In-Flight Broadband Connectivity: Architectures and Business Models for High Capacity Air-to-Ground Communications

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***Abstract*—In-flight broadband connectivity (IFBC) is a significant open market for mobile network operators considering more than 3.3 billion passengers being served by airlines in 2015. On-board broadband services are provided via air-to-ground (A2G) connectivity through direct A2G communications (DA2GC) and satellite A2G communications (SA2GC). Available on-board connectivity systems have significant limitations: high latency in SA2GC and low capacity in DA2GC. The customer expectancy is multi-Mbps connections in every seat which leads to capacity requirements of Gbps to the aircraft. Creation of high capacity IFBC requires a collaborative interaction between different industrial partners. For this reason, we investigate A2G architectures in terms of economic and technical perspectives, and propose business models by identifying new roles and positioning them in the A2G business ecosystem. In addition, we provide an extensive summary of the state-of-the-art and future improvements for A2G communications.**

***Index Terms*—In-flight broadband, Air-to-ground Communication, Satellite Communication, Business Modeling**

I. Introduction

TODAY, users demand high speed broadband connectivity regardless of their location and time. To this end, in-flight connectivity has recently attracted significant research attention from both industry and academia. While passengers tend to use their own devices, and expect to directly access the Internet at high performance, in-flight broadband connectivity (IFBC) solutions are only partially able the meet this demand of passengers. Hence, the IFBC creates large-scale market opportunities for mobile network industry considering more than 3.3 billion passengers in 2015 [1].

Some airlines are currently offering on-board Wi-Fi services based on satellites. Satellite A2G communications (SA2GC) is a natural choice considering transcontinental flights. However, satellite connection is not a long-term solution for the in-flight connectivity market due to long transmission latencies. On the other hand, continental flights have a significant share in the airlines market. More than 800 million passengers travelled within Europe in 2015 [1]. Therefore, direct A2G communications (DA2GC) has a growing customer base. The main advantage of next-generation DA2GC will be a new LTE service in the cabin, comfort login and high-sustaining bit rates. In the current satellite-based solutions, passengers are required to connect to Wi-Fi for the in-flight connectivity. With DA2GC, users can maintain their cellular connection (LTE, and 5G in future) without any connection break. DA2GC is the only alternative to provide applications with quality-of-service (QoS) requirements such as video call, streaming and phone calls due to latency problems of SA2GC. Although DA2GC ground stations can be placed in petroleum platforms and islands, DA2GC will have limited transcontinental coverage. Hence, a full-scale A2G connectivity solution requires a hybrid network via DA2GC and SA2GC as in Figure 1.

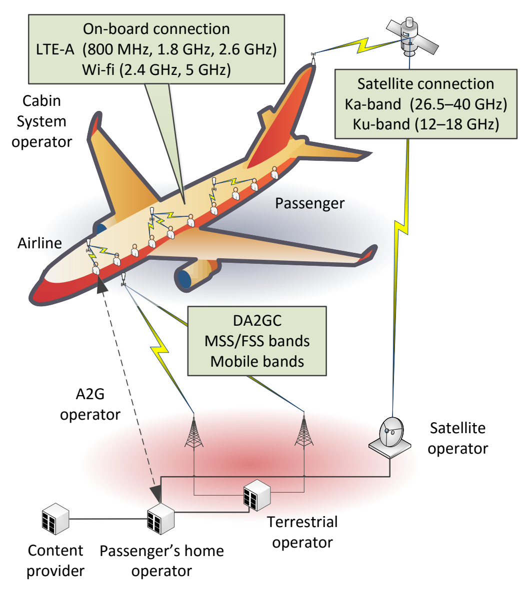

Fig. 1. A2G communication chain.

Gogo Inc. already deployed more than 200 DA2GC ground stations across US and Canada based on CDMA2000 [2]. However, this service has low data rates due to bandwidth limitations (up to 9.8 Mbps/cell). In addition, Deutsche Telekom

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and Inmarsat are deploying the European Aviation Network (EAN) by installing 300 ground stations in Europe to provide A2G connectivity up to 75 Mbps/cell [3]. LTE-based trials in Europe typically can achieve 26-30 Mbps average data rate in the forward link (ground-to-aircraft) [4], [5]. Since customers expect multi-Mbps on-board connection, IFBC systems require Gbps links to aircraft [6]. To provide these data rate levels, DA2GC requires more spectrum, increased spectral efficiency, and improvements by communication techniques as provided in 5G, which is discussed in Section II-B.

