INVITED PAPER

The Role of High-Altitude Platforms (HAPs) in the Global Wireless Connectivity

The role of HAPs in providing global connectivity for future communications systems and services is discussed in this paper.

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ABSTRACT | Since 1990s, the investigations of aerospace communication segment have not only been concerned with satellites, but increasingly with lower altitude repeaters flying in the stratosphere. They are the so-called high-altitude platforms (HAPs) with important advantages with respect to satellites in terms of reduced cost of implementation, deployment, and launch. However, HAPs are characterized by a reduced coverage, as compared with satellites. Nevertheless, in recent literature, HAPs are not regarded as competitors of the satellite technology. On the contrary, the emphasis is on the effective and seamless integration among heterogeneous aerospace segments (GEO, LEO, and HAP) and aerospace segments with terrestrial wireless networks in order to globally extend the broadband wireless connectivity. This paper is focused on the role of HAPs in providing global connectivity in future communication systems and services. Potentialities, enabling technologies, and challenges are presented from the perspective of the integrated terrestrial/HAPs/satellite communications infrastructure.

KEYWORDS | Beyond 4G (B4G); communication networks; connectivity; convergence; fourth generation (4G); high-altitude platforms (HAPs); integration

I. INTRODUCTION

A key objective of future communication systems is the seamless integration of advanced multimedia services over heterogeneous networks such as terrestrial fixed and wireless networks and satellite communication systems. In case of fixed networks, operators have already employed an integrated approach using the IP protocol stack with minor adjustments to provide services seamlessly between satellite and terrestrial networks in the core network [1]. However, the level of penetration of satellite-based communications in the current telecommunication infratructure is low, mainly because of two drawbacks, these being the end-to-end transmission control protocol/internet protocol (TCP/IP) throughput degradation over satellite links and the restricted satellite capacity in point-to-point mode.

To this end, another infrastructure has gained the attention of wireless world in recent years, i.e., high-altitude platforms (HAPs). HAPs are quasi-stationary aerial platforms located at a height of 17–22 km above Earth's surface in the stratospheric region of the atmosphere [2]–[4]. HAPs exploit the best features of both terrestrial and satellite communication systems in many ways, e.g., large area coverage, low propagation delays, and hence strong signals as compared to satellites, broadcast/multicast capability, low upgrading cost, incremental deployment, less ground-based infrastructure, and short landing and takeoff times for maintenance purposes [5]. They can fly on demand to serve different regions. For the same allocated bandwidth in a specified area, terrestrial systems require large number of base stations. On the other hand, Geostationary Earth Orbit (GEO) satellites have cell size limitations due to large footprints on the Earth's surface

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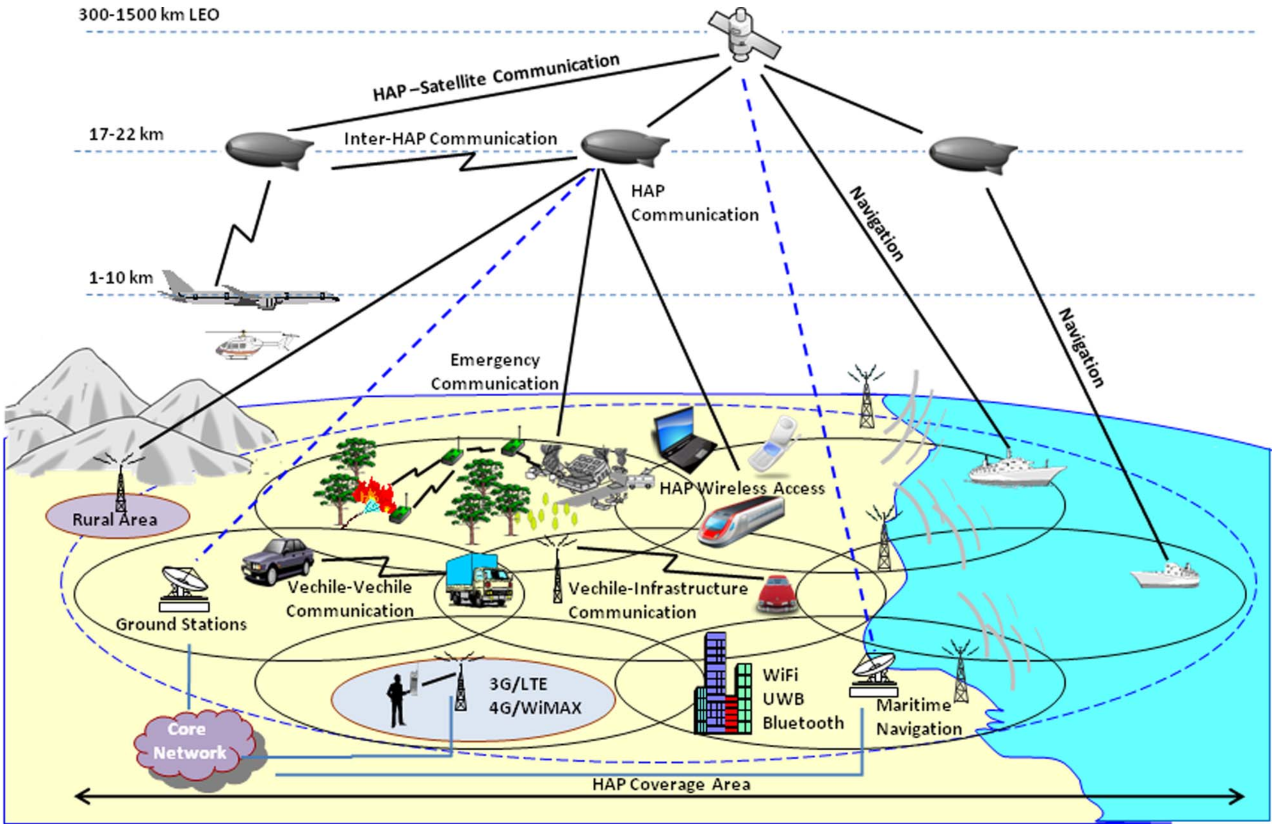

Fig. 1. *Conceptual framework for future generation communication networks based on terrestrial/HAPs/satellites integration.*

and non-geostationary satellites face handover problems and the need to deploy the entire constellation [2], [6], thus requiring high launching costs to place them in orbits. In this case, HAPs seem to be an attractive choice. However, HAPs have some constraints such as the need for refueling and problems with maintaining stabilization in the air.

