. That is the second challenge we try to address in our paper, by presenting an adaptive beamforming-based solution for aerial Internet provisioning. However, on average, most of the flight path is above waters. Given that, we propose that beamforming transceivers can be docked on stationery ships deployed in the vast waters (such as the ocean). Nevertheless, certain services would be delay-sensitive, and accessing their on-ground servers or cloud may not be feasible (in terms of delay). Similarly, certain complex services may require resources in addition to the flight-local femto-cloud. That is the third challenge we try to tackle in this paper, by proposing that the traditional fog computing (which is a cloud-like but localized pool of resources) can also be extended to the waters on the ships harboring beamforming transceivers. We name it Floating Fog. In addition to that, Floating Fog will enable several new services such as live black-box. We also present a cost and bandwidth analysis to highlight the potentials of Floating Fog. Lastly, we identify some challenges to tackle the successful deployment of Floating Fog.

Keywords Aerial users · Cloud computing · Edge computing · Fog computing · Marine fog

1 Introduction
The aerial commute is becoming an increasingly preferred way of traveling due to affordability and technological revolution in the aviation industry. According to the Swedish flight monitoring service, there are up to 202,157 flights flying across the world at a time [48]. This number is expected to increase in the near future. Moreover, most of the flights fly over the oceans because most of the Earth consists of water. Along with other busy routes over the oceans, the route between Europe and America [North Atlantic Corridor (NAC)] is one of the busiest routes in the world. On average, almost 1200 flights fly over the NAC per day, which makes it one of the busiest long-haul aerial routes [40].

Onboard passengers carry connected devices that mostly remain idle, and hence, their potential can be tapped. On average, there are around 100 passengers onboard on a single flight [15]. With technological advances and widespread use of mobile computing devices, on average, each passenger carries three or more Internet-connected devices such as a tablet/laptop, smartphone, and other e-health equipment [13]. Due to tremendous development in on-device computing, these devices are becoming more and more resourceful, hence, making a case for enabling complex services (such as machine learning-based, smart healthcare, augmented reality, and so on). Furthermore,
since onboard devices mostly remain underutilized, it creates an opportunity to combine their resources and tap their potential through femto-cloud [32] (further explained in Sect. 4). Although there would still be cases where tasks would be offloaded to an even more reliable and larger pool of resources, such as a cloud. But that would be with financial and privacy costs [2].

However, high-speed, consistent Internet connectivity is required to meet the expectations of aerial users for certain complex services. Currently, in commercial airlines, the airborne Internet provided to areal users does not satisfy areal users’ applications and services due to high cost, low bandwidth, and other restrictions, etc. Furthermore, if cloud access is required (for example, for cloud services such as task offloading), it can only be obtained via satellite-based Internet. However, given the vast distance between a satellite and an aircraft (almost 36,000 km), the average end-to-end latency is around 600 ms [50]. Such a delay is only suitable for non-real-time applications like web browsing, and modern resource-rich devices are unable to conduct any complex delay-sensitive tasks. As the first major contribution of this paper, we suggest aerial Internet provision using adaptive beamforming technology. Traditional beamforming sends focused signals to the receiving equipment (in this case, an airplane), allowing for faster and more reliable communication [33]. Adaptive beamforming, on the other hand, can dynamically steer a radio beam toward a specific user to maximize array gain to reduce inter-cell interference and extend network coverage [11]. As a result, cloud access would be substantially faster, because of a far more consistent and high-bandwidth Internet. That would, however, only be true until an airplane is above the earth.

On average, the majority of the flight time is spent over water, necessitating the extension of computing and networking resources to vast oceans. When we extend the cloud to a localized pool of resources (computation, storage, memory, applications, data), it becomes fog computing [3]. Since fog is localized, it can be strategically extended, along with transceivers, to waters (e.g., ocean) through stationed ships (we term it Floating Fog). This serves two purposes. First, the required stable and faster Internet can be seamlessly provided (through adaptive beamforming) to the aerial users, regardless of where the plane is flying above the ocean. Second, through fog computing, the necessary resource pool would be available throughout the aerial commute for the sake of task/data offloading—enabling complex services [3]. Fog nodes can be docked on a ship and deployed in the waters (such as an ocean). The backbone connectivity can be provided directly through marine cables. The average distance between a Floating Fog and an aerial user (35,000 ft.) would be much less than that of a satellite (36,000 km) [33]. Hence, latency can be reduced significantly, to serve delay-sensitive applications as well.

With Floating Fog, a new set of services can be created. One of the most noteworthy ones is the live black box. Aircraft’s black-box feed can be communicated to Floating Fog in at least near real-time, eliminating the dependency of searching for the black-box in the case of an unfortunate event of an air crash [19]. Similarly, opportunistic computing such as opportunistic healthcare can be enabled. We shed more light on this in Sect. 2. We then provide a detailed technical architecture of Floating Fog, along with its deployment and communications (Sect. 3). To assess the feasibility of our proposed Floating Fog, we go into the details of cost and bandwidth analyses, as well as the role of femto-cloud, in Sect. 4. Later in the article, we present some key challenges and future research directions in this domain (Sect. 5).

