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Christoffel Kotze

A Broadband Apparatus for Underserviced Remote Communities

Connecting the Unconnected

UNIVERSITY OF CAPE TOWN
IYUNIVESITHI YASEKAPA • UNIVERSITEIT VAN KAAPSTAD

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Preface

We stand on the brink of a technological revolution that will fundamentally alter the way we live, work, and relate to one another. In its scale, scope, and complexity, the transformation will be unlike anything humankind has experienced before.
—Klaus Schwab[1]

Access to broadband Internet is the key to participation in the emerging Fourth Industrial Revolution (4IR), with those on the wrong side of the digital divide automatically excluded. This book investigates how broadband Internet can be provided to remote and isolated communities through the use of satellite and other enabling technologies, in the form of a self-contained broadband apparatus. It discusses how the proposed design can help bridge the digital divide by removing one of the main hurdles to adopting technologies: infrastructure. In turn, the book explores how the lack of infrastructure, especially with regard to connectivity and electricity, can be addressed by exploiting new technological advances in a number of fields, notably the newly proposed large broadband satellite constellations. In closing, it uses concrete examples to demonstrate the potential positive impacts of a "broadband ecosystem" on economics, governance and society, and on achieving the United Nations' Sustainable Development Goals.

Yzerfontein, South Africa — Christoffel Kotze

[1]World Economic Forum. 2016. The Fourth Industrial Revolution: what it means, how to respond https://www.weforum.org/agenda/2016/01/the-fourth-industrial-revolution-what-it-means-and-how-to-respond accessed 18 April 2017.

Introduction

Unlike the three industrial revolutions that preceded it, which followed a linear evolutionary pace, the Fourth Industrial Revolution (4IR) is developing following an exponential path driven by simultaneous rapid breakthroughs in almost all fields of technology, creating a global transformative disruption across virtually every industry. A key characteristic of the 4IR is the creation of cyber-physical systems (Griffor 2017)—the result of the integration of intelligent networks, systems and processes. The key enabler of the 4IR is broadband Internet connectivity.

Currently, almost 3.4 billion people across the globe are not connected to the Internet. Such connectivity is the primary measurement of a twenty-first-century scenario of inequality—that of the "digital haves and have-nots"—commonly referred to as the "digital divide" [2]. Individuals and communities on the wrong side of the digital divide will by default be excluded from partaking in the 4IR and any future benefits, it could bring, exacerbating existing inequalities. A 2014 McKinsey study concluded that a target user will adopt broadband Internet service on the condition that it is readily available, accessible, affordable and applicable—to the community or the individual concerned (Sprague 2014). It, therefore, stands to reason that the entry point for bringing any underserviced community "online" is to ensure, first and foremost, that the infrastructure to support the service is available. The enabling infrastructure needed includes electricity, hardware and communication service to solve the so-called last-mile challenge (Thota 2013). The last-mile challenge is the result of a number of factors, with remoteness and lack of infrastructure typically being the primary barriers to connection. The World Economic Forum cites lack of infrastructure to be the main reason why almost a third of the global population cannot connect to the Internet, with 31% having no 3G coverage and 15% being without electricity, which includes almost a third of sub-Saharan Africa[3]. This study aims to address these challenges by investigating potential

[2]Internet World Stats. 2018. *INTERNET USAGE STATISTICS - The Internet Big Picture, World Internet Users and 2018 Population Stats*. https://www.internetworldstats.com/stats.htm accessed 17 November 2018.

[3]Biggs, P. Ed. 2018. *The State Of Broadband 2018: Broadband Catalyzing Sustainable Development*. First ed. Geneva: UN Broadband Commission.

BARC Logo—Broadband Apparatus for Underserviced Remote Communities

technological solutions to provide access to broadband Internet services in a novel way to remote, isolated communities in the form of Broadband Apparatus for Underserviced Remote Communities (BARC).

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About the Author

Christoffel Kotze established a boutique technology strategic advisory company in 2012 after a successful corporate career spanning two decades. This company specialises in providing assistance to digital transformation projects within organisations, with a special interest in the use of technology resources to support sustainable development. Current research interests include space technology, dematerialisation through digital transformation and solutions to the "digital divide". He is an M.Phil. (Space Science) candidate at the University of Cape Town. Other qualifications include a Bachelor of Commerce with Honours (Information Systems) at the University of Cape Town, Bachelor of Science (Physiology and Microbiology) at the University of Pretoria, Diploma in Datametrics (Computer Science) at the University of South Africa, and a number of strategy-focussed executive management courses at the Graduate School of Business from the University of Cape Town, and also ISACA Certified in the Governance of Enterprise IT (CGEIT) and TOGAF 9 Certified (Enterprise Architecture) —chris@noez.co.za (+27 83 627 9392).

Broadband Access for Remote Un-serviced Communities

Abstract

This chapter starts by exploring the various reasons why currently almost 50% of the global population has no access to broadband internet. The latter part of the chapter discusses some enabling technologies to address this issue.

The world is experiencing one of the greatest revolutions ever, driven by the massive flow of information between billions of information technology users around the world, every second of the day, largely enabled by the convergence of the so called SMACT (Social, Mobile, Analytics, Cloud and Internet of Things) technology cluster in smart devices, currently dominated by the smartphone. This information and communication revolution has significantly lowered the entry barrier to trade, allowing millions of new participants into the market with little more than a smartphone as an "office". The glue holding the whole system together is broadband internet access, which by default becomes the basic requirement for entry into this ecosystem. But, what about the "unconnected masses" who are excluded from participation in this internet-enabled economy? How can they be empowered? What are the possible solutions?

1 The Digital Divide

The US Department of Commerce has defined the "digital divide" as the difference between two groups of technology users; on the one extreme, a group of people with access to the very latest computing hardware, software, content, internet, telephony connectivity, training and skills, as opposed to the other end of the social spectrum, where a group exists with little to no access of any of the "digital

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privileges" of the other group.[1] A more expanded view proposed the concept of "digital inequality", where in addition to inequality of equipment, factors such as the 'autonomy of use', required skills, social support network and purpose of the use of technology are also taken into consideration (DiMaggio 2001).

The reason for the existence of the "digital haves and have-nots" has been studied extensively and causative factors have been found to be a combination of social and spatial factors, e.g. where the person lives, income level, age, education, gender even ethnicity (Warf 2001). However, in a global economy enabled by internet access and at macro level, countries with high levels of digital penetration will find it increasingly difficult to trade with countries with low levels of digital integration at ground level.

Though the availability of broadband infrastructure is still the primary exclusion factor for un-connected communities worldwide, the establishment of the connection alone is however not a guarantee of adoption of internet services. There are a number of additional barriers to overcome before a service will be adopted by a target community. A study by the ITU (International Telecommunication Union) concluded that a target user community will adopt a broadband internet service on condition that the following four primary adoption conditions are met.[2]

- Infrastructure—The physical service needs to be made available to the region in a manner that makes fiscal sense to the service provider.
- Cost—The service needs to be affordable to users within the target area. Currently an estimated 57% of the global population cannot afford the internet.[3]
- Capability—If the basic service is available and affordable to the target population, do they have the means to access the service in terms of skill and ancillary equipment required?
- Relevance—Lastly, if all other conditions are met, how applicable is the use of the service to the target community? If there are no relevant needed services available in the region in the local language, chances are that the target population will not see a benefit.

Figure 1 clearly shows that the affordability of internet services is an issue across all regions. Europe has the fewest barriers of adoption, with only affordability as an issue, whereas the African continent is challenged by all four barriers of adoption.

Adoption barriers for the use of satellite broadband are essentially the same as for terrestrial broadband, however satellite broadband does provide a ready opportunity to at least eliminate the "availability" barrier. With a large rural population—over 63% of the Sub-Saharan population live in rural areas as opposed to

[1]McConnaughey, J.W., Lader, W., Chin, R. and Everette, D. 1998. *Falling through the Net II: New data on the digital divide*. Washington DC: National Telecommunications and Information Administration.

[2]Biggs, P. Ed. 2018. *The State of Broadband 2018: Broadband Catalyzing Sustainable Development*. First ed. Geneva: UN Broadband Commission.

[3]UNCTAD. 2017. *Information Economy Report 2017—Digitalization, Trade and Development.* Geneva: United Nations.

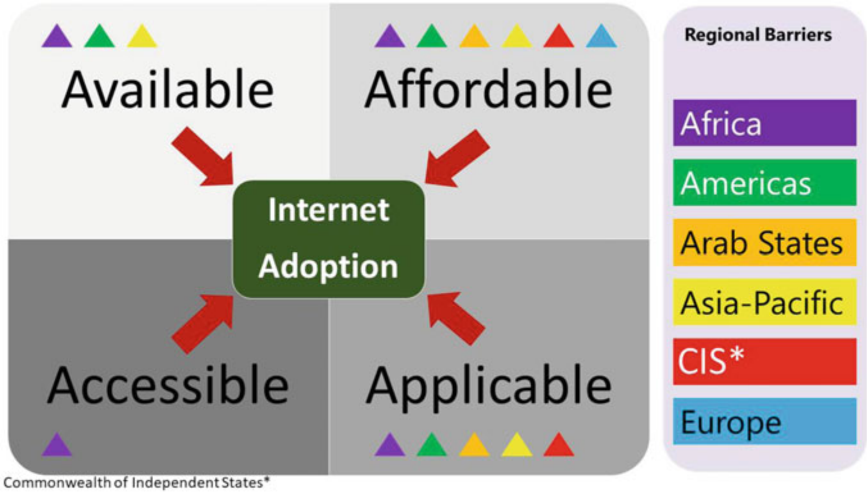

Fig. 1 Barriers to broadband internet adoption (see footnote 6)

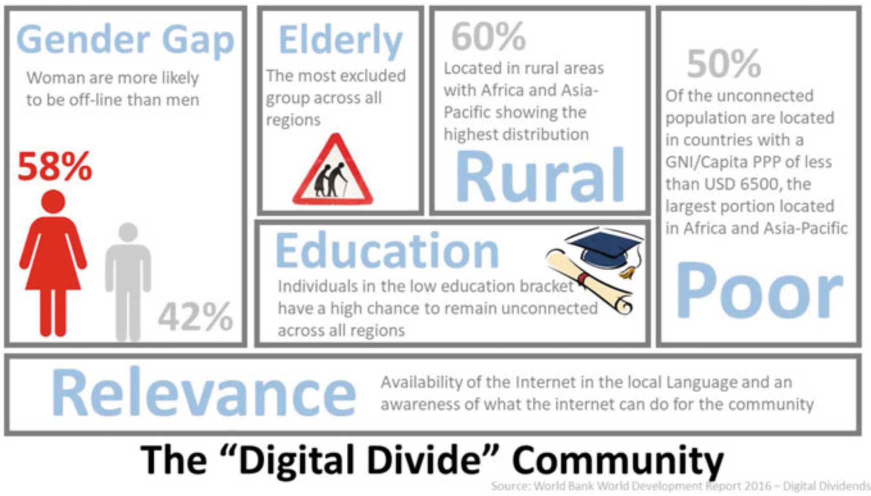

Fig. 2 Profile of the "digital divide" (World Bank. 2016. *Digital Dividends.* (Public 102725). Washington DC: World Bank Group.)

26% in the EU—Africa is well suited for the delivery of satellite broadband to rural communities. Figure 2 describes the typical "digital divide" community, i.e. a poor elderly lady with little to no education, living in rural Africa, has a very high likelihood to be digitally excluded as opposed to a young city dweller in the developed world.

In 2014 Huawei Technologies created the Global Connectivity Index (GCI) to track global digital transformation in 50 countries based on the analysis of 40 indicators. The index groups different nations into three groups—Starters, Adopters and Frontrunners. Designed to provide insights for policymakers tasked with transformation to the digital economy, it has highlighted a disturbing trend, confirming an increasing gap between "Starters" and "Frontrunners". In sociology the "Matthew Effect", a term coined by Robert K. Merton, refers to a situation where advantage propagates further advantage and vice versa—i.e. the rich get richer (Rigney 2010). The 2017 GCI scores show the "Frontrunners" pulling ahead of the "Starters" by a significant margin, exhibiting a "Matthew effect" in connectivity, with the digital divide in fact becoming a "digital chasm". If the lagging nations, typically also the more economically disadvantaged, are not able to play catch-up to the middle group of nations, it will hamper their ability to compete economically.[4] As stated before, the term "digital divide" is a multi-faceted concept involving a bouquet of digital technologies; however the availability of internet and bandwidth (access speed determines the type of content with which a user can engage) is the entry point to the digital economy. Internet access is therefore generally regarded as the "go to" metric to gauge the presence and extent of the digital divide for a specific demographic (Fig. 3).

Africa has the lowest global rate of internet penetration with less than 35% of the total population connected as opposed to North America with more than 90% connected. Bandwidth distribution indicates a bleaker trend, with the gap between the Least Developed Countries and Developed Countries increasing to a factor of 23, as indicated by Fig. 4. Access speed is a key determinant of what type of content a user will be able to engage; the more feature-rich the content, the higher the bandwidth requirement. Low-bandwidth generally creates a secondary level of inequality by preventing users from meaningfully interacting with feature-rich content. A low bandwidth user, typically in a developing country, will be prevented from meaningful access to video-rich content and peer-to-peer interactions, ironically a hallmark of remote education applications such as the typical MOOC (Patru 2016). Globally there has been approximately a sixfold, increase in available bandwidth from 34 Tbps in 2008 to 185 Tbps in 2016.[5] Looking at bandwidth distribution, the picture becomes much skewed. In contrast to the average of 140 kbps per user at the top end of the scale in the developed world, for those at the bottom end in the Least Developed Countries it's only 6 kbps.[6]

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[4]GCI. 2018. *Huawei Global Connectivity Index 2018.* https://www.huawei.com/minisite/gci/en/index.html accessed 14 December 2018.

[5]Internet World Stats. 2018. *INTERNET USAGE STATISTICS—The Internet Big Picture, World Internet Users and 2018 Population Stats*. https://www.internetworldstats.com/stats.htm accessed 17 November 2018.

[6]ITU. 2017. *ICT Facts and Figures 2017.* https://www.itu.int/en/ITU-D/Statistics/Documents/facts/ICTFactsFigures2017.pdf accessed 14 January 2018.

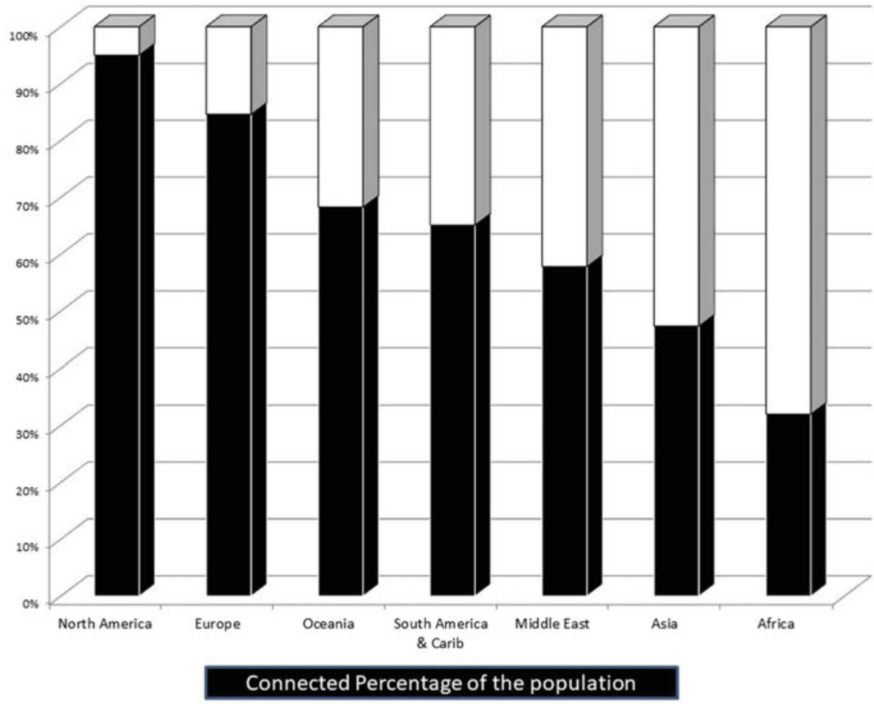

Fig. 3 Global internet connectivity (see footnote 5)

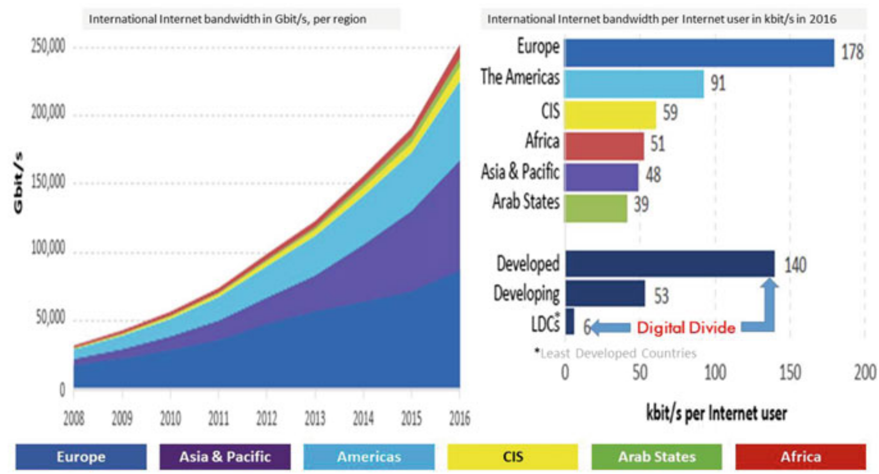

Fig. 4 Global bandwidth distribution (see footnote 7)

On the positive side there has been an almost tenfold increase in available bandwidth from 2008, with the 2016 global aggregate speed almost 250 Tbps. Between 2015 and 2016 alone, global internet bandwidth grew by 32%, with Africa showing the highest regional growth at 72%.[7]

2 Satellite Broadband

On October 4, 1957, the USSR placed the first man-made object into orbit in the form of a man-made satellite called "Sputnik". Whilst the initial use of space technology was largely driven by a politico/ military agenda inspired by the Cold War zeitgeist, the commercial possibilities soon became apparent. The modern satellite industry is classified into four distinct sectors (Table 1), with commercial communication satellites dominating the satellite services industry, representing 35% of all mission types. Eutelsat KA-SAT 9A, a very large HTS (High-Throughput Satellite), placed into Geostationary Equatorial Orbit (GEO) in late 2010, and could be considered the first dedicated broadband satellite.[8] Using spot beam technology, it offered users high-speed internet access with downlink speed of up to 20 Mbps and a potential uplink speed of 6 Mbps. Spot beam technology deploys a conus "beam" to a specific geographical area, which allows for local channels for a defined target area by using signal scrambling that allows the re-use of the frequency spectrum to increase capacity (Reudink 1978). Though the current

Table 1 The satellite industry sector classification[a]

Satellite industry		
Sector	Application	Revenue
Launch	Getting a space craft off the ground into orbit	USD 5.5 billion
Satellite manufacturing	Design and build satellites	USD 13.9 billion
Ground services	Consumer Equipment—Satellite TV, radio, and broadband equipment etc. Network Equipment—Gateways, VSAT, NOC & SNG	USD 113.4 billion
Satellite services	Telecommunications, PNT, Earth Observation, Science, National Security	USD 127.7 billion

[a]Mueller, D. 2017. *What Are the Uses of Direct Current? 25 April 2017. (accessed February 16, 2018).* https://sciencing.com/uses-direct-current-7394786.html accessed 16 February 2018.

[7]Albulet, M. 2017. *FCC Application Technical Document - "SPACEX V-BAND NON-GEOSTATIONARY SATELLITE SYSTEM - ATTACHMENT A TECHNICAL INFORMATION TO SUPPLEMENT SCHEDULES."*. https://www.ucsusa.org/nuclear-weapons/space-weapons/satellite-database?#.XEBRb81S_IU accessed 21 July 2017.

[8]Howell, D. 2015. https://www.techradar.com/news/internet/broadband/satellite-broadband-what-you-need-to-know-1151205 *(accessed April 14, 2017).* https://www.techradar.com/news/internet/broadband/satellite-broadband-what-you-need-to-know-1151205 accessed 14 April 2017.

contribution of satellite broadband is the lowest of the sector, it is growing with a subscriber base that approached two million in 2016.[9] Further growth is driven by increased adoption of converged technology such as high resolution (4K& UHD) "Smart TV" and the increasing use of broadband based streaming services such as Netflix.

The broadband satellite industry is undergoing significant technological innovation, most notably via new development of High Throughput Satellites in lower MEO (Medium Earth Orbit) and LEO (Low Earth Orbit) orbits. Reducing latency and increasing bandwidth whilst at the same time driving down costs, is making satellite broadband the "go-to" technology to connect the "un-connected". Consumer confidence has also improved to a significant extent, with satellite broadband operators competing well against terrestrial providers in two performance categories, namely "best peak offerings" such as xDSL and fibre in terms of the speed to price ratio with the added ability to introduce broadband in areas not serviced by any terrestrial service.[10] Latency issues are still problematic for certain applications, but non-GSO systems are offering a potential solution in problem application areas.

Currently the broadband segment is well poised for growth, having already recorded a significant (50%) revenue growth over the initial 5 year period and "delivering on advertised performance" according to the FCC's latest State of Broadband Report.[11] The market already has at least five major systems currently available: Eutelsat Tooway, HughesNet, Inmarsat Global Xpress, SES-O3b, and ViaSat Exede. Additionally, a number of major projects have been announced that will add significant additional bandwidth in the short and medium term. ViaSat in conjunction with Boeing has announced the ViaSat3 program, an example of an extreme high throughput broadband satellite system. This three-satellite constellation will provide global coverage through the deployment of three geostationary 'ViaSat3' high capacity satellites, each capable exceeding one Tbps of network capacity.[12] At the time of the announcement in 2016, the company stated that each of the three satellites will add more bandwidth than the cumulative capacity of all the operational telecommunications satellites at the time. The first satellite is scheduled for launch in 2019. SES has also announced a planned expansion to their current global O3B offering to form a system called "O3B-POWER" claiming that it will "better" the ViaSat-3 output by 300% once fully operational translating into a significant amount of satellite bandwidth available for connectivity use.[13]

[9]State of the Satellite Industry. 2017. *State of the Satellite Industry Report June 2017.* Washington D.C.: Satellite Industry Association.

