TV White Space Broadband for Rural Communities Using Solar Powered High Altitude Platform and Terrestrial Infrastructures

White Paper

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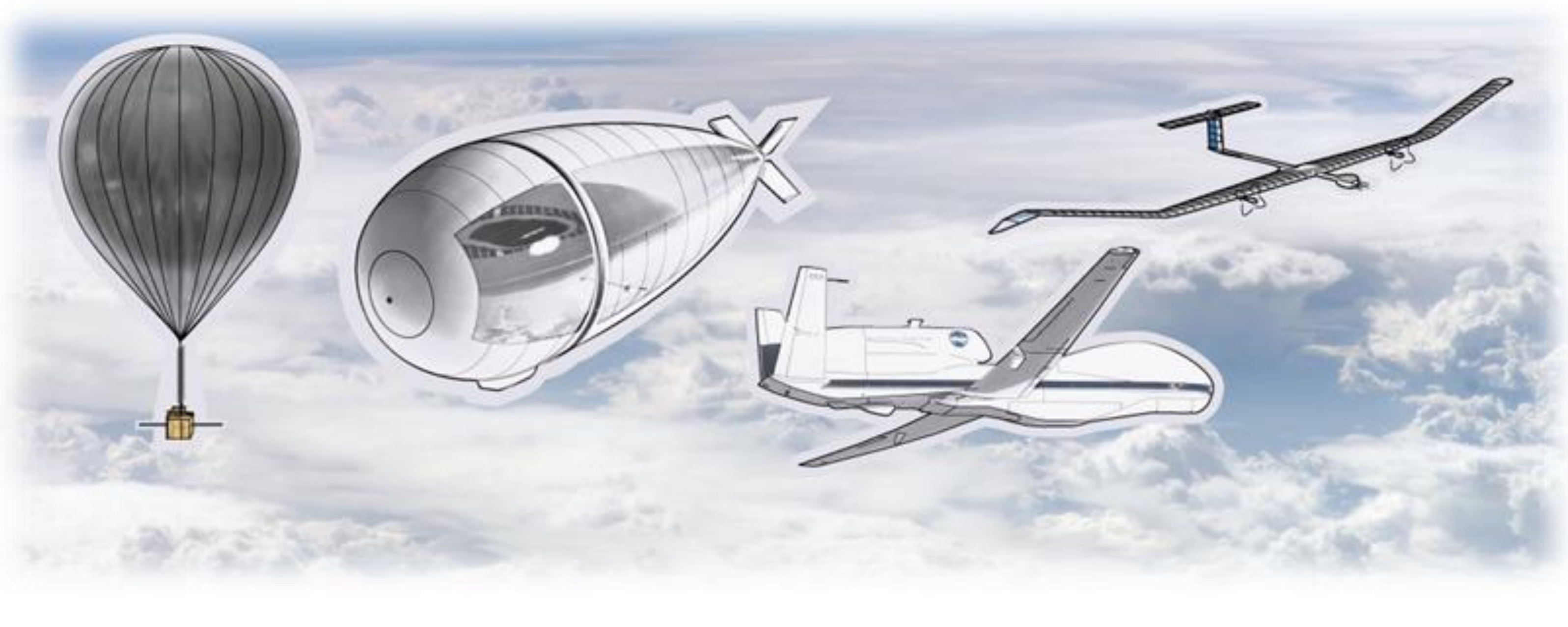

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ABSTRACT

This white paper introduces the delivery of low cost, high availability wireless communications for tropical rural areas, from a meshed network of limited availability high altitude platform (HAP) and terrestrial wireless links and infrastructure. A mesh network of HAPs connected via millimeter wave or free space optical inter-platform links, which are connected into the core fiber network at multiple geographically separated locations using high bandwidth backhaul links, has the potential to provide a flexible and fully sustainable infrastructure. Powered exclusively by solar energy and exploiting TV White Space and cellular radio spectrum, the network is able to intelligently adapt the low availability nodes and resources to make best use of available energy, while satisfying the multimedia traffic demands of users and devices.