IFBC market has also significant challenges in terms of business modeling [5]. To provide IFBC in the European airspace, at least 48 states (including non-EU states) with different frequency regulations need to participate. Thus, multiple operators in different countries are required to work together to provide on-board connectivity via DA2GC. In [5], some initial sketches of business models are proposed, but not analyzed in any greater depth. The authors distinguish between "Ecosystem-models", with a multitude of business players that interact to provide the passenger service, and "All-in-one"-type models, where a single player dominates the provisioning of the service. This could either be an operator providing connectivity or an in-flight entertainment provider. We see it as less likely that a single player will be able to dominate the services, and therefore this paper focusses on the Ecosystem-type business models.

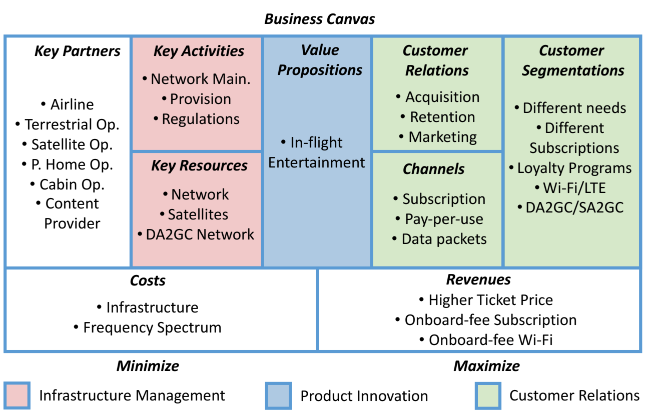

Fig. 2. Business canvas for A2G operator.

Figure 2 shows the business canvas for A2G operator. A2G operator is an intermediary between ground network and passenger network through terrestrial and satellite operators. Business canvas is highly utilized in describing, analyzing, developing and revising business models [7]. As illustrated in the business canvas for A2G operator, multiple business activities will be shared among the key players: airline, content provider, cabin system operator, passengers' home operator, terrestrial operator and satellite operator. In the IFBC market, airline and home operator are the front-end players that are directly in touch with the customers. Hence, the front-end players will be responsible for the customer relationship management as presented with green color in Figure 2. The technical responsibilities (Red part of the business canvas) will be shared among the back-end-players: the operators. Cabin system operator will provide Wi-Fi and LTE connections in aircraft. Connectivity with the ground network will be provided by an intermediary A2G operator through terrestrial and satellite operators. Content provider will provide content for the passengers. Eventually, the network will create value for passengers: in-flight entertainment as in the blue region in Figure 2. Business models aim to minimize the costs such as infrastructure and frequency spectrum, and maximize the revenues via higher ticket price and on-board fee.

The main contributions of this paper are three-fold. Firstly, we provide an extensive survey of the available A2G systems and their future in Section II. Secondly, the players and their activities in the business-ecosystem are defined in Section III. In addition, we propose A2G architectures and investigate their feasibility. Lastly, three business models are proposed to manage the value and money exchange between the players in Section IV. For the ecosystem-type business models, it is critical for companies to find a value and revenue generating business model; hence we investigate the business network while including both technical and business perspectives.

II. The A2G Market: Today and Future

The following subsections summarize the current and future technologies for SA2GC and DA2GC.

A. SA2GC

Almost all commercially available A2G systems utilize satellite-based solutions to provide IFBC. Connection with satellites is provided with an antenna placed on top of aircraft. SA2GC operators provide Wi-Fi connectivity for passengers on-board, and use different business models. Some airlines prefer to offer the service for free to acquire more customers. Others are charging an additional fee for the service. Some SA2GC operators offer subscription and limited data plans. Despite the market penetration, current SA2GC via geostationary-orbit (GEO) satellites has limitations in transmission latency around 500 ms (round-trip-time (RTT)).