[10]See footnote 6.

[11]FCC. 2018. *2018 Broadband Deployment Report.* (Broadband Progress Report). Washignton, DC: FCC.

[12]Henry, C. 2016. *Dankberg: ViaSat 3 Satellite Will Have More Capacity than the Rest of the World Combined.* https://www.satellitetoday.com//telecom/2016/02/10/dankberg-viasat-3-satellites-will-have-more-capacity-than-the-rest-of-the-world-combined accessed 2016.

[13]Henry, C. 2017. Generation of O3b satellites that will have more than triple the capacity of ViaSat's future ViaSat-3 constellation. *SpaceNews* 11 September. https://spacenews.com/ses-building-a-10-terabit-o3b-mpower-constellation/ accessed 3 December.

In addition to the expansion of existing systems, there have been a number of "mega constellations" announced by Boeing, OneWeb and SpaceX. Frequency applications by the three companies at the FCC indicate a total of almost 16,000 broadband satellites if all were to be deployed. To put this figure into perspective according to the current Union of Concerned Scientists satellite database, as of November 2018 there were 1957 operational satellites in orbit, of which most were communication satellites, a figure dwarfed by the application of 3000 satellites for Boeing alone and more than 11,000 for SpaceX.[14] These very large constellations all feature a blend of technologies featuring "mixed" orbits, multiple frequency bands and small footprint "steerable" user-terminal antennae.[15]

3 The "Last-Mile"

Last-mile is a figurative term used in the telecommunications sector referring to the link between the telecoms infrastructure in place and the end user. It has nothing to do with physical distance, which could be very short, as in the link from a telephone pole to a house, or thousands of miles in the case of a satellite link. For a large portion of the global population, bridging the "Last-Mile" remains the principal problem preventing the provision of broadband internet services. The more remote the area, the higher the likelihood of no connection, as putting down physical cable infrastructure such as fibre optics is impractical or not even possible normally due to cost, accessibility and/or maintenance issues. There are a number of ways to connect the "Last-Mile". These are normally deployed in a "fit-for-form" fashion depending on the nature of the last mile customer location, guided by the 3A's: availability, accessibility and importantly affordability. The internet service provider (ISP) as a commercial enterprise will typically not deploy to an area if there is no financial incentive to do so.

In addition to all the direct technological infrastructure requirements, the user has to have access to basic infrastructure to enable functioning of all components. A user needs an account with an ISP, an organization providing basic internet access and related services such as e-mail domain hosting to an end-user. It will normally provide the user with the physical data transmission means to connect the user location with the ISP "backbone", typically referred to as the "Last-Mile". User access to the internet basically requires connecting the end-user and the data source through their respective ISP. This ultimately boils down to the successful linking of the "Last-Mile" between the service provider and end-user, provided it is available, accessible and affordable to the end-user. It also needs to make financial sense to the

[14]Union of Concerned Scientists. 2018. *UCS Satellite Database*. https://www.ucsusa.org/nuclear-weapons/space-weapons/satellite-database?#.XEBRb81S_IU accessed 14 January 2019.
[15]See footnote 7.

Table 2 "Last-Mile" connections

Typical last mile connection technology		
DSL—digital subscriber line		
Physical	Supports high speed	Inexpensive
Fiber optics—dedicated fiber to premises		
Physical	Very high delivery speeds	Very expensive
LAN—Local Area Network		
Physical	Supports very fast local delivery	Costly
Radio—Cellular communications, 3G, LTE etc.		
No physical link	Supports high speed	Very expensive
Satellite technology		
No physical link	High speed—latency can be an issue with GEO satellites and service speed can be influenced by severe weather conditions anywhere in the transmission path	Perceived to be costly
Wireless Network—Wi-Fi and WiMAX		
No physical link	Fast access	Not cost effective for low numbers

supplier (profit) and in addition, the supporting infrastructure needs to be available, e.g. electricity and service roads. The most popular technologies used to bridge "the last mile" are indicated in Table 2.

4 Basic Requirements for Internet Access in Rural Communities

There are five base "components" a user needs available in one place to access the internet—the "Internet" itself, electricity, hardware, software and communication services. The Federal Networking Council (FNC) officially created a definition for the "Internet" in 1995 describing it as follows:[16] "Internet" refers to the global information system that:

(i) Is logically linked together by a globally unique address space based on the Internet Protocol (IP) or its subsequent extensions/follow-ons;
(ii) Is able to support communications using the Transmission Control Protocol/ Internet Protocol (TCP/IP) suite or its subsequent extensions/follow-ons, and/or other IP compatible protocols; and

[16]NITRD. 1995. *Networking and Information Technology Research and Development*. https://www.nitrd.gov/fnc/Internet_res.pdf accessed 25 May 2016.

(iii) Provides, uses or makes accessible, either publicly or privately, high level services layered on the communications and related infrastructure described herein."

The 2017 UNCTAD Report on the Information Economy indicates that global internet powered e-commerce had grown from no contribution less than two decades before to a value exceeding 25 trillion USD by 2015.[17] The proliferation of the digital economy has unfortunately also expanded the global electricity consumption footprint significantly to drive the requirements of the internet components.

Electricity

To store and process data, all digital devices need a certain amount of electricity in the form of DC (Direct Current) to provide the constant flow of electrons required by the components of the circuit boards that process the data.[18] A Berkeley Lab report predicts that electricity use ascribed to internet data centres will reach 70 billion kWh by 2020, the equivalent of approximately eight large nuclear reactors.[19] If not for predicted increases in efficiency over current systems, these data centres would likely be using two hundred billion kWh by 2020 (Koomey 2010). The emergence of the Internet of Things (IoT) as a mainstream technology has the potential to increase internet-related electricity consumption even more. By 2025 some 152,000 new devices are estimated to engage the internet every minute.[20] As opposed to the primary electricity consumption ascribed to the internet to power ever-increasing large data centres, the electricity requirement of the end-user hardware is quite minimal, as depicted in Table 3.

For urban users the availability of access to electricity normally is not a problem in most areas of the world where, on average, 96.4% of the urban population has access, as opposed to 73% of the rural population.[21] On a regional scale, the difference between urban and rural can be much more pronounced, especially in Sub-Saharan Africa, a region with ironically the fastest growing population in the world—by 2035 this region will also have the youngest population in the world[22] (see Fig. 5).

[17]See footnote 3.

[18]Mueller, D. 2017. *What Are the Uses of Direct Current? 25 April 2017. (accessed February 16, 2018).* https://sciencing.com/uses-direct-current-7394786.html accessed 16 February 2018.

[19]Helman, C. 2016. *Berkeley Lab: It Takes 70 Billion Kilowatt Hours A Year To Run The Internet.* https://www.forbes.com/sites/christopherhelman/2016/06/28/how-much-electricity-does-it-take-to-run-the-internet/#3eedc6d71fff accessed 12 May 2018.

[20]Kanellos, M. 2016. *How To Keep The Internet Of Things From Breaking The Internet.* https://www.forbes.com/sites/michaelkanellos/2016/06/16/how-to-keep-the-internet-of-things-from-breaking-the-internet/#7a2b2edd6a7c accessed 12 May 2018.

[21]SE4ALL. 2018. *Sustainable Energy for All.* https://datacatalog.worldbank.org/dataset/sustainable-energy-all accessed 22 November 2018.

[22]Bello-Schünemann, J. 2017. *Africa's population boom: burden or opportunity?* https://issafrica.org/iss-today/africas-population-boom-burden-or-opportunity accessed 25 February 2018.

Table 3 User-end broadband power requirement[a]

	Broadband "User End" power requirement				
"Last-Mile"	ADSL	Fiber Optic	LTE/xG	Satellite	Wi-Fi
Consumption	4–20 W	12–60 W	3.5–12 W	50–100 W	2–60 W
Access device	"Feature Phone"	Notebook	PC	Smartphone	Tablet
Consumption	2–6 W	20–100 W	90–350 W	2–6 W	2–6 W

[a]Energy Use Calculator. 2019. *Energy Use Calculator*. http://energyusecalculator.com/ accessed 12 February 2019

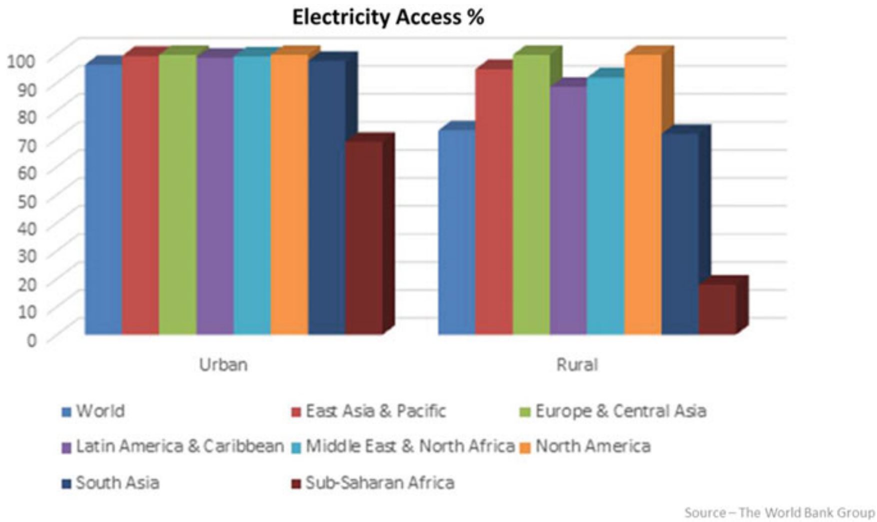

Fig. 5 Global Access to Electricity Availability—Urban vs Rural (see footnote 21)

Renewable energy sources have the ability to provide a decentralized electric power supply on a small scale that can be deployed rapidly making it ideal for low-power applications in isolated areas. Renewable energy and battery technology has been developing rapidly over the last decade, benefiting from new materials and manufacturing techniques to drive down costs and boost efficiency.

Hardware

Internet connectivity will only be possible if a user has the basic necessary hardware to engage the internet. The hardware needs to support two main functions;

- Connect—link the user to the ISP, normally though some type of modem (modulator-demodulator) used to "translate" the digital source into the correct analogue format used by the transmission medium.
- Interface—a hardware device with the necessary software allowing the user access to engage the internet e.g.—computer, smartphone, tablet etc.

The hardware requirement can be fully integrated as in the case of a smartphone. It can also be a combination of separate components such as a satellite receiver with a separate modem connected to a Wi-Fi access point where a user might access it with a tablet computer.

Software
Internet connectivity requires two basic functional software components:

- An operating system capable of supporting TCP/IP to complete the link to the ISP and authenticate the user, e.g. Android, iOS, Linux, etc.
- A web browser to allow the user to "surf the net" and interact with the internet, e.g. Mozilla Firefox, MS Explorer etc.

For a user to overcome the limitations imposed by the lack of infrastructure in a remote area all the above technology and services need to be combined into a functional system.

5 Bridging the Last Mile in the Era of Mega Constellations

As stated previously the broadband mega-constellations planned within the next few years have the potential to revolutionize the lives of the unconnected masses. Does it also provide an opportunity to reconsider the way in which satellite broadband can be integrated into the daily lives of the people? What if it were possible to create a device with the ability to deliver broadband internet to any remote community—integrated into a familiar object, without the need for power or communication infrastructure to be available at the target site. What if such a product could be integrated into the daily lives of unconnected individuals and communities in such a way that full acceptance of the technology is achieved to the maximum benefit to all stakeholders? To take the example of GPS (arguably the most widely used "space technology" by individuals and businesses alike), when it first found its way from its military roots to the commercial market, it was merely a niche market for navigation devices providing basic numerical data in the form of GPS III in 1998.[23] The technology gained additional traction when the intentional dilution of precision was discontinued, which prompted manufacturers like Garmin and Tom-Tom to bring easy-to-use personal navigation devices to market. These devices focused on providing a map-based user-interface navigation service, as opposed to the raw navigation data only—placing GPS technology in the hand of the masses. As the technology evolved, the ubiquitous square antenna defining the initial devices started to disappear. Today GPS technology is rather a sub-set of a converged device or service e.g. smartphone or Airbnb.

[23]Mark Sullivan, 'A brief history of GPS', https://www.pcworld.com/article/2000276/a-brief-history-of-gps.html accessed 15 May 2019.

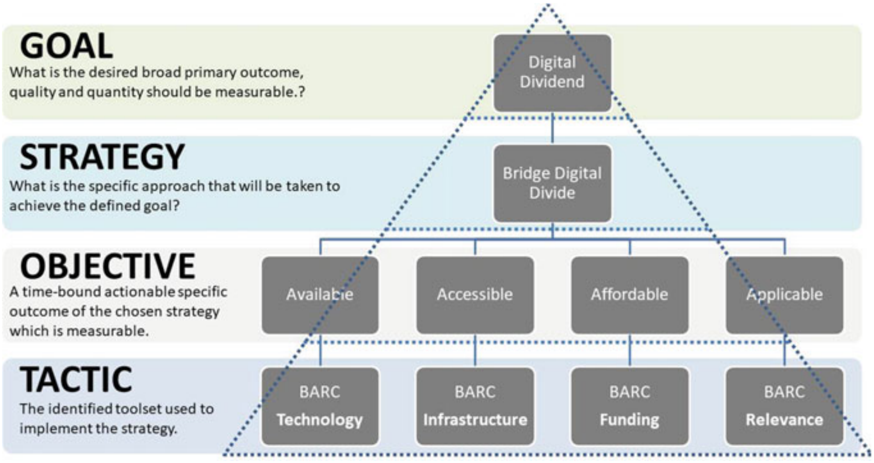

Fig. 6 GSOT model: Strategic framework positioning of the intended facility

The projected increase in broadband satellite capacity over the next decade, will present similar opportunities, especially to communities where there are currently no services. Satellite broadband could be seamlessly integrated into such a community through innovative design. A proposed apparatus developed in this work, to connect a remote community to the internet, proposes just that; a device incorporating all the necessary requirements to deliver a practical broadband internet experience to remote users. Our goal is to not only develop a concept that provides adequate power for communication needs but also creates an environment to optimise use, e.g. by providing charge points for user devices and light at night to extend productive use of the device packaged in a functional form.

Currently there are over 4 billion people without access to broadband internet who therefore cannot benefit from the "Digital Dividend" due to the preventative factors such as the "4A's" as discussed earlier. A principal preventative barrier for most of the unserved communities globally is the lack of infrastructure, i.e. the "Last-Mile". A product that can bridge the "Last-Mile" whilst providing the ability to address the other barriers of broadband adoption effectively presents an improvement opportunity for the broadband-disenfranchised masses. The first step in designing such as product referred to in this study as BARC (Broadband Apparatus for Underserviced Remote Communities), is to define a macro view in order to position the product using a generic GSOT (Goal, Strategy, Objective, Tactic) model, as illustrated in Fig. 6. The model is best illustrated as a hierarchical pyramid, at the top-end framed by a single "What" and at the base, one or more "How's"—the tactics—bound together by a strategy and objectives. The proposed product can therefore be framed as indicated by where the base layer is represented by different features of the intended solution which triggers the requirements process.

5.1 Enabling Technologies

Apart from broadband satellite technology, two additional technologies are of specific interest notably, renewable energy power generation and LED illumination.

Renewable Energy

There are primarily two types of proven renewable energy technologies that can be deployed with relative ease to provide power to small under-serviced communities;

- **Photovoltaic** (PV) technology generates electricity when light shines on a semiconductor material. Since its introduction by Bell Labs in 1954, PV have found their way into multiple applications, from powering satellites and space missions to pumping water in the desert.[24] The technology has gone through a number of iterations as new materials have become available. Traditional first-generation crystalline silicon-based PV have been superseded by second generation "thin film" flexible panels, expanding the application footprint. The third generation, characterized by non-silicon-based materials allows radical application expansion including the ability to "print" or "spray" PV materials on different surfaces an shapes.[25] PV technology is by far the most popular technology for rapid roll-out of power at un-serviced sites providing an unmatched level of decentralized capability, e.g. from a "pocket" solar powered "energy bank" for a smartphone to large panels driving a reverse osmosis desalination system for a coastal community.
- **Wind** produces electricity by converting the kinetic energy of the wind into rotational force through the use of a propeller driven turbine to spin a generator. Small wind generators are not as complicated as the large commercial systems typically deployed at a windfarm—but they are less efficient. These small generators can be deployed effectively in remote areas which experience windy conditions frequently. The efficiency of the technology has improved through new materials and improved blade design and generation through direct-drive systems (Kishore et al. 2014). Wind power can be used in areas unsuitable for PV or to compliment PV see Table 4.
- **Fuel Cells** In addition to the staple of solar and wind power technologies, there have been notable developments in fuel cell technology, including hydrogen fuel cells, methanol and biofuel, etc. Fuel cells generate electricity through an electrochemical reaction between oxygen and a hydrogen to produce water as effluent.[26] This process is extremely energy efficient (80–95%). In addition, the heat profile of the fuel cell can also be used for heating or cooling. One of the biggest advantages of a fuel cell is that, since it essentially is a battery running on

[24] NREL. 2017. *Solar Innovation Infographic.* https://www.nrel.gov/solar/infographic.html accessed 14 February 2019.

[25] Energy.gov. 2013. *Solar Photovoltaic Cell Basics.* https://www.energy.gov/eere/solar/articles/solar-photovoltaic-cell-basics accessed 12 December 2016.

[26] Kurtz, J. 2016. *Hydrogen and Fuel Cells for IT Equipment* (NREL/PR-5400-66610). Golden, CO: NREL—National Renewable Energy Laboratory.

Table 4 Renewable energy for remote communities[a]

Solar cells—photovoltaic (PV)				
Advantages	Very low eco impact	Low opex	Ease of use	Portability
Disadvantages	Limited power supply	High capex	Day only—needs storage system	Efficiency determined by environment
Small wind turbine				
Advantages	Cost effective—depending on location	Can produce power as long as the wind blows	Relatively portable	Small installation footprint
Disadvantages	High opex	Mechanical failure	Spare part availability in rural areas	Efficiency determined by environment

[a]Fong, D. 2014. Global Network Institute—Sustainable energy solutions for rural areas and application for groundwater extraction. http://www.geni.org/globalenergy/research/sustainable energy-solutions-for-ruralareas-and-application-for-groundwater-extraction/Sustainable-Energyfor-Rural-Areasand-Groundwater-Extraction-D.Fong.pdf. accessed 14 July 2017

"fuel", it solves the energy storage problem normally associated with wind and solar power. Cost and lack of true portability for systems with a practical generation capacity currently limits the usability of fuel cell technology for remote communities. Though current portable versions are not practical for remote communities as yet (typically requiring hydrogen in cartridges), development in technology of fuel cells and peripherals (e.g. solar hydrogen generators) does hold potential for applications in rural communities in the future. There are a number of commercial initiatives internationally driving the research into fuel cells, most notably by the platinum mining industry wanting to create new markets for its product, which can ultimately lead to the development of a practical power-generating unit for rural communities.[27]

LED

"Light Poverty" refers to people without the benefit of "decent" light at night. This is typically a function of not having access to electricity, resulting in a number of constraints after dark, including movement, security and productivity amongst others. Almost 17% of the global population spends up to 1000 times more money per unit of light than the "on-grid" populace, forced to burn a mixture of fuels to provide light, resulting in the equivalent greenhouse-gas emissions of 30 million automobiles.[28] LED illumination provides a high Lumen output, using very little power. This, coupled with their high longevity compared with other lighting

[27]Minerals Council South Africa. 2017. *Powered by Platinum—Factsheet 2017*. http://chamberofmines.org.za/industry-news/publications/fact-sheets/send/3-fact-sheets/381-chamber-of-mines-fuel-cell accessed 13 January 2018.

[28]Mills, E. 2015. *Can technology free developing countries from light poverty?* https://www.theguardian.com/global-development-professionals-network/2015/jul/30/can-technology-free-developing-countries-from-light-poverty accessed 19 July 2017.

technologies, makes LED illumination ideal as a supplementary service for a device, such as BARC, rolled out in remote areas.

6 Goals and Structure of This Study

The purpose of this study is sixfold;

1. Investigate how the "Last-Mile" challenge can be addressed to supply broadband to underserviced (i.e. lacking infrastructure) communities through the use of a BARC enabled by existing and emerging technology, including satellite broadband, renewable energy etc.
2. Define the requirements for such a device based on the "4A" framework—Available, Accessible, Affordable and Applicable.
3. Explore and evaluate several possible conceptual designs to select a concept design for further development.
4. Propose a detailed design based on a requirements framework for such a device and explore practical challenges, constraints and solutions.
5. Explore the benefits flowing from of such a design for the various stake-holders in terms of identified challenges affecting internet adoption, i.e. how will the design bridge the digital divide, create a digital dividend and support the attainment of the SDGs?
6. Explore potential models to fund such a design.

This study is divided into seven chapters. The first chapter introduces the concept of a device to deliver a practical broadband internet experience to users at underserviced locations, presenting the "digital divide" and "Last-Mile" as challenging concepts. Chapters 2–4 address the various aspects of the design process, from establishing requirements to presenting a detailed design. The fifth chapter is dedicated to an assessment of the potential impact of broadband introduction to unserved communities ("digital dividend"). Chapter six investigates potential funding models. Chapter seven concludes the study with suggestions for additional research into the topic.

Requirements Definition

A typical requirement analysis will normally include some degree of user consultation, which is not the case in this project as the "opportunity" is based on observed trends, data and recommendations from institutions such as the ITU, UN, WEF and the World Bank Group. The four barriers to broadband adoption were described in Fig. 1. The development approach is therefore centred on a product that will eliminate these four preventative factors, leading to the successful adoption of broadband services by unconnected communities.