INTRODUCTION

Information and Communication Technologies (ICT), including mobile telephony and broadband communication services, play a key role in the economic growth and societal development of a nation. Broadband penetration, however, varies dramatically across different parts of the world. In developed countries, coverage guarantees are in place (often at greater than 95%). In many developing countries of the world (low and middle income earning countries), infrastructure in cities can be well developed, e.g. 4G communication is available in Nigerian cities [1]. However, in rural/remote areas the situation can be markedly different, with poor quality (or no) internet access, and limited mobile coverage. This is caused by the lack of infrastructure, unreliable electricity supply and a limited core telecommunication network. It is not commercially viable for the mobile operators to deploy conventional wired/wireless communication networks in these areas due to the lower population density and purchasing power. Rural communities in developing countries are also characterized by limited access to basic utilities, education and health services. In order to improve the wellbeing of the citizens and generate new business opportunities, cost-effective and low energy-consuming networking solutions should be provided in rural communities to fast-track connection to essential amenities and to provide access to valuable information and services.

Access to available spectrum and management of the spectrum are key components of a wireless telecommunication network. Spectrum sharing has been considered as a promising approach to promote more efficient use of the underutilized resources. One classical application is the use of Television White Space (TVWS) technology which has significant potential in underserved rural communities to provide affordable broadband services. Due to the favorable propagation characteristics, wireless signals in the TV bands can cover a wider area compared to those at higher frequencies. TVWS technology utilizes the unused TV broadcasting spectrum in the UHF band on a secondary basis without causing harmful interference to the primary TV receivers [2]. This is particularly beneficial to the areas with a large proportion of vacant UHF channels like Nigeria [2]. Some African countries have undergone pilot projects on TVWS (such as [3] in South Africa) to provide broadband access. Apart from the license-exempt approach, it is envisaged that licensed bands, owned by an operator, could also in principle be used, subject to regulatory approval. This can be facilitated by emerging spectrum sharing frameworks such as licensed shared access (LSA) investigated in the European Union [4]. Here, the LSA users are permitted to access licensed spectrum based on a set of sharing rules including spectrum usage rights [4]. This allows Quality of Service (QoS) guarantees for both incumbent users and LSA licensees.

A low cost and sustainable network architecture is another essential element to rolling out broadband in hard to reach rural areas. High altitude platforms (HAPs) which are solar powered

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planes that operate at an altitude of 17-22km, can deliver wireless services, without the need for significant and expensive ground based infrastructure [5]. The capture and conversion of solar energy to electricity is becoming widespread, with solar panel conversion efficiencies approaching 30% [6]. Battery technologies are also improving, providing cost effective storage for ground based equipment, and high energy storage per unit mass for specialist applications. Given the advancements in the above key enabling technologies and coupled with new lightweight materials, practical HAP systems are poised to become reality in the near future. According to Transparency Market Research the market for HAPs will exceed US$4.77bn by 2023 [7]. We expect the number of HAPs within 15 years to be 5-10 times the number of civilian passenger aircraft flying today, and 100-200 times the number of satellites, given the developments in progress, the potential applications, and the modest costs of manufacture and operation. Constellations of these HAPs, equipped with wireless technology, will be able to provide localized spot capacity on demand to any part of the service area, making them highly effective in covering regional areas, especially rural areas. There are a number of active and well-funded research projects in the HAP area, most notably Google's Skybender and Facebook's Aquila that are both developing solar powered aircraft. Also, Thales Alenia Space is developing the Stratobus airship HAP, and Airbus' Zephyr aircraft has been operating for several years with its limited payload capability [8].