Our main contributions in this paper are as follows:

- We present an architecture of adaptive beamforming-based Internet communication for aerial users,
- We propose extending fog computing to vast waters (Floating Fog) to enable complex services (including live black-box) and make use of the reliable Internet provided through adaptive beamforming. We provide a technical architecture and deployment details in this regard,
- For feasibility point of view, we perform a cost analysis and bandwidth analysis of Floating Fog in the perspective of existing solutions, and
- We highlight several open research issues and future directions.

2 Background and motivation

To serve the purpose of providing Internet in an aircraft, several solutions have been presented in the literature, and we can categorize them into satellite-based solutions and ground-to-air (G2A) link-based solutions.

2.1 Satellite-based solutions

Due to the global coverage of satellite, it is one of the popular choices for providing Internet to the flights, although much slower. The basic infrastructure of satellite-based Internet provisioning is shown in Fig. 1. For covering a large geographic area, geosynchronous equatorial orbit (GEO) satellites are usually used to provide Internet. However, due to the huge distance between a flight and a satellite (average 36,000 km) and the four-way handshake mechanism of satellite communication, the average end-to-end delay incurred is approximately 600 ms [50]. Four-way
handshake, in the current context, is the total delay incurred from request generation of Internet content to the provision of the requested content to the user. This process initiates via a request by user equipment (UE) to satellite, then the satellite requests for the content from Internet service provider (ISP) on the ground, then the ISP sends the required content to satellite, and satellite sends that content to the UE.

Usually, a direct satellite-receiver system is deployed on an airplane, along with backchannel communication infrastructure and a network installed in the aircraft. This system provides Internet to passengers through a Wi-Fi connection. If we consider the distance from the ground to satellite as 36,000 km, the one-way propagation delay from the ground to satellite is 120 ms. Hence, the propagation delay in a four-way handshake is 480 ms. Such delay can only allow basic web browsing, and limits modern devices to perform many complex tasks (e.g., remote monitoring through wearable, telemedicine, and online-gaming). This way, the devices remain underutilized throughout the period of commute, which can be up to tens of hours.

Cost is another main concern in satellite-based solutions. For instance, the cost of installing equipment on aircraft to provide satellite-based Internet is almost $500,000 [33]. Due to expensive equipment, uplink/downlink channel cost, and maintenance cost of the satellite, and so on, the data transfer charges in satellite communication are between $300 and $2000 per month [33]. Therefore, commercial flights charge a significant amount for Internet service. For example, British Airways charges £8 per hour from passengers onboard. In addition, airlines providing Internet have several restrictions (e.g., Air China provides in-flight Internet but it is not allowed on smartphones) [12]. Also, different airlines can not provide uninterrupted high-speed Internet throughout the journey.

Some notable approaches for providing Internet in an aircraft utilizing satellite links can also be found in the literature. Khan presented a satellite links-based approach, by exploiting the low earth orbit (LEO) satellite, instead of the GEO satellite, which significantly reduces its scalability [22]. Reid et al., also discussed the use of LEO, however, focusing more on using LEO communication for augmenting navigation [39]. Starlink is another Internet provision system exploiting LEO satellite [27]. Although it is relatively better than conventional satellite-based solutions in terms of latency and bandwidth, however, it has several limitations including low coverage and requires a huge number of satellites for decent coverage. Also, it is very costly (i.e., $90 per month) and is functional in some parts of the USA and Canada. Moreover, it is still in experimental stages and expected to gain claimed bandwidth in 2026 (only suitable in dense populations). Volner argued in their work that Internet access in the aircraft and passengers accessing it creates security concerns, nevertheless, safety can be improved by communicating key data to a ground station (GS) [47].

However, given the bandwidth of satellite-based Internet, it might not be very practical (which we try to resolve through our proposal in this work).

2.2 Ground-to-air link-based solutions

Contrary to the satellite-based solution, some researches investigated G2A links for Internet provisioning. Sakhaee and Jamalipour presented an in-flight Internet solution through both satellite and GSs [41]. This scheme uses a cluster of aircraft and a large cache to store recently requested Internet content and share it locally within a cluster through the cluster head. Although the proposed solution prefers GSs for Internet delivery, but as an aircraft flies away from those GSs (installed on a seashore in the
case of flights flying over ocean), it relies on satellite-based links only. Jalali et al., proposed a hybrid approach that exploits both satellite links as well as a ground base station to provide Internet to passengers onboard. This approach gives preference to G2A links, but due to lack of (ground) base stations covering the flying aircraft’ range, in most of the cases, the proposed system relies on satellite [20].