1 New Product Development

Any new product development is ultimately motivated by fulfilling a need of some kind, typically observed as the gap between the current "status quo" and an envisioned "improved" future scenario brought forth through the introduction of the intended product. This is a complex process (often considered part art, part science) of striving to produce usability through balancing "needs & wants" against practical "realities". The "Design Thinking" school of thought describes this gap between the status quo and the envisioned better future as the "inspiration space" or "the opportunity that motivates the search for solutions" (Brown 2008). The success of any new product introduction is dependent on the ability of the target market to accept the intended change that will be effected by the product.

Kanter (2012) states that people will rather "remain mired in misery than to head toward an unknown" when describing the introduction of "excess uncertainty" as one of ten reasons that people will quite often resist change. Resistance to change is therefore one explanation for why novel products, when entering an environment where their purpose is not fully understood as a familiar concept, have a high

C. Kotze, *A Broadband Apparatus for Underserviced Remote Communities*,
Southern Space Studies, https://doi.org/10.1007/978-3-030-15766-1_2

chance of being marginalised or completely ignored.[1] New product development by its very nature is therefore a challenging endeavour; in order to be successful it needs to introduce change. The new product therefore needs to overcome inherent resistance to change, by presenting itself in a clear light in such a way that the intended user perceives benefit of use. The designer needs to position the product in such a way as to maximise the user-centric benefit by asking the question—"How will the user benefit from using this product?" A good example being by way of the question Disney asked when planning Disneyland, namely, "How will it provide the customer with a magical experience? (Stefan Thomke 2012). The more focussed the question, the better the opportunity to define functions and constraints; in the Disneyland case, what will prevent or enable the said "magical customer experience".

Through the years a number of processes have emerged to guide the product designer, the choice of methodology normally being dictated by the intended product "arena". Each methodology though starts with producing a set of requirements to guide the process. For the requirements development of the BARC, aspects of two apparently conflicting methodologies were used, namely—classical "requirements engineering" as well as "Design Thinking".

"Design Thinking" emphasizes a human-centric approach, with the design process involving rapid, low-resolution prototype designs, where the designer is guided by viewing the problem to be solved from an empathic perspective of the intended user. This method is well suited to ill-defined real-world problems that can be expressed as conceptualised designs relatively quickly. As opposed to producing a set of specifications, this method attempts to capture the needs of the potential customer by creating "desirability" of use (Vetterli et al. 2013). In the context of this study "Design Thinking" is applied in an attempt to produce "desirability" against the minimum acceptance criteria of broadband by the target population, i.e. the 4A's.

Requirements Engineering as typically associated with software and information systems, concerns itself with the interrelationship between the "real-world" goal; functions and constraints applicable to the intended system in order to produce "precise specifications" to predict behaviour and guide future evolution (Zave 1997). An Information System is defined as the product of the synergistic action of three primary components, namely people, processes and technology (Keen 1993). The BARC can be therefore be seen as an incidence of an information system. As such, development tools rooted in the information systems world were thus considered for aspects of the requirements determination process.

Though mostly associated with the development of information systems and associated IT fields, the System Development Lifecycle, commonly referred to as the SDLC can be effectively deployed as a macro approach to overall product development. The SDLC approach for this review will be based on the one as

[1]Sørensen, J. 2013. *The simple reason products fail: Consumers don't understand what they do.* https://qz.com/132070/the-simple-reason-products-fail-consumers-dont-understand-what-they-do accessed 12 February 2018.

defined by the USA's National Institute of Standards and Technology (NIST), describing it as an overall process used from initial development to eventual retiring of a system (Radack 2009). The basic SDLC is typified by a five-phase iterative process describing the product life cycle—initiation, development, implementation, operation and disposal. The initiation phase starts with conversion of the "product story" (i.e. the reason for the product's creation) into a set of requirements, the requirements definition. The Project Management Institute (a global professional organization for project management) describes the requirements definition as the most important phase of the product lifecycle (Daniels 2000). Product requirements are normally split into two broad categories, functional and non-functional requirements.

Functional Requirements (FR) basically define "what" the product should achieve, with each "feature" or function described as single requirement in a clear, unambiguous way according to IEEE Standard 830-1998.[2]

Non-Functional Requirements (NFR) specify criteria that can be used to assess the operation of a system, rather than specific behaviours or capabilities. They define "how" the system should deliver the "what" that it is supposed to do. In other words, they specify the 'quality characteristics' of the system. Functional requirements are generally expressed as statements of the form "shall do" whereas non-functional requirements are statements of the form "shall be".

Though there are numerous models and methodologies available to guide basic requirement setting, the one chosen for this project is an adaption of the so-called "FURPS+" model, an acronym for Functionality, Usability, Reliability, Performance and Supportability. The original FURPS model was developed by Robert Grady of Hewlett Packard, as an internal product quality model, to provide a consistent way of identifying and categorising FR's & NFR's (Grady 1994). It involves five basic categories (1FR + 4NFR's) and the "+", for additional quality categories as dictated by the situation. For this project an amended version —"FURPS + CA" was used, with the "+CA" representing the "4A's" as minimum "Customer Acceptance" criteria identified by an ITU study for a remote community to accept broadband[3] (Fig. 1).

The next section develops the requirements definition using the guidelines and FURPS + CA model put forward in this section.

2 Requirements Definition

The formal requirements development starts by positioning the BARC via a "product story". In marketing a product story is a means to effectively communicate the "what, how & why" of a product to the intended audience in an informal,

[2]IEEESTD. 1998. *IEEE Std 830-1998—Recommended Practice for Software Requirements Specifications*. 1. IEEEE.

[3]ITU. 2017. *ICT Facts and Figures 2017*. https://www.itu.int/en/ITU-D/Statistics/Documents/facts/ICTFactsFigures2017.pdf accessed 14 January 2018.

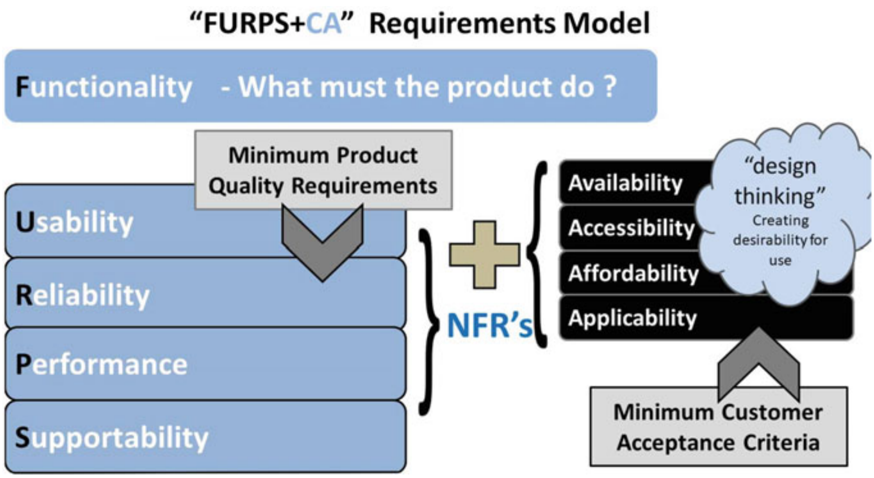

Fig. 1 Requirements determination using amended FURPS + CA

easy-to-understand way. The "product story" therefore serves as the foundation to expose the requirements. The product story is written in such a way as to cover the "customer acceptance criteria" as identified by the ITU study—earlier referred to as the 4A's—and which are highlighted in the following product story.

2.1 The Product Story

The BARC will have the ability to make broadband internet AVAILABLE to any remote community. Producing and storing its own electricity, with the means to accommodate the latest satellite communication technology, it is not dependent on any pre-existing utility infrastructure. The BARC will give communities practical ACCESS to broadband internet, by supplying all the necessary ancillary services the user will need to use the internet effectively, such as charge points and illumination at night. The system will provide infrastructure for remote environmental data collection, laying the foundation for innovative funding models to enhance AFFORDABILITY. Local culture and language will be incorporated to make the benefits of using broadband internet clear and APPLICABLE to the intended community. The BARC "product story" can be further distilled using the FAB (Features + Advantages + Benefits) framework to create a basis for an initial requirements definition (see Table 1):

To start the requirements' definition process, it is useful to imagine and list the possible actors and the expected basic interactions between them and the proposed device in achieving the intended goal, i.e. obtain the advantage of broadband access. These use-cases will also attempt to cover the possible scenarios that will prevent the successful use, i.e. not achieving the goal. The output will be a list of

Table 1 Features, advantages and Benefits Analysis

	BARC—FAB analysis
Features	Self-contained broadband internet system, using satellite communication and renewable energy technology, with the ability to collect local environmental data
Advantages	Can be deployed in most remote areas, not dependent on any existing infrastructure and providing all required supporting services for broadband internet use (e.g. power and lighting)
Benefits	Allows the community to benefit by utilising broadband internet anytime of the day or night, whilst also providing charge points for access devices to community and guest users

scenarios and actors which will later be used to link back to the identified requirements. The application of a use-case methodology for this study involves a template to describe each interaction broadly and classify the different scenarios as: [DAILY] (normal everyday use), [PERIODIC] (periodic required actions) and [EXCEPTIONAL] (rarely encountered) use cases.

Table 2 illustrates the basic use-case template which was used to construct the different use-case scenarios

There are nine basic scenarios envisioned for the successful use of the system;

1. Daily use activities, Table 3. Use-case 01.
2. Remote management activities, Table 4. Use-case 02.
3. Remote data use, Table 5. Use-case 03.
4. Activities surrounding guest users, Table 6. Use-case 04.

Table 2 The basic use-case template

Use-case number and description of the use-case and the excepted frequency of use classified as [DAILY], [PERIODIC] and [EXCEPTIONAL]	
Description	Text description of the use-case
Actor [X]	Who is the primary "actor" in the use-case identified as: [CT] = Construction Team [DC] = Data Customer [FE] = Field Engineer [FT] = Field Trainer [GU] = Guest User [OU] = On-site User [RM] = Remote Management
Flow	A stepwise description of the interactions between the actor and BARC to conclude a successful use-case
Alternative flow	An alternative stepwise description of the interactions between the actor and BARC to conclude a successful use-case
Pre-conditions	What must be in place for the use-case to be realised?
Post-conditions	What must take place if any after the use-case is concluded?
Exceptions	What will prevent the use-case to complete successfully?

Table 3 Use-case 01

Use-case #1: Broadband access [Daily]	
Actor	Onsite user [OU]
Description	This use case prescribes the way in which the [OU] will interact with the system to access broadband
Flow	1. [OU] access device attempts to link to the pre-defined Wi-Fi access point 2. On wireless authentication the system presents the [OU] with the [OU] “log-on” screen requesting authentication 3. [OU] authentication 4. On successful authentication the [OU] is granted broadband access for period of time based on policy 5. The [OU] session ends when the [OU] logs off or the time quota runs out and the access device logs the [OU] off
Alternative flow	At any time during the session the [OU] can terminate the session by using the “log-off” button and return the access device to the charge dock
Pre-conditions	Satellite broadband is available, Wi-Fi is operational, access device is available, available access device is charged, [OU] is registered on the system, [OU] is authenticated successfully
Post-conditions	Usage data is updated
Exceptions	Any system function is not available, [OU] fails to be authenticated

Table 4 Use-case 02

Use-case#2: Remote maintenance [Daily]	
Actor	[RM] Remote maintenance
Description	This use case prescribes the way in which the remote monitoring maintenance will interact with the system to monitor system functionality
Flow	1. The use-case begins when [RM] accesses the telemetry database of all linked BARC devices 2. Update telemetry management reports for devices 3. Conduct daily routine maintenance 4. Identify error trends 5. Identify improvement opportunities 6. Report errors to field support where applicable 7. Ensure data connection for external customers 8. Update asset data daily
Alternative flow	[RM] is notified automatically of any urgent error condition as defined by policy
Pre-conditions	Communication is available to remote device, telemetry database is accessible and telemetry management system is available
Post-conditions	Notify field maintenance team of any reportable conditions. Telemetry management returns to monitoring mode only
Exceptions	Communication with remote system function is not available. Telemetry management system is not available

Table 5 Use-case 03

Use-case #3: Remote data use [Daily]	
Actor	[DC] Data customer
Description	This use case prescribes the way in which data collected from a BARC is used by a [DC]
Flow	Basic flow for the use case involves the consumption of data directly or indirectly by an authorised consumer 1. The use case begins when raw-data is transmitted from BARC to a cloud repository 2. Data is classified and stored 3. Data asset value updated* 4. [DC] user is authenticated in accordance with policy guidelines 5. On authentication [DC] is allowed access to relevant data in accordance to policy and regulatory frameworks 6. Meta data on use is collected against user 7. [DC] terminates session
Alternative flow	[DC] cannot access data, reports problem as per policy
Pre-conditions	BARC in normal operation, transmitted used in accordance to relevant regulatory framework
Post-conditions	Data transfer confirmed
Exceptions	Error conditions with data transfer. Notify field maintenance of any reportable conditions with transfer

*A note on the value of the "data asset". The monetary value of data could be influenced based on the time of access. The example could be data valuable for an agricultural futures company might be more time sensitive than the same data looked at later by a climate scientist

Table 6 Use-case 04

Use-case #4: Guest users [PERIODIC]	
Actor	[GU] Guest user
Description	This use case prescribes the way in which a [GU] will interact with the system using a self-supplied access device e.g. cell phone or tablet
Flow	1. The use case begins when [GU] obtains a use token 2. [GU] powers "on" the access device 3. [GU] links to Wi-Fi access point broadcast by BARC 4. MAC address of [GU] access device is registered on BARC 5. On wireless authentication the system presents the user with the user "log-on" screen requesting acknowledgment of condition of use 6. [GU] is granted a broadband access quota based on policy in terms of access token 7. The user session ends when the time quota runs out and the access device logs the user off
Alternative flow	[GU] terminates session prior to quota running out
Pre-conditions	[GU] has access device, either using own access device or using site-supplied access device
Post-conditions	BARC updates consumption data against [GU] access device profile
Exceptions	[GU] is supplied quota over-ride by remote management

Table 7 Use-case 05

Use-case #5: Field training [PERIODIC]	
Actor	[FT] Field trainer
Description	This use case prescribes the way in which the [FT] will interact with the user base when training is required
Flow	1. The use case begins when [FT] is notified of a new installation request for a BARC 2. [FT] conducts site inspection in accordance with policy 3. [FT] conducts basic user training for use of new BARC
Alternative flow	1. [FT] is notified of a new training request on an existing BARC site 2. [FT] conducts basic user training for use of new BARC
Pre-conditions	Knowledge of local site conditions and access to site and required resources
Post-conditions	Training objectives are met
Exceptions	[FT] cannot access site

Table 8 Use-case 06

Use-case #6: Dismantlement [EXCEPTION]	
Actor	Construction team [CT]
Description	This use case prescribes the way in which the [CT] will conduct on-site operations when an installed BARC is removed from a site
Flow	1. The use-case starts when [CT] is notified of a need to dismantle a BARC 2. [CT] conducts site inspection in accordance with policy and set time scale 3. [CT] notifies [RM] and BARC is disconnected from monitoring 4. [CT] dismantles BARC 5. BARC is removed from site 6. Site is restored to pre-installation conditions
Alternative flow	Site is not accessible to [CT] within required time scale
Pre-conditions	• Community has been notified and agreed to dismantlement • Access to site • Required parts and other resources are available
Post-conditions	Site where BARC was recovered is reconditioned as per defined policy
Exceptions	BARC cannot be recovered

5. Training in the field, Table 7. Use-case 05.
6. Dismantlement, Table 8. Use-case 06.
7. Field maintenance, Table 9. Use-case 07.
8. Emergency repair, Table 10. Use-case 08.
9. Installation, Table 11. Use-case 09.

The first use-case attempts to describe the basic scenario of daily use by an on-site user i.e. the prime customer refer Table 1.

The second use-case (Table 4) attempts to describe the remote management scenario, a crucial link in the service supply chain. Apart from the daily remote

Table 9 Use-case 07

Use-case #7: Field maintenance [PERIODIC]	
Actor	[FE] Field engineer
Description	This use case prescribes the way in which the [FE] will interact with the system when a preventative maintenance is required
Flow	1. The use case begins when [FE] is notified of a fault or field maintenance request on an installed BARC 2. [FE] conducts preventative maintenance or carries out repairs in accordance to maintenance guidelines
Alternative flow	N/A
Pre-conditions	Access to site and parts are available to [FE]
Post-conditions	Return BARC to normal operation. Report on any notifiable conditions observed on-site
Exceptions	Field engineer cannot access site

Table 10 Use-case 08

Use-case #8: Emergency repair [EXCEPTION]	
Actor	[FE] Field engineer
Description	This use case prescribes the way in which the [FE] will interact with the system when an emergency repair is required
Flow	1. Basic flow for the use case begins when [FE] is notified of an emergency repair request on an installed BARC due to one of two conditions a. Remote management cannot connect to BARC b. Remote management detects an emergency condition 2. [FE] conducts emergency repair in accordance within the agreed period defined by the policy guidelines
Alternative flow	[FE] conducts emergency repair, but not within the agreed period defined by the policy guidelines
Pre-conditions	Access to site and parts are available to Field Engineer as demanded by the situation
Post-conditions	• Return BARC to normal operation • Notify management of any additional reportable conditions observed on-site
Exceptions	[FE] cannot repair problem on-site

management, this function is also responsible for pro-active maintenance, trend analysis and to ensure a reliable flow of data to customer—on-site and external.

The third use-case (Table 5) attempts to describe the remote data use scenario, an important use-case as it represents a potential revenue opportunity.

The fourth use-case (Table 6) describes the activity of any user using the system temporarily i.e. not a permanent member of the user community, for example a visiting health service provider. Such use can be short-term or for an extended period.

Table 11 Use-case 09

Use-case #9: Installation [EXCEPTION]	
Actor	[CT] Construction team
Description	This use case prescribes the way in which the [CT] will conduct on-site operations when a new BARC is installed
Flow	1. The use case begins when [CT] is notified of a need to install a BARC 2. [CT] conducts a site inspection in accordance with policy 3. [CT] confirms site suitability 4. [CT] arranges installation date with community 5. [CT] installs BARC 6. [CT] runs test sequence 7. [CT] links BARC to remote management 8. [CT] activates BARC for normal operation 9. [CT] installation is signed-off and handed over to [RM]. 10. Training team is notified
Alternative flow	1. [CT] finds site not directly suitable for installation 2. [CT] recommends remedial action to make site suitable for installation 3. Installation is relocated or rescheduled for the site
Pre-conditions	• A suitable site has been identified for installation of a BARC • Community has agreed to installation • Access to site, parts and other resources are available
Post-conditions	BARC is active for operation
Exceptions	[CT] finds site not at all suitable for installation and installation is aborted

The fifth use-case (Table 7) describes any activity of personnel dispatched to site to engage in training. Training can take two forms, i.e. primary trading and periodic reinforcement training.

The sixth use-case describes any activity of personnel dispatched to site to dismantle the equipment. Use-case 07 and 08 dals with routine maintenance and emergency repair.

The final use-case describes the installation of the system at the new site.

2.2 Functional Requirements

The Functional Requirements specify "What" must the system do. There are eight functional requirements identified:

Functional Requirements

1. F01: Provides broadband internet functionality.
2. F02: Produces electricity for system use and for use by customers.
3. F03: Stores electricity to supply power in absence of availability.
4. F04: Provides its own structure to house all functional components.
5. F05: Allows remote monitoring of the device by off-site stakeholders.

6. F06: Provides charge points to users to power access devices.
7. F07: Provides light to allow use of the facility at night.
8. F08: Collects sensor, usage and meta-data.

2.3 Non-functional Requirements

The “quality requirements”, which in this case are split into two main groupings, i.e. the “Base Requirements”, which are basically the non-negotiable expected quality requirements, and a set of additional “acceptance” criteria.

2.3.1 User Acceptance Requirements (“4A’s”)

The 4A’s defines the minimum acceptance requirements for broadband acceptance as identified by the UN Broadband Commission study that needs to be satisfied before a community will accept broadband.[4] These will arguably form the most important design challenge as it will determine whether the product will be accepted or not. These requirements must be used to create a “desire” in the target user to “want to” use the product.

1. Availability
   a. U01 Everyone in the community is aware of the availability of the product
   b. U02 Product is equally available to all members of the community.
2. Accessibility
   a. U03 The product is close to the user within a short walking distance
   b. U04 All users have access to the necessary tools to engage broadband
   c. U05 All users have the necessary skills to engage broadband.
3. Affordability
   a. U06 The system is sponsored for use
   b. U07 Users can afford to use the system.
4. Applicability
   a. U08 Use of the product is relevant to local needs
   b. U09 Benefit is associated with use of the product.

[4]Biggs, P. Ed. 2018. *The State Of Broadband 2018: Broadband Catalyzing Sustainable Development*. First ed. Geneva: UN Broadband Commission.

2.3.2 Performance Requirements

The "base" non-functional requirements are the essential qualitative requirements or Performance Requirements for BARC. They are identified by the last four elements of the FURPS model, namely; Usability, Reliability, Performance and Supportability.

1. Usability
   a. P01 Ability to be optimised for multiple conditions
   b. P02 Easy to assemble—within two working days
   c. P03 Easy to use—users can be trained within a day
   d. P04 Visibility—clearly visible day and night
   e. P05 Provides wireless access from a minimum 20 m distance.
2. Reliability
   a. P06 Mean time before failure > 26 000 h
   b. P07 Robust—able to withstand normal environmental conditions
   c. P08 Power redundancy for 24 h.
3. Performance
   a. P09 Broadband uptime 95% minimum
   b. P10 Response time—average latency < 500 ms
   c. P11 Accuracy— < 2% packet loss
   d. P12 Workload—support a maximum of 80 concurrent users at 100 kbps
   e. P13 Scalable—adjusts to available bandwidth.
4. Supportability
   a. P14 Low Planned Maintenance—twice yearly on site
   b. P15 Easy to maintain—on-site component replacement must take less than 8 h
   c. P16 Compliance—must conform to all applicable local and national regulations
   d. P17 Upgradable—can accommodate future upgrades.