GEO satellite operator generally uses Ku-band satellites due to their availability and wide coverage. There are several players who utilize Ku-band satellites for SA2GC such as Gogo-2Ku [11] and Panasonic [12]. SA2GC with Ku-band can provide capacity levels up to 70 Mbps per aircraft, and with high-throughput-satellites (HTS) the achievable data rate can reach up to 100 Mbps with frequency re-use and spot-beam technologies [10], [11]. Broadband low-earth-orbit (LEO) satellite initiatives, e.g. OneWeb, could be an alternative solution for low latency and high capacity A2G connectivity with their close Earth orbit (≈1200-1500 km) [13]. However, the first LEO broadband satellite system will be operational not before 2022. Thus, we envision that IFBC will be provided by SA2GC via GEO satellites and, where possible, by DA2GC via ground base stations in near future.

B. DA2GC

DA2GC utilizes ground base stations to connect aircraft and ground network. This way, latency problems of on-board broadband services can be alleviated because cell range will be between 50-100 km based on inter-site distance (ISD), and $5-10$ ms RTTs can be achieved [6]. Compared with GEO (36000 km and 500 ms RTT) and LEO satellites (1500 km and 30 ms RTT [13]), DA2GC provides significant improvement for the latency, and enables IFBC to offer applications with QoS requirements such as video calls. However, for seamless connection in transcontinental flights, DA2GC and SA2GC will complement each other such that SA2GC will provide connectivity, where DA2GC is not available or too congested.

In DA2GC market, the most significant player is Gogo Inc. with ATG-4 product which operates at 850 MHz with 4 MHz bandwidth based on EV-DO CDMA2000 standard [2]. Gogo ATG-4 can achieve up to 9.8 Mbps per cell and provides on-board connectivity for the flights in North America with more than 200 ground base stations. However, Gogo suffers from low bandwidth levels, so the company heads for satellite-based solutions to provide high data rate levels. Deutsche Telekom and Inmarsat are deploying EAN, which is a hybrid SA2GC/DA2GC connectivity by using S-band frequencies (2x15MHz) [3]. EAN will initially have 300 ground stations to provide DA2GC coverage for Europe, and provide up to 75 Mbps per cell. This capacity will be shared by the number of aircraft in the cell, and then the resulting capacity per aircraft is shared by the passengers on-board. Chinese Government entities are also performing tests at 1785-1805 MHz (20 MHz bandwidth) for TD-LTE technology, and providing coverage with more than 17 base stations in China's air routes with CDMA EV-DO standard [4].

For the IFBC market, European airspace is an important open market currently serving more than 800 million passengers per year [1], [4]. However, it is also a challenging environment due to the different regulations by different countries. For this reason, a report [4] was published on the frequency regulations and company trials for broadband DA2GC services in Europe. Based on this report, Deutsche Telekom, Nokia and Airbus have tested an LTE-based ground stations having 100 km ISD [4], [5]. According to their results, A2G link at 2.6 GHz (bandwidth 2x10 MHz) provides typically 26-30 Mbps in the forward link (ground-to-aircraft) and 17 Mbps in the reverse link (aircraft-to-ground) with less than 60 ms latency for an aircraft at 10 km with 800 km/h speed. However, DA2GC requires increased spectrum resources to provide high achievable data rates to be an alternative solution for SA2GC.

1) Frequency Regulations for DA2GC: ECC report [4] describes the frequency designation discussions and possible regulations to make use of the current spectrum in Europe. For solving the bandwidth problem, spectrum repurposing/transferring is also proposed by the ECC. For DA2GC at 5855-5875 MHz and 1900-1920 MHz, there are some regulatory efforts to provide harmonization in European states [14] and [15], respectively. However, these bandwidths cannot provide the data rates that can be alternative solution for the SA2GC currently having 70-100 Mbps. Thus, spectrum sharing with mobile satellite services (MSS) as complementary ground component and fixed satellite services (FSS) as moving platforms may be promising for DA2GC. The FCC in US also considers possible frequency sharing between DA2GC and FSS in 14-14.5 GHz band [4]. To summarize, the discussion about the DA2GC frequency spectrum is an important open issue.

2) Towards 5G: The Next Generation Mobile Networks (NGMN) Alliance proposed the key performance indicators (KPI) for future (2020+) 5G IFBC [6]. Based on their estimations, each user will have 15/(7.5) Mbps download/(upload) speeds on average, so that 1.2/(0.6) Gbps download/(upload) speed is required per aircraft with the assumption of 20% active users per aircraft and 400 passengers in each aircraft. To achieve these data rates, DA2GC systems require increased spectrum, increased spectral efficiency and improved network management with 5G technologies.