Tadayon et al., proposed a solution for providing-in-flight Internet through ground cellular base stations. They exploited the long-term evolution (LTE) infrastructure for Internet access [44]. Gupta and Aggarwal presented an Internet provisioning scheme limited to flights flying over the ground [16]. In the proposed solution, authors suggested the idea of providing Internet from GS to the aircraft in its vicinity, which acts as a gateway. That gateway aircraft is responsible for providing Internet to the other aircraft. GoGo Internet has been introduced by AirCel (rebranded as Gogo Business Aviation). Gogo uses ground cellular base stations in the USA to provide Internet to flying aircraft. They adopt the same mechanism of handover that is used in cellular networks on the ground, with certain limitations [31].

Medina et al., in their works [28] proposed a solution that extends ad hoc networks of aircraft flying across the ocean. In the envisioned solution, Internet is provided through GSs. The GSs can only provide Internet to an aircraft within its vicinity. Therefore, aircraft connected directly to the GS acts as a gateway, relaying Internet communication to the other aircraft that could connect to the gateway aircraft. This forwarding is extended on a hop-by-hop basis, making a mesh of aircraft in the sky. Although in this scheme, the authors tried to eliminate the reliance on expensive satellite links, aircraft far away from the GS (and the gateway aircraft) face a significant delay and packet loss.

In one of our previous works [18, 33], we presented an airborne Internet solution that exploits underwater fiber optic cable (UOFC) to provide Internet access to the base station (stationary ships stationed in the open ocean called oceanic station). In the proposed solution oceanic stations use adaptive beamforming to provide Internet access to a flying aircraft across the ocean through the line of sight (LoS) communication. Although through this scheme, Internet provisioning has much improved in terms of delay, nevertheless, this scheme does not take into account resource aggregation (through femto-cloud) and task offloading to a fog node. We try to overcome this issue in our current work.

2.3 Summarizing issues with the existing approaches

There are certain problems with all the aforementioned solutions. All satellite-based solutions have inherited the problem of huge delay and cost. This makes them unsuitable solutions especially for modern Internet applications that require very low latency (e.g. remote monitoring through wearable, telemedicine, etc.). Whereas, the G2A-based solutions have their limitations, such as most of them are only appropriate for flights flying over the ground rather than over the ocean [16, 31, 41]. Moreover, they also lack in terms of reliability and scalability.

Similarly, the solutions specifically devised for airborne Internet for flights flying across oceans have their own set of problems. For example, although Reference [28] try to solve the problem of airborne Internet to some extent, through an ad hoc network which is not scalable because in a denser network (during peak hours), the performance degrades significantly and it becomes extremely difficult to provide reliable Internet. Hence, it is not suitable for several applications that require high bandwidth and low latency. Whereas, in Reference [33], adaptive beamforming is used for LoS communication with high bandwidth, but the issue in this scheme is it’s limited scope. Since this solution is only devised for flights flying over the submarine optical fiber cables (within LoS), therefore, it does not provide Internet access to flights flying away from the vicinity of the proposed oceanic BSes.

3 Floating Fog architecture

In this section, we elaborate on the architecture of Floating Fog, connected through UOFCs, to provide Internet and computing resources to onboard aerial users.

In the Floating Fog architecture, we propose the deployment of stationary ships (each referred to as Floating Fog Station (FS) in the ocean. For simplicity sake, each FS is stationed in the ocean at equal distance from each other as shown in Fig. 2.

Each stationed ship (FS) has two major components. One is the communication part (in this case, adaptive beamforming), and the other is the computing resources part, for which, fog computing paradigm comes into play. These FSes are linked to UOFC and have the same power, terminal, and other required equipment as UOFC landing stations, as shown in Fig. 3.

Service ships are used for the maintenance, operating, and servicing of UOFCs.

Aside from FSes, infrastructure can be built on remote islands to act as a base station (BS), which we refer to as an island station (IS). Given that there can be a wide range of potential use-cases of such Internet provisioning, there can be several stakeholders interested in this kind of infrastructural deployment, for example, ISPs, governments (within their maritime borders), airlines, technology giants (such as Cisco), and so on.
These FSes can then be dedicated to serve as BSes for aircraft, ships, helicopters, drones, not only for Internet access but also for navigation. Along any of the UOFCs, these dedicated FSes are stationed at equal distances from one another.

These FSes can therefore be used as dedicated BSes for aircraft, ships, drones and helicopters, not only for Internet access but also for navigation. Along any of the UOFCs, these dedicated FSes are stationed at equal distances from one another.

The LoS communication channels (unobstructed) is used between FS and aircraft, as well as between FS and IS.