Conceptual Design

"Humans have always been emotional and have always reacted to the artefacts in their world emotionally." —Alan Cooper.[1] Take the example of the Apple iPod, launched in the 4th quarter of 2001, it took the market by storm and literally turned Apple Inc.'s fortunes around. From selling 125,000 units in its first year, it became one of the bestselling products of all time. When it was discontinued in 2014, it had sold in excess of 400 million units.[2] It was not the first MP3 player—that honour belongs to the MPMAN-F10 launched 1998.[3] It was also not the cheapest; on the contrary it was criticised for being too expensive and it was also locked in the Apple ecosystem. So, why was it so successful? There certainly were many factors, but two things stood out, namely a truly intuitive design and seamless integration with the iTunes platform, taking the complication out of music management—in other words, a pleasant user experience packaged as a quality product.[4] The creation of a pleasant UX (user experience) therefore is key to create a product that is:

- Desirable—Product creates attraction and provides satisfaction on use;
- Usable—Product is easy to use; and
- Useful—Product performs the tasks required of it.

[1]Weprin, M. 2017. UX Design Managers: The Good, The Bad, and The Ugly—Revisited. <https://uxdict.io/ux-design-managers-the-good-the-bad-and-the-ugly-revisited-760c738a66ea> accessed 31 March 2018.
[2]Costello, S. 2018. This is the Number of iPods Sold All-Time. <https://www.lifewire.com/number-of-ipods-sold-all-time-1999515> accessed 17 January 2019.
[3]Ionescu, D. 2009. Evolution of the MP3 Player. <https://www.pcworld.com/article/174725/evolution_of_the_mp3_player.html#slide1> accessed 31 March 2018.
[4]Adner, R. 2012. Innovation Success: How the Apple iPod Broke all Sony's Walkman Rules. <https://knowledge.insead.edu/blog/insead-blog/innovation-success-how-the-apple-ipod-broke-all-sonys-walkman-rules-2791> accessed 30 March 2018.

C. Kotze, *A Broadband Apparatus for Underserviced Remote Communities*, Southern Space Studies, https://doi.org/10.1007/978-3-030-15766-1_3

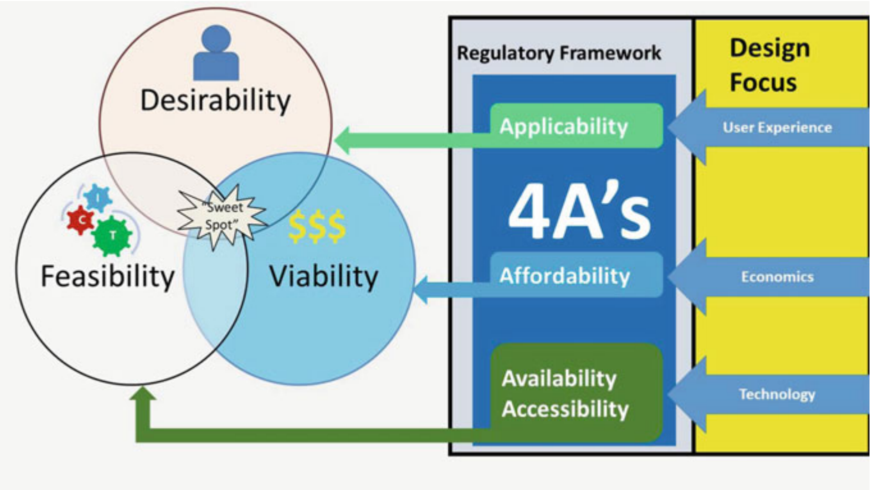

Fig. 1 Conceptual design framework showing the linkage between acceptance criteria and design focus areas

The "design thinking" philosophy with its human-centric "empathic" approach was chosen as primary design guide for the iPod. Tim Brown, the CEO of IDEO (who designed Apple's first mouse) summed up "design thinking" as a methodology to meet the "needs and desires" of people in such ways that it is technologically possible and creates both customer value and market opportunity (Brown 2008). In addition to UX the design also needs to take into account the economics of the design and available technology in terms of the key user requirements and any regulatory requirements. The ideal design will be the optimal intersection of desirability, feasibility and viability within the identified framework of opportunities and constraints. Figure 1 illustrates these required design focus areas and their relation to the four identified acceptance criteria. The same will apply for the requirements identified by the FURPS model Fig. 1.

1 Design Philosophy

The generic design philosophy was to create a design to satisfy not only the technical requirements but to do it in such a way that will invite the user to explore the use of the product. This can be translated into the following practical design statement.

> Create a familiar form that can blend into any rural environment, adding additional function over and above the intended technical performance to serve the community in a larger way through form.

In this context the words “larger way” mean that the community derives utility from the product in ways that significantly exceeds the original goal.

One can think of the example of the product providing shelter during the day from sun and rain, which is purely a function of the form, but then at night it adds illumination to the area which is a technical performance feature. Another example could be to be associated with storage of collected water, which could be particularly relevant in Sub-Saharan Africa where, in addition to the lack of reliable electricity; ready access to water remains a problem in many rural areas. Providing these associated functions to the community could enhance community acceptance of the product and willingness to use the full bouquet of services.

This suggests that technologies that can support designs featuring smooth, flat surfaces will be designs of particular interest. Such “flat” technologies include satellite broadband antenna systems, integrated thin-film PV technology and ultrathin LEDs. In addition to satisfying the identified requirements and constraints as referred to in the above section, the use-case scenario analysis also indicates that a modular design might be more appropriate to aid installation and maintenance. Design concepts will be modular from component level to functional level, making it possible to add additional functions when it becomes available.

The proposed BARC design will support the ability to easily integrate with other BARC systems should additional capacity be required to create a local network following a P2P (Peer to Peer) model.

2 Design Concepts

The philosophy behind the design was to create an “apparatus” with a basic recognizable form that can blend into any rural environment. Form can add additional functionality over and above the intended technical functionality by providing very basic services as well. A design that can, for example, provide shade during the day and an illuminated area at night could be put to regular use by the community and visiting support services (e.g. health services) alike. Another example could be storage of collected water, which could be particularly relevant in Sub-Saharan Africa where in addition to the lack of reliable electricity, ready access to water remains a problem in many rural areas. Providing these associated functions to the community could enhance community acceptance of the product and willingness to use the full bouquet of services provided these services are packaged in a relevant UX.

Process

This concept product development process followed the “top-down” variant of the “Innovation Funnel” approach using a single screening process[5] (IfM 2018)—an appropriate option for the scale of the intended development. The basic design concept was broadly defined as a rough sketch to identify the key components and

[5]IfM. 2018. Innovation Funnel. <https://www.ifm.eng.cam.ac.uk/research/dstools/innovation-funnel/> accessed 12 May 2018.

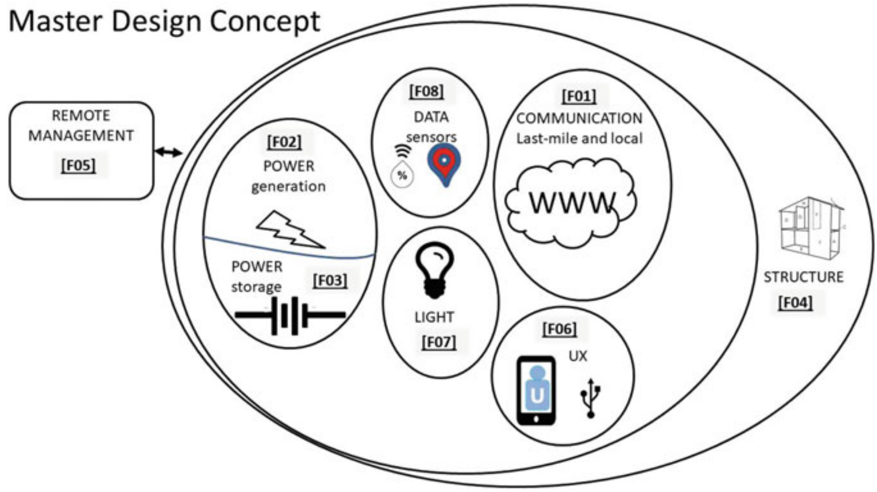

Fig. 2 Master Design Concept

refined as a diagram to indicate the different components in relation to each other as represented by Fig. 2. The master design concept identifies the main functional "modules"—power, data, communications and light, which are integrated into the structure. The initial eight functional requirements as identified (refer Sect. 2.2), were mapped as indicated by F01 to F08. The user interface (UX) is positioned "away" from the structure, as it will only "exist" when used. This master concept was applied to a number of ideas that were inspired by common forms and/or objects normally associated with a convergence of people. From the initial idea shortlist, five ideas were selected to generate design concepts. The following sections describe each of these five design concepts.

2.1 C1—"Rondavel" Concept

The first design option drew inspiration from African architecture. The "Rondavel" is a traditional type of housing comprising a cylindrical structure with a distinct conical shaped thatched roof that is prevalent in Southern Africa (Steyn 2006) (Fig. 3).

This design concept features a conical-hexagonal roof which is supported by a central pillar and a number of smaller peripheral support pillars which are interlinked horizontally at roof level. It consists of a round roof support section clad in canvas with integrated PV collectors. The underside of the "roof" sections will feature integrated ultrathin LED's on the ground-facing side to provide an even distributed light at night. LED strips are also integrated in the outside facing support pillars for visibility at night. The small hexagonal panel at the top of the roof contains the communication and data collection systems. The central support pillar

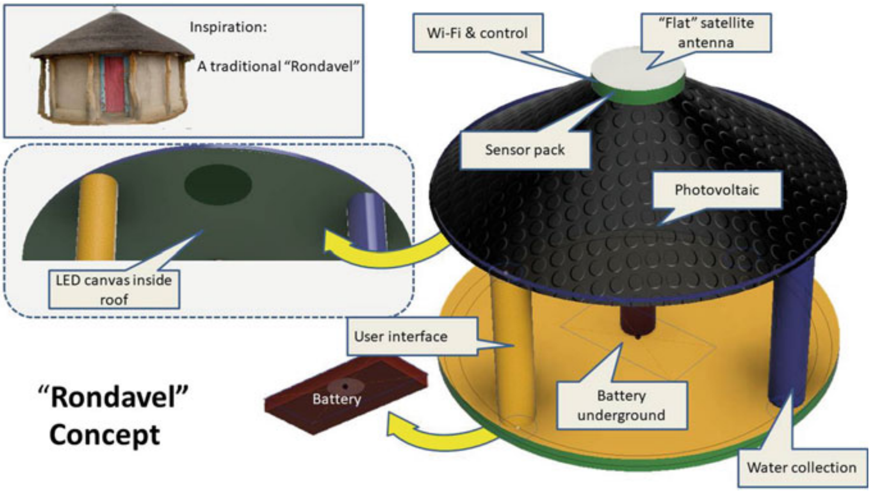

Fig. 3 "Rondavel" Concept

links the communications systems and the power storage unit, which is housed underground for safety, security and structural reasons. The central support pillar also contains all the user charge points, additional sensors and all other electronics not housed in the top or bottom sections. The roof section contains micro-channels to divert rainwater to a collector, installed around the base of the roof, where it is diverted via one of the support pillars for harvesting.

The "Rondavel" is a familiar shape in Southern Africa which is relatively easy to construct and adaptable to many surface conditions. The design caters for all of the functional requirements as defined in initially.

2.2 C2—"Cantilever Umbrella" Concept

This concept features a collapsible "roof" centrally suspended from a cantilever frame. The frame is anchored to a flat base at ground level where the battery packs are held. The roof cladding is made of canvas with integrated PV collectors; with the ground-facing underside of the roof featuring integrated ultrathin LED's similar to the previous design concept (Fig. 4).

An umbrella construction typically features a canopy supported on a collapsible frame normally mounted on a central pole with the purpose of providing the user protection against the sun. The cantilever umbrella design—a departure from the traditional central pillar umbrella—optimises the functional area underneath the umbrella whilst allowing access the frame for functional use.The roof section contains channels to divert rainwater to a central collection point for rainwater harvesting. The data collection module is located on the top of the vertical section of the frame which also houses an enclosure containing all the control and local

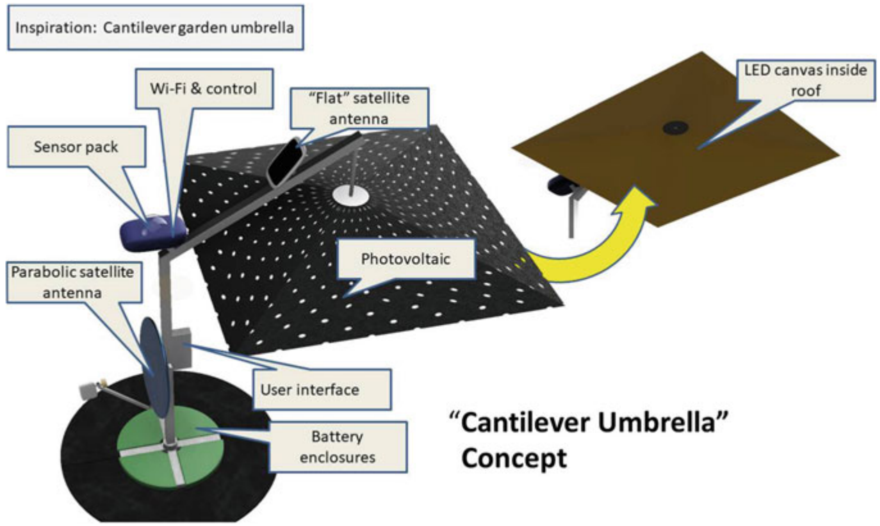

Fig. 4 "Cantilever Umbrella" Concept

Wi-Fi communication. The design caters for the use of both a "flat" and parabolic satellite antennae; The flat panel is mounted on top of the cantilever section of the frame, whilst the parabolic is mounted on the vertical section of the frame. A round utility area on top of the base contains the batteries and other functional modules and charge points for users. This design is relatively easy to construct and can be collapsed under special circumstances and satisfies all of the functional requirements as initially defined.

2.3 C3—"Back2Back Bus Stop" Concept

This design took inspiration from the common bus stop shelter. Almost all public transport systems feature some form of shelter where passengers board or leave the transport—a bus stop. Most of these shelters share at least two common design features—an enclosure providing shelter and a place for the waiting passengers to sit. This design features a "V-shape" roof section housed in a frame connected to a seat section.

The bench used to seat users also functions as a storage area for the batteries of the local power module. The flat sections flanking the "back support" section (coloured red in Fig. 5) contain the user-interface, featuring charge points for utilisation by users. The roof frame sections are covered with canvas with integrated PV collectors, with the ground-facing flipside of the roof featuring integrated ultrathin LED's similar to the other design concepts. A tubular frame section connects two supporting pillars of the roof located at the bottom of the "valley" formed where the two roof sections meet. All control modules and Wi-Fi access

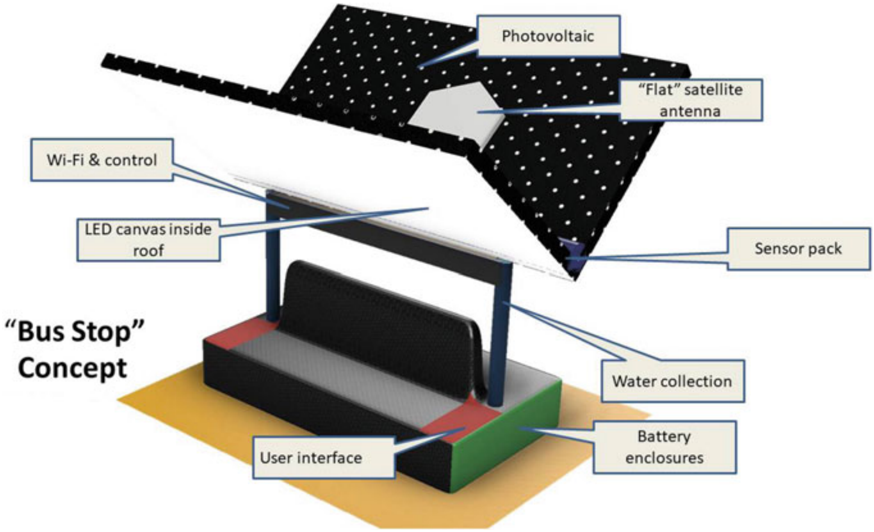

Fig. 5 "Back-to-back Bus Stop" Concept

points, used for local communication, are also housed within this frame section. The "Last-Mile" communication module is contained in an enclosure featuring a flat panel satellite antenna, mounted on one of the PV roof sections. A tubular section running end-to-end at the base of the roof serves as part of the support structure securing the roof, but also contains the sensor module for data collection. The "V-shape" of the roof creates a natural opportunity for water harvesting and the roof itself contains canals to aid this process by diverting rainwater to a central collection point. This unique design shape offers an additional degree of user functionality in that it offers integrated seating for users in addition to supplying shelter from the sun. The design meets all the functional requirements as defined.

2.4 C4—"Smart Tank" Concept

This design option takes its functional inspiration from the central role water plays in any community. In the developing world, access to safe potable water is limited and most water needs to be carted daily from source to usage point, usually by women and children. According to UNICEF, globally women and girls daily spend 200 million hours per day in the process of collecting water, time that could have been used for productive work and education.[6] Localised rainwater harvesting can

[6]UNICEF. 2016. UNICEF: Collecting water is often a colossal waste of time for women and girls. <https://www.unicef.org/media/media_92690.html> accessed 12 May 2018.

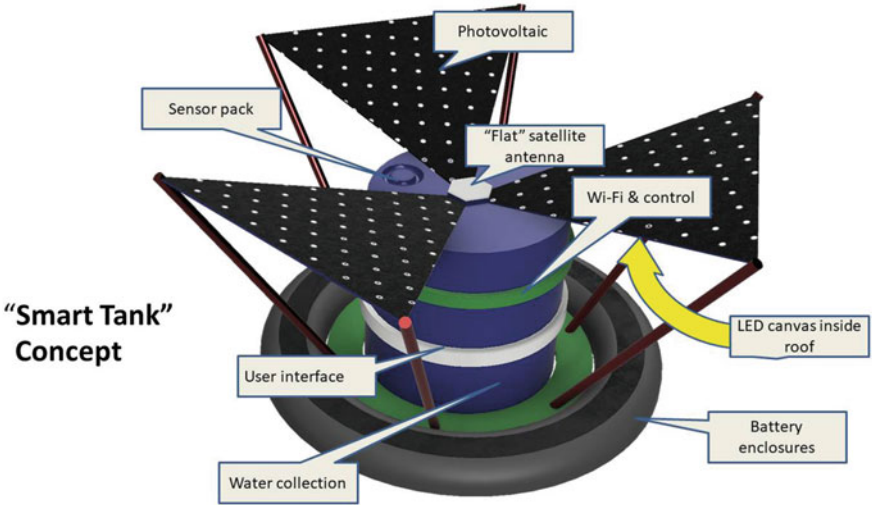

Fig. 6 Rainwater harvesting "Smart Tank" Concept

help to alleviate this problem through capture and storage of rainwater to ensure amore continuous access to water (Wisser 2009). Demand for water storage tanks has grown significantly in recent years (Fig. 6).

The concept revolves around the integration of the BARC into a rain water harvesting system. A rain water harvesting tank (5,000 to 10,000 litres) is used as the central support structure. The design shape was inspired by the "nuclear warning" symbol featuring three flat trapezoidal roof frame sections. These roof sections are each supported by two adjustable primary support pillars connected at the corners of the "wide side" of the trapezoid, terminating at an angle into a support structure located around the base of the tank. The batteries and control systems for the power module are housed in a torus shape surrounding the structural base where the support pillars of the roof sections terminate. This structure can also be used to provide seating for users. The other end, the "narrow" side of the trapezoid, is attached to a mounting module situated on top of the tank at a tilted angle. The roof sections feature the same arrangement of canvas with integrated PV collectors and ground-facing ultrathin LED's as seen in the previous designs concepts. The data collection module is contained in an enclosure mounted on top of the tank. The local Wi-Fi communication module and other control systems are housed in a circular structure installed towards the top of the water tank. A similar structure is located towards the base of the tank, which houses the user interface i.e. charge points. The slight angle of the roof section and water guiding micro-channels divert rainwater to a circular structure used to mechanism guide harvested water into to the rainwater tank. A flat panel satellite antenna is mounted on top of the aforementioned water collection point.

The design needs a certain degree of preparation at the intended deployment site before it can be deployed in the form of a level plinth on which to rest the tank. In addition to shade, this design provides a much-needed function for many communities of rainwater collection and storage in the developing world. The design caters for all of the functional requirements as set initially defined.

2.5 C5 "Car-Port" Concept

Canvas-covered car-ports are a common sight at public areas around the world, normally featuring a very basic construction consisting of a frame covered by a sun-blocking fabric. The reference design option took inspiration from a very basic carport with a flat roof. The concept features two rectangular planar frames (bottom and top) linked together by four support pillars to form a three dimensional "box". Beams connected to the "top" planar frame form the roof. The bottom planar frame features adjustable "feet" to accommodate uneven terrain. The support pillars are made from hollow square tubes. Storage batteries are housed in the four corner structure tubes which also contain charge points. A square section containing the communication and data collection system featuring a "flat" satellite antenna is integrated on the roof surface. The roof cladding is made of canvas with integrated PV collectors, with the ground-facing underside of the roof featuring integrated ultrathin LED's similar to the first design concept (Fig. 7).