HAPs can be used to serve different scenarios such as broadcast/multicast HDTV signal, high-speed wireless access, navigation and position location systems, intelligent transportation systems, surveillance, remote sensing, traffic and environmental monitoring, emergency communications, disaster relief activities, and large-scale temporary events. In addition, one of the most promising capabilities of HAPs securing their role in fourth-generation (4G) and beyond 4G (B4G) networks is to provide high throughput backhaul links for ground-based pico- and femto cells, thus minimizing the traffic burden in the mesh networks of the respective cellular systems. This paper discusses the evolution of HAPs and their role in the provision of 4G and B4G services in a secure, efficient, and cost-effective manner. The premise is that the ultimate goal can be achieved by the integration of terrestrial, HAPs and satellite networks. A generic framework for future generation communication networks based on integration of different communication infrastructures and employing an all IP-based core network is shown in Fig. 1.

The organization of the paper is as follows. Section II describes types of aerial platforms that can be used for HAP-based communication systems and their operation, the regulatory environment, and some representative HAP related projects. Section III presents HAP system architectures and configurations of integrated scenarios for global connectivity. In Section IV, advanced technologies supporting global connectivity are described. Section V is about global services from HAPs and Section VI illustrates the potential and challenges of the integrated terrestrial/HAPs/satellite communication infrastructure. The paper ends with concluding remarks.

II. AERIAL PLATFORMS, REGULATORY ENVIRONMENT, AND RESEARCH PROJECTS

A. Types and Operation of Aerial Platforms

The concept of aerial platforms is not new and hot air balloons have been used in the past for meteorological and recreational purposes [2] as well as in the role of simple passive repeaters for bouncing radio signals [3]. However, it has been late 1990s when one of the most influencing mentions of the idea of using aerial platforms for modern wireless communications purpose as an intriguing alternative to satellites appeared in [3]. This idea raised a number of research issues, some of the more important being in the area of aeronautics, which are affecting the choice of platform type, materials used, design, and operation. One of the most restrictive conditions in selecting the most appropriate airborne vehicle for telecommunication services is posed by the basic requirement to keep quasi-stationary position above the served area on the ground. This not only restricts the flight speed and/or trajectory of the airborne vehicle but also poses station-keeping requirements to withstand stratospheric wind and its changes on different time scales, thus directly impacting the design of the platform. Taking this into account, the operating altitudes around 20 km with mildest winds, on average, came as a natural choice, requiring the minimum effort to compensate for unpredictable movements due to wind and wind gusts, which exhibit displacement and change of inclination. The change of inclination can be compensated with the use of beamforming antennas and a gimbal system at the bottom of the platform. The vertical displacement due to vertical winds is practically negligible, while the horizontal displacement, caused by horizontal winds, needs to be compensated with a suitable propulsion mechanism. The extent of displacement and the means for its compensation are closely related to the type of the airborne vehicle.

The basic classification of airborne vehicles used for HAPs into aerostatic and aerodynamic platforms is based on the underlying physical principle that provides the lifting force. Aerostatic platforms are making use of buoyancy to float in the air, whereas aerodynamic platforms use dynamic forces created by the movement through the air. Alternative naming, also used in the literature, refers to lighter than air for aerostatic platforms and heavier than air for aerodynamic platforms.

Aerostatic platforms appear in the shape of balloons and airships. In order to provide buoyancy, they make use of a lifting gas in an envelope, most commonly diatomic hydrogen and helium. Balloons are usually unpowered platforms, and since the flight cannot be controlled easily they are usually manned or tethered. Airships, on the other hand, are normally unmanned powered platforms, capable of staying in the air for weeks and months. The main drawback of aerostatic platforms is their size. In order to compensate for thin air in lower stratosphere, a huge volume is needed, giving rise to dynamic drag, when in flight, as well as representing a huge challenge for takeoff and landing. On the other hand, the size of the platform represents an advantage, as it is easier to accommodate larger and heavier payloads and on the large area it is also possible to generate power using solar cells.

Aerodynamic platforms, on the other hand, exploit the aerodynamic lift for flying in the air. They cannot stay in the air unless they move forward, which is why they have to circle above the coverage area and thus maintain quasi-stationary position. Given the density of the air at the operating altitude around 20 km, aerodynamic platforms require large size wings to obtain sufficient lift, hence also the radius of the circular flight of such huge platform must be in the range of a few kilometers. Clearly, due to the circular flight the platform also requires some compensation for antenna pointing.

Aerodynamic and aerostatic platforms have each their advantages and disadvantages, but none is commercially available as yet for the delivery of HAP-based communication services. In fact, although both based on mature underlying technologies, they are at different stages of development when it comes to their use in the stratosphere, and are also subject to different perception and acceptability criteria. Further development and modifications are thus needed for HAPs to move from research to commercial operation not only in technological sense but more importantly in terms of flight regulations. Considering this it is expected that initial use of HAP-based communication services can be for event servicing and disaster relief applications using existing manned and unmanned aircraft equipped with application specific modular payloads. For longer operation aircraft will operate in shifts, requiring handoff between ascending and descending HAPs in order to maintain continuous connectivity [7]. In the medium term the capabilities of aircraft HAPs is expected to improve significantly. The main utilization of HAPs in this phase is foreseen in developing countries with unavailable broadband infrastructure, requiring some notable improvements in the areas of propulsion, advanced materials, energy storage, and power generation. Finally, on the longer term, it is expected that airships will also become available for safe and long-term operation in stratosphere and will start replacing aircraft-based HAPs. Compared to aircraft these platforms will provide virtually unlimited payload capacity as well as large surface area for power generation using solar energy. As such they will complement and extend the terrestrial infrastructure also in developed countries, and in some cases potentially becoming also a competing technology to terrestrial fixed and mobile broadband technologies.

B. Regulatory Environment

Regardless of the selected type of aerial platform the operation of HAP-based communication systems is on the one side subject to radio-frequency (RF) spectrum regulation, globally governed by the International Telecommunications Union—Radiocommunication Sector (ITU-R), and on the other side to aeronautical regulation, which is predominantly concerned with the aspects of safety in controlled civilian airspace.

The ITU-R has allocated several frequency bands for HAPs to provide different broadband multimedia applications in millimeter-wave band and International Mobile

Telecommunications (IMT)-2000 services in third generation (3G) frequency bands. ITU-R allocation currently specifies:

- 300 MHz in each direction in the 47/48-GHz band worldwide on the secondary basis shared with satellites for all HAPs communications [8];
- 300 MHz in each direction in the 31/28-GHz band also on the secondary basis in over 40 countries worldwide excluding all of Europe for fixed broadband services [9];
- 2.1-GHz IMT-2000 band to be used for the provision of 3G services to users [10].

Under consideration for WRC 11 agenda is also the use of the 6-GHz band for IMT-2000 gateway link [11].