The spherical geometry of the Earth’s surface confines the LoS communication range (LCR). The maximum LCR can be calculated by using the average altitude of an aircraft \( H_a \) and the radius of the Earth \( R_e \). All the aircraft are assumed to be flying at the average altitude level, taken as:

\[
H_a = 10.688 \text{ km (i.e., 35,000 ft.)}.
\]

Therefore, the maximum possible radius \( R_{\text{max}} \) of a transmission cell can be determined by the LCR between FSes and aircraft, which can be found as:

\[
R_{\text{max}} = \arccos \left( \frac{R_e}{R_e + H_a} \right) \frac{\pi R_e}{180^\circ}.
\]

Here \( \arccos \) function is the inverse of a cosine function. The difference between cosine inverse and \( \arccos \) is that \( \arccos \) is for the first two quadrants. Whereas, \( R_{\text{max}} \) is the maximum transmission range and it can be computed as 368.98 km using Eq. 3, by setting the radius of Earth \( R_e = 6378.137 \text{ km} \) and height of flying aircraft from sea level is approximately \( H_a = 35,000 \text{ ft.} \approx 10.688 \text{ km} \), as shown in Fig. 4.

The oceanic distance between Lisbon, Portugal and New York, USA is roughly 5900.472 km (3186 Nautical Miles). Each BS is responsible for a 368.98 km radius, as previously indicated. It is expected that the width of two adjacent overlapping section is 10 km. Also, based on the
calculated maximum radius of a single transmission region, we’ll need at least 8 transmission regions (cells) to bridge the North Atlantic Ocean between the United States and Europe if all FSes are regarded to be at the same distance from each other (cell).

Although the minimum received power varies from hardware to hardware, we take the minimum received power required to maintain the up/down-link connection $P_{th}$ as $-100 \text{ dBm}$ [33]. A transmission power of 57.8 dBm is required to provide full coverage to $R_{max}$. In addition, smart antennas with high directional gains are used to reduce transmission power requirements. For this purpose, all aircraft and BSes are fitted with planar smart antennas, which must be capable of computing the very exact signal’s arrival direction and azimuth planes.

The antennas operate using adaptive beamforming. Adaptive beamforming is a technique for directing a narrow radio beam to a specific receiver/destination in order to take advantage of array gain, extend network coverage, reduce inter-cell interference to improve signal strength. It significantly enhances the range of transmitting signals and can be used in data communication between devices moving with high speed (e.g. in satellite to aircraft communication).

In our case, data is exchanged between the aircraft and the FS via the adaptive beamforming approach.

This not only significantly increases the possible transmission distance, but also boosts the data rate. Within the airplane, Wi-Fi is utilized to send and receive data to and from onboard devices [25]. In our situation, beams are directed with an optimal signal to noise ratio (SNR) from/to G2A and air to ground (A2G). A pilot or beacon message is sent by each FS. The airplane that is flying in the transmission vicinity of a cell, scans for beacon/pilot message of FS. A connection is established between airplane and the FS with the stronger beacon signal.

As shown in Fig. 5, the injectors/extractor are utilised to connect the FSes to the UOFC. These connections can be installed through maintenance and installation tools [17]. The injectors/extractor keep the undersea optical fibre system’s capacity without interfering with existing traffic, according to [33]. To/from the primary UOFC, multiple single-mode optical fibre signals can be inserted and withdrawn.

The above-mentioned scheme extracts Internet content from the UOFC on using extractor through optical to electrical converters. Similarly, while delivering queries/data to the Internet, electrical to optical converters are employed on the injector. With orthogonal frequency division multiple access (OFDMA), any current radio access technology (RAT) can be employed. The FS is in charge of allocating resources (such as time and frequency). Because existing 4G RATs (such as WiMax and LTE) are OFDMA-based, they are a good fit for RAT in the current architecture.

Given that the suggested system has specific limits (e.g., $R_{max}$), the described technologies can be modified to meet the specific needs. In the proposed solution, the cell radius $R_{max}$ is about 369 km. In some WiMax versions, the ranging method improves $R_{max}$. To deal with the large transmission cell radius of A2G and G2A communication links, the conventional RAT ranging mechanism must be updated. To achieve improved QoS, a sophisticated scheduling algorithm can make a difference in allocating the optimal amount of slots to an aircraft. For communicating between FSes and GS (ground/landing), we can use current signalling mechanisms.

On average, an aircraft can potentially stay connected with particular FS for about an hour before a handover is needed. Handover occurs in the same way that it does in most mobile ad hoc network (MANET)/vehicular ad hoc network (VANET) systems, i.e., when the signal power of the serving FS drops below a particular threshold as compared to the targeted/next FS (according to the direction the aircraft is flying) [18, 33].

In the Floating Fog, computing resources play a vital role. The computing resources (processing, memory, storage, application) are provided through fog computing. Since adaptive beamforming would provide the communication, accompanied fog node on the FS would provide resources for data or task offloading. Fog node can cache content according to the usage pattern (of the aerial users) or importance of particular content. Hence, quick access is provided, ensuring a better quality of service (QoS) and eventually, enhanced quality of experience (QoE).
tasks that are beyond the capacity of UE (or even femto-cloud) can be offloaded to fog node (residing on FS). This way, complex services can be created, such as opportunistic healthcare (including air ambulance and tele-medicine, for any onboard patient) [1, 26, 45, 49], augmented reality, and other machine learning-based services. Floating Fog can offer a new set of services as well. With a reliable and high bandwidth on-the-fly Internet availability, an aircraft would be able to transmit critical black-box data to the GS (server), enabling live black-box. It would be very critical in avoiding unexpected situations, and especially, in the case of an unfortunate air crash, it would eliminate the dependency on searching for a lost black-box (historically, which can be very expensive and time taking process) Similarly, cloud can be involved when necessary, such as to access particular data or service, or even more complex tasks, such as deep learning-based .