The roof section contains channels to divert rainwater to a central collection point where it could be used for rainwater harvesting. This familiar shape is

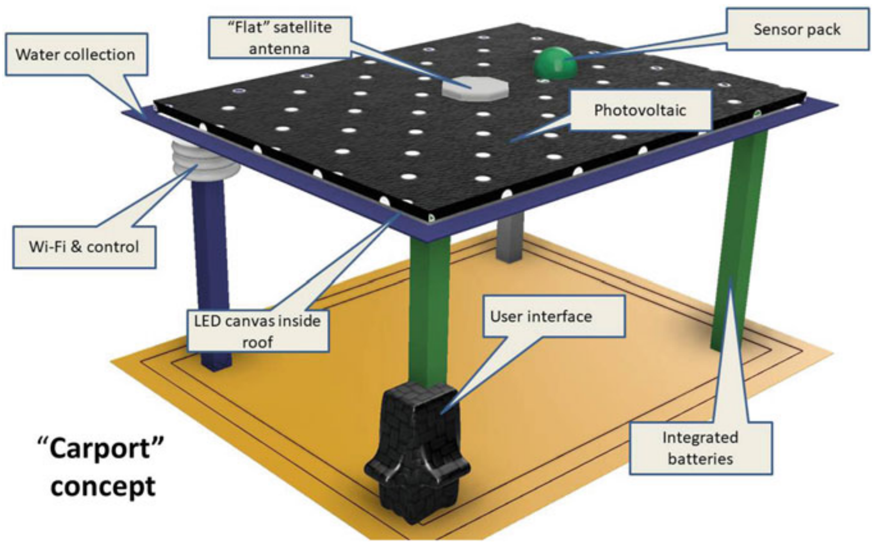

Fig. 7 Reference "Car Port" Concept

relatively easy to construct and adaptable to many surface conditions, because of its adaptability this design concept can be deployed virtually anywhere. The design caters for all of the functional requirements as initially defined.

3 Concept Selection

To evaluate the five designs—all having unique features which can benefit the community—a variant of a Pugh Matrix was used. This decision support technique was developed by Stuart Pugh (Pugh 1991) and is widely applied for concept section from a list of alternatives. The process involves laying down a list of selection criteria against which concepts are evaluated. Selection is aided by comparing the products in the selection pool against a reference product. The reference product is allocated a neutral score against each of the selection criteria. That is, if an evaluation scale of 1 to 5 is used, the reference product will be allocated a "3" against all criteria. Each of the other alternative choices will subsequently be rated and allocated a score reflecting its performance relative to the reference design or product in terms of the evaluation criteria, i.e. either better, worse or equivalent to the reference. Selecting the reference design involved an internet search of the available "Commercial Off-The-Shelf" systems with the ability to create a wireless access at remote locations lacking infrastructure using solar power generation, storage batteries, Wi-Fi access point and a satellite links.

Systems such as the Renewable Energy Satellite Internet Skid[7] and the container-based "CONTAINER DD v.5" from the Digital Doorway[8] project in South Africa (DigitalDoorway 2018) were investigated. The Digital Doorway product was found to be more comparable to the design concepts than the Renewable Energy Satellite Internet Skid.

3.1 Reference Concept

The "CONTAINER DD v.5" is the marketing name for the product produced by the "Digital Doorway project.[9] It is essentially a closed container housing three user terminals accessible inside via a door. On the roof of the structure a number of photovoltaic panels are mounted to generate electricity. Batteries housed in the container are used to store the generated power. It features a parabolic satellite

[7]BlueTide. 2015. BlueTide Communications premieres skid for remote and emergency communications needs. <https://www.bluetidecomm.com/index.php?option=com_content&view=article&id=55:bluetide-communications-premieres-skid-for-remote-and-emergency-communications-needs&catid=9&Itemid=275> accessed 24 November 2017.

[8]DigitalDoorway. 2018. Hardware. <http://www.digitaldoorway.org.za/index_main.php?do=hardware> accessed 12 May 2018.

[9]The "CONTAINER DD v.5" is an existing design that is available and was used as a reference concept for the evealuation using a Pugh matrix.

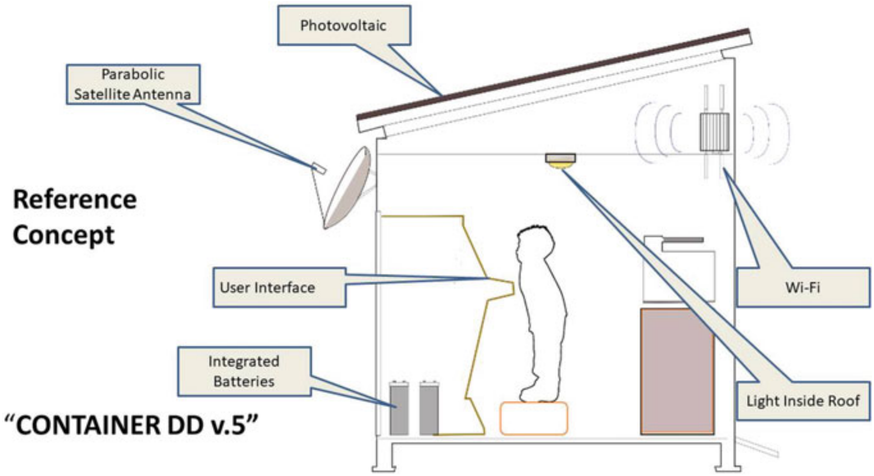

Fig. 8 Reference Concept "Container DD v.5" (see footnote 9)

antenna to receive a broadband internet signal anywhere and the signal is distributed locally using Wi-Fi. The design caters for all of the functional requirements as set out initially, with the exception of the full sensor module. For the purpose of a reference design the assumption was made that such a module could be integrated in the design with relative ease, as all the communication and power structures to support it already exist (Fig. 8).

3.2 Selection Process

A basic Pugh Matrix (Table 1) was constructed as a decision support tool to evaluate the five concepts against a reference to propose a final selection. This process involved creating a list of eleven selection criteria, with each criterion allocated a weighting (W) from 1 to 3 according to the perceived importance.

The selection criteria attempt to provide a lens to view the product from additional perspectives of form, function and practicality. As all the designs need to conform to the functional requirements, it is included for completeness as the very first selection criterion. The other nine criteria evaluate the concepts from different angles related to form, function and installation. Each design concept was scored individually against the selected criteria using a scale of 1 to 5 where: [1 = Worst], [2 = Bad], [3 = Neutral], [4 = Good] and [5 = Best]. Where C1 to C5 (C1 = "Rondavel", C2 = "Umbrella", C3 = "Bus Stop", C4 = "Smart tank", C5="Car-Port"). The last column named "RC" is used for the reference concept.

Table 1 Pugh Matrix Concept selection matrix

#	Criteria	W	Concept Score*					
			C1	C2	C3	C4	C5	RC
1	Meets all the functional requirements	3	3	3	3	3	3	3
2	Form provides additional function—high score represents a high degree	3	3	3	4	5	3	3
3	Provides shade—low score represents low degree	3	5	1	3	3	5	3
4	Site topography dependence—low score indicates a high degree of reliance	3	2	3	2	1	4	3
5	Complexity of form—low score indicates more complicated	2	3	2	1	1	4	3
6	Required degree of site preparation—Low score indicates a high degree of reliance	2	2	3	2	1	4	3
7	Water required for construction—low score represents low degree	2	3	3	3	1	3	3
8	Ability to endure windy conditions	2	3	1	2	3	3	3
9	Ease of delivery of materials—low score represents les ease	1	3	3	2	1	3	3
10	Effectively aids rainwater harvesting—high score indicates high degree of effectiveness	1	2	1	4	5	2	3
11	Visibility—high score clearly visible day and night	1	3	1	3	5	2	3
Un-weighted score			32	24	29	29	36	33
Weighted score			0	−16	−8	−10	11	0
Score* refer Sect. 3.3								

3.3 Scoring

Each selection criterion was allocated a weighting from 1 to 3. Each concept was scored against the criteria using a scale of 1 to 5 where:

$$[1 - \text{The Worst}][2 - \text{Worse}][3 - \text{Neutral}][4 - \text{Better}][5 - \text{The Best}]$$

The median score, namely 3, was subtracted from the allocated score and multiplied with the allocated weight, to reflect the relative importance which was applied to each score to create a weighted total that was used for the final selection.

$$C_x = \sum_{i=1}^{n} W(S_i - 3)$$

where

- C_x = Design Concept C1 to C5.
- W = Criterion weight

- S_i = Criterion score
- n = 11

3.4 Final Concept Selection

The “Car-Port” concept (C5) scored the highest overall score against the reference relative to the other designs, both in the weighted and the un-weighted category. The “Rondavel” (C1) design came second and scored the same as the reference in the weighted category. The lowest score was allocated to the “Umbrella” (C2) concept due to the form providing significantly less functionality than the other conceptual designs.

Detailed Design

This chapter deals with the translation of the high-level conceptual design to a detailed design, implemented as hardware and software. We begin by defining the design statement for the product followed by a review of the available technology on the market looking at "tried and proven" but also focussing on the emerging technology. Secondly we define a high-level architecture to guide the process of developing a more granular functional perspective to produce the modular architecture. The chapter concludes with a check of the design against the constraints defined in Chap. 2 (non-functional requirements).

1 Design Statement

In order to guide the detailed design process it is necessary to create a "design statement" to frame the product in terms of function and visual appeal. Functionally BARC is an all-in-one solution combining an electrical power source energy and communications technology in order to link underserviced remote communities to the internet. The product will be primarily enabled by the use renewable electric power and satellite communications technology. The visual appearance of the product is a very important consideration in the conversion of the concept to the final product design. Symmetric designs are considered to be a natural preference in design of the observer as it conveys "balance, harmony and stability" strengthening product "recognition and recall" (Lidwell et al. 2010). The following design statement will guide the final design process;

> Functional simplicity with an emphasis on the visual appearance by maintaining a symmetric form characterised by flat surfaces with no protruding objects, using energy effective, environmentally safe standardised components and open source software.

C. Kotze, *A Broadband Apparatus for Underserviced Remote Communities*,
Southern Space Studies, https://doi.org/10.1007/978-3-030-15766-1_4

In addition to the functional requirements, the visual appearance of the design will influence the technology selection. For example, a parabolic antenna does not necessarily satisfy the symmetric requirement of the above design statement. To ensure the original functional requirements guided the design within the constraints of the design statement a high-level functional diagram was produced (Fig. 1). Each of the eight functional requirements previously identified, were allocated to five broad technical groupings representing the "master" functional modules;

1. Communication: All requirements dependent on the provision of communication to and from the device.
2. Effector: For this purpose any requirement that creates an effect based on sensory input such as the light switching on at night.
3. Power: Any requirement to do with the generation, storage and provision of electrical power.
4. Sensor: All requirements to do with detecting and recording of events from the surrounding physical environment.
5. Structure: Requirements to physically accommodate all components of the system on the operational site.

This diagram was used to perform a review of available technology which could potentially be used create the product within the constraints of the visual design statement.

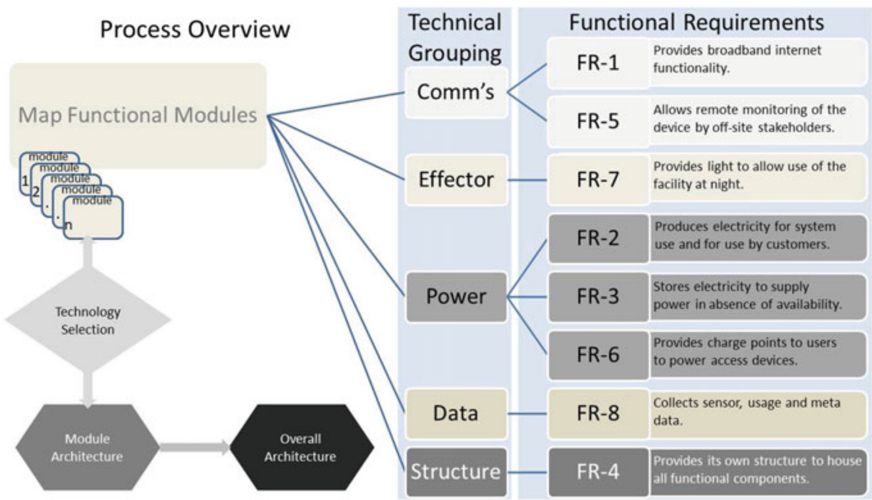

Fig. 1 High-level functional diagram for detailed product design

2 Available Technology

The availability of technology is the key determinant to make a technical design a reality. To ensure the best fit-for-function technology selection it is necessary to review what technology is available to enable the technical functions identified in the previous section namely; Communication, effector, power generation, data collection and provision of structure. Each technology stream is explored further in this section in terms of "the tried and proven" and secondly "emerging" technology.

2.1 Communication Technology

Communication technology is arguably the most important component in BARC in that it supports the primary functionality of the intended product. There are two separate communications technology requirements identified for the communications module—"Last-Mile" link and the "local" link.

2.1.1 "Last-Mile" Link

This study is in essence about addressing the "Last-Mile" problem. The suitability of satellite communication to resolve the "Last-Mile" problem has to do with its broad reach, not requiring terrestrial infrastructure to get a signal to remote areas. As it is very difficult to make repairs to satellites in orbit, satellite systems are designed with several layers of redundancy leading to uptimes close to 100% (see Table 1).

On the negative side—the typical problems associated with satellite broadband are perceived high cost and latency, which can be an issue depending on the orbit of the satellite in use. Whereas cost has a number of determinants, latency is a function of physical constrains framed by the orbit altitude which will ultimately determine the turnaround time between client and source.

In addition to cost and latency, environmental factors can also influence the use of satellite technology. "Rain-fade" is the term used to describe a loss of satellite signal due to moisture related environmental effects (Grémont 2004). The attenuation of rain-fade can be calculated for a location by using formulas such as the ITU-frequency scaling formula to calculate power compensation during signal disruptive rain (Jena and Sahu 2011). Rain fade is more significant for smaller antennas and the high-frequency bands featuring wider bandwidth such as the Ku and Ka bands.

Table 1 Orbit and latency

Type of orbit	Altitude (km)	Latency (ms)	Examples
GEO	35 785	500–600	YahSat
HEO	7 971 to 45 170	60–900	**Sirius 3**
MEO	>2 000 < 35 785	130–150	O3b, Viasat-1
LEO	200 to 2000	<20	LeoSat

The cost of a broadband satellite service comprises two elements namely hardware and subscription cost. Hardware cost is mostly determined by the choice of antenna. Though there are different service models, the typical one will include a monthly fee normally including a tranche of data which once depleted, will be charged per unit which again can differ depending on the time of the day. Substantial reduction in cost per unit has made satellite broadband increasingly affordable and is expected to continue as additional capacity is added. One of the problems with the continual addition of capacity has been putting pressure on available spectrum. Ka-Band in particular is increasingly getting congested. The planned mega-constellations will therefore be looking at innovative use of Q/V band to take free up more Ka-band. The planned mega-constellation of Boeing is a typical example; by combining the Ka- and V- bands in two separate systems it enables sharing and re-using of frequency bands by each satellite.[1] Unlocking the true potential of these new mega constellations will depend how well the market can develop the ground equipment with the fast beam-steering and pointing requirements to optimally connect to these constellations.[2]

2.2 Antennas

Satellite connection holds the key to bridging the digital divide, however the intended mega-constellations of broadband satellites will in actual fact be contributing to the digital divide if it is not made accessible to the billions of unconnected people globally. At Satellite 2017 it was stated that key to satellite internet access is not necessarily adding additional massive capacity, but to make the user terminal very affordable for the poor. Thomas Choi from ABS (Asia Broadcast Satellite) quoted a figure of USD 100 for a complete kit, as the target price point in order to make it affordable for the poor.[3] The Flat Panel Antenna (FPA) is not a new concept—having been deployed in the form of phased array antennas for years—it has been hamstrung by cost and performance issues preventing the technology of becoming a serious contender to the traditional parabolic dish systems. Driven by the requirement of users to be "ever connected" the in-flight connectivity market has become a strong driver of FPA's, which can be integrated with the fuselage of an airliner without compromising the drag coefficient significantly. One of the technologies driving FPA's is phased array. New generation phased array based antennas hold great promise for satellite communications, especially in applications

[1] de Selding, P. 2016. *Boeing proposes big satellite constellations in V- and C-bands.* https://spacenews.com/boeing-proposes-big-satellite-constellations-in-v-and-c-bands/. Accessed 17 July 2017.

[2] Satellite Evolution Group. 2018. *Flat panel satellite antennas ready for takeoff.* https://www.satellite-evolution.com/single-post/2018/02/28/Flat-panel-satellite-antennas-ready-for-takeoff. Accessed 7 May 2018.

[3] Werner, D. 2017. *Cheap satellite terminals key to bridging digital divide, execs say.* https://spacenews.com/cheap-satellite-terminals-key-to-bridging-digital-divide-execs-say/. Accessed 17 July 2017.

not currently served by the industry due to constraints imposed by the conventionally parabolic dish systems. As opposed to traditional satellite tracking communications which requires a RF beam to be focussed at the satellite—typically through a movable parabolic dish—Phased Arrays create a the focus from an array of very small fixed antennas.

A phased array antenna consists of many "radiating elements" with individual phase shifters which form beams via phase shifting of each element in such a ways as to steer the beams in a specific direction though constructive or destructive interference also known as "beam-steering".[4] As this process is completely electronic the beam can be directed instantaneously in the desired direction no need for mechanical tracking mechanisms. This is by no means new technology; in actual fact it is well understood, with a number of practical applications such as a system for high quality video links to aircraft using satellites patented in the 1990's already *U.S. Patent No. 5,463,656*.[5] The technology had been held back significantly as it needed to overcome technical challenges (e.g. how to miniaturise components) and improve performance whilst trying to make it affordable to developing countries. Technological advances in different industries have now allowed companies to overcome these challenges to produce antennas that have no moving parts and are completely software controlled. Phasor Solutions is one of the companies developing products for the market that promise a revolutionary impact. PHASOR[6] has developed a very thin (2.54 cm) antenna system, featuring individual modules which can be used in conjunction with each other and shaped to any surface, e.g. an aeroplane fuselage, eliminating the need for mounting external structures on the aircraft. Taking a different approach, Kymeta's "mTENNA"[7] utilises metamaterials for holographic beam forming and tracking, with transmission and receiving on a single aperture. This compact antenna subsystem has a "flat" lightweight design, and a claimed ability to handle secure point-to-point broadband connections in excess of 100Mbps. These antennas have a lower power appetite than older generation phased array technology—featuring auto-acquisition of satellites in any orbit—can also be combined to increase throughput. As it features electronic steering, there are no moving parts which increases reliability (Fig. 2).[8]

Alcan Systems[9] another new entrant into the FPA market uses, phased array based on liquid crystal technology. The company promises a fast switching FPA with the ability to access high-throughput satellites in any orbit which is affordable,

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[4]Wolff, C. 2018. *Phased Array Antenna*. http://www.radartutorial.eu/06.antennas/Phased%20Array%20Antenna.en.html. Accessed 20 April 2018.

[5]Polivka, A. L., Zahm, C. & Harris Corp. 1995. *System for conducting video communications over satellite communication link with aircraft having physically compact, effectively conformal, phased array antenna*. https://patents.google.com/patent/US5463656A/en.

[6]Phasor. 2018. Phasor's Technology. http://www.phasorsolutions.com/phasors-technology. Accessed 20 April 2018.

[7]Kymeta. 2018. *Products & Services*: *Introducing Revolutionary Mobile Connectivity*. https://www.kymetacorp.com/kymeta-products/#productMtenna. Accessed 22 March 2018.

[8]Ibid.

[9]Alcan Systems. 2018. *Liquid Crystal Phased Array Technology. Affordable. Scalable.* https://www.alcansystems.com/technology/. Accessed 1 December 2018.

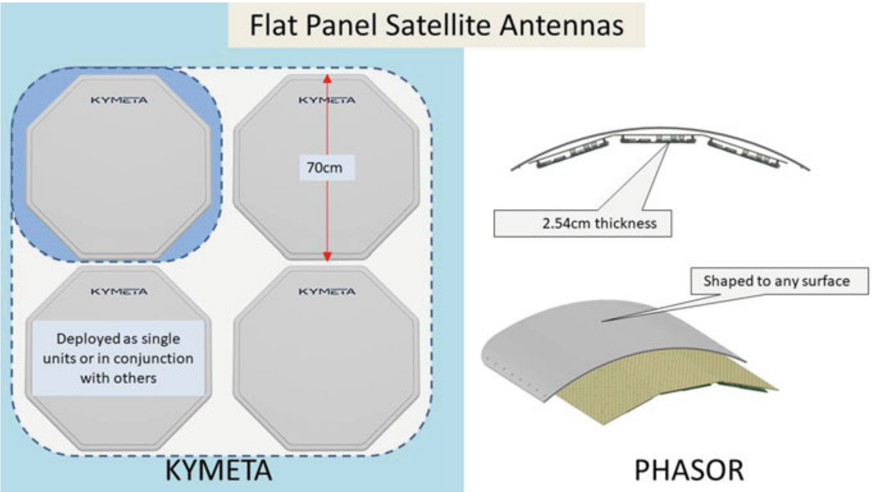

Fig. 2 Examples of new generation Flat Panel Antennas (see footnotes 7, 9)

scalable and virtually maintenance free after installation. A version is planned for the satellite broadband consumer market for under 1000 Euro.[10] From a design perspective flat antennas allow for more flexibility than what is possible with the traditional parabolic dish antennas which is difficult to integrate into a flowing design albeit new technology.

2.2.1 Local Link

In 1985 the FCC opened up bands of wireless spectrum for communication purposes without the need for a government licence in the 900 MHz, 2.4 GHz and 5.8 GHz range ("garbage bands"), which were already allocated to RF using equipment for other purposes than communications e.g. microwave ovens. To ensure industry compatibility the IEEE published a standard in 1997 namely IEEE802.11a/b,[11] which came to be known as "Wi-Fi". Apple was the first major manufacturer to adopt the technology in 1999 with the introduction of the Apple "AirPort."[12] The normal configuration for a Wi-Fi network involves the deployment of at least one WAP (Wireless Access Point)—hardware device consisting of a router and antenna system connecting resources to clients—commonly referred to as a "Hot Spot". From a design point of view three considerations will influence the choice of protocol:

[10] Henry, C. 2018. *German startup takes Kymeta-like LCD approach to flat panel antenna manufacturing.* https://spacenews.com/german-startup-takes-kymeta-like-lcd-approach-to-flat-panel-antenna-manufacturing/. Accessed 6 June 2018.

[11] IEEE802.11. 2018. *IEEE 802.11 WIRELESS LOCAL AREA NETWORKS.* http://www.ieee802.org/11/. Accessed 20 April 2018.