Although most attractive types of platforms for HAP-based communication systems assume unmanned vehicles, the aeronautical regulation for safety reasons currently requires at least one pilot onboard of each aircraft while in civilian regulated airspace, with voice and data communications capability with air traffic control (ATC). So, one of the main hurdles to overcome in order to make HAPs an integral part of global communication systems is to create appropriate regulations for unmanned aircraft that will ensure safety risk in the same range as with manned aircraft. For HAPs flying well above the conventional civilian airspace, which extends up to approximately 15 km, this regulation only applies to takeoff and landing phases, so a solution with a ground-based remote pilot providing full control via radio link might be an acceptable regulatory compromise once it is proven equally or even more safe as conventional approach with the pilot onboard. Based on the growing confidence in technology after the initial missions, the regulation with respect to long duration unmanned flights is also expected to become more HAP friendly.

C. Research Projects on HAP-Based Communication Systems

Many research projects have been dedicated to solve different issues related to HAPs since their evolution, but only some of the most representative are mentioned below, while more comprehensive overview is available in [12]. The first HAP program was the Stationary High Altitude Relay Platform (SHARP) initiative in Canada but the first commercial application for video telephony and internet services from HAPs (250 platforms in the 47/48-GHz band) was initiated by Sky Station Inc. in the United States [9], [13]. The data rates for fixed services were planned to be 2 Mb/s in uplink and 10 Mb/s for downlink, whereas for mobile applications these were 9.6–16 kb/s for voice and 380 kb/s for data. This project was canceled, but it was followed by a number of commercial and academic research projects worldwide, as for example, the Skynet project in Japan, the StratSat (Strategic Satellite) initiative in the United States, the High Altitude Long Operation (HALO) project in the United States [54], [55], initiatives in Korea, etc. [12]. In order to assess potential applications of HAPs for remote sensing to support disaster management and mitigation, situational alertness of disasters and postdisaster evolutions [15], a research activity on High Altitude Long Endurance (HALE) platforms [56] was conducted by the directorate of research and development in the office of critical infrastructure protection and emergency preparedness in Canada. In addition, considerable efforts have been made to investigate HAPs potential applications in providing wireless fixed and mobile services.

The European community has paid considerable attention to this evolutionary technology and funded several HAP related activities through the research Framework Programme and European Cooperation in Science and Technology (COST). The research projects of main interest that focused on the integration of HAPs in the existing communication infrastructures and forthcoming 4G communications were HeliNet (NETwork of Stratospheric Platforms for Traffic Monitoring, Environmental Surveillance, and Broadband Services) [14], [15], CAPANINA (Communications from Aerial Platform Networks Delivering Broadband Communications for All) [16], [17] and COST Action 297—HAPCOS (High Altitude Platforms for Communications and Other Services) [18].

The HeliNet was a three-year project running from January 2000 until March 2003. It was addressing aeronautical and energetic issues and developing three prototype applications. On the one hand, it was focusing on the design of a scaled size prototype of solar powered plane and investigation of energy balance using solar and hydrogen cells, and on the other hand, on vehicle localization, environmental monitoring, and broadband communications. With respect to the broadband communications the research areas included the system level design, the propagation and diversity issues, modulation and coding techniques, resource allocation and network protocols, and the antenna design and development.

The CAPANINA project as continuation of the HeliNET project ran from November 2003 until January 2007. The aim of the project was to develop low-cost broadband technology for HAPs and provide users with ubiquitous broadband wireless access (BWA) in hard-to-reach areas and inside high-speed vehicles (e.g., high-speed trains traveling at up to 300 km/h), essentially addressing both fixed and mobile users. The CAPANINA system offers bidirectional high-capacity links to ground terminals which were designed to be able to provide a variety of services such as broadband internet, video streaming, and video on demand [17]. In this respect both, millimeter-wave band as well as free-space optical (FSO) communications were investigated and also demonstrated during three trial missions using different RF and FSO payload configurations on:

- tethered atmospheric balloon (trial 1 in 2004);
- stratospheric balloon (trial 2 in 2005);
- scaled-size Global Observer aircraft (trial 3 in 2006).

The HAPCOS four-year COST Action started in 2005 with the main objective of increasing the knowledge and understanding the use of HAPs for delivery of broadband communications and other services by exploring, researching, and developing new methods, analyses, techniques, and strategies for developers, service providers, system integrators, and regulators.

III. ARCHITECTURES AND SYSTEM CONFIGURATIONS FOR GLOBAL CONNECTIVITY

HAPs have better link budget and low propagation delays as compared to satellites due to their low altitudes, however, they have limited coverage area. Therefore, in the framework of heterogeneous networks for future communication systems HAPs and satellites networks can work in conjunction with terrestrial networks and great advancement could be visualized in future communications when HAPs will be fully operational systems. In addition, advancement in technology pushes technology developers, network operators, and users towards seamless integration of existing communication infrastructures [19]. The key issues in this integration are context-aware architectures, integrated traffic modeling, cross-layer approaches, and unified radio access network for all access technologies. The role of HAPs in forthcoming communication systems is of great significance in these integrated scenarios. Different architectures and service scenarios have been proposed during the last two decades to achieve this goal [19]:

- standalone HAP architecture;
- multiple HAPs architecture;
- integrated terrestrial/HAPs system;
- integrated satellite/HAPs system;
- integrated terrestrial/HAPs/satellites system

We present in brief the above architectures highlighting that only the last two categories can support a really global connectivity, and thus constitute the main focus of this paper.

A. Standalone HAP Configuration

HAPs possess strong capabilities to be used as standalone infrastructures, providing wireless access to users on the ground. In fact, HAP can be seen in this configuration as an elevated base station with coverage radius in the range of about 120 km at an elevation of approximately 10°. Based on ITU recommendations, HAPs can serve areas with footprints of radius more than 150 km [20], thus providing services on a regional basis. In reality, however, broadband services are only expected to be available in multicell coverage at an elevation angle down to 30°, i.e., in the radius of approximately 60 km from the HAP.

The major applications of standalone HAP configuration, depicted in Fig. 2, include emergency communications, disasters relief missions, short-term social/business/sports events, and large-scale high-demand scattered events such as Olympic Games or World Cups. The platforms can facilitate users directly, but usually they will be connected to an external network through a gateway [21].

