Implementing Solar-Powered HAPS for Rural broadband Connectivity: Concepts, Challenges & Mitigation

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Abstract—This paper examines the implementation of solar-powered High Altitude Platform Stations (HAPS) for rural broadband connectivity. It outlines some technical considerations and concepts associated with implementing HAPS as a communications infrastructure. To realise the potentials of solar HAPS for rural broadband connectivity, some key technology, business and policy questions must be addressed. For instance, to meet service demands, the solar-HAPS platform must remain aloft for long periods without running out of power (endurance), which is a technology challenge. Also relevant are non-technology issues like fitness-for-purpose and business viability, which are often overshadowed by technology problems but yet consequential. An aggregation and analysis of these implementation concepts may be helpful for both technology and policy decisions in the bid to address rural connectivity gaps.

I. Introduction

Rural broadband connectivity is a critical element needed to extend the digital economy to the unserved or underserved regions of the world. According to some estimates about 750 million people are currently not able to connect to any kind of broadband network; another 3.3. billion though within coverage of mobile broadband cannot use the internet [1]. An International Telecommunications Union (ITU) report estimates that only 53.6% of the global population are using the internet, and about 86.6% of these live in developed countries while only an alarming 19.1 % of people in least developed countries (LDCs) use the internet [2]. This clearly shows the profound nature of the 'broadband divide' especially in Sub-Saharan Africa and South Asia. It is therefore imperative to explore innovative and cost effective means of providing broadband coverage to these rural and remote locations.

Traditionally, communications connectivity is provided using terrestrial or satellite based infrastructure. These infrastructure options have both technical and economic costs which make them expensive to deploy. Investors make investment decisions based on return on investment (ROI), and will not deploy these infrastructure if the business case is not justifiable. Deploying communications infrastructure in rural or remote locations attract higher investment costs due to population density, topography and other related considerations. Some rural and remote locations have significantly impossible terrain which will attract huge engineering and logistical costs. All considered, underserved or unserved populations continue to experience lack of broadband access and consequently alienated from the digital ecosystem.

However, an alternative infrastructure option with the potentials of providing easily accessible broadband is being researched and experimented on. These potentially novel infrastructure options are called High Altitude Platform Station (HAPS) which are essentially aerial vehicles located at an altitude of 20 to 50Km [3] from the earth's surface well above civilian aviation

Fig. 1. Stratobus HAPS (Airship) by Thales Alenia

Fig. 2. Loon HAPS (Balloons)

traffic. HAPS can be implemented in a variety of forms either as lighter than air (LTA) platforms e.g. balloons or airships (see figures 1 & 2); or as heavier than air (HTA) platforms like fixed-wing aircraft (see figure 3). Whatever the form, the potentials of using HAPS to beam broadband internet in the rural areas has received attention from governments, industry and academia [4]. For instance, the likes of Google, Airbus, Facebook, HAPSMobile, BAE and several others are exploring this innovative way of providing connectivity using HAPS.

In this paper, section I gives an overview of rural broadband connectivity gaps and available connectivity options like the HAPS infrastructure. Section II describes various implementation concepts like endurance, energy management and various challenges limiting the potentials of solar-HAPS; while section III explains the benchmarks and relevant technical and non-technical considerations for HAPS use case. Section IV, details the empirical considerations for establishing HAPS ideal implementation scenario. In section V, the futuristic concept of deploying multiple fixed-wing solar-HAPS network is discussed. Finally, section VI draws conclusions on the work and considers future work.

II. Solar HAPS Endurance & Energy Management Algorithms

The potentials attributable to HAPS for rural connectivity are significant but there are challenges hindering its commercial implementation and adoption. These challenges largely have to do with its endurance i.e ability to remain airborne for a reasonable length of time without refuelling. Solar-powered HAPS make use of the energy from the sun to power its operations. Solar is a cheap and clean source of energy but solar panel efficiency and battery technology are still lagging in terms of expected capabilities. The world record for solar conversion efficiencies held by Alta Devices for their gallium arsenide (GaAs) solution (very light weight material tailored for solar-HAPS), is about 29.1% for single junction cells and 31.6% for double junction cells [5]. Leading battery technology by Sion Power Corporation has specific energy of about 500Wh/kg for lithium metal types, an improve-ment from 350Wh/kg for lithium sulphur (Li-S) used in Airbus Zephyr [6]. This technical reality puts a limitation on the endurance of the solar-powered HAPS. The longest record of solar-HAPS endurance is held by Airbus's Zephyr S HAPS model which remained airborne for 25 days [7]. Implementing efficient energy management algorithms may significantly improve the endurance of solar-HAPS inspite of limitations in battery technology and solar panel efficiency.