To calculate the time for an aerial user to utilize floating fog resources (from particular fog node), It is important to know time an aircraft remains in the vicinity of a FS. Through Eq. 3 we calculated that each FS is responsible for covering a 368.98 km radius.

Therefore, by covering both directions of an aircraft the maximum communication range for a fog node is twice of coverage area in radius. Which then be calculated as 737.96 km.

Moreover, a commercial aircraft’s average speed is around 725 km/h [6]. As a result, an aircraft’s connection time to one FS is calculated as:

\[ T_{con} = \frac{S_a}{C_{area}} \]  

(3)

Whereas, \( T_{con} \) represents the total duration an aircraft is linked to a FS, \( S_a \) is the speed of an aircraft, and the coverage area of a FS is \( C_{area} \). As a result of the preceding equation, the total time of an aeroplane connected to a fog node is around an hour (58.9 min).

As a result, a passenger onboard can use the fog resources (processing and storage) for nearly an hour. We discuss computing offloading in section, however storage management is right now out of the scope of this paper.

There can be a variety of ways to power an FS. As most of the time FS would be berthed (stationary), the power consumption would mainly be for communication (beam-forming) and fog computing resources. An FS can be powered through solar panels, windmills, tidal waves, or an onboard nuclear reactor [46]. For the ships closer to the shore, techniques such as cold ironing can be used to power them [42].

4 Potential of Floating Fog

To realize the potential of the deployment of fog computing in waters, we must analyze its commercial as well as technical aspects, which we present in this section.

4.1 Cost analysis

For analyzing the cost, we have to establish the fact that currently, the aviation industry relies on satellite-based Internet access. Cost is a major concern with satellite-based solutions. For instance, the cost of installing the equipment on aircraft to provide satellite-based Internet is almost $500,000 [33]. Whereas, due to expensive equipment, there is uplink/downlink channel cost and maintenance cost of satellite. While the data transfer charges in satellite,
communication are $300–2000 per month [33, 36]. Therefore, commercial flights charge a significant amount for an Internet service. For example, British Airways charges £8 per hour from an onboard Internet user.

Similarly, accessing a cloud (for its resources or cloud-based application) has its own compromises. Firstly, the cloud needs Internet connectivity for resources (computing and storage resources). Secondly, cloud services are not free. The Amazon Web Service prices range from $0.10 to $0.40 per core per GHz per hour [43]. Whereas, for storage, Amazon charges up to $0.0405 per GB [7].

On the other hand, Floating Fog can provide greater reliability and efficiency, at a significantly lower cost. As mentioned earlier that we require 57.8 dBM to cover $R_{max}$ This power is equal to 501 W. The cost of one MWh through wind is almost $10 and $5 if we use solar energy [35]. Furthermore, one MWh for 501 W would be around 1996 h (almost 83 days). This cost comparison shows that the energy required to communicate between fog nodes and aircraft is far lesser than the monetary cost of satellite communication. Also, it is worth mentioning that this power is not required all the time. As a significant number of tasks are not offloaded to fog node (and maybe offloaded to aircraft-local femto-cloud or local fog node). The local fog node can be a Raspberry Pi, which is far less expensive than cloud datacenters.

### 4.2 Bandwidth analysis

Bandwidth is one of our main motives in proposing Floating Fog. Certain current and future applications have specific bandwidth requirements, especially, as more and more Internet of Things (IoT) applications emerge on the market, including smart healthcare. With the advancements in communications (such as 5G), bandwidth requirements would become stricter and more application-specific. Examples include high-definition telepresence, requiring 24 Mbps with 50 ms latency; remote monitoring; telemedicine (tuberculosis treatment through video directly observed therapy, voice pathology detection [14]); smart and opportunistic healthcare (a doctor available during their commute hours can assist online [1]); infotainment [38]; 5G Tactile Internet-based services [3], and so on. Providing bandwidth better than what aerial users currently get (recalling average delay of 600 ms) is not limited to making possible new use-cases (e.g. live black-box). Depriving aerial users of the technologies they make use of on the ground is also a significant under-utilization of human and device’s resources, during several hours of commute, which can be greatly minimized. The improvement of data rate depends on various factors, through the interplay of which, we can enhance the data rate. We present those factors in Eq. 4.

\[ C = b \times \log_2(1 + SNR). \]  

Whereas $C$ is the achieved data rate, $b$ is the frequency band, and $SNR$ is signal to noise ratio. If we have a frequency band of 15 MHz, and $SNR$ value of 20 dB then by Eq. 4, the achieved data rate is almost 100 Mbps. This data rate is enough for having four simultaneous high-definition telepresence applications. Similarly, 25 Mbps is required to transmit 88 mandatory parameters for a live black-box [51]. The aforementioned data rate achieved in the case of Floating Fog can handle black-box data of 4 flying aircraft per fog node at a time. Moreover, The data rate required to transmit basic health data (e.g. body temperature, blood pressure, EEG, ECG and so on) is 100 kbps to 1 Mbps [24]. However, for telemedicine through voice, video, and medical imaging, the data rate required varies from 50 kbps to 10 Mbps [8]. The data rate requirement for certain applications are shown in Table 1.