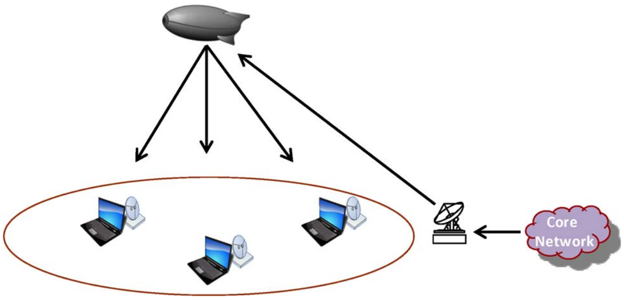

Fig. 2. ***The standalone HAP configuration for temporal or permanent coverage of a specific area.***

This configuration is the baseline configuration of all projects so far and has been studied extensively in the literature, with theoretical analysis simulations, measurements, but also several trials and demonstrations.

B. Constellation of Multiple Interconnected HAPs

In order to extend the coverage and/or capacity of a HAP-based communication system, a network of multiple HAPs can be employed, where HAPs are connected via ground stations or, in case of HAPs with switching payload capabilities, by interplatform links (IPLs). The latter in particular brings the new element for investigation compared to the previous architecture, which due to the operating environment can make use of either microwave or optical links. While IPLs notably increase the complexity of the payload, they significantly reduce the system requirements for the ground segment by providing system support independent of terrestrial networks, and provide flexibility in system requirements and improved coverage especially in remote areas [22]. However, they are limited by onboard processing systems and power constraints.

This architecture can cover a broader area on the Earth, essentially making use of a network in the sky, as depicted in Fig. 3. Several projects addressed such networks of HAPs. For example, it has been demonstrated in [23] that 16 HAPs can serve Japan with the minimum elevation angle of 10°, whereas an architecture of 18 HAPs is feasible to cover the whole of Greece including all the islands [24].

Instead of extending the coverage area, multiple HAPs can also be deployed in some planar or vertical arrangement so as to cover the same single coverage area. By exploiting spatial discrimination, such multiple HAPs configurations provide incremental rollout and systems can be expanded on demand for higher capacity [25]. Multiple HAPs can be deployed to provide services in the same geographical area resulting in strong cell-edge coverage. In [26], a feasibility study of uplink system performance of

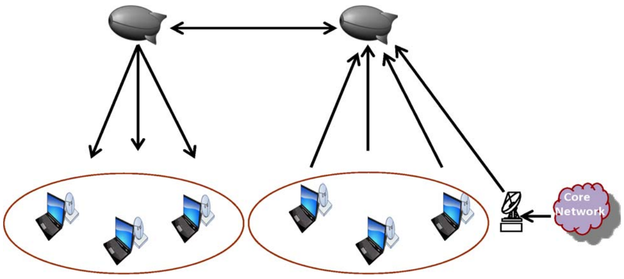

Fig. 3. ***A constellation of multiple interconnected HAPs.***

wideband code-division multiple-access (WCDMA) system is provided using a multiple HAPs configuration. In response to increasing traffic load and type of service demands, there is the possibility of deploying 3–6 HAPs covering the same cell area.

C. Integration of HAPs and Terrestrial Infrastructure

In the case of potential integration of HAPs and terrestrial infrastructure most efforts have been concentrated on the investigation of coexistence of 3G/4G services via HAPs and terrestrial networks. The main focus has been on capacity or interference issues, resource allocation strategies, and the average performance in different parts of the integrated network, all crucial topics to study for an efficient integration scheme. A typical investigated configuration is depicted in Fig. 4.

The capacity of integrated HAP-terrestrial CDMA system with sharing band overlay configuration has been investigated in [20]. For high-mobility users, directional antennas are used to increase the capacity. The coexistence capability of HAPs with multiple-operator terrestrial deployments of worldwide interoperability of microwave access (WiMAX) is investigated in [27]. Here a single HAP and multiple terrestrial base stations are considered in the HAP coverage area to provide services to fixed users with a directive antenna mounted on the roof to receive signals from HAP. The system model uses the same cellular structure for the HAPs and the terrestrial base stations. The worst case occurs when the user terminal is interfered by the base station of the same cell.

With increasing capacity demand and further decrease of the cellular coverage area in 4G and B4G networks, HAPs and more generally unmanned aerial vehicles (UAVs) at various altitudes can be considered as an efficient backhaul for dislocated islands of heterogeneous wireless networks consisting of pico- and femto cells, as well as for WiFi hot spots and distributed wireless sensor networks.

D. Integrated Satellite/HAPs System

The first configuration involving HAPs and capable of providing truly global connectivity is the one integrating satellites and HAPs. This is a configuration that comes to treat the long-distance satellite link. Essentially the HAP system acts as a wireless access loop to the global network. The TCP problems for long links are very positively addressed through this proposal while the coverage of special earth parts (islands, mountainous regions, etc.) is carried out in an economic way. A typical configuration of integrated satellite/HAP system is illustrated in Fig. 5.

E. Integrated Terrestrial/HAPs/Satellites System

The advancement of systems and services towards 4G and B4G wireless communications is to provide seamless delivery of broadband multimedia applications over heterogeneous networks. While HAPs have many advantages over terrestrial and satellite networks, the integration of existing and emerging HAPs technologies with terrestrial and satellite networks is vital for profitable long-term operation. The corresponding system architecture for the integrated terrestrial/HAPs/satellites system is shown in Fig. 6.

The HAPs employment in integrated scenarios mitigates hard-to-tackle multipath effects in terrestrial systems because of their greater visibility and the problem of long propagation delays in geostationary satellites owing to their low altitudes. The HAPs master control station

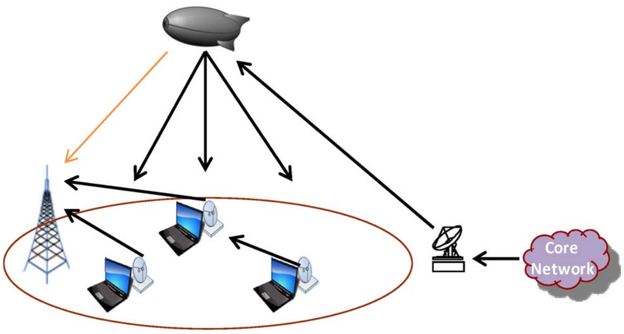

Fig. 4. ***HAP as an integrated element in the terrestrial infrastructure.***

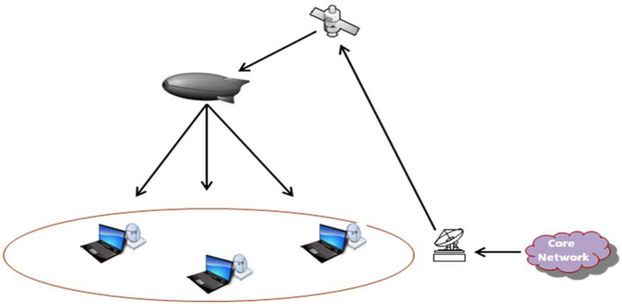

Fig. 5. ***HAP as the first/last mile of the satellite network in integrated satellite/HAP system.***

possesses functionalities of control and management to perform resource allocation and traffic management activities inside a single platform coverage area. In order to visualize the integration concept, there is need to exploit bandwidth availability, coverage in integrated scenarios, proper interfaces between terrestrial and space segments (satellites and HAPs), and investigations at very high-frequency ranges for space segments [28]. The main challenges involved in developing such communications infrastructure are high quality-of-service (QoS) provisioning, context-aware services and architectures, seamless integration at user level, integration of services, different access technologies and protocols, exploitation of heterogeneous systems, integrated traffic modeling, and different techniques (cross-layer approaches) to investigate these issues [29].