In this article, we describe a low cost and fully sustainable wireless communication system for hard to reach tropical rural areas, delivered from a meshed network of solar powered HAPs and terrestrial base stations. Nigeria is the case study country, although the proposed architecture could be equally applicable in other tropical countries. Innovative application of TVWS and shared cellular spectrum delivered from HAPs is introduced for connections to the users. The article also discusses how a high availability system can be potentially developed by exploiting spatial diversity when millimeter wave (mm-wave) bands and Free Space Optical (FSO) are used for HAP to ground backhaul links, despite rain outages and heavy cloud in tropical countries, which tend to create unreliable links.

NIGERIA HAP SYSTEM MOTIVATION AND BACKGROUND

ECONOMIC AND SOCIAL IMPACT OF BROADBAND EXPANSION IN NIGERIA

Ubiquitous access to mobile and broadband services by all citizens is identified by the Nigerian Government as important to national economic growth. Studies have shown that 10% increase in mobile penetration can increase the Gross Domestic Product (GDP) growth rate and Total Factor Productivity (TFP) in Nigeria in the long run by 2.8% and 4.2% respectively [1]. Internet access will allow local communities to establish online businesses, improve work efficiency, and understand wider business market, thereby creating wealth. For example Fig. 1 shows four villages (Inisa Titi, Aato, Ijimoba, Osinmo) located in Ejigbo South Local Council Development Area (LCDA) of Osun State in Nigeria where the primary occupation of the inhabitants is farming. The communities suffer from limited and unstable mobile 2G/EDGE services. A specific relevant application of broadband and 5G access to such communities is to provide farmers with access to weather forecasts and crop prices that can help them improve crop yield and sales respectively. Furthermore, rural dwellers will be able to participate in government e-agriculture endeavors, e.g. the Agricultural Transformation Agenda which has been used for the distribution of seeds and fertilizers directly to farmers through vouchers sent to their mobile phones. This will directly impact food production and lead to improved earnings for the farmers. Over time new technology more reliant on precision farming methods can be adopted (e.g. efficient application of nutrients, water and seeds based on site-specific soil conditions).

5G and broadband can also enable more effective delivery of public services and support social development. For example, affordable broadband and 5G will provide access to expert medical professionals and the police through mobile tools. Mobile phone based health initiatives, such as mHealth which has been used to manage antenatal visits in rural areas of Nigeria, will improve health services, and deliver healthier communities. In addition, broadband access can improve learning through access to the vast educational resources on the internet.

CURRENT TELECOMMUNICATION STATE IN NIGERIA

Although Nigeria has over 9 Terabits/s of capacity via submarine cable landings on the shores of Lagos, this capacity has not been effectively distributed, especially to rural areas. In 2013, the Nigerian Universal Service Provision Fund (USPF) carried out a study to identify parts of the country that have limited or no access to telecommunication services. It showed that an estimated 36.8 million people receive very poor mobile services or none at all in underserved/unserved rural areas of the country [9]. According to the Nigerian Communication Commission (NCC), the number of base stations nationwide was 30,176 at the end of 2014 [10]. However, 60,000 base stations in total are needed in order to fill the coverage gap and solve the issue of poor network performance. One of the fundamental challenges of adoption of mobile and broadband technology in Nigeria is the associated high cost. Apart from high installation costs, frequent vandalism of the telecommunication infrastructure also discourages potential investments. Besides, the operators are constrained by heavy taxes and multiple regulations set by federal, state and local government [1]. Unreliable power supply is another limiting factor. This situation has forced the mobile operators to resort to alternative power sources. Diesel generators are often used to provide power for terrestrial base stations. They represent a significant proportion of the overall capital expenditure and operational costs.

Fig. 1. Case Study Area: Ejigbo South LCDA Osun State, Nigeria

HAP-Terrestrial Mesh Network

HAP-Terrestrial network architecture

To address the above deployment challenges, innovative technologies and radical changes to the network architecture are needed to deliver low cost and reliable broadband in rural areas. In Fig. 2, a high-level view of the proposed HAP-Terrestrial mesh network architecture and key design aspects are illustrated. Here, three types of communication links are considered:

- Direct *UE-Terrestrial Node* (TNd) and *UE-HAP* access links,
- *HAP-TNd* and *HAP-Core* wireless backhaul links,
- *HAP-HAP* wireless backhaul links, also known as inter-platform links (IPL).