With the very basic communication resources that we have stated so far providing the data rate of 100 Mbps is sufficient to fulfill the needs of aerial users. Because, firstly, not all the passengers use the Internet all the time. Secondly, data rate requirements for users vary and only a few passengers require a very high data rate (and the requirement of those passengers can be easily met with the given data rate). Given that, the data rate can still be increased either by elevating $b$ or/and increasing the value of $SNR$. We note here that by increasing frequency band $b$, the data rate can be increased linearly. Whereas, increasing $SNR$ results in a logarithmic improvement in data rate. $SNR$ can be improved in certain ways such as by reducing path loss, efficient channel estimation, and reducing interference by using better hardware, and so on. However, there is a trade-off between high data rate and power consumption (for beamforming). As if we increase the range of the beam, the bandwidth will be compromised.

### 4.3 Leveraging femto-cloud

Considering that the devices on board are mostly idle and almost immobile during the trip, they provide the basis for reliable and stable resource aggregation of multiple devices. Femto-cloud refers to the combination of resources from edge devices (smartphone, laptop, IoT devices) [32]. Modern devices are equipped with very sophisticated processors (octa-core, 2+ GHz) and memory (up to 8 GB). These devices mostly remain idle during flight and are not fully utilized. This is mainly due to the poor (yet expensive) internet. Even though powering the devices is not a problem, as most flights have charging stations. While a better internet (like the one we propose) would allow users in the air to access their preferred applications (e.g. cloud-based services), we can also get more out of these devices.
and human potential. Access to a cloud would only be necessary if a service is specific to a cloud service provider (e.g., Dropbox, YouTube). Otherwise, the cloud would be expensive [7] and less privacy friendly [2] and can therefore be avoided (especially when it comes to outsourcing various tasks). The combined resources of passengers’ devices on board can easily form a micro-data center. If we assume that the average RAM of a smartphone is 2.4 GB [34] and the number of passengers on board is 200 with a processing speed of 2 GHz per mobile device, then the cumulative RAM of all passengers is 480 GB and the cumulative processing power of 400 GHz for the duration of the flight (which can be over 17 h). These statistics show that most high-performance servers cannot have such a large processing power and primary storage. In other words, we can process cloud-like tasks locally on regular smartphones without spending money and without setting up resource-intensive data centers. For example, the above RAM is enough for more than three IBM QRadar SIEM All-in-One Virtual 3199 with 30,000 events/s and 1,000,000 flows/min [10].

### 4.3.1 Use cases and scenarios for femto cloud in aircraft

There are a number of use cases and scenarios for on-board passenger device collaboration, referred to as femto-cloud.  

**Scenario 1** instead of offloading heavy tasks (e.g., based on machine learning) to an expensive resource (e.g., a cloud), multiple idle devices can split the task into subtasks and execute them. Since most devices on board are idle and have little problem charging, this is quite feasible.

**Scenario 2** with COVID-19 and otherwise, it is essential to be on top of health monitoring, especially when traveling. Some of the passengers on board have different backgrounds, health issues and travel experiences. A sophisticated health system that closely examines each person’s case and provides health analysis, guidelines (based on travel history, destination, susceptibility to disease, etc.) is very useful. This is also possible if certain health data is shared among passengers (keeping privacy in mind). Again, it is important to have a femto-cloud on board.

**Scenario 3** flexible on-board entertainment, such as multiplayer on-board games, for which multiple nodes need to interact with each other, creating a femto-cloud. When game processing becomes resource intensive, other on-board devices (including those that are not part of the on-board gaming network) can make their resources available for offloading tasks (as in Scenario 1). The offloaders can be incentivized in different ways, which is a different topic and we have covered in our paper.

### 5 Challenges and future research directions

The concept of Floating Fog has significant future potential if we understand the challenges on the way and address them. In this section, we enlist several noteworthy research challenges, that can be interesting research topics.