Another important area in this regard is FSO technology. The favorable propagation conditions in the region above troposphere not only allow optical communication links between HAPs but also links between HAPs and satellites based on optical technology. With respect to IPLs, FSO technology provides significant advantages over RF due to lower power and volume requirements for the payload while providing higher link capacities and no need for frequency planning [30]. The use of FSO links between HAPs and satellites also reduces complexity of the satellite front-end requirements for both transmission/reception operations, i.e., the fading mitigation techniques can be employed on the HAPs reducing the hardware processing requirements for satellites. In addition, the data rates of the system could be increased by establishing high-capacity optical links [31].

In [32], a layered system and services model has been proposed as shown in Fig. 7. This architecture comprises five layers for provision of different services: global satellites including HAPs, global cellular communications, global wireless local area network (WLAN), global wireless personal area network (WPAN), and global broadband personal area network (B-PAN). Each layer of the architecture is based on different hardware and software levels and different frequency ranges to providing services and other features by communicating among various layers and within each layer. In addition to providing services to niche areas, the space segment of the architecture in integrated scenario can be used for delivery of multimedia applications, localization and navigation services, internet, and communications in disasters relief situations.

The users' terminals design and provision of both uplink and downlink services depend upon technological and commercial tradesoffs [32]. Both the uplink and downlink services to user terminals can be provided by means of HAPs or uplink services by means of HAPs and downlink services directly by satellites.

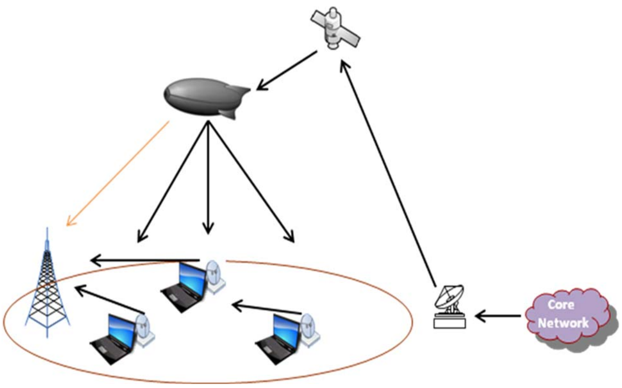

Fig. 6. ***Integrated terrestrial/HAPs/satellites system for global connectivity.***

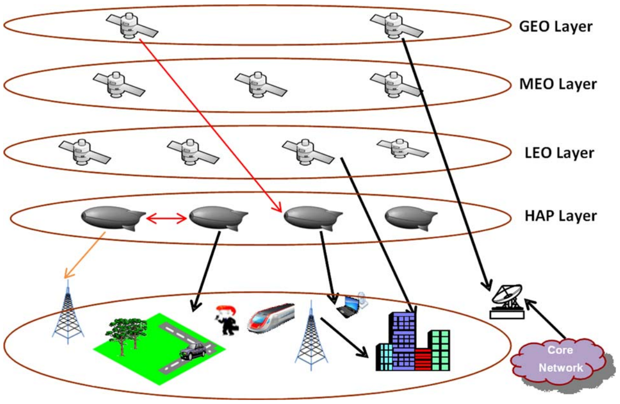

Fig. 7. ***Multilayer approach for integrated scenarios.***

IV. TECHNOLOGY ADVANCES ON HAPs FOR SUPPORTING GLOBAL CONNECTIVITY

Extensive research has been going around exploring the potential benefits of HAPs in order to provide the best quality of global services. In deciding the technologies to include in HAPs, one of the key concerns is the tradeoff between cost of implementation and practical advantage. The first two system architectures described in Section III consider relatively independent operation of HAP systems, merely providing a gateway to other networks, if needed. While this proves sufficient for some specific services such as disaster relief and short-term event servicing in remote areas, HAPs are expected to operate in the longer term also in developed countries with preexisting communication infrastructure. In this view, special attention has been paid in research activities to adapt advanced communication technologies for HAPs communication environments and ensure efficient integration of HAPs in the future heterogeneous wireless access network infrastructure. HAP-based systems will thus have to apply modern wireless system concepts which increase the link and system capacity, improve spectrum efficiency and optimize utilization of resources, guarantee harmless operation alongside and with other wireless networks, and ensure robust operation in hostile radio propagation environments. These concepts typically rely on various advanced approaches and techniques such as adaptive coding and modulation, different diversity techniques, advanced radio resource management, smart antennas, free-space optics (FSO), multiple-input–multiple-output (MIMO) concept, spatial multiplexing, space-time processing and coding, cross-layer design and optimization, the cognitive radio concept, and dynamic spectrum management. However, they may not be directly applicable to HAPs due to large coverage area and predominantly line-of-sight propagation conditions. In particular, special attention needs to be paid to the interference received from other systems as well as interference caused to other systems, and in this respect smart antennas and cognitive radio concept with dynamic spectrum management are seen as key enablers for harmless coexistence and side-by-side operation of heterogeneous wireless access systems.

A. Smart Antennas

Smart antennas in general are cooperative phased arrays capable of advanced signal processing to support spatial beamforming and spatial coding with the aim to avoid causing or to cancel interference in selected directions. Implementation of smart antennas in the millimeter-wave bands can prove difficult due to the small wavelength and the immature technology.

The antenna subsystem of HAPs communication payload comprises phased array antennas or light weight reflector for communication with ground switching stations through gateways [33]. The cellular patterns formed by HAPs, using separate spot beam antennas, make the ground communications susceptible to interference and require high gain directional antennas to support better coverage and high capacities. Efforts have been made to find suitable antenna design and techniques to ensure communications via HAPs with minimum interference with other infrastructures in coexistence scenarios. ITU has proposed a digital beamforming-based multibeam phased array antenna for HAPs-WCDMA system [33]. Extensive treatment of antennas for HAPs is available in [34].