Fig. 3. Zephyr HAPS by Airbus

However, not many publications have addressed energy management algorithms precisely as conceived by this paper for high altitude platforms. Moreover a few industry HAPS projects like Airbus's Zephyr which has recorded some level of success in this regard do not have publicly available information on its energy management techniques. Energy management algorithms that can keep solar HAPS platform airborne for months or years will be regarded a significant technological breakthrough. It must be mentioned however, that not all approaches focus on the energy management algorithms as the main element for endurance. The conventional approach is to keep seeking out incremental improvements in battery technology and solar panel efficiency as the main factors for extending endurance. Improvements in these technologies are also expected to include better size, weight and power (SWAP) profiles. While this is a technically sound approach to explore, these improvements are still far from reaching expected levels needed for sustained long endurance. In all technical considerations the level of insolation possible at different times of the day, year or part of the hemisphere are constraints that must be considered as well [8]. So the complexity of achieving the level of endurance needed for solar HAPS within all the constraints mentioned is significant.

Hwang et al [9], proposed a design framework for high altitude long endurance solar unmanned aerial vehicles with the aim of aiding solar aircraft designs. The framework did not consider energy management algorithms but highlighted integrating essential technologies like light, high efficiency solar conversion and storage devices, ultra-light-weight airframe materials as critical for solar aircraft. However, Zhang et al [10], considered the use of fuzzy state machine (FSM) as an energy management strategy to control power flow. In this design a hybrid electric aerial vehicle using photovoltaic, fuel cell and battery was considered and does not fit the operational framework of the strictly solar aircraft under consideration. The optimisation and restructuring of the mission profile configuration was proposed by Rajendran et al [11]. This approach emphasises the need to follow optimal paths that will maximise the energy from the sun, however, this method did not consider any specific use case. Its mission profile strategy was limited to the cruise, ascent and descent phases which does not consider any specific service scenario like using HAPS to beam broadband signals. In such scenarios, the mission profile alone does not completely define the power or energy requirement of the mission; the entire service segment (payload etc.) has to be considered as well. Amorosi et al [11], proposed a method where the energy consumption for a rural cellular network could be managed by using a combination of UAV and terrestrial networks powered by solar panels and batteries to balance the energy requirements. The technique is based on the design where high level tasks like baseband processing and handovers are carried out by terrestrial base stations while low level functions are carried out by hardware hosted on the UAV. This method however, differs from the unique case considered in this paper where only aerial vehicles are considered, moreover this approach assumes the availability of a terrestrial network which may not be the case. A rules-based energy management system was proposed by Anicho et al [8], this approach relies on constantly monitoring the level of solar power available and switching to back-up batteries when required. In certain scenarios especially during night time phases of the mission it could trigger gliding manoeuvre to further conserve energy. During such extreme scenarios, the energy management algorithm ensures that power and payload systems are shut down. These extreme measures put platform endurance at the highest priority (after flight safety and security) in order to push the platform into the next cycle of sunlight. Regardless of the approach, the main requirement is to ensure that the HAPS platform remains aloft to keep providing connectivity for months and years; though still a distant but necessary milestone.

III. Analysis of HAPS Ideal Implementation Scenario

This section examines HAPS ideal implementation scenario especially in relations to satellite and terrestrial systems. It attempts to establish that HAPS has a unique implementation gap it is designed to fill. This gap can be shown to be a function of subscriber density and practical footprint area. Designers, technical analysts and decision makers can explore this benchmark to decide when HAPS is the best wireless infrastructure solution for the use case. Subscriber or user density benchmarks is explored to determine which technology solution best satisfies a viable business case. It also provides key technical parameters to benchmark all three technologies, HAPS, terrestrial and satellite systems. It further provides empirical considerations to define the ideal HAPS implementation scenario with respect to terrestrial and satellite systems.

It is important to define the parameters with which to benchmark the different systems. This will enable easier comparisons and establish empirical considerations for justifying conclusions. The benchmarks to be analysed are both technical and non-technical elements like footprint, system capacity, subscriber density and system cost which does have significant impact on choice of solutions.