TABLE I
NGMN'S 5G DA2GC KPI REQUIREMENTS [6]

Parameter	***Requirements***
Data rate	*Download: 15 Mbps/active user* *Upload: 7.5 Mbps/active user*
Latency	*10 ms*
Mobility	*1000 km/h (Max.)*
Aircraft Density	*60/18000 km^2*
Traffic Density	*Download: 1.2 Gbps/aircraft* *Upload: 600 Mbps/aircraft*

Millimeter Wave (mmWave) frequencies have been attracted significant research attention due to available amount of bandwidth $\approx$500 MHz and more. With low wavelengths of mmWave, large antenna arrays can be realized to provide high array gains to compensate for the high path-losses. Large antenna arrays also enable advanced antenna techniques such as multi-user beamforming, and interference cancellation. Hence, high spectral efficiencies can be maintained with mmWave systems by modulation schemes such as 256QAM, 1024QAM, and 4096QAM (8, 10, and 12 bits/symbol, respectively). However, for utilizing mmWave frequencies, feasibility analysis for DA2GC is required considering e.g. the effects of rain and atmospheric attenuations.

5G will provide advanced network coordination techniques like cooperation of terrestrial and satellite networks, advanced resource allocation, mobile edge cloud and virtualization. Some content, for example a live football match, can be multicast to passengers. In addition, cabin operator may utilize smart caching techniques to offload some traffic from A2G links by edge cloud functionalities. Network virtualization/slicing techniques will enable onboard IoT services for non-critical applications such as cargo monitoring, CCTVs and temperature monitoring.

3) Open Problems and Challenges for DA2GC: The most critical challenge in DA2GC is the frequency regulations as outlined in Section II-B-1. Depending on the regulations, an aircraft may need to utilize multiple bands and roam between terrestrial networks and satellite networks to provide seamless connectivity. In addition, DA2GC ground station deployment problem imposes a significant open research issue to reduce the cost of providing IFBC. To this end, DA2GC ground stations can be placed in existing base station towers to utilize existing fiber and grid infrastructure. Furthermore, flight corridors can be exploited to reach a cost-effective deployment for DA2GC. In addition, the interference between ground and in-cabin LTE networks is another open research problem. Both networks may experience high interference when aircraft is flying close to the ground (especially<3000 m). For this reason, in-cabin network cannot use the licensed ground LTE spectrum for low altitudes. To avoid this problem, cabin system operator can utilize license assisted access (LAA) based LTE standards to provide seamless cellular connectivity in all phases of the flight.

III. Business Modeling: The Players

We envision that the future IFBC will be provided by the cooperation of different players in a business eco-system. Thus, this section includes all players and definition of their roles. However, some players can combine multiple roles in the chain. The economical relationships between these players are covered in Section IV.

A. Passenger

The main purpose of A2G chain is to provide IFBC for passengers. Passenger may be charged for this service by airline via higher ticket price and/or their home operator via subscription/pay-per-use. The IFBC market has a growing customer base with more than 3.3 billion passengers worldwide and 800 million passengers in Europe in 2015 [1].

B. Airline

Airline is not direct player in the technical part of the A2G business. The role of airline in A2G chain is providing hosting for cabin system operator's equipment: DA2GC/SA2GC antennas and in-cabin network equipment. However, airline is a front-end player in the market, thus they will take advantage of the service by charging higher ticket prices and/or acquiring more customers via new service offering. In Europe, there are currently 387 airlines with 6,586 aircraft in service and 7,560,360 flights in 2015 [1].

C. Cabin System Operator

Management of the in-cabin network will be performed by cabin system operator. Cabin system operator will provide two types of services: Wi-Fi for non-QoS-guaranteed services, and LTE for QoS-guaranteed services and operator services. Any additional price will be charged by cabin system operator such as Wi-Fi only services for non-SIM devices. Cabin system operator is also a customer of the terrestrial and satellite operators who buys SA2GC and DA2GC services, respectively. This way, cabin system operator will work with multiple terrestrial operators located in different countries. For these reasons, cabin system operator becomes a new player in the A2G chain unlike the available in-flight internet services (e.g. Gogo) where the terrestrial operator also performs as cabin system operator.