The capacity requirement for these different types of links is heavily dependent on the applications. Wireless sensors and voice services are typically low data rate (from several kilobits per second), whereas High Definition (HD) videos require a considerably higher data rate (e.g., 20 Mb/s for 4K videos), and dozens of gigabits per second may be needed for a wireless backhaul link. In terms of spectrum for HAP based communications, the access network (*UE-HAP*) could reuse the existing licensed bands owned by the operators, or TVWS as a low cost and wide coverage alternative. Dedicated mm-wave or FSO links could be used for high capacity wireless backhaul (*HAP-TNd*, *HAP-Core* and *HAP-HAP*). With solar powered HAPs, this is a truly sustainable system. Furthermore, the limited infrastructure required on the ground makes it highly resilient to disasters and attacks. Finally, the ability of rapid deployment and quick scaling with demand, and its potentially very low cost per unit area served, makes this meshed method ideal for unserved and underserved areas.

Use cases

- **Ubiquitous coverage**: the delivery of wireless coverage can solely rely on a meshed network of solar powered HAPs in the situation where terrestrial infrastructure is not available. Here, at least one of the HAPs can connect to the core network on the ground via mm-wave or FSO. Providing broadband services to remote rural communities and communicating with wireless sensors distributed across a large area are typical applications for this scenario.
- **Highly reliable connections**: the HAP system can assist the existing terrestrial base stations to improve network resilience and maintain an acceptable level of QoS. This is well suited to the power outage and natural disaster scenarios. HAPs can also be deployed to offload the traffic burden from terrestrial infrastructure in order to provide consistent user experience. Furthermore, the backhaul availability could be significantly improved with the diversity built into the system.
- **Energy efficient network:** with the dynamic constellation of HAPs and advanced beamforming technology, it is possible to switch off/deactivate part of the network to save energy during low traffic periods. The remaining active HAPs could adjust the antenna beams to serve a wider coverage area.

Design Considerations

Different architectures have been proposed for HAP systems, to deliver continuous coverage and capacity enhancement [5]. The deployment strategies need to take the local environment and

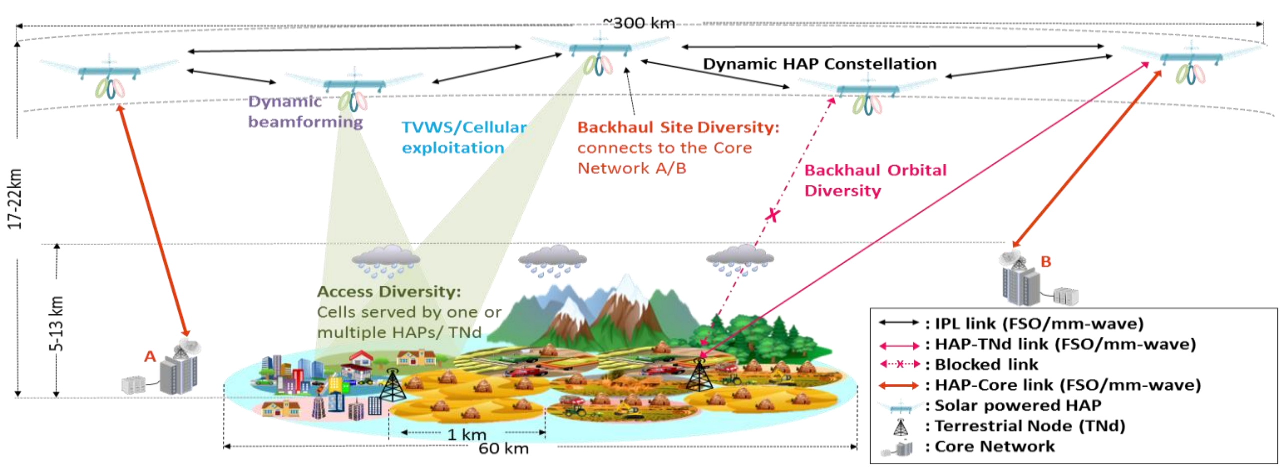

Fig. 2 Integrated HAP-Terrestrial Mesh Network Infrastructure

economic implications into consideration. The main design considerations for the proposed architecture are described below.