A. Area of Footprint

The footprint defines the service area or coverage of the system on the surface of the earth [12]. It is possible to divide the footprint into smaller cells or spot beams for better frequency utilisation. Using circular footprint configuration under certain simplifying assumptions like neglecting the variation in received power density, the footprint of a geostationary (GEO) satellite orbiting at an altitude of about 36500 Km above the equator line will cover a third of the earth's surface with a footprint size of 8000 Km radius, while a low earth orbit (LEO) satellite at 1000 Km has a coverage of 2500 Km radius [13]. In contrast, a HAPS platform at 22 km with 5-10 degrees elevation angle has about 65 Km radius while a terrestrial base station can cover a range up to 30 Km radius [12], [13]. The circular footprint areas are summarised in the table below and will be used for further analysis within the work.

B. System Capacity

In this regard system capacity will be defined by the power configuration or consumption dimension of the system. For instance, current GEO satellite systems are rated at about 5kW with 100-200 spots [14], a metric to define the system capacity. Terrestrial systems have defined power capacity depending on cell size or

TABLE I
Circular Footprint Area by Technology

	Diameter (km)	Footprint Area (km^2)
Satellite spot beam	1300	1330000
HAPS footprint	130	13300
Terrestrial network	40	1300

configuration. A macro cell can have an installed system capacity of about 1kW, depending on number of sectors while micro cells have lower power configurations [15]. In the case of HAPS, power dimensioning can vary depending on the type of HAPS platform under consideration. For the purpose of this analysis a solar powered fixed wing HAPS will be considered. Typical power capacity for such HAPS may be within the region of 0.5 - 10kW or more depending on solar panel surface area [16]. The significance of the system capacity in terms of power rating is very crucial to determining communications payload configuration and number of users that can be serviced by any instance of technology deployed.

C. Subscriber Density

Subscriber density defines the number of subscribers per square kilometer of a geographical area. This is a critical matrix to estimate the user concentration within a region. The density of subscribers can be conveniently estimated by population distribution statistics within the specified geographic area. The global population distribution which is accessible from the Center for International Earth Science Information (CIESIN) can be used to estimate population distribution of any particular area globally. Dong et al proposed a user demand model for HAPS based primarily on population density [12]. However, in this work the subscriber density is further considered a function of the footprint area and used as an indicator parameter. This indicator becomes the primary basis for defining suitability of deploying any of the technologies and for specifically showing the ideal HAPS use case. It is already standard operating procedure in terrestrial network planning to use population density, mobility patterns and propagation environment to plan cellular networks and to determine size, type and location of base stations. Clearly urban propagation environment, population density and traffic and mobility patterns differ significantly from a rural one. Terrestrial and Satellite network projects already capture these factors in justifying business case, cost benefit or ROI analysis. In this work similar parameter will be proposed to facilitate empirical validation of the exact use cases for HAPS deployment. This may further clarify HAPS status as a complimentary technology with respect to terrestrial and satellite systems.

D. System Cost

The deployment of any type of technology has a cost component to it and will directly affect the sustainability of the technology. Only the capital expenditure (CAPEX) or initial deployment cost of the technologies are considered in this paper. Operational cost considerations are quite relevant but not covered within the scope of this analysis and may vary significantly depending on specific deployment scenarios. Satellites are by far the communications infrastructure option with the highest initial deployment cost. For instance GEO satellites can cost any where between 200-300 million dollars from design to launch, which is a substantial investment [16]. HAPS platforms are currently valued between 1-3 million dollars, about three orders of magnitude lower than GEO or even LEO satellite constellations which cost billions of dollars [16]. However, with terrestrial systems, the cost varies depending on scope of project in terms of geographical reach and terrain. With terrestrial systems the scope and investment for infrastructure is significant and has to be confirmed commercially viable before initiation. One way of determining this of course is by the subscriber density. In urban regions like cities and towns, terrestrial infrastructure is considered a viable option as the subscriber density supports the business case for significant investments. This huge investment cost without corresponding justifiable subscriber market is one factor inhibiting the availability of terrestrial infrastructure in rural and remote locations, in addition to difficult terrains which also increases cost. This work proposes to identify the thresholds for which HAPS emerges the best communications infrastructure option over terrestrial or satellite.

IV. Empirical Analysis of HAPS Use Case

A comparison between the technologies can be made by considering the number of data subscribers that could be supported by one instance of each technology and the size of the representative footprints for that technology. For the purpose of comparison it will be assumed that the systems are populated by hypothetical subscribers that require a 500 kbit/s continuous service. This rate represents a typical rate for mobile subscribers, and an upper limit for mobile satellite systems.

A. Assumptions and Methodology

In this sub-section, the empirical methodology for the comparison is explained in some detail to provide insight for the thresholds proposed.