[12] Apple. 1999. *About Your AirPort Card.* https://support.apple.com/MANUALS/0/MA434/en_US/AboutYourAirPortCard.PDF. Accessed 1 December 2017.

- **Coverage Area**. The area in which user will be able to connect to the service within acceptable limits. This can be influenced, apart from distance from the access point, by building materials, interference and any other obstructions. Coverage area can be increased depending of the deployed protocol and technology, such as Multiple Input Multiple Output (MIMO) systems that deploy multiple antennas to achieve higher performance. Newer protocols such as IEEE802.11ac allow for dynamic beam forming to prioritise certain clients via focused directional beams if so required.
- **Utilization**. The Wi-Fi network's capacity will need to take into account the intended number of end users, which will determine technology choice.
- **Security**. Wi-Fi signals can be intercepted thus potentially comprising confidential information. This is especially of importance in terms of privacy legislation. IEEE802.11i protocol supports Wi-Fi Protected Access v.2 (WPA-2), a security protocol featuring encryption standards such as Advanced Encryption Standard (AES). WPA-3[13] a more robust Wi-Fi security standard has been announced by the Wi-Fi alliance in June 2018. The standard, which is able to integrate with WPA-2, will feature stronger cryptographic strength for stricter data security compliance requirements e.g. the Commercial National Security Algorithm (CNSA). From a user interface perspective it will allow users to choose less complex passwords whilst still offering resilient authentication which will assist designs rolled out to a less computer literate audience.

2.3 Data Collection

Introduction of two major sensor laden consumer technology products—Nintendo's Wii[14] and Apple's iPhone[15]—set in motion a major demand cycle for electronic sensors (Bryzek 2014). In 2007 the market already absorbed 10 million of these sensor laden systems, by 2014 this figure had grown to 10 billion units. Today, primarily driven by the ever expanding smartphone market, a plethora of robust Micro-Electro-Mechanical Systems[16] (MEMS) are available on the market for reliable data acquisition, for virtually any application.

To collect data BARC needs to be equipped with any number of sensors which will be connected into the communication system and the raw data transmitted to a cloud-based data repository. The IEEE initially defined the IoT (Minerva et al. 2015)

[13]Wi-Fi Alliance, W. 2018. *Wi-Fi Alliance® introduces Wi-Fi CERTIFIED WPA3™ security*. https://www.wi-fi.org/news-events/newsroom/wi-fi-alliance-introduces-wi-fi-certified-wpa3-security. Accessed 20 July 2018.
[14]Ewalt, D. 2006. *Nintendo's Wii Is A Revolution*. https://www.forbes.com/2006/11/13/wii-review-ps3-tech-media-cx_de_1113wii.html#2d2a47fd75bb. Accessed 22 June 2018.
[15]Apple. 2007. *Apple Reinvents the Phone with iPhone*. https://www.apple.com/newsroom/2007/01/09Apple-Reinvents-the-Phone-with-iPhone/. Accessed 14 November 2018.
[16]MEMSnet. 2018. *MEMSnet. Information Portal for MEMS and Nanotechnology community*. http://www.memsnet.org/mems/what_is.html. Accessed 28 April 2019.

as "A network of items—each embedded with sensors—which are connected to the Internet". From such a perspective BARC will in itself be both IoT device and data collection hub.

The Android sensor framework provides a standardised way to access and utilise sensors in a simplistic way by identifying sensors and their capabilities, monitor sensor events and acquire data and meta-data. The intention for this design is therefore to utilise the Android sensor framework platform to govern three broad categories of sensors:[17]

1. *Motion sensors*; measure linear and rotational acceleration along three axes including accelerometers, gravity sensors, gyroscopes, and rotational vector sensors.
2. *Environmental sensors*; including barometers, photometers, and thermometers used to measure environmental parameters including; ambient air temperature and pressure, illumination, and humidity. Specialised sensors can be added to measure Volatile Organic Compounds, CO_2 and PM2.5 (Particulate Matter) data, which can help to understand pollution patterns.
3. *Position sensors*; determine the geographical location, and physical position and orientation of a device. The envisioned sensors include Global Navigation Satellite System (GNSS) such as GALILEO,[18] GLONASS[19] and GPS,[20] orientation sensors and magnetometers.

These technological developments on multiple fronts are rapidly making the concept of an "electronic skin" (Rim et al. 2016) which can monitor a variety of parameters (physical, chemical, biological etc.) simultaneously a reality. Such sensors will allow for direct integration into a structure or direct application onto a surface. The Nokia "Morph", introduced in 2008, was a design study of such a concept.[21] The Morph was essentially a cell phone albeit one being flexible and stretchable featuring a number of built-in sensors to interact with its environment. Researchers at the University of Colorado have produced "E-Skin" (Zou et al. 2018) which is a synthetic skin with the unique ability to regenerate itself in addition to being able to detect airflow, humidity, temperature and touch (Fig. 3).

[17]Android. 2018. *Sensors Overview*. https://developer.android.com/guide/topics/sensors/sensors_overview. Accessed 29 April 2018.
[18]GSA, 'Galileo is the European global satellite-based navigation system' https://www.gsaeuropaeu/european-gnss/galileo/galileo-european-global-satellite-based-navigation-system. Accessed 28 April 2019.
[19]GLONASS, 'Information and Analysis Centre for Positioning, Navigation and Timing' https://www.glonass-iacru/en. Accessed 24 April 2019.
[20]GPS, 'GPS: The Global Positioning System' https://www.gpsgov. Accessed 24 April 2019.
[21]Nokia. 2008. *Nokia. The Morph Concept*. http://research.nokia.com/morph. Accessed 30 July 2018.

Fig. 3 Evolution of flexible sensors over a decade (see footnote 21, Zou 2018)

2.4 Effector Module

When Audi announced in 2009 that it would replace all incandescent lights in their top of the line R8 with LEDs, it was an indication just how reliable the technology had become. Other manufacturers followed suit and today LED technology features on virtually all car models in one way or the other. This versatile, adaptable and constantly evolving light source has therefore become the “go-to” technology for most modern outdoor lighting solutions. Though normal visible spectrum LED lights come in all shapes in sizes, they have the attributes listed in Table 2.

The choice of LED solution will be dictated by the following design consideration:

- Beam angle—there are basically two functional types, *directional*, which comes in different angles, or *omnidirectional.*
- Brightness—measured in lumens (lm).
- Colour temperature—also known as Correlated Colour Temperature (CCT), is a way to describe the shade of white of a LED and is measured using the Kelvin[22] scale.
- IP Rating—(Ingress Protection)[23] refers to the degree of protection provided by electrical enclosures against intrusion of solid objects, dust, and water. The higher the IP rating the more resistant the LED will be against environmental conditions.
- Placement—LED light fixtures operate well in most environments, handling cold and moisture better than other type of outdoor illumination sources.

[22]Holland, A. 2017. *Lighting 101: Color Temperature—What is the Kelvin Scale?* Holland, Andrhttps://www.larsonelectronics.com/blog/2017/12/12/led-lighting/lighting-101-color-temperature-what-is-the-kelvin-scale. Accessed 28 April 2018.

[23]Engineering Toolbox. 2017. *The Engineering Toolbox*. https://www.engineeringtoolbox.com/ip-ingress-protection-d_452.html. Accessed 23 November 2017.

Table 2 Attributes of LED lights

Attributes of LED Lights	
Low energy usage	Generates little heat
Longevity	Can operate in cold temperatures
Produces little to no IR or UV radiation	Shatterproof and shock resistant housings
Non toxic (no mercury or harmful gasses)	Available in different "whites" and colours

2.4.1 Ultrathin LED

In recent years a number of manufacturers have introduced products into the market featuring extremely thin LED's with the ability to be applied to a variety of substrates, including flexible and stretchable material (Fig. 4). These new generation LED's use a fraction of the power of conventional LED's (as much as 15 times less), and require 40% less physical volume, are dimmable and suitable for submersible applications.[24] These lights represent a lower low total cost of ownership in that they are easy to install, cool to the touch, flexible, lightweight and are a naturally diffused light source allowing maximum design flexibility to integrate light into structures in ways previously not possible. This technology offers unique possibilities from a design perspective due to the physical flexibility of the product, ingress protection and the low power requirements.

2.5 Power

Small-scale off-grid renewable power generation systems typically utilize photovoltaic (PV) technology or small wind-turbines. The World Bank sponsored Energy Sector Management Assistance Program (ESMAP) provides global resource maps for both solar[25] and wind[26] power generation. The data supports the choice for PV as opposed to wind energy for Sub-Saharan applications as indicated in Fig. 5. PV power generation is a well-established technology with global generating capacity in already exceeding 385GW in 2017.[27] Due to large scale solar power adoption programs globally—most notably in China and Europe—the cost of PV has shrunk significantly in certain cases as low as 0.03 USD per kWh. Bifacial solar cells with the ability to collect irradiance from the front and the back face of the panel, allows for designs where surface reflection can be utilised for to boost power generation output with as much as 30% (Hezel 2003). A fast-growing niche segment in the PV market is the manufacturing of stable cost-effective, high efficiency (16–22%),

[24]Rohinni. 2018. *Create in ways you've never imagined*. Create in ways you've never imagined. 2018. http://www.rohinni.com. Accessed 1 May 2018.
[25]Global Solar Atlas. 2018. *Global Solar Atlas*. https://globalsolaratlas.info/. Accessed 1 June 2018.
[26]Global Wind Atlas. 2018. *Global Wind Atlas*. https://globalwindatlas.info/. Accessed 1 June 2018.
[27]IRENA. 2018. *Renewable capacity statistics*. Abu Dhabi: International Renewable Energy Agency.

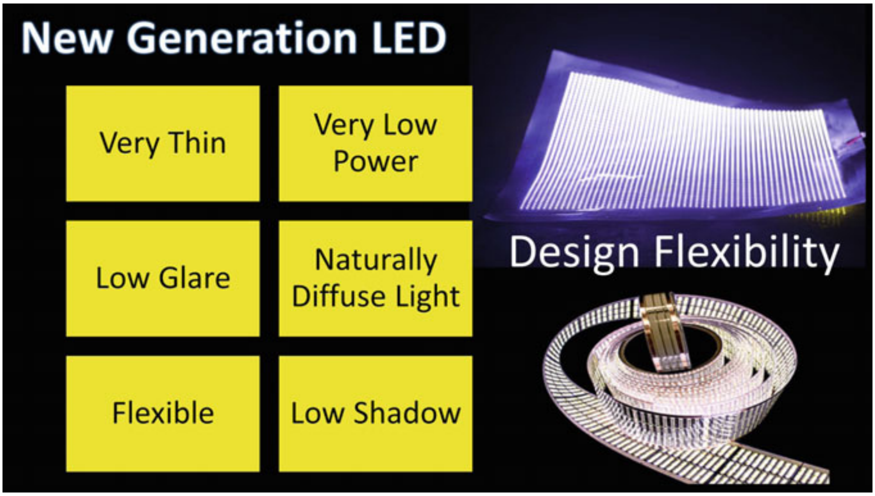

Fig. 4 New LED light technology (Nth-Light. 2018. *Printing the impossible* < *br* > . https://www.ndeg.com/. Accessed 28 April 2018

CIGS (Copper, Indium, Gallium & Selenide) "thin film" PV cells.[28] Though cadmium—a toxic material—is often associated with CIGS and thin film PV, there are manufactures e.g. Midummer[29] Solar in Sweden producing cadmium-free CIGS. This technology enables the manufacturing of very light and flexible PV modules that can be integrated in previously impossible applications, such as integration into different materials as "frameless" panels (Fig. 6).

Tarpon,[30] a company in Norway, has integrated thin film PV into canvas used for sailing to create a hardy material with a claimed power generation ability of 120 watts per m^2 see Fig. 6.

From a design point of view, the concept of PV integrated into material is of extreme interest as it will allow for design forms not possible with traditional rigid "framed" solar panels.

Charge controllers and Inverters

In addition to the PV collectors a solar system needs charge controllers and inverters. The charge controller ensures the correct charge rate and in so doing prevents damage to the battery and improves lifetime. It also prevents the solar panel discharging the battery at night. PV installations will also require an inverter for AC applications.

[28]NREL. 2017. *Solar Innovation Infographic.* https://www.nrel.gov/solar/infographic.html. Accessed 14 February 2019.

[29]Midsummer. 2018. *Environment.* http://midsummer.se/technology/environment. Accessed 1 May 2018.

[30]TarponSolar. 2018. BRUKSOMRÅDER. http://tarponsolar.no/bruksomr%C3%A5der.html. Accessed 1 May 2018.

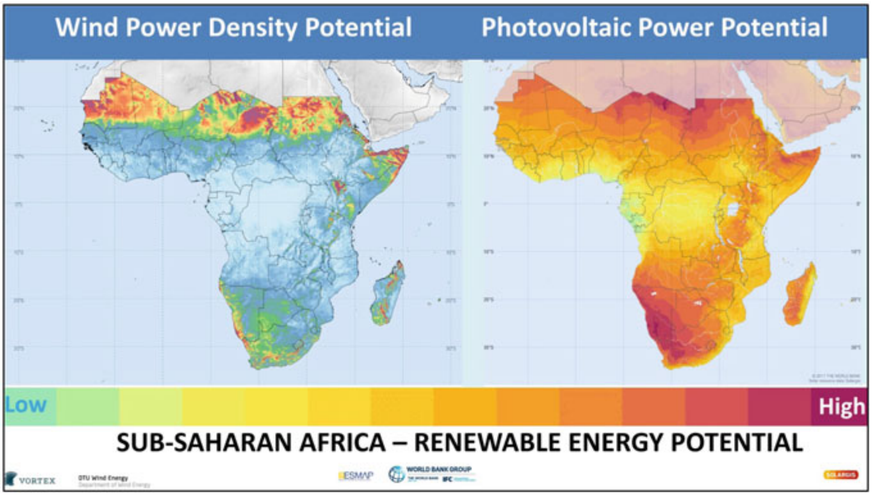

Fig. 5 Wind and photovoltaic potential of sub-Saharan Africa

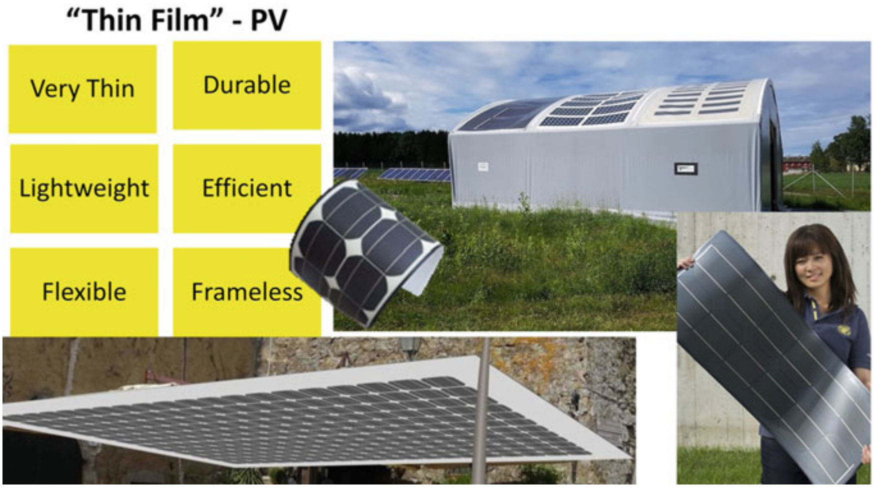

Fig. 6 Examples of new PV technology

Charge Storage
Charge storage is a major consideration for a PV installation to supply power to the application when solar illumination is absent or too weak for adequate charging. There are a number of ways to calculate the storage requirements for the system but all are a function of three factors:

- How much power can the solar panels generate?
- How much power is used by the application?
- How long must the application be supported during no power generation?

There are many different battery solutions available for different demands, as detailed in the battery comparison table[31] in Appendix A. From a design perspective virtually all of the specifications listed in the battery comparison table need consideration, though the specific energy density (expressed as Watt hours produced per kg) is normally the main deciding factor (e.g. a lead acid battery will not be a consideration for a mobile application such as a smartphone). The second deciding factor is how long the battery takes to charge and thirdly how long the battery lasts before it needs to be replaced, an important consideration for solar power, where the batteries will be exposed to daily charge cycles. Battery technology has been evolving significantly, driven by the mobile phone industry, emerging electric car industry, drones, robotics and electric bikes, amongst others. The industry is trying to find solutions around the constraints imposed by lithium-ion batteries. There are some emerging technologies addressing specific application pain-points such as lifespan, charge time, safety and weight. Technology such as gold nanowire batteries—it does not degrade even at extreme charge cycles and Solid state lithium-ion—can function in extreme temperature ranges.[32] Though these technologies show great promise they are not available on the market as yet. Graphene batteries on the other hand not only offer extremely short charge times but are starting to become available on the market for a range of applications. Spanish company Grabat[33] energy has a number of graphene options for applications such electric bicycles, which could be used in this design. These batteries have a high energy density, are very light and compact, and offer short charge times which can be well integrated into the design.

3 Architecture Definition

The product architecture definition is based on information documented in the use-case scenarios discussed in Chap. 2. It identified and categorised system customers and the master modules, subdivided into sub-modules. To effectively represent the customers and modules in the diagrams, the following naming convention was adopted see Fig. 7:

- System customers: Two capital letters between curly brackets e.g. "{CN}".
- Master modules: Two capital letters between square brackets for the master module e.g. "[MM]".

[31]Epec. 2018. *Battery Cell Comparison.* http://www.epectec.com/batteries/cell-comparison.html. Accessed 1 May 2018.

[32]Langridge, M. & Edwards, L. 2018. *Future batteries, coming soon: Charge in seconds, last months and power over the air.* https://www.pocket-lint.com/gadgets/news/130380-future-batteries-coming-soon-charge-in-seconds-last-months-and-power-over-the-air. Accessed 2 November 2018.

[33]Grabat. 2018. *Clean and Sustainable Energy for All - Energy storage systems based in graphene technology.* https://www.grabat.es/en. Accessed 2 November 2018.

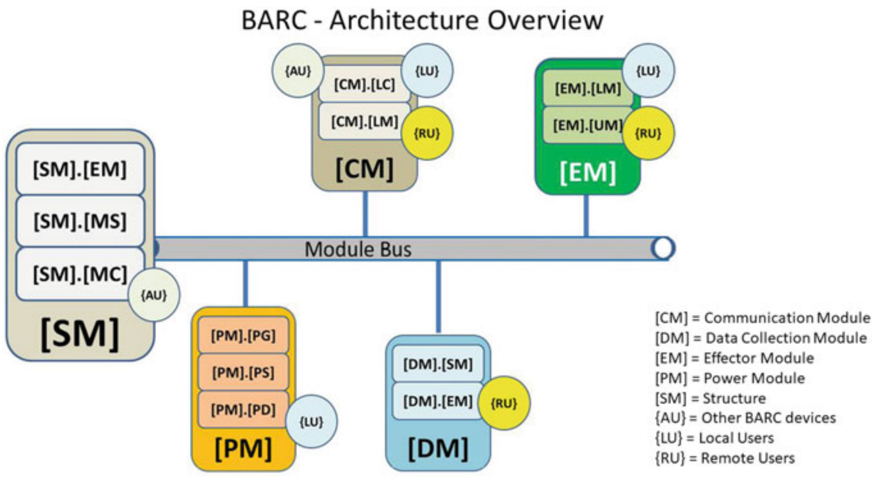

Fig. 7 BARC System Architecture Overview

- Sub-module: Master module name followed by a "dot" and two capital letters in square brackets e.g. [MM].[SM].

A key feature of the architecture is the use of a "module bus" which represents a reticulation system integrated into the structure which is used to interlink all modules to a master control unit. All modules thus interact indirectly with each other via this unit, creating an easy interface for maintenance and future upgrades. This module has built-in redundancy to reduce operational risk.

4 System Module Architecture

For each of the functional modules the same approach was followed, create an abstraction of the module in the form of a "Module Overview Diagram" and a key component list each allocated a function number, which can form the basis of a costing exercise—not included in the scope of this design study.

4.1 [SM]: Structural Support Modules

Key to the design is the structural module favouring strong lightweight, weather resistant construction materials with virtually no maintenance as the ideal. The module has two principal functions see Fig. 8:

1. Provide the physical frame of the design which is used to accommodate all the modules physically.
2. Create the mechanism for the logical integration of all the different modules.

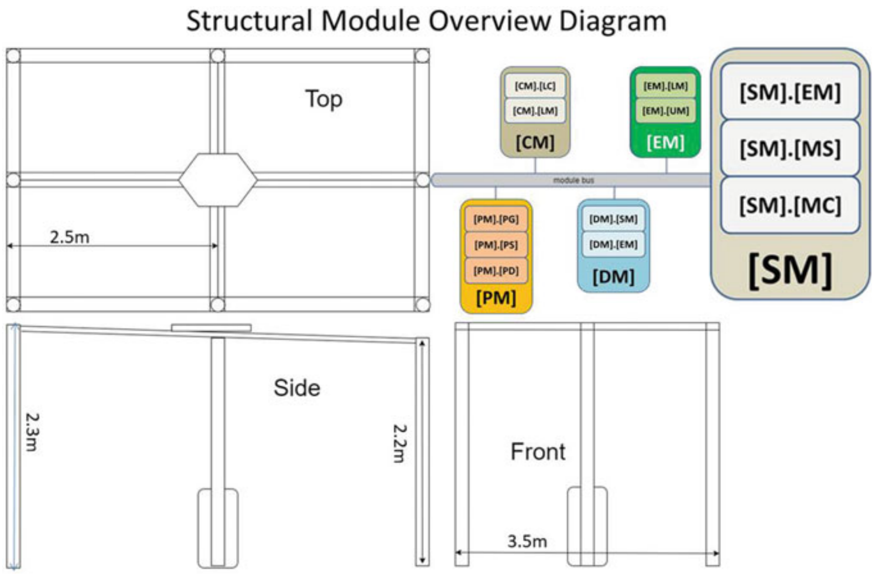

Fig. 8 Structural module overview

4.1.1 [SM].[MS]: Master Structure

A Master Structure is responsible for the structure and reticulation required to interlink all the modules. It features a reticulation system integrated into the structure which is used to interlink all modules to a master control unit—referred to as the "module bus" in the architecture diagrams.