LINK OUTAGE

Mm-wave in bands 31/28 GHz and 47/48 GHz (licensed for HAPs), and FSO are very promising line-of-sight (LoS) solutions for wireless backhaul as well as localized access network, as the antennas are likely to be more compact and can generate highly directional beams which substantially reduce interference. However, in tropical countries like Nigeria, link outages need to be carefully considered when designing the HAP backhaul system to ensure high reliability. Link outage of mm-wave band and FSO are caused primarily by rain attenuation and heavy cloud respectively. In tropical countries, conventional wisdom suggests that such links cannot be used in practice due to the heavy and frequent rainfalls. An approximate link outage can be readily calculated by ITU-R PN.837, and is in excess of 30 dB for a link outage of 99.9% from a HAP at the edge of a 30 km radius coverage [11]. Spatial correlation of rain events for mm-wave and cloud for FSO are typically 30 km and 1000 km respectively [12] [13]. In addition to weather based attenuation, the communication links may also suffer from outages arising from interference and unreliable energy sources.

However, it is the overall system rather than link performance that is of interest here. The margins added to individual links can be reduced by 10-20 dB with just one alternative HAP and terrestrial site. Thus, a meshed network of HAPs could feasibly create the diversity necessary to deliver the required system availability. Key to this would be the exploitation of diversity that is underpinned by the mesh network of HAPs connected via the mm-wave/FSO inter-platform links (inter-platform links sit well above the clouds, which tend to be located in the first 5 km of the atmosphere). Three types of diversity could be of use here, including *Access Diversity*, *Backhaul Orbital Diversity* and *Backhaul Site Diversity* as illustrated in Fig. 2. In previous work on combating rain attenuation, site diversity (a cell served by two or more terrestrial base stations) and orbital diversity (a cell served by two or more HAPs) for an access network are considered [5] [12]. However for remote areas with limited terrestrial telecommunication infrastructure, site diversity may not even exist in this case. Instead, we use *Access Diversity* to describe a cell that can be served by at least two access nodes (either HAPs or TNds or a combination of both). Besides, the availability of backhaul is of equal importance for a network with highly dynamic topology. Therefore, sufficient backhaul diversity consisting of *Backhaul Orbital Diversity* (in a two-tier system, a terrestrial access node can connect to the core network via different HAPs) and *Backhaul Site Diversity* (employing multiple spatially separated HAPs to form a mesh network from which at least one HAP is able to connect to the core network) is needed to ensure that traffic is backhauled to the core network. The aim is to deploy a fully self-sustainable HAP-terrestrial mesh network to provide 5G and broadband access. Although each individual link may have low reliability due to weather based outage or replacement/maintenance issues, together, there can be sufficient access/backhaul to deliver a highly reliable network.

ENERGY CONSUMPTION

Although high reliability and capacity can be achieved by building sufficient redundancy into the system, such network requires higher energy consumption, which is another major concern of the telecommunication industry in Nigeria. Diesel generators are often used to provide power for terrestrial base stations and make up a significant cost of an overall deployment. Replacing diesel generators with solar panels coupled with batteries has the potential to significantly reduce costs and prolong the flight time of the HAPs. Solar panels are multiple times more effective at high altitudes (above 5 km), where the sun beams travel through less air mass and are not obstructed by the clouds, compared with ground deployments. For example, solar panels in conjunction with rechargeable batteries are a crucial component of Facebook’s Aquila project, where the current aim is to achieve continuous flight in the stratosphere, consuming 5 kW of power, for up to 90 days at a time [8]. The same solar energy approach is also at the heart of Google’s Loon project, with one of their test flights lasting 187 days in the stratosphere [8]. In order to build a telecommunication system heavily reliant on solar powered HAPs, the energy sustainability and efficiency of the overall HAP-terrestrial infrastructure need to be analyzed. This includes the replacement interval of HAPs and detailed energy consumption model.