B. Cognitive Radio and Dynamic Spectrum Management

The dynamic spectrum management facilitated by the use of cognitive radio concept has the potential to ensure harmless coexistence and side-by-side operation of different wireless technologies in terrestrial, stratospheric, and satellite segments in potential future unlicensed or shared frequency bands. In fact, with their flexibility and inherent drawback of being a secondary system even in their designated frequency bands HAPs lend themselves as a perfect platform to make use of cognitive radio concepts and thus better adapt to the served area.

As opposed to smart antennas the dynamic spectrum management tends to avoid causing and receiving interference by searching for a portion of the spectrum that is not being used, instead of shaping the radiation pattern. It assumes that user terminals and access networks comprehend computational intelligence about resources and services, are able to infer the user needs based on the context, and adapt transmission or reception parameters to meet those needs in most efficient way, taking into account also the environment in which it operates [35].

The cognitive radio concept has already been recognized as one of the enabling technologies for integration of HAPs with other technologies. As such it was investigated by different authors in order to 1) enhance the coexistence performance and to balance the usage priority of shared spectrum [36], 2) increase the available capacity in a common coverage area [37], or 3) exploit inherent broadcast capabilities and large coverage area of HAPs for dynamic configuration of cognitive radio devices in terrestrial networks and beaming of policies for dynamic spectrum access, thus helping the cognitive radio system to be optimized in a global domain [38].

With its elevated position HAP can also collect the information from the wireless nodes in its footprint about the cognitive radio parameters such as interference level, throughput and bandwidth requirements of applications, etc. Based on this information HAP can synthesize a frequency usage map and use it to optimize transmission parameters of terrestrial wireless nodes, or alternatively, it can send this information for processing and optimization to the ground control center.

C. Diversity Techniques

Diversity in general is a technique that makes use of two or more statistically independent radio paths to improve the transmission reliability. The probability that all radio paths exhibit deep fade is very low, so if all received signals are properly combined, the system performance can be significantly improved. The statistically independent paths can be obtained by [39]:

- separation of receive or transmit antennas (spatial diversity);
- transmitting the same information at two carrier frequencies (frequency diversity);
- retransmitting signal in different time instances (temporal diversity);
- transmitting the radio signal in different directions (angle diversity);
- applying different polarization at transmit antennas (polarization diversity).

Clearly, in order to increase the transmission reliability diversity techniques reduce the capacity of the communication system by sacrificing radio resources. In the case of diversity reception either the best received signal should be selected (selection diversity) or all received signals should be combined into one signal for data estimation (combining diversity).

Due to predominantly line-of-sight (LOS) channel conditions in HAP operating environment propagation channels are highly correlated, so most diversity techniques are not applicable. The exception may be spatial diversity on the ground or use of multiple HAPs.

D. Multiple-Input–Multiple-Output

The MIMO systems, based on multiple antennas on transmit and receive side, offer the promise of link reliability, increased capacity, high spectral efficiency, and high gains by exploiting space-time processing techniques without any additional bandwidth or power requirements under different propagation environments. One of the key concerns of MIMO technology is to find suitable geometrically small size antennas ensuring low mutual coupling between individual antenna elements. In this respect compact antennas with polarization and in particular 3-D feature of electromagnetic waves are expected to play a significant role in MIMO technology [52], [53]. Particularly, the application of MIMO compact antennas to the HAPs communication systems is of foremost interest in order to achieve diversity and spatial multiplexing gains. In addition, the application of onboard MIMO compact antennas can help in eliminating synchronization problem and interference mitigation within HAPs and other infrastructures in HAPs communication links. In this area, several studies have been found in literature focusing on satellite communications and not much attention is paid to HAPs. In [40], a study about application of different compact MIMO polarization antenna configurations to multiple HAPs, operating at 30° and 20-km altitude, for capacity evaluation, spatial correlation, and mutual coupling between antenna elements has been conducted. The HAP diversity system provides superior performance as compared to the single HAP case and the MIMO-cube antenna provides a better capacity than both the MIMO tetrahedron and vector element antennas due to the higher number of acquired HAP platforms. The capacity degrades due to correlation and mutual coupling but still significant gain can be achieved compared to a single HAP case. However, there is a need to investigate the effects of this application on the interference between HAPs and satellites in the downlink in shared frequency bands, cochannel interference effects between IMT-2000 ground stations and HAPs links and capacity evaluations in the case of integrated scenarios.

In general, though, the classical MIMO approach is seen to have a limited applicability in HAP-based communication systems due to predominately LOS channel conditions, negligible signal scattering at millimeter-wave bands, the use of directional antennas, and limited size of the platform. As an alternative, two or more HAPs interconnected by IPLs can form a virtual MIMO (V-MIMO) system. Such system has been investigated in [41] for provision of broadband wireless access to a collective terminal with multiple antennas mounted on high-speed trains. The study analyses the performance of transmit diversity based on space-time block coding (STBC) using fixed wide-lobe receive antennas, and compares it to the reference receive diversity scheme based on best HAP selection that requires highly directional and steerable antennas, as investigated in [42] and [52].

E. Free-Space Optics

FSO technologies can provide large bandwidths and have the ability to support high throughput links. In case of FSO communications attenuation due to different weather effects is negligible above the tropospheric region. Due to their immunity to propagation conditions and high spectral efficiency as compared to microwave links, optical communication technology can be used to establish high data rate IPLs and HAPs-satellite links to serve as broadband backhaul communication channels, which will play important role to globally distribute and receive data in integrated scenarios. By using optical links, data can be downloaded from Low Earth Orbit (LEO) satellites to HAPs at rate of 10 Gb/s [30], [31]. There are some challenges to establish such communication links. In order to reduce misalignment errors caused by motion and vibration instabilities of satellite and HAPs, precise pointing, tracking, and acquisition algorithms need to be applied [43]. Other factors are Doppler shift in the received signal caused by the relative high speed of LEO satellite and optical carrier choice for transmitter design [31], [44].

F. Cross-Layer Design and Optimization

HAP-based communications require efficient utilization of resources because the available resources of bandwidth, transmit power, and battery-storage energy are limited. The existing layered architecture or internet protocol stack does not exploit efficiently the available resources and is a suboptimal solution to the system performance improvement [4], [32]. To meet the demands of future communication systems, the broadband networks need to be optimized by taking into account the quality-of-service (QoS) demands from the applications and the challenges from physical medium. In this view, cross-layer approaches provide better resource utilization and tradeoffs using the knowledge and parameters of other protocol layers and propagate this information among different protocol layers. This results in efficient system design but at the expense of increased system complexity. The cross-layer design concept is expected to address the issues of variability in data rates, total transmission delays and jitter, end-to-end latency, packet reordering, and QoS control in 4G and B4G networks. In addition to optimizing network radio resources, this concept avoids the need of deploying extensive backbone infrastructure for global connectivity to different technologies. The recently proposed cooperative cross-layer joint source and channel coding scheme to mitigate propagation impairments in IP multimedia applications are required to exploit in integrated scenarios for global connectivity [45]. Taking into account the similarity of HAP-based communication systems and terrestrial wireless systems in most parameters but propagation conditions, the same cross-layer approaches can be applied as in terrestrial systems, just optimized to HAP specifics.