D. Satellite and Terrestrial Operators

Satellite and terrestrial operators provide backhaul connection between cabin system operator and ground network. Satellite operator provides A2G connectivity for non-QoS applications via satellites and connectivity to the evolved packet core (EPC) of the passengers' home operator. Terrestrial operator provides DA2G connectivity and backbone connectivity to the EPCs of the passengers' home operator and A2G operator for the applications with QoS requirements. For DA2GC coverage in Europe, approximately 1300 and 320 ground stations are required for 100 and 200 km ISDs, respectively (This calculation based on dividing the European continent area to circular cell areas.). As in Section II-B, DA2GC requires increased spectrum and spectral efficiency with 5G to provide high sustaining bit rates. In the business modeling, we assume that DA2GC can provide high sustaining bit rates and utilized as the main A2G channel for continental flights.

E. Passengers' Home Operator

Passengers' home operator provides on-board connectivity services via A2G chain. A2G operator can be considered as a roaming partner for passengers' home operator, and connection between passengers and their home operator as a tunnel connection. Therefore, passengers' home EPC provides Home Subscriber Server and Authorization-Authentication-Accounting. Passengers' home operator is a front-end player and directly in touch with the end-users. Home operator will offer on-board subscription and pay-per-use deals to their customers. These services increase connectivity time of subscribers, and they are more expensive than connectivity on ground. Thus, IFBC will improve home operator's average revenue per-user (ARPU). Home operator can also utilize in-flight connectivity service for advertisement campaigns such as "services even in the sky".

Passengers' home operator can also act as a terrestrial operator by deploying DA2GC ground stations. Since home operator has nationwide coverage in their country of operation, capital expenditures (CAPEX) of DA2GC may be lower by using their existing network. Mobile network operators (MNO) having IFBC will have competitive advantage in the market; thus, this competition will push all MNOs to join A2G eco-system to increase their revenues by providing service and/or becoming terrestrial operator.

F. A2G Operator

A2G operator is an entity that manages A2G connection for cabin system operator via terrestrial and satellite operators depending on type of data traffic and location of aircraft. It is a consortium of all involved terrestrial and satellite operators. Cabin system operator and passengers' home operator can optionally be part of the consortium. A2G operator acts like a virtual operator/customer, who buys services and capacity (radio/backhaul) from satellite and terrestrial operators. Cabin system operator acts like virtual operators/customers of A2G operator. A2G operator is a roaming partner for passengers' home operator.

A2G consortium is required for several reasons. Considering Europe, an aircraft will pass through multiple countries' airspace, and each country has different frequency regulations, different home operators (more than 100 MNOs) and different terrestrial operators. Therefore, cabin system operator and home operator need to make tens of separate agreements with terrestrial operators in every country. This condition will create challenges for new-comers trying to enter the business. To avoid such problems, one unified contact point for all partners can be realized with the A2G consortium. This way, different operators can handle the frequency regulations in their countries, and new home and cabin system operator can enter the market with an agreement to all partners through A2G operator.

There are different possibilities for A2G architecture in terms of the role of A2G operator.

- **Business Entity:** A2G operator can be assumed as a business entity, and its only role is to manage the interaction between terrestrial operators at different countries. As in Figure 3(a), A2G operator will not own any network equipment, and different terrestrial operators will be connected with home operator's EPC through different links. In this architecture, the A2G operator will operate as a clearing house in which the interaction between home operators and multiple terrestrial operators will be managed through a single contract. However, this architecture significantly limits capabilities of the system due to limited possibility of advanced cooperation between terrestrial networks.
- **One A2G EPC:** In this case, A2G operator will own network infrastructure. Terrestrial networks in different countries belonging different companies will be connected to a shared A2G EPC as in Figure 3(b). This way, different terrestrial networks can employ advanced cooperation techniques such as seamless connection through the borders, efficient scheduling and resource allocation, and coordinated multi-point techniques. One A2G EPC will also facilitate newcomers to enter the market because there is no need to build a new network for the ground communication. New terrestrial operator can utilize the existing communication networks; thus, this architecture provides low CAPEX. In this architecture, passengers will be connected to the ground network through A2G operator's packet data network gateway. Therefore, there will be policy exchange between A2G operator and home operator through home and visited network's policy and charging rules functions.
- **New Network:** The last architecture is building completely new network which is owned by a single A2G operator acting as both terrestrial and cabin system operator as in Gogo model. However, this structure requires extremely high investment for a single organization, and it is economically ineffective.