The basic structure consists of eight vertical poles supporting horizontal support beams interconnected by cross beams, all connected using connector pieces. Each vertical pole consists of two sections, a bottom one terminating in an adjustable "foot" piece and a top section terminating in a connector piece. The structure can support a roof area of 17.5 m^2, the front vertical poles are slightly higher than the back to create a slight incline to assist water run-off. Key features include:

- "Plug and Play" assembly of components for ease of on-site construction of the system, with all components fitting together using a series of connectors, secured using a bolting system.
- Integration of reticulation for power and system communication into structural components using "plug-in" connectors.
- All structural components are made out of lightweight anodized aluminium.
- No structural section is longer than 2.2 m to facilitate transport.
- Integration points for the components of the other modules on the surface of selected structural components.

In total there are 55 primary structural components. Refer to Appendix B: Structural module bill of material for the component "bill of materials" breakdown of this submodule.

4.1.2 [SM].[MC]: Master Control Module

This is the "heart of the system" which controls all the functional modules, this module houses all hardware and software required to integrate all modules. A central point of failure for the system, two units are used in the design, an active one and a redundant one. These two units are physically housed in the base of the left and right vertical front base unit poles. Key features are:

- Central connector for all system control reticulation linking all modules indirectly.
- Power distribution centre to all the modules.
- Allows monitoring and remote control of all the modules.
- Automatic fail-over redundancy.

4.1.3 [SM].[EM]: Expansion Interface Module

This module is essentially a subset of the Master Control Module ([SM].[MC]). It provides the ability for BARC systems in the same vicinity to be linked up to each other, enabled by the local communications sub-module ([CM].[LC]). This module gives each BARC system a "Unique Identity Token" to identify the deployed devices. It will be used as an asset tag by remote management, for local networking with other units and for data encryption. Data encryption is an important consideration, as each BARC system will be collecting data for a multiple data-owner scenario where privacy needs to be guaranteed. To avoid complexity in encryption key management a multi-authority Attribute Based Encryption (Li et al. 2013) will be implemented in the module. The concept of Attributed-Based Encryption (ABE) was introduced to allow data to be encrypted using a set of descriptive user attributes in combination with the private key (Sahai and Waters 2005). Three attributes will be used for the Attributed-Based Encryption as well to construct the "Unique Identity Token" which will consist out of the combination of the following attributes:

A. Serial number—a unique number allocated to each manufactured system.
B. Configuration number—describes the specific hardware configuration of the specific system.
C. Geolocation—latitude and longitude of the device as determined by GNSS sensors.

Both the serial and configuration number will be stored as a 64-byte string generated using the SHA-256[34] algorithm as per the following example:

> Serial number S\N1234567890 will be represented as:
>
> 0AADAACA98BA919462FAC75D5CA55118067F151B7ACD08F86ADEEEE03AB22708

The geolocation component (Bartock 2015) is of specific importance as an enabler to resolve security challenges associated with "Infrastructure as a Service" cloud computing technology which will be utilised by BARC. A geolocation attribute will also allow for the implementation of "geo-fencing" i.e. the ability to trigger a software based event based on the state of the location coordinates. A specific BARC system will thus have the ability to behave in different ways depending on the deployed area, making compliance with local regulations easier to manage.

4.2 [CM]: Communication Module

Responsible for the communication functions between the device and any other device it needs to connect to. The module is interconnected with all the other modules via the "module bus". The technology review section demonstrated the advantage of wireless technology for deployment in remote areas. Functionally the module consists of two sub-modules responsible for local and remote communication ("Last-Mile"). For the local communications two versions of Wi-Fi technology were selected: 802.11 g for all local devices and 802.11ac for additional BARC systems. Flat panel satellite technology is suited to the flat surface structure intended by the design statement (refer Sect. 4.1). All components of this module are mounted in enclosures mounted on top and underneath the roof structure utility mounts forming part of the structure module bus.

This module is further divided into two sub-modules "local" [CM].[LC] and a "Last-Mile" [CM].[LM].

4.2.1 [CM].[LC]: Local Communications Sub-Module

This sub-module is responsible for all communications between the system and any on-site device. There are two different system customer groupings served by this module. Firstly it provides a Wi-Fi signal to enable internet access through a device such as a basic Android tablet to on-site users. Access is provided in an indirect fashion with the access point connected to the internet via a proxy to minimize downloads of identical material and so preserve internet bandwidth of the "Last-Mile" link. The access point will use 802.11 g Wi-Fi technology and connect

[34]NIST FIPS 180-4. 2015. *Secure Hash Standard (SHS).* FIPS 180-4. Boulder, CO.: NIST.

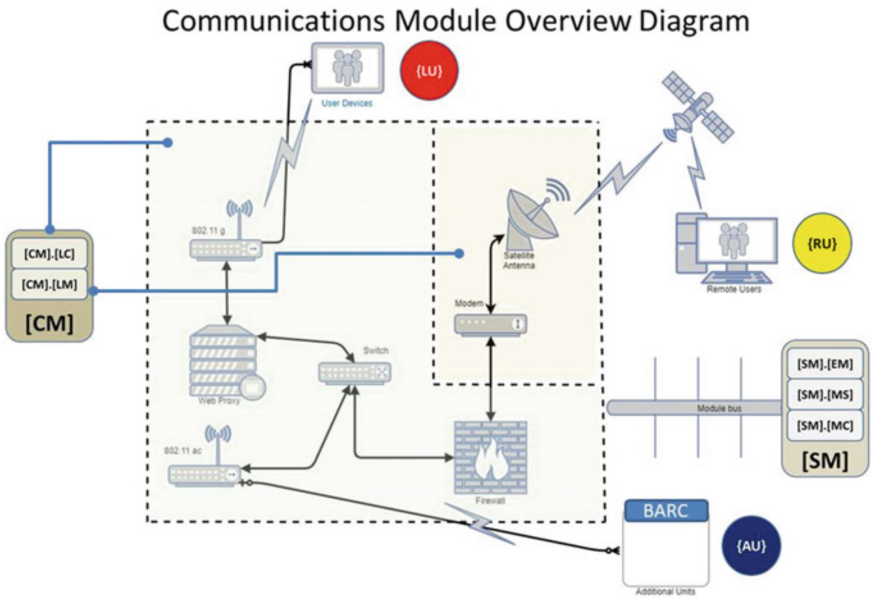

Fig. 9 Communications module overview

to the "web-proxy" via an internal switch and firewall to the external link router. The choice of 802.11 g Wi-Fi ensures backward compatibility to all the older Wi-Fi standards and is an ideal choice in areas where user access devices might use older technology Wi-Fi. The second purpose of this sub-module is to link multiple BARC systems in the same area to each other. 802.11ac Wi-Fi will be the technology of choice as it supports beam forming and high speed links. Beam forming is an important feature as it allows the signal to be aimed directly from one BARC to the other as opposed to a broadcast contributing to greater efficiency and practical throughput in excess of 1 gbps. 802.11ac technology will coexist efficiently with the 802.11g technology used for the user signal without interference see Fig. 9.

4.2.2 [CM].[LM]: "Last-Mile" Communications

This module is responsible for bridging the "Last-Mile" communications, enables the device to link to the internet i.e. taking care of the "Last-Mile". It uses a FPA satellite antenna with the ability to access high-throughput broadband satellites constellations. The antenna technology should have the ability to auto locate the chosen constellation. Technically the module consists of the aforementioned FPA and a relevant modem which is connected to the firewall of the local communications sub-module ([CM].[LC]). The module is mounted on top of the roof structure and connects with the other modules via the module bus. The module is the direct link between the local system and remote users including:

- Remote management, responsible for the everyday management of the system.
- Remote customers, an entity paying for the use of any aspect of the system e.g. a data user.

Table 3 Communications module component list

Sub-module	Functional component	Component reference
[CM].[LC]	Wi-Fi accespoint-1 802.11 g	[CM].[LC].LAP-G
	Wi-Fi accesspoint-2 802.11ac	[CM].[LC].LAP-AC
	Web proxy	[CM].[LC].WPX
	Component switch	[CM].[LC].CSW
	Firewall	[CM].[LC].FW
	Enclosure	[CM].[LC].ENC
[CM].[LM]	Satellite FPA	[CM].[LM].SFPA
	Satellite modem	[CM].[LM].SATM

Table 3 lists the breakdown of the sub-modules into functional components and the allocated component reference.

5 [EM]: Effector Module

The EM is responsible for creating an “effect” that is of benefit to its customers on receipt of a conditional sensory input. It is functionally connected via the module bus to the sensor modules of the “Data Module” providing the sensory input. Functionally the module consists out of two sub-modules, one to provide light at night for the local users and the second in the form of a utility interface to accommodate a temporary effector. Temporary effectors might differ based on the purpose of the deployment. An entomologist interested in studying the effectivity of electronic malaria mosquito repellents, might use the temporary effector interface to deploy an effector such as an ultrasonic transducer in combination with the relevant sensors (Enayati et al. 2007). The data will be provided to the remote user and study is completed the temporary effector interface will be available for a different purpose. Technically the EM uses flexible flat panel LED technology for the “light” module and standard USB connectivity. The module serves local as well as remote users and consists out of two sub-modules.

5.1 [EM].[LM]: “Light” Module

This module’s primarily function is to provide an illuminated area under the roof of the unit which can be used by the local community at night. In addition to this it can also act as a warning device under certain circumstances. This module utilizes four ultrathin LED flexible panels mounted on a flexible mounting panel attached to the bottom of the roof section of the structural module (refer Fig. 10). Each of the panels contains colour RGB (Red, Green and Blue) addressable LED panels with the ability to emit light in a variety of colours depending on the input from an sensor driven control panel. Based on input from the sensors of the Data Module it

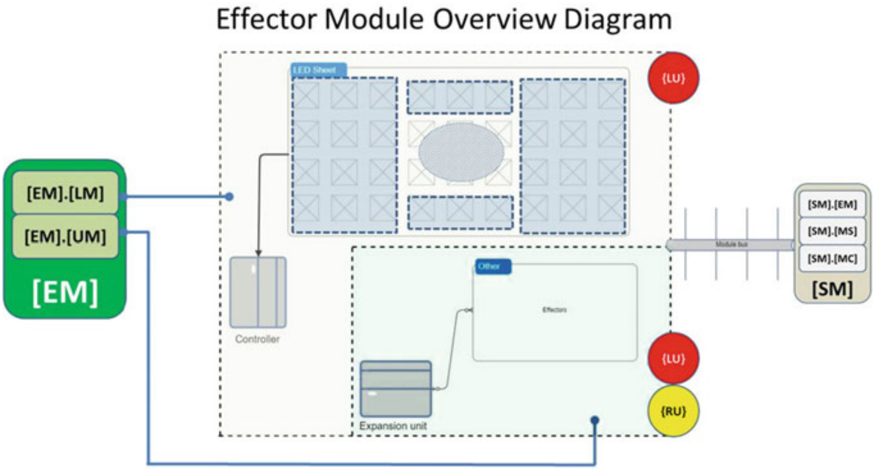

Fig. 10 Effector module overview

switches the light on at a predetermined Lux level of ambient light. A controller unit connected to the panels adjusts colour and intensity based on the sensors input and time of day or predetermined warning conditions. Under normal conditions the panels will gradually increase in intensity at night until a predetermined time when it will change in colour and intensity to limit the effects of light pollution (Falchi et al. 2011).

5.1.1 [EM.UM]: Utility Module

This module's primarily function is providing additional effector services to both the local community and remote users. Each of the four expansion units can connect up to two different types of effectors using a standard USB connectors such as USB-3[35] or higher. These units connect to expansion points of the structure module located on the roof frame or the vertical poles. Each of the expansion units takes input from sensors in the Data Module and reacts to it in a predetermined way. Examples of such effectors can include audio speakers and infrared light panels. Application of this module for example to firstly the community and secondly to remote users:

- Mosquito control—an electronic mosquito trap can be used as such an effector where mosquitos act as disease vectors e.g. Rift Valley Fever and malaria. Studies have shown mosquitos are attracted to blue and green artificial LED light, which can be switched on at appropriate times and coupled to an electric mosquito trap (Tchouassi et al. 2012).

[35]USB. 2011. *USB 3.0 Connectors and Cable Assemblies Document Rev. 1.02*. https://www.usb.org/document-library/usb-30-connectors-and-cable-assemblies-document-rev-102. Accessed 25 March 2019.

Table 4 Effector module functional component list

Sub-module	Function	Component reference
[EM].[LM].	Large LED panel-Front	[EM].[LM].LLEDF
	Large LED panel-Back	[EM].[LM]. LLEDB
	Small LED panel-Left	[EM].[LM].SLEDL
	Small LED panel-Right	[EM].[LM].SLEDR
	Back panel-Left	[EM].[LM].BPL
	Back panel-Right	[EM].[LM].BPR
	Control unit	[EM].[LM].MCU
[EM]. [UM].	Expansion unit1-Front	[EM].[UM].EX1F
	Expansion unit2-Back	[EM].[UM].EX2B
	Expansion unit3-Left	[EM].[UM].EX3L
	Expansion unit4-Right	[EM].[UM].EX4R

- Scientific studies—an infrared light panel and camera can be used in conjunction with an ultrasonic receiver to photograph bats coming into the area of the system. Certain types of bats are known carriers of serious zoonotic diseases for example the Ebola virus and identification and concentration of known carriers can be used for epidemiological studies (Leroy 2009).
- Warning system—the LED panels can be used to change colour and used in conjunction with a speaker system to create an effective warning for the community based on local sensor input or remote intervention. A tsunami warning can be directed via remote control to a vulnerable community.

Table 4 lists the sub-module breakdown per function and allocated component reference.

6 [DM]: Data Collection Module

The DM is responsible for collection and processing of data this module provides input to a number of other modules which it is connected to via the module bus as well as to remote customers via the Communications Module. Functionally the module consists of two sub-modules. The first module contains a standard sensor pack which is similar to all deployed BARC units. This module uses an adapted Android sensor framework and deploys three broad categories of sensors namely,

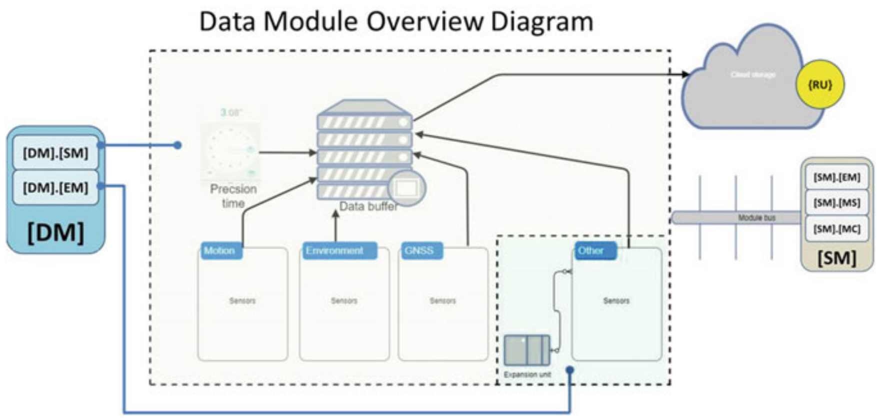

Fig. 11 Data module overview

motion, environmental and GNSS sensors.[36] The second module provides a utility interface to accommodate up to four temporary sensor packs provided by remote users for their own purposes. All components are housed at various specialised expansion points of the structure module located on top and below the roof frame as well as the foot pieces of the vertical poles. The module is also responsible to provide a standardised time-stamp and geolocation meta-data to all data collected by the sensors using data obtained from the GNSS sensors. All raw data collected by the sensors are collected in a data buffer and "stamped" with meta-data before being sent to a centralised cloud-based storage container, available for retrieval. The module serves local as well as remote users and consists out of two sub-modules see Fig. 10 (Fig. 11).

6.1 [DM].[SM]: Standard Data Collection Sub-module

This sub-module collects a standard dataset from a set battery of sensors across all BARC systems. Sensors are either hardware, (which collects raw data directly from the environment), or software based, where values are calculated in the cloud based on the collected raw data. There are three main categories of sensors, either hardware based or software based:

1. Motion sensors
   a. Hardware—accelerometer and gyroscope.
   b. Software—gravity, linear acceleration, rotation vector and significant motion.

[36]Android. 2018. *Sensors Overview*. https://developer.android.com/guide/topics/sensors/sensors_overview. Accessed 29 April 2018.

2. Environmental sensors
   a. Hardware—humidity, illuminance, barometric pressure, temperature, CO_2 and particulate matter.
   b. Software—dew point and absolute humidity.

3. GNSS
   a. Hardware—GPS, GLONASS and Galileo.

6.2 [DM].[EM]: Expansion Sub-module

This sub-module allows for additional sensor packs to be connected to the system to collect data not in the scope of the standard data set. Remote users who need to collect unique data-sets from the area where the BARC system is deployed thus have an opportunity to provide a customized sensor pack which can be connected to the system. Each of the four expansion units can accommodate a single sensor type. They connect to expansion points of the structural module with two located on the roof frame and another two located on the lower foot sections of the vertical support poles. The foot section in this case refers to the part of the support structure making direct contact with the ground allowing sensors attached sensors to penetrate the soil for example. Examples of application of these units:

- Soil humidity—a sensor pack can be added to one of the bottom locations to measure the moisture content of the soil.
- Air quality—sensors measuring for example airborne volatile organic compounds.

All data collected on behalf of the customer is processed via the data buffer and in addition to time and geolocation metadata is allocated a customer ID tag. The data is subsequently transmitted to a "cloud" repository for collection by the customer. Table 5 lists the breakdown of the sub-modules into functional components and the allocated component references.

7 [PM]: Power Module

This module is responsible for generation, storage and distribution of electrical power for the BARC system. This module consists of three submodules responsible for electrical power generation, storage and distribution. The module distributes the power to all modules via the module bus which is integrated into the Structural Module (refer Sect. 4.4.1). The power requirements of the system defines the size of the PV surface area, and therefore is ultimately responsible for the dimensions of

Table 5 Data module functional component list

Sub-module	Function	Component reference
[DM].[SM]	Sensor—Accelerometer	[DM].[SM].MSA
	Sensor—Gyroscope	[DM].[SM].MSG
	Sensor—Humidity	[DM].[SM].ESH
	Sensor—Illuminance	[DM].[SM].ESI
	Sensor—Barometric	[DM].[SM].ESB
	Sensor—Temperature	[DM].[SM].EST
	Sensor—CO_2 & PM	[DM].[SM].ESG
	Sensor—GNSS	[DM].[SM].GNSS
[DM].[EM]	Expansion unit1.Front Top	[DM].[EM].DEX1F
	Expansion unit2.Front Bottom	[DM].[EM].DEX2F
	Expansion unit3.Left Top	[DM].[EM].DEX3L
	Expansion unit4.Right Bottom	[DM].[EM].DEX4R

the roof area and the structure supporting it. The module consists out of three sub-modules.

7.1 [PM].[PG]: Power Generation Module

This module is responsible for the generation of electrical power using PV, it consists out of a charge controller and a single "roll-up" PV canvas. The thin film photovoltaic segments—Copper-Indium-Gallium-Selenium technology—are integrated into a very durable "on-extending laminated fabric"[37] with the ability to produce 120 W/m^2. The communications module enclosure covers a portion of the of the total 17.5 m^2 allowing for at least 15 m^2 available for the PV arrays allowing for a maximum output of 1.8 kW. This sub-module also contains a fully redundant charge control system, a very important component when working with Lithium ion battery technology as it is very important to ensure that the cells are not overcharged i.e. to continue charging the cell once it reaches a 100% state of charge. Overcharging can lead to a runaway thermal reaction presenting a fire hazard which could be difficult to deal with (Lisbona and Snee 2011).

7.2 [PM].[PS]: Power Storage Module

This module stores the electrical power generated by the PV canvas in a distributed battery storage system consisting of four battery storage units. The system is fully redundant, i.e. two of the units can supply the required power to the BARC system

[37] TarponSolar. 2018. *BRUKSOMRÅDER*. http://tarponsolar.no/bruksomr%C3%A5der.html. Accessed 1 May 2018.

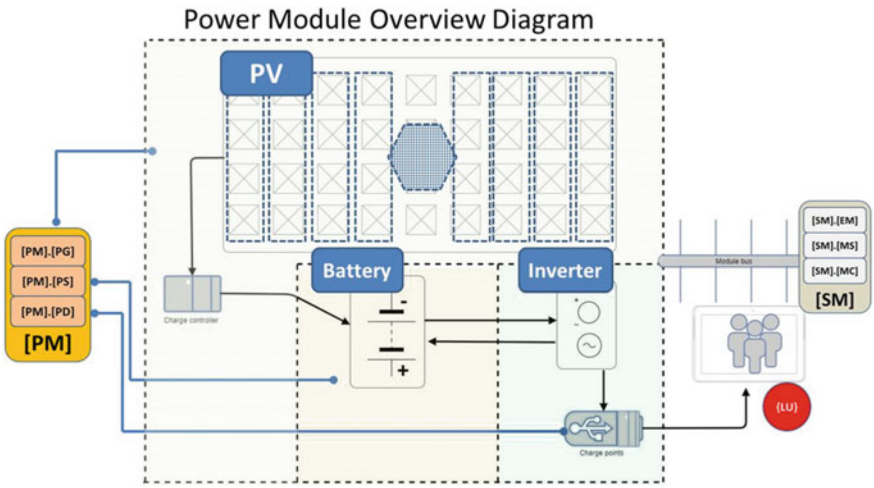

Fig. 12 Power module overview

see Fig. 12. All four units are all interconnected using the module bus and feature load balancing and automatic failover. The four power storage units are attached to the base of the central vertical support poles. Each unit consists of a charge controller, a battery and a connector interface. Lithium ion battery technology is currently best suited for this application. Although it is expensive, it is relative light and compact compared to other battery technologies, an important consideration for the design. Lithium ion batteries also have a higher depth of discharge and longer lifetime and are maintenance-free when compared to other batteries. There is a down-side to the use of Lithium ion batteries however, as the technology relies on a flammable non-water-based electrolyte with a fire hazard associated with its use (Ribière et al. 2012). The Samsung Note 7 "exploding batteries" scandal involving the flagship "Galaxy Note 7" product brought the very real issue of the danger involved with Lithium ion batteries to public attention.[38] It also showed how important preventative design is when deploying Lithium ion battery packs. Each of the sub-modules will be equipped with a fire suppressant system capable of dealing with Lithium ion fires and preventing a runaway reaction.[39] Though the initial design as described is built around the use of Lithium ion technology, the nature of the design of the power storage units makes it possible to accommodate newer battery technology as it becomes practically available.