V. GLOBAL TELECOMMUNICATION SERVICES VIA HAPs

As discussed in Section III, HAPs can be used as standalone structures or in integrated scenarios to provide different broadband multimedia multicast/broadcast services (e.g., 3G/4G, DVB-H, WiMAX) and real-time services (e.g., VOIP, traffic monitoring) [43]. Extended research has been carried out to decide on the most appropriate services to provide over integrated HAPs satellites or terrestrial HAPs satellites configurations.

A. Broadband Wireless Access (BWA)

HAPs can be used to provide broadband services to both mobile and fixed users with data rates of the megabit per second order, at the frequency bands allocated by ITU to HAPs. The expected services are audio/video streaming, ISDN access, distributed games, distance education, high resolution video conferencing, medical applications, web browsing, large files transfer, and Ethernet line bridging [28], [43]. These services can be delivered efficiently by relaying information over hybrid terrestrial/HAPs/satellite networks resulting in wider coverage areas, distribution of services without overloading the terrestrial segments, and the reduced overall costs.

B. Beyond 3G Services

4G communication systems require high data rates and high capacity communications links with appropriate QoS at low cost. The ITU Working Group 8 illustrated the benefits from 3G/4G services via HAPs [46], declaring that HAPs can facilitate various types of mobile, fixed, and portable terminals and use different frequency bands for establishing backhaul links. To provide the same functionality and services requirements, HAPs and universal mobile telecommunication systems (UMTSs) will use the same round trip times (RTTs) [43]. HAPs also avoid the need for large terrestrial infrastructure because 3G/4G services require smaller cell sizes and hence more ground-based infrastructure.

There has been a trial for mapping the 3GPP service classes, distinguishing between conversational, interactive, streaming, and background service classes as defined in [47] and [48], onto integrated terrestrial-HAP-satellite system [49]. The main distinguishing factor among these classes is delay sensitivity. Conversational class represents the most delay-sensitive class, while background class is virtually delay insensitive. Conversational and streaming classes correspond to real-time services, while interactive and background classes mainly indicate internet applications. Mapping of these service classes and types of services onto segments of an integrated system is given in Table 1.

Table 1 Mapping of Services to the System Segments

System segment	Type of service
Terrestrial	Conversational - audio/video/data
	Interactive - data
	Streaming - video/data
	Background - data
HAP	Conversational - audio/data
	Interactive - audio/data
	Streaming - audio
	Background - data
Satellite	Streaming - audio
	Background - data

C. Multicast/Broadcast Services

Due to increasing demands of users for ubiquitous access to multimedia services, 3GPP has introduced multimedia multicast and broadcast concept in future communications networks. Some of the services (e.g., digital video/audio broadcasting) have already been provided by terrestrial and satellite networks. The provision of these services is highly dependent on the operating environment and hence can have high operational costs. In this respect, HAPs can provide cost-effective solutions to build standardized low-cost receivers. The onboard HAPs base stations would be similar in principle, but more complex as compared to conventional terrestrial base stations as they will serve large number of cells [46]. The HAPs technology would implement two types of onboard payloads: one for satellite-HAPs links and the other for HAPs-terrestrial links and hence extra hardware requirements on terrestrial and satellite segments would be reduced. In addition, in integrated scenarios, return channel to satellite (RCS) can be provided by HAPs which reduces the congestion issues in terrestrial segments [31], [45]. Furthermore, HAPs provide strong signals strength which help in reducing the repeaters required to provide DVB/DAB services in outage areas (blank spots).

D. Emergency and Disaster Recovery Services

HAPs can be used in emergency communications and Earth observation systems with great advantages. In case of natural disasters (e.g., earthquakes, floods) HAPs can be rapidly deployed to restore the communication services in affected areas while allowing users to use the same handheld devices. In addition, with terrestrial backhaul links overloaded or damaged, HAPs or UAVs in general can play a key role in collecting real-time data from wireless sensors or radio-frequency identification (RFID) technology deployed in the disaster area.

E. Backhaul Interconnection via HAPs

One of the key use cases for HAPs as an integral part of the future wireless infrastructure is provision of backhaul links for the small and omnipresent pico- and femto-cells in 4G and B4G networks, since not all the traffic will be able to be routed through the meshed network foreseen to interconnect corresponding base stations. Moreover, provision of backhaul via HAPs can make noncontiguous deployment of pico base stations easier, effectively only aiming at meeting access network capacity demands and not solving the transport network demands with the mesh network of base stations. This is particularly important in the rollout phase of a new network. Similar use case on the shorter time scale is the provision of backhaul gateway links for WiFi hot spots and interconnection of dislocated offices/sites/facilities requiring common access to a firewalled company Intranet.

Similarly, HAPs and/or UAVs can be used to collect and backhaul data from wide spread distributed wireless sensor networks on the ground, making them independent of terrestrial fixed or wireless networks. This is particularly important for wireless sensor networks deployed in remote areas, for instance, for applications such as environmental monitoring, pipeline monitoring, monitoring of landslides, monitoring of volcanic activity, etc. Moreover, HAPs equipped with appropriate sensorial payload can also be used for decentralized collection of Earth observation data. In this context, an interesting scenario is the optical data transfer from one HAP to another over a relay geostationary satellite, essentially making up a global wireless sensor network.

From the backhaul link perspective HAPs could be also used in the global wireless infrastructure to relay the increasingly huge amount of data collected by LEO Earth observation satellites to the ground centers. HAPs would essentially break the satellite terrestrial link to weather-independent high-capacity optical link between satellite and HAP, making it possible to download data in the short time pass of satellite, and the fixed RF and/or FSO link between HAP and ground station subject to atmospheric weather conditions but with reduced throughput requirements.

VI. TERRESTRIAL/HAPs/SATELLITES GLOBAL CONNECTIVITY POTENTIALS AND CHALLENGES

Based on the demands of ubiquitous access of mobile and wireless services and dynamic business models, the wireless industry is anticipating individual entities to be the integrated part of the global communications infrastructure for future communications networks. A possible generic framework for 4G/B4G communications based on the integration of existing and upcoming technologies is shown in Fig. 1.