One A2G EPC architecture will be promising for A2G chain because it is economically effective compared to the new network architecture, and provides superior performance compared to the business entity architecture through advanced cooperation techniques.

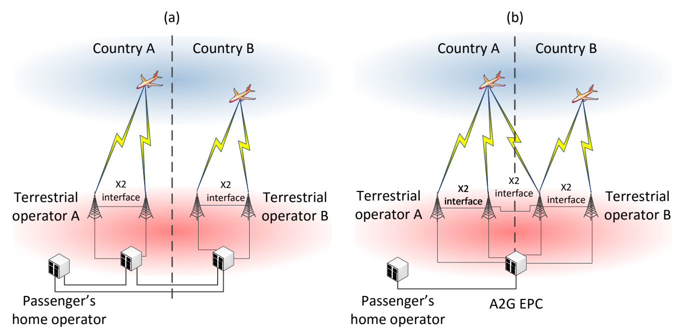

Fig. 3. A2G architectures (a) Business Entity, and (b) One A2G EPC.

G. Content Provider

Content provider offers content for passengers such as movies, music. Some special offers can be provided for the passengers through special agreements with cabin system operator and passengers' home operator. In addition, content provider may offer tailored content available off-line that will be stored in cabin system operator's equipment for a storage fee. With A2G communication, content provider can increase their revenues since online time of users will increase.

IV. A2G Business Models

A2G market is a collective business ecosystem consisting of many players, and creates value through interactions instead of stand-alone strategies [8], [9]. The proposed value comes from the IFBC, where passengers can use their own devices and reach content in the Internet. In this section, we propose and investigate three business models to analyze the value and cash flow among the players.

A. Cash Flow

In this business model, every service is charged by its provider as in Figure 4(a), and this model is called as "Cash Flow". Passengers may be charged by their home operator via subscriptions or pay-per-use deals/ by airline via higher ticket price/ and by content provider via content fee. Passengers' home operator receives service and on-board fee from passengers, and pays fee for the extended coverage to its roaming partner: A2G operator. Since the creation of this service requires a new network with its own CAPEX, home operator can charge on-board fee for their extended coverage. Hence, this on-board fee is not a roaming fee that will be abolished in EU states in 2017.

Airline can charge passengers with higher ticket price and can charge cabin system operator to host equipment because extra weight in aircraft will increase costs of flights. However, airline will also pay cabin system operator for the connectivity. Content provider receives content fee from passengers. On the other hand, content provider will pay storage fee to cabin system operator for off-line available contents stored in cabin system operator's equipment. Cabin system operator receives connection fee from airline, but they will pay for both A2G