TELEVISION WHITE SPACE

In many countries, including Nigeria, TVWS is free for secondary use making it a low cost solution for data provision. It could be flexibly exploited alongside cellular bands in rural areas. However, there are also additional challenges associated with the use of TVWS spectrum. The available frequency bands need to be identified to ensure the coexistence of the primary and secondary systems. For example, a geo-spatial approach is proposed in [2] to quantify the available TVWS in Nigeria. Since the channel allocation for TV broadcasting in developing countries is fairly stable, it is sensible to use a static or semi-static database to maintain channel usage information. Interference management is another important aspect in developing a TVWS based access network. Unlike terrestrial cellular bands, TVWS bands have strict sharing criteria with the primary user (TV system). Assuming multi-element phased array antennas on the HAP, it is possible to control the coordination distances and the antenna beamforming characteristics required to control the interference from HAP to terrestrial base stations. Approximately 200 array elements could be deployed for TVWS bands (assuming half-wavelength spacing) in a 3m diameter antenna array. Given the size of HAPs (wingspan 30–60 meters), larger arrays could be deployed with additional elements, given the large surface area available on the HAP, e.g. beneath the wings [8]. It is possible through antenna beam shaping on the HAPs to tightly control interference, such that the rate of power roll-off from the center of the beam is significantly faster out of the cell than with terrestrial system. Of critical importance will be how to control the position of HAP, beam size and shape, and how such beams will coexist with terrestrial systems, including those terrestrial base stations that form the HAP-terrestrial system.

RESOURCE MANAGEMENT

Linking all of the above individual aspects together requires effective network spectrum and topology control, taking into account the instantaneous and forecast spatial-temporal requirements for capacity demand, weather conditions, available power, HAP availability, and interference mitigation. Intelligent algorithms can be used to control the HAP positions, and the positions and shapes of individual beams on the ground, to make best use of available frequency resources and satisfy user demands. This is especially challenging as the control mechanism for this type of architecture will be partially distributed due to the highly dynamic nature and the lack of fixed backhaul. As a result, the coordination among neighboring HAPs introduces increased signaling overhead and latency. To tackle this issue, novel intelligent techniques such as machine learning (ML) based algorithms can be employed to improve the robustness of the network as well as reduce the signaling exchange. For example, reinforcement learning (RL) is a sub-area of machine learning (ML) which has been extensively applied to dynamic spectrum access (DSA). The objective is to find solutions with the most accumulated reward by trial-and-error. For example in [14], a case-based RL algorithm was developed for dynamic spectrum assignment in wireless networks with dynamic topologies. Transfer learning is another relevant emerging ML technique. The aim is to accelerate the learning process in a new task by leveraging the knowledge already obtained from a similar task. In [15], a transfer learning scheme for resource management in multi-hop backhaul networks was proposed to reduce the coordination information flow and improve system QoS.

CONCLUSIONS

In this article, a novel network architecture has been proposed to deliver low cost, high availability broadband in tropical rural areas, delivered from a meshed network of solar powered HAPs and terrestrial base stations. It is anticipated that the mesh configuration could dynamically control the nodes used to cope with variable link availability caused by weather based outages and unreliable energy sources. The key is to exploit the diversity that is underpinned by the mesh network of HAPs linked via the mm-wave/FSO inter-platform links. Innovative application of TVWS and shared cellular spectrum delivered from HAPs is introduced for connections to the users. This article also discusses the resource management challenges and possible solutions (e.g. machine learning techniques) to improve the robustness of the network and reduce the signaling overhead.

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BIOGRAPHIES

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