In addition to providing services to niche areas, HAPs can also serve urban areas with higher signal strengths by incorporating onboard base stations of both terrestrial and satellite segments. This reduces the hardware requirements for both terrestrial and satellite segments. Such systems can greatly benefit in terms of efficient spectrum sharing, improved link budget, and reduced delay. Thus, onboard HAPs base stations will require multistandard baseband processing based on a multiprocessor array network to provide simultaneous processing on multiple air interfaces. The advancements in microtechnologies and nanotechnologies have made possible to build nanoscale devices which will help to a great deal to develop efficient transmission techniques and energy-efficient devices for these communication systems.

The benefits of HAPs can be exploited to provide future integrated services including internet services, 4G broadband communications, intelligent transportation systems, and radio-location and navigation services in the framework of global scenario comprising the global navigation satellite systems (GNSSs) such as the global positioning system (GPS) and Galileo. Generally, it is recognized that as a local component of a GNSS, the HAP can enhance the required navigation performance (RNP); that is, accuracy, availability, integrity, and continuity, with respect to terrestrial components.

In order to provide internet and Intanet services to meet the increasing number of users at high data rates and high mobility, the future integrated systems require integrated traffic modeling based on cross-layer approaches, context aware architectures and services, and location awareness [32]. HAPs provide attractive solutions to achieve these goals by overcoming the problems of end-to-end TCP/IP throughput degradation and capacity in point-to-point mode in satellite links [45]. For a multilayered terrestrial-HAPs-satellite network the implementation of an adequate routing and admission control strategy to choose the best path for resource allocation between two different terminals is of great importance. In the multilayered terrestrial-HAPs-satellite network, stratospheric platforms provide onboard processing and carry out routing, switching, and traffic management functions between terrestrial-based user terminals and the satellite master control station (S-MCS), responsible for the overall system supervision.

In order to provide multimedia services in the integrated scenarios at high data rates, large bandwidths are required. Thus, new adaptive spectrum sharing techniques required to be developed and spectral efficiency of future wireless communication systems has to be increased. At higher bandwidths spectral efficiency can be increased due to link adaptation, adaptive antenna arrays and multiuser scheduling, and fast retransmission schemes [50]. Software-defined radio will assemble the foundation on the basis of which flexible transmission schemes and protocols will be developed to support high capacities to work in multistandard environments [38], [46].

One of the main concerns for HAPs is power consumption and energy storage. To be able to meet such requirements, adaptive wireless concepts and sophisticated scheduling algorithms based on advanced models are required. In addition, the distortions in microwave chain [57] requires sophisticated microwave and RF hardware implementations, including advanced microtechnologies and nanotechnologies to develop energy-efficient systems.

To provide broadband services via HAPs in integrated scenarios, large capacities are required. This requires the exploitation of higher frequency bands. Lower frequency bands support mobility and require low power consumption but at the expense of reduced system capacity. In case of higher frequency bands the capacity is larger but the coverage is worse. Therefore, they require large transmission powers or small cell sizes to provide better coverage. The higher transmission powers lead to higher emissions and thus, higher frequency bands are more susceptible to interference. In order to cope with these problems, radio front-end hardware in conjunction with advanced channel models at higher frequency bands incorporating spatial information are required to be developed.

In addition, the novel communication technologies such as MIMO and OFDM have shown significant impacts on the efficient utilization of available resources, optimized QoS, and minimization of the cost of multitechnology wireless networks. The design of advanced antenna techniques for HAPs to be used in integrated scenarios involves numerous challenges such as traffic engineering, mobility handling, transceiver designs, system reconfiguration, and techniques to mitigate interferences which result when HAPs will operate in coexistence scenarios with other systems. These include interference in shared frequency bands with satellites, HAPs and satellites downlinks channels interference, HAPs interference with terrestrial infrastructures, and reverse link cochannel interference. Thus, in order to investigate these effects, realistic channel models [51], possibly based on advanced antenna techniques, are required.

From the discussion above it is obvious that business models for commercial use of HAP-based communications have to take into account two perspectives [12], [58] that may be in some cases aligned but in others just opposite, i.e., the perspective of the HAP operator and of the service provider. Broadband models are particularly price sensitive and it is beyond the scope of this paper to estimate the cost and profits of different HAP-based services and scenarios. Besides, business modeling also depends on the timeline of the development of technologies as well as regulatory provisions for commercial deployment of HAP-based communication systems [58], [59]. In the light of this it can only be concluded that the use of HAPs is expected to start with emergency and disaster relief missions providing existing communication services via aerial platforms in the form of manned airplanes and tethered aerostats. With the development of aeronautical part and improvement of their capabilities HAPs in the form of unmanned airplanes and airships, capable of longer term missions, will provide broadband communications to fixed users in developing countries with underdeveloped or missing terrestrial infrastructure. In this phase, it is expected that HAPs might start generating revenue from service provision. Currently, least clear are business models for the commercial use of HAPs in developed countries. In this case, the most promising types of applications appear to be provision of backhaul for terrestrial base stations, hot spots, and wireless sensor networks on the one side, and for broadcast/multicast applications on the other.

VII. CONCLUSION

The HAPs are expected to provide, in a cost-effective manner, a multitude of telecommunication and other services over large areas. Compared to terrestrial telecommunication systems, the HAPs offer high signal arrival angle, largely unobstructed signal path, and large coverage area—like satellite-based systems but at lower cost. They can use most of conventional base station technology and terminal equipment. Compared to satellites, they do not require any launch vehicles, and they offer much shorter signal path. They can be brought down to Earth for upgrading or repairing, and be redeployed again. They can be kept quasi-stationary or be moved from one place to another on their own. Solar-powered platforms are environmentally friendly, and aerostats require less energy than aerodynes to do the same work in space.

HAPs have been under development for a number of years but many issues remain to be solved such as the adequate materials to be used, endurance and station keeping, and fuel and refueling issues. International cooperation is needed here to treat these questions and avoid incompatible standards and regulations that may restrict the chances of global applications of this technology.

This paper discussed the future generation wireless communication systems and the key enabling technologies. Particularly, we have examined the upcoming HAP technology and its role in providing global connectivity in future generation wireless networks. The well-established satellites and terrestrial communication infrastructures can facilitate users individually in remote and urban areas with well-known limitations. The emerging HAP-based technology has strong potential to become the third communication infrastructure. Since HAPs have specific and complementary advantages to terrestrial infrastructures and satellite communications, they are expected to play significant role in future generation wireless communication systems. This paper also discussed HAPs architectures, possible scenarios in which HAPs can be interconnected to other networks, global services via HAPs, and future technological challenges and issues in providing global connectivity. The future of wireless communications lies in the fully integrated hybrid architecture of existing and forthcoming technologies. ■

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