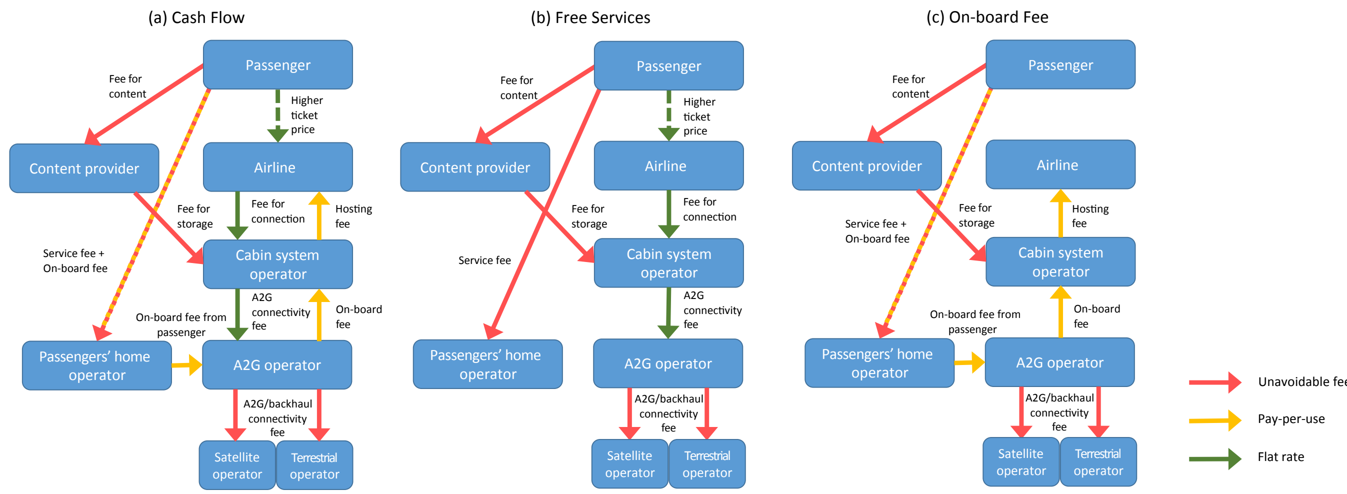

Fig. 4. Proposed business models (a) Cash flow, (b) Free services, and (c) On-board fee.

connection and equipment hosting. In addition, cabin system operator may also provide some Wi-Fi services for passengers especially for non-SIM devices, but this flow is omitted for the sake of simplicity. A2G operator receives fees from home operator and cabin system operator for the connectivity, but pays for A2G and backhaul connection, and on-board fee to cabin system operator that comes from users. Terrestrial and satellite operators receive connectivity fee from A2G operator, but they pay for infrastructure and frequency spectrum.

Figure 4(a) shows the cash flow business model. Red arrows represent fees that are always present if the service is exploited or not. Since the resources of satellite and terrestrial operators are allocated for A2G operator, the connectivity fee is unavoidable. Content provider and home operator will charge customers for their subscriptions. However, on-board connectivity depends on whether users exploit the service or not. Therefore, the on-board fee charged by home operator to passengers is pay-per-use and represented with a yellow arrow. In the same way, hosting fee, on-board fee to A2G operator and cabin system operator also depend on the amount of data transfer. Green arrows represent the price charged to the airline and have flat rates such as fee for connection charged by cabin system operator and A2G connectivity fee charged by A2G operator. The dashed green arrow between the passenger and represent the price that may not be exploited because some airlines may try to attract more customers by offering this service for free.

B. *Free Services*

The second business model is "Free services" in which some of the services are provided for free for passengers as in Figure 4(b). In this model, the price for the in-flight connectivity is free for passengers; however, the cost of the service may be reflected to the ticket price by airline. This way airline can attract more passengers and increase their customer base. In the free services model, airline is the entity who distributes the income to the other partners. Airline pays connectivity fee to the cabin system operator. Cabin system operator pays A2G connectivity fee to A2G operator, and A2G operator pays satellite and terrestrial operators. Passengers still should pay fee to their home operator and content provider for their normal subscriptions. Free services model is especially promising for big airlines to promote their brands. Since this service introduces a new cost to airline, this model would be undesirable for low-cost airlines. Some low-cost airlines may still use this model, and compensate the cost of this service by the increase in the number of passengers without charging higher ticket price.

C. *On-board Fee*

The primary objective of low-cost airlines is to provide lowest possible price for plane tickets, and the market for low-cost airlines is highly competitive. In free services and cash flow models, airline will likely to compensate the costs of the service by charging higher ticket price. For these reasons, we propose "On-board Fee" business model in which airlines do not charge any fee for the in-flight connectivity as in Figure 4(c), and this service is sold through passengers' home operator via subscriptions or pay-per-use deals. This way, airline can keep their costs the same while offering in-flight connectivity service. In this model, the revenue is collected by home operator, and the fees are pay-per-use depending on the utilization of the network. Home operator pays for the on-board connectivity fee to A2G operator. Cabin system operator charges A2G operator for providing networking, and pays hosting fee to airline based on the amount of usage. This way, low-cost airlines can make income and offer a new service without adding an additional cost to their system.

V. Conclusion

In this paper, we propose new architectures and ecosystem-type business models for A2G operator. Since different companies have different goals, multiple business models will coexist in the market. A full scale A2G communication requires a hybrid solution based on SA2GC and DA2GC. SA2GC will provide transcontinental connectivity, and DA2GC will provide applications with QoS requirements in continental flights. In near future, the coexistence of A2G connectivity via LEO satellites and 5G mmWave frequencies has very high potential to meet the latency and data rate requirements of the IFBC.

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