A mean data rate S, 0.5 Mbps is assumed for this calculation but can be more in typical application scenarios, but this value suffices. The area of the footprints A, in km^2 is derived from the radius of each footprint as already explained. With the available information, the maximum number of subscribers that can covered by each technology based on the practical system payload capacity can be derived.

Terrestrial networks are well suited to urban and suburban regions where the subscriber density is high, and along main roads in rural regions. Rural macrocells tend to set a lower limit to the population density that can be supported by terrestrial systems. This essentially determines a minimum threshold, typically this is about 10^{-2} subscribers per km^2.

In very sparsely populated regions, for example deserts, terrestrial infrastructure is not cost-effective so broadband satellite services are used [17]. The high gain satellite beams required to satisfy the satellite link budget have footprints of about 1000km diameter. These small footprints, and downlink power limits, set an upper bound to the subscriber density that can be supported of about 10^{-5} subscribers per km^2.

Regions that have population densities between 10^{-2} and 10^{-5} subscribers per km^2 are challenging to both terrestrial and satellite planners. They represent rural areas where the population is very low, for example hill farming communities. The business case for providing terrestrial coverage needs to be strong to justify the provision of infrastructure. With satellite systems the challenge is to provide very stable and narrow beams that offer a high enough power to support a larger subscriber population. It is this area where HAPS could be capable of providing a usable service.

Table II shows the typical subscriber densities for each technology and illustrates the gap between the lower limits of terrestrial systems and the upper limits of satellite systems.

TABLE II
Communications role for HAPS

	Typical Values		
	Diameter (km)	Min Subscribers per km^2	Max Subscribers per km^2
Satellite spot beam	1300	10^{-7}	10^{-5}
HAPS footprint	130	10^{-5}	10^{-2}
Terrestrial network	40	10^{-2}	10^{4}

It can be seen from Table II that HAPS could be used to support regions where the population density is too sparse for terrestrial systems, but too dense for satellite systems. This may serve as a useful benchmark to determine what implementation scenarios are most suitable for HAPS as a service option. In emergency scenario, HAPS has a strong case for its deployment both in proactive and reactive situations. However, from the above analysis it is also clear that HAPS uniquely fit into service gaps where either terrestrial or satellite systems cannot be deployed due to weak business cases or non-existent infrastructure like in rural and remote locations.

V. Multiple Solar-HAPS Networks

Implementing a network of solar-HAPS will effectively extend the reach and coverage of such networks for rural connectivity. In the fixed-wing solar-HAPS domain the use of multiple platforms to form a network is still futuristic. The basic configuration of such a network will demand techniques for coordinating all the HAPS in the network to dynamically provide area coverage to fixed and mobile users. The use of manual methods (direct human input) to coordinate such a network will entail considerable operational complexity and cost. Consequently, the authors of this paper have been examining the use of algorithms like Reinforcement Learning (RL) and Swarm Intelligence (SI) to coordinate multiple fixed-wing solar-HAPS for communications coverage [18]. The challenges of coordinating multiple fixed-wing solar-HAPS differ significantly from applications using balloons e.g. Project Loon which uses multiple balloons. The Loon balloons are navigated using predictive models of the winds and autonomous decision-making algorithms while intelligently routing information through the network of balloons [19]. However, for fixed-wing solar-HAPS technology there is no current deployment of multiple HAPS due to the challenging dynamics of the physics of flight and the cost of prototyping such a network. In order to investigate the multiple fixed-wing solar-HAPS problem, a simulation based approach using computer software models is implemented. Next generation multi-HAPS networks are expected to be semi or fully autonomous platforms capable of making high level decisions with minimal or no human input; a significant technological challenge.

VI. Conclusions and Future Work

This paper aims to highlight energy management algorithms as critical for extending the endurance of solar-HAPS especially for rural broadband connectivity. It is also important to define the exact role and best implementation scenario for HAPS as a communications infrastructure option. HAPS have a place in the provision of communications services between the outer edge of terrestrial networks and the sparse populations supported by satellite systems. This corresponds to area where the population density lies between 10^{-2} and 10^{-5} subscribers per km^2. Using this benchmark will enable designers and decision makers validate the case for deploying HAPS especially in the remote and rural areas where the coverage gap is critical and demands urgency.

Future work will keep exploring the concepts articulated in this paper especially effective energy management algorithms for improved endurance. Highlighting the role of HAPS as a strategic communications infrastructure for national and regional governments to address rural broadband connectivity and disaster management is imperative.

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