#### 5.1 Resource allocation

Resource allocation in the case of Floating Fog is different from a regular data-center/fog. This is mainly due to several variables involved in the resource allocation process. First of all, the flights are moving at high speed, hence, determining the required resources could be a complex task. The primary objective of any computing framework is to provide sufficient resources for the tasks offloaded to it. However, that could result in the over-allocation of resources. In that case, resources remain underutilized, which may result in the degradation of the performance of the other tasks or even the entire system. On the other hand, if the fog computing system is unable to provide sufficient resources to accomplish particular offloaded tasks from the end-user, it results in quick redundant and unnecessary offloading. This also degrades the performance of the system and consumes more energy and bandwidth. Therefore, careful allocation of resources by the fog server is of grave importance. Optimal resource allocation allows the prediction and customization of resources alongside managing the resources for highly heterogeneous devices and diversified data [23]. Proper resource allocation policy allows inter-fog server resource synchronization.

| Table 1 Required data rate for some notable applications | EEG, ECG | 1 Mbps [24] |
|----------------------------------------------------------|----------|-------------|
| Telemedicine through video, audio and imaging            | 10 Mbps  | [8]         |
| Internet for family (Movie on demand, Video conference, Web browsing) | 10 Mbps  | [30]        |
| Live blackbox                                            | 25 Mbps  | [51]        |
| MMOG Thumper                                             | 23 Mbps  | [9]         |
| High definition Telepresence                             | 24 Mbps  | [14]        |
| Tom Raider                                               | 29 Mbps  | [9]         |
| Brain to Computer Interface                              | 26 Mbps  | [29]        |
Moreover, resource allocation plays a vital role in deciding the execution of the offloaded task locally on the fog server or further offloading to the cloud. With the femto-cloud in our architecture, it would be important to determine the participating devices (because, even though mostly onboard devices would be idle, it does not mean that they would be willing to lend their resources throughout the trip). For that sake, there should be a master fog node onboard that keeps track of participating devices, their contributions, and the incentives for them (e.g., reciprocating task execution).

5.2 Scalability

Scalability is one of the major problems with fog computing and makes it more complicated in the case of Floating Fog. The Floating Fog deployment has to solve two major challenges. Firstly, scalability of the oceanic FS to provide the benefits of Floating Fog to other ships sailing in the ocean. It also opens doors for other Floating FSs by deploying fog servers at ships sailing far away from the existing fog servers deployed right over the UOFC. This may be possible by enabling realistic and robust inter-fog communication. Secondly, the scalability in the air, i.e., providing the benefits of fog computing to those aircraft that are not in the vicinity of LoS communication from the Floating Fog server. This is a challenging task due to the high-mobility and random trajectories of aircraft flying in the sky.

5.3 Security and privacy

Security and privacy are the fundamental requirements of any system. These attributes are more challenging when using public networks (Internet). In case of sensitive data such as health-related, location-based, and so on, the fog must introduce an additional security layer [21]. The fog would be responsible for both communication and data security. Communication security is vital in the case of offloading tasks to fog or cloud. Whereas, data security (e.g., through encryption) would be important since data has to be stored on fog nodes, even if temporarily. Furthermore, it would be important to filter the data to avoid any unnecessary communication (e.g., to the cloud). Here, it should also be noted that since security would be an additional layer, it would create an overhead and might affect the overall response time. Hence, it would be a compromise.

5.4 Interoperability

Interoperability is a desired attribute of fog computing. Especially in the case of Floating Fog, there is a very diverse and highly heterogeneous environment. A requirements-driven interoperable architecture for fog is required, which may be customized according to the situation. Such architecture may also be implemented through multi-protocol translation [4, 5].

5.5 Incentives for offloading service

The significant problem that discourages tasks to be offloaded is the lack of economic incentives. Avoiding offloading without any benefit is common in inter-device offloading (i.e., a mobile device does not allow other mobile devices to use its resources through task offloading without any financial benefits). Incentives may be in the form of air miles, shopping discounts, and so on. However, the incentive may not necessarily be monetary but based on a reciprocal computing model. For example, a mobile device \( m_1 \) may allow the other device \( m_2 \) to offload a task, but in return, \( m_1 \) is expecting from \( m_2 \) to execute its tasks as well. This incentive-based offloading is one of the most complex challenges in offloading to fog servers as well as inter-device offloading. It is worth noting that local computing through inter-device offloading is the fastest way to get results [23].

5.6 Floating Fog maintenance

The durability of fog nodes and other devices is a critical issue to address. In contrast to the static environment of cloud computing, fog nodes require frequent maintenance due to their dynamic environment. In our case, the fog nodes are installed on stationary ships in the open ocean, which makes the problem of maintenance and durability of the devices more challenging. The joining and leaving with/from fog nodes is a frequent process. Therefore, fog service deployment and migration approaches need to be more agile and efficient. In addition to the computing, communication maintenance is also a matter of importance. Although this work is mostly about resource offloading but communication part is also discussed. There are certain specific aspects that are challenging in the successful deployment of the Floating Fog.

5.7 Communication feasibility

A detailed proof of concept for the use of beamforming for airborne communications has already been mentioned in one of our previous papers [33]. Moreover, there are certain satellite-based solutions that are already in use. To better justify our case, we made some assumptions.

- The velocity of the aircraft is known and equal.
- In this architecture, we consider the Shanwick route (the busiest) of all routes.
To expand services and extend this solution to more customers (airlines), the service provider needs to increase resources. More capacity and scalability require higher costs, including more spectrum, more antenna arrays, and more power.

While there are many deployed and working systems around the world that use beamforming to communicate over long distances. However, there are certain aspects that are particularly challenging and require further investigation.

5.8 Speed

Commercial aircraft fly at speeds approaching 750 km/h. This speed is very high for tracking an object. However, the planes do not move in a linear direction but on a curve/arc (due to the curvature of the earth). Also, the distance between the hovering FS and the flying aircraft is large, resulting in a larger radius. Therefore, the angular velocity is much lower than the actual velocity. When the distance between the aircraft and floating fog station is small, the rate of change of angle is high. However, in this case, the distance between the aircraft and the floating fog station is very large, so the angular rate of change for beam steering is comparatively smaller.
5.8.1 Congestion

Another notable problem in the successful use of floating fog is the number of aircraft handled by a single floating FS. Nearly 1200 flights pass over the NAC on a daily basis. There are also 8–10 different flight routes used by different airlines (depending on the origin and destination). To better justify our case, we need to make some assumptions. Also, there must be a distance of 15 min between 2 planes (both horizontally and vertically) [37]. All this data definitely reduces the number of aircraft maintained by a single hovering FS. However, there is still a need for a detailed study to solve this problem. One of the preliminary solutions is machine learning since most of the data and parameters are known.

6 Preliminary results and discussion

We add some preliminary results for the proposed work. We used Java over the CloudSim toolkit for our performance evaluation. The cloud in our analysis consists of a datacenter with a host with the following configuration: Xen as Virtual Machine Manager (VMM), x86 architecture, Linux operating system and a virtual machine (VM) with 2048 MB RAM and a host with 16,384 MB from RAM. In the case of Fog, a data center broker is set up to act as a Fog node and has a VM with 512 MB from RAM. The tasks are executed on this Fog node.

Figure 6 shows the application execution feasibility in terms of delay. The figure depicts that most of the
applications can only be executed on floating fog due to their delay constraints. As the matter of fact, average delay for cloud computing for aerial users is almost 600 ms. However, there are some applications that can afford more delay (for example web-browsing and emails, etc.), such applications can be executed on cloud for load balancing over Floating Fog. Figure 6 summaries that, the delay tolerant applications that can afford the delay of more than 600 ms are forwarded to cloud if, floating fog has significant load. However, applications that has the delay requirement of less than 600 ms, can only be executed on floating fog. In addition the delay tolerant applications are executed on floating fog if the floating fog servers are idle or doing very little execution at that particular time.

Figure 8 shows the processing delay (for tasks ranging from 10 to 1000 BI) in milliseconds in the case of clouds and fog. For a 10 BI task (task 1), the delay for cloud is 167 ms. For fog, the delay remained at 10 ms for the same size task. This shows the impact of fog in terms of processing delay compared to the cloud scenario. For a 20 BI task size, the delay is 602 ms for the cloud but 73 ms for the fog. The trend continues up to very large tasks (more than 10,000 BI), as shown in Fig. 9. Figure 9 shows the results obtained with different task lengths. Even though the fog generally reduces the processing delay significantly, there is a limit to its efficiency, and this limit depends on the length of the task that the fog can handle (i.e., the processing power of the fog). The difference between the processing delay by the cloud and the fog decreases when the size of the tasks increases noticeably. For tasks with 10–1000 BI, the performance of Fog and Cloud shows a similar trend. For tasks larger than 10,000 BI, the delay of Fog is higher than that of Cloud. For a task length of 10,000 BI, the processing delay with Cloud is 83,811 ms and with Fog is 102,293 ms. This shows that based on the processing capacities defined in our setup, Fog has to offload the tasks to Cloud since the tasks are larger than the feasible processing limit of Fog. If Fog is unavoidable even for very large tasks, Fog’s capabilities can be improved.

We also compare the bandwidth consumption of cloud vs. fog, over the core network. Figure 7, clearly shows a significant bandwidth reduction in case of floating fog as compared to cloud. This difference is increasing as the number of aerial users increases.

We will conduct detailed experiments in our future works.

7 Conclusion

In this paper, we have tried to address three major problems (poor and expensive Internet connectivity, resource under-utilization, higher end-to-end delay) of aerial passengers, interested in making the desired use of their onboard devices and gadgets. We presented a new concept of extending fog computing to vast waters and term it Floating Fog. Floating Fog consists of adaptive beam-forming transceivers (that provide faster Internet) and fog computing resources (that cache content and also offers its resources for task offloading). Through Floating Fog, we can enable a new set of enriched services such as live black-box, opportunistic healthcare, air ambulance, telemedicine, AR/VR, telepresence, and so on. We noted that the cost of providing 1 MWh through Floating Fog would cost $10 through wind energy and $5 through solar energy. While in the case of the current satellite-based Internet, the cost of only installing the required equipment could be as much as $500,000. Similarly, the bandwidth we can achieve through Floating Fog can be as low as 100 Mbps which is significantly higher than satellite-based Internet.

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