[38]Lopez, M. 2017. *Samsung Explains Note 7 Battery Explosions, And Turns Crisis Into Opportunity.* https://www.forbes.com/sites/maribellopez/2017/01/22/samsung-reveals-cause-of-note-7-issue-turns-crisis-into-opportunity/#42796da824f1. Accessed 25 November 2018.
[39]Maloney, T. 2013. *Extinguishing Agents for Lithium-ion Batteries.* Washington DC: FAA; FAA.

7.3 [PM].[PD]: Power Distribution Module

This module manages the distribution of electrical power for internal and external use, i.e. for the device itself and its users. It comprises the reticulation system built into the structural modules, which connects a fully redundant inverter system to the battery storage units. In addition to supplying system power; the module also acts as the physical user interface. It provides charge point units for on-site users built into the vertical support poles at the back of the unit, these units can be replaced as new technology becomes available. The initial design provides for the most popular charge point formats, with the focus being the lower power consuming technology provided used by USB 3.0. It also caters for Thunderbolt,[40] USB-C[41] and "2-pin" to allow for devices with higher power needs most likely the requirement guest users to the site. The system is equipped with an intelligent power "throttling" feature to prevent abuse and allow access for guest users. A number of biometric readers are built into the centre vertical support poles which can be used in conjunction with the aforementioned intelligent charge system to allow guest users access to the facilities offered by the BARC system. A key controlled master control switch is provided to allow the system to be switched off physically in case of a re-boot requirement.

Table 6 lists the breakdown of the PM sub-modules into functional components and the allocated component references.

Figure 13 depicts the system architecture a 3D model of the proposed design.

8 Conformance to Requirements

The final step in the process was to ensure the design satisfied the set of initially defined requirements. Three sets of requirements were initially set, namely Functional Requirements, Performance Requirements and User Acceptance Requirements. All the Functional Requirements (refer Sect. 2.2) are met by the detailed design, as the design architecture was guided by the Functional Requirements. Performance Requirements (refer Sect. 2.3.2) are listed below with a note on conformance for each;

- P01—Ability to be optimised for multiple conditions;
  - Modular design.
- P02—Easy to assemble—within two working days;

[40]Maggie Tillman and Dan Grabham, 'Thunderbolt 3 explained: Taking USB-C ports to the next level'. https://www.pocket-lint.com/laptops/news/139323-thunderbolt-3-explained-the-one-port-to-rule-them-all. Accessed 25 April 2019.

[41]Tom Brant, 'What Is USB-C? An Explainer'. https://www.pcmag.com/article/332797/what-is-usb-c-an-explainer. Accessed 25 April 2019.

Table 6 Power sub-module component list

Sub-module	Function	Component reference
[PM].[PG]	PV canvas	[PM].[PG].PV
	Charge controller x 2	[PM].[PG].$CC_{1–2}$
[PM].[PS]	PSU × 4	[PM].[PS].$BS_{1–4}$
	Fire suppressant system × 4	[PM].[PS].$FS_{1–4}$
[PM].[PD]	Inverter × 2	[PM].[PD].$IV_{1–2}$
	USB-3 Charge points unit × 16	[PM].[PD].USBA/$USBC_{1–16}$
	Thunderbolt-3/USB-C × 4	[PM].[PD].$THBT2_{1–4}$
	2Pin Charge points unit × 4	[PM].[PD].$2PN_{1–4}$
	Biometric readers × 4	[PM].[PD].$BIO_{1–4}$
	Master control switch	[PM].[PD].MXS

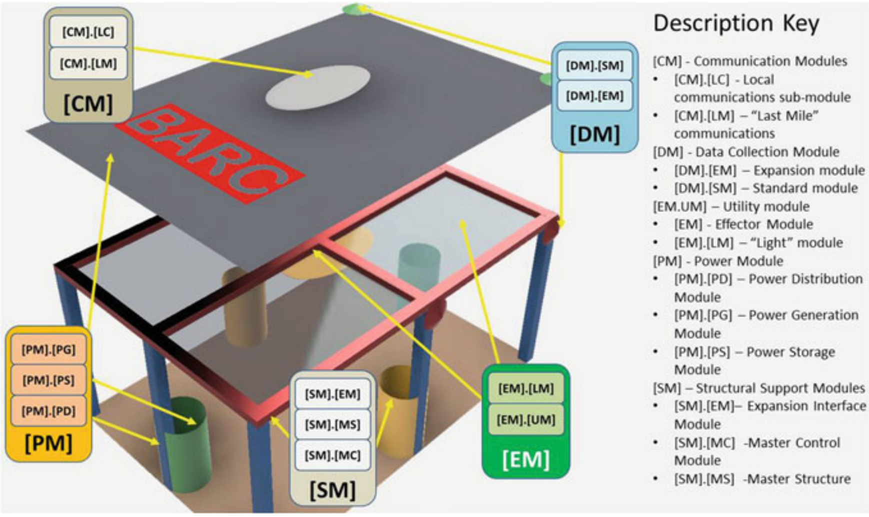

Fig. 13 BARC architecture overlay on 3D model

- Plug and play assembly.

- P03—Easy to use—users can be trained within a day;
  - Allows for the use of biometrics and standard charge points.
- P04—Visibility—clearly visible day and night
  - Large structure, Illuminated at night.
- P05—Provides wireless access from a minimum 20 m distance

 - 802.11 g Wi-Fi technology exceeds the requirement.

- P06—Mean time before failure > 26,000 h
  - Weatherproof materials and redundant systems.
- P07—Robust, able to withstand normal environmental conditions.
  - Use of weather-proof materials such as anodized aluminium and high ingress protection rated equipment.
- P08—Power redundancy for 24 h
  - Uses fully redundant battery system.
- P09—Broadband uptime 95% minimum
  - Satellite broadband exceeds the specification.
- P10—Response time—average latency < 500 ms
  - Can be met provided lower orbit constellations are used and assisted by the built in webserver.
- P11—Accuracy—< 2% packet loss
  - Within range of satellite broadband technology but will be influenced by weather.
- P12—Workload—support a minimum of 100 concurrent users at 100 kbps
  - A 10 mpbs can be readily provided by satellite broadband and the design also provides a built-in webserver.
- P13—Scalable—adjusts to available bandwidth
  - Flat panel satellite antennas with auto tracking ability can dynamically exploit new broadband constellations and deliver it to site.
- P14—Low Planned Maintenance—twice yearly on site
  - Long life material and remote management.
- P15—Easy to maintain on-site component replacement must take less than 8 h

- Modular "plug and play" design.

- P16—Compliance must conform to all local regulations.

  - Uses renewable technology and environmentally safe components—will not be deployed if it cannot meet local regulations. Data will be collected in accordance to the General Data Protection Regulation of the EU.[42]

- P17—Upgradable can accommodate future upgrades

  - Modular design "plug and play design".

The User Acceptance Requirements (refer Sect. 2.3.1) are a function of the social impact of the design and will be dealt with in the next chapter, dealing with the potential impact of the implementation of such a product into the intended demographic.

[42] European Commission '2018 reform of EU data protection rules' https://ec.europa.eu/commission/priorities/justice-and-fundamental-rights/data-protection/2018-reform-eu-data-protection-rules_en. Accessed 19 December 2018.

Impact

The world is rapidly changing through the process commonly referred to as digital transformation. This process, formally defined as "The application of *digital capabilities* to processes, products, and assets to improve efficiency, enhance customer value, manage risk, and uncover new monetization opportunities", is reshaping society. The world is rapidly changing through the process commonly referred to as digital transformation. This process, formally defined as "The application of *digital capabilities* to processes, products, and assets to improve efficiency, enhance customer value, manage risk, and uncover new monetization opportunities", is reshaping society.[1] Digital capabilities refers to a process or action characterised by one or more of the following attributes: "Electronic, scientific, data-driven, quantified, instrumented, measured, mathematic, calculated and/or automated."[2] The "SMACT" group of technologies referring to Social Media, Mobile Tech, AI and Analytics, Cloud and IoT, is currently considered to be the main enabler of digital transformation. The transformative power of SMACT lies in its ability to rapidly add new users to current networks in the form of sensors, people and other networks, thereby increasing the utility of the overall network. With over three billion people not connected to the internet the introduction of BARC technology has the potential to add a substantial amount of value to the existing internet. Maximum value of a networked society can only be achieved through global connectivity and the provision of internet in an affordable manner to all people. In this chapter the potential impact of BARC are explored against four key impact areas: Society, Economics, Sustainability and Governance.

[1]Schmarzo, W. 2017. *What is Digital Transformation.* https://infocus.dellemc.com/william_schmarzo/what-is-digital-transformation/. Accessed 28 November 2017.
[2]Ibid.

C. Kotze, *A Broadband Apparatus for Underserviced Remote Communities*, Southern Space Studies, https://doi.org/10.1007/978-3-030-15766-1_5

1 Society

The primary goal of introducing a product like BARC is to bring about positive change to underserviced communities. One of the most pressing problems in the world today sadly enough is still hunger. Present in virtually all countries to some extent, but much more prevailing in poorer countries, almost 98% of global hunger is linked to underdeveloped countries, where in some cases up to 73% of the population could be affected.[3] The uncertainty in the ability of a country or an individual to have access to adequate food supply is referred to as food-insecurity. This condition causes stress in individuals and communities alike, leading to social upheaval and ultimately even political instability. The desired position is therefore to create food-security—defined by the World Food Summit[4] as creating the condition where "all people at all times have access to sufficient safe and nutritious food for an active and healthy life." According to the Food and Agriculture Organisation (UN FAO) globally the number of people subject to chronic hunger is sadly increasing, affecting 11% of the global population in 2016.[5] Hunger can be caused by a number of diverse factors but persistent hunger is primarily caused by poverty. The poor lack the resources to obtain nutritious food either directly or indirectly by not having access to the means of production. Hunger in itself ironically can be a cause of poverty in the first place. Poor health caused by malnutrition and malnourishment can leave person less able to compete in the labour market causing poverty, leading to a vicious circle making it difficult for the affected person to escape. Malnutrition occurs when people—especially to infants and developing children—do not have access to essential nutrients. Trace elements and micronutrients are crucial for a normal, healthy development and growth in humans. Three of these are of particularly importance according to the World Health Organisation (WHO) namely Iron, Vitamin A and Iodine with deficiencies creating a long-term impact.[6]

- Iron—Anaemic conditions caused by a basic iron deficiency in foodstuffs in developing countries are often further exacerbated by parasitic and infectious diseases like malaria, TB, HIV etc. In developing countries 50% of pregnant and 40% of preschool children are thought to be anaemic to some degree. Anaemic conditions can be undermine the health of the affected person ranging from

[3]Borgenproject. 2016. *Global Poverty 101.* https://borgenproject.org/rise-against-hunger-an-organization-striving-to-create-a-tangible-impact/. Accessed 2 December 2016.

[4]Committee On World Food Security. 2012. Committee On World Food Security—Thirty-Ninth Session. Rome: FAO, 2012. *COMING TO TERMS WITH TERMINOLOGY Food Security Nutrition Security, Food and Nutrition Security*. 15 –20 October 2012. Rome: FAO.

[5]FAO. 2018. *The State of Food Security and Nutrition in the World 2018*. http://www.fao.org/state-of-food-security-nutrition. Accessed 3 May 2018.

[6]eLENA. 2017. *e-Library of Evidence for Nutrition Actions (eLENA)—Nutrients.* https://www.who.int/elena/nutrient/en/. Accessed 6 June 2017.

increased maternal and childhood morbidity, impaired development both mental and physical (Bailey et al. 2015).

- Vitamin A—Reduced immune resistance to disease, night blindness and retarded growth in children are caused by Vitamin A deficiency (Bailey et al. 2015). In the developing world 250 million are estimated to be Vitamin A deficient. Each year an estimated 370,000 children become blinded by Vitamin A deficiency of which 50% will statistically die within 12 months of loss of sight.[7]
- Iodine—A range of serious conditions can result from iodine deficiency, especially during pregnancy, causing spontaneous abortion, stillbirth, and is linked in certain areas of Africa and Asia to a serious irreversible form of congenital mental retardation called cretinism (Bailey et al. 2015). Normal cognitive development in children can be severely retarded by iodine deficiency which can be easily reversed by simply adding iodized salt to the diet.

Though the introduction of broadband infrastructure to remote underserviced villages will not directly prevent malnutrition it does enable two very powerful mechanisms for proactive prevention and intervention—Education and Healthcare.

1.1 Education

Quality early childhood education fosters social and emotional development in addition to providing basic language and cognitive skills. Lack of education creates a disadvantage early in life for a large portion of the world's children contributing to increased inequality. Ensuring universal education with traditional methods necessitates the training of at least 26 million primary school educators around the world with Africa having the greatest need. Unfortunately most countries are experiencing a shortage of teachers in addition to facing the problem of underqualified teachers.[8]

The mechanism of delivering instruction from teacher to student is the one aspect that has benefitted from technological development through the ages. Long-distance education has formally been in existence since the late 1800's when the first distance education began via mail, with the first generation of "correspondence study" (Moore and Kearsley 2011). Distance education has subsequently expanded utilising successive generations of new delivery technology, e.g. radio and television. Communication technology has evolved especially rapidly with the advent of the internet age. As data rates increase and cost decreases the opportunity to present distance students with a rich multimedia experience has been growing consistently. These new powerful mechanisms of delivery have presented educators with the opportunity to challenge existing models using disruptive innovation.

[7]Vitamin A deficiency. 2017. *Micronutrient deficiencies - Vitamin A deficiency.* https://www.who.int/nutrition/topics/vad/en/ accessed 17 June 2017.

[8]Richardson, E. 2014. *Teacher motivation in low-income contexts: An actionable framework for intervention.* (Fall). UNESCO.

The MOOC (Zhenhong et al. 2013) concept (Massive Open Online Course) was established when Stanford University made available certain courses for free on the internet. Following Stanford's lead, a growing number of established academic institutions also started to make available some of their courses free of charge to encourage mass participation in continued education. Most of the top universities in the world currently have MOOCs in place in one form or the other, either through their own delivery mechanisms or through MOOC portals such as Coursera (www.coursera.org). In addition to the aforementioned, a number of MOOCs from non-traditional educational institutions started theme-oriented practical courses in areas such as language learning (e.g. Duolingo www.duolingo.com), promotion of computer coding (e.g. Codecademy www.codecademy.com) or general digital skills (e.g. Udemy www.udemy.com). Virtually all MOOCs in addition to the traditional web interface are also enabled for mobile devices via free apps available for the two popular mobile platforms (Android and iOS) to deliver the course in a format suited for the smaller device screen. Mobile devices allow students the freedom access to content from virtually anywhere as long as the broadband connection is available. Teachers are able to use additional techniques such as gamification on platforms, for example KhanAcadamy.[9]

Mobile devices also make available low-cost video cameras that can be used in interactive educational session over existing free to market platforms such as Skype. MOOCs are mostly free, the only direct cost being the access hardware and access to broadband internet.

There are other challenges though, especially in the developing world, where over and above the basic ICT requirement aspects, access language and computer literacy needs consideration (Castillo at al. 2015). In this aspect Artificial Intelligence (AI) may offer additional opportunities. In China Liuilisho offers an AI service teaching English to 70 million people. The course uses natural language and adapts to the pace of each individual user.[10]

The Sway4edu2[11]—Satellite Way for Education, uses satellite technology to provide broadband for education. The European Space agency (ESA) sponsored project is an example of a successful remote education project. In South Africa's Mpumalanga province twelve very remote schools have been provided with a Ku-band satellite link, laptops, a projector and an AV system. Teachers and students of these schools can now benefit from all the advantages offered by availability of internet connectivity through fresh content and teaching methods. The project also makes available interactive training for the local teachers for further education and certification.

New technologies, such as affordable Virtual Reality (VR) headsets, offer interesting alternatives to a classic classroom scenario, with each student having

[9]Khan Academy. 2018. *You can learn anything. For Free. For everyone. Forever.* https://www.khanacademy.org/ accessed 18 January 2018.

[10]Liulishuo. 2018. *Your Personal AI English Teacher.
*. https://www.liulishuo.com/en/index.html accessed 2 May 2018.

[11]SWAY4Edu. 2017. *SWAY4Edu - Satellite Way for Education.* https://business.esa.int/projects/sway4edu accessed 17 March 2017.

access to a multimedia experience.[12] Exciting opportunities exist for MOOCs to be built with the help of communities to reflect the unique indigenous knowledge of those communities.

Education additionally can play a very positive role in support of primary healthcare through programs supporting behaviour favouring healthy living. Awareness programs for mothers to combat malnutrition can be delivered to support intervention programs and enable intra-village collaboration.

1.2 Healthcare

ICT has become a very important tool in healthcare systems across the globe and is an integrated feature of modern healthcare. Hospitals are filled with ICT systems to provide not only administrative functions but also the essential integration of medical records and modern diagnostic equipment. ICT can play an important role through e-Health in remote underserviced areas, especially in the developing world. Initially the term "telemedicine" was used to describe any form of remote healthcare application, normally involving real-time communication between the two parties, typically using audio and video technology (Della Mea 2001). The primary advantage of ICT systems is the ability to collect data and provide communication to link remote areas poor in diagnostic and skill resources to facilities rich in those, such as hospitals and clinics staffed by skilled professionals. The term eHealth is mostly used nowadays to acknowledge the extensive role the internet plays as part of a greater health system. The Space Technology Applied to Rural Papago Advanced Health Care (STARPAHC) (Freiburger et al. 2007) was one of the earliest telemedicine projects demonstrating the use of satellite communication technology in rural healthcare which took place in the 1970's. New technological developments are opening up new possibilities.

Social Media applications can also be used to provide support to allow health workers and patients to exchange information through a familiar interface. The nature of social media like Facebook can also be used as a "sensor" to detect and monitor outbreak of diseases (Charles-Smith et al. 2015). Advanced analytics on collected data can be used in many innovative ways to aid healthcare in the developing world. In the aftermath of the 2010 Haiti earthquake, data analysis was used to anticipate communicable disease outbreaks by tracking meta-data from cell phones of people's movement from affected areas.[13] In Tanzania a communication system using SMS was used to manage reorder levels of anti-malaria drugs (Barrington et al. 2010). The future potential is expected to be much greater as more data are collected from areas previously excluded and increasingly advanced automated analytic techniques start to emerge in the form of AI. Ironically the lack

[12]Jarrett, N. 2016. *10 Simple Ways To Use Google Cardboard In The Classroom.* https://edtech4beginners.com/2016/02/25/10-simple-ways-to-use-google-cardboard-in-the-classroom/ accessed 31 May 2018.
[13]Howell, K. 2017. *How Big Data is Impacting the Developing World.* https://epics.ieee.org/big-data-impacting-developing-world/ accessed 14 April 2017.

of any pre-existing technology investments in rural areas provides opportunity as the new technology can be adopted without any legacy system investments creating additional adoption barriers.

Mobile technology particularly has special potential for rural healthcare provided communication is available as devices are increasingly affordable and plentiful. Two examples of application of basic mobile technology is the EpiCollect and Mobile Midwife systems. EpiCollect technology allows a field-user to collect data and submit it to a web-hosted repository to assist in epidemiology.[14] In Ghana the "Mobile Midwife" application introduced in 2010 is an example of a very basic m-Health system (LeFevre et al. 2017). The system provided a simple SMS or voice messaging system to relay information between patients, midwives and the local health facility through the duration of a pregnancy, dealing with general information and serving as an alert agent. The system has subsequently been rolled out in Nigeria. Technology has also been used to drastically reduce river blindness (Onchocerciasis) in West Africa by using remote sensing satellite data, modelled environmental data in conjunction with in situ data to create micro maps of target areas for onchocerciasis elimination activities (Kelly-Hope et al. 2015). Elimination of river blindness has the added benefit of potentially opening up 25 million hectares of land for economic exploitation.[15]

2 Economics

The 2016 World Bank Development report refers to the phrase "Digital Dividends" as the potential economic benefit realisation through the global spread of digital technology implementation. The economic impact of broadband introduction has been the subject of numerous studies using different target populations to quantify an impact quantum as represented in Table 1. In all cases a positive impact on the economy is recorded when broadband is introduced. Studies do show that a certain threshold of broadband penetration needs to be reached for it to have an initial impact on the economy.

Once this initial broadband threshold is reached the economy will benefit with each additional 10% of broadband penetration amplified by the network effect (Wadhwa 2018). Initial studies found fixed broadband to have the highest impact on the economy, though the benefits from the availability of mobile broadband are increasing in importance as well (Khalil et al. 2009). Mobile internet in low-income developing countries has been found to have a higher impact based on availability and a high number of basic subscriptions (Katz and Koutroumpis 2013).

[14] Epicollect. 2017. *Mobile & Web Application for free and easy data collection.* http://www.epicollect.net/instructions/ABOUTUS.html accessed 12 April 2017.

[15] World Bank. 2014. *Forty Years Later: The Extraordinary River Blindness Partnership Sets its Sights on New Goals.* http://www.worldbank.org/en/news/feature/2014/07/03/forty-years-later-the-extraordinary-river-blindness-partnership-sets-its-sights-on-new-goals accessed 23 July 2017.

Table 1 Effect of broadband access on GDP

Study	Countries included	Period	% increase in GDP per 10% increase in fixed broadband penetration
Qiang et al. (2009)	High income economies	1980–2006	1.2% impact on per capita GDP
Qiang et al. (2009)	Low income enemies	1980–2006	1.4% impact on per capita GDP
Czernich et al. (2011)	25 OECD 300 observations	1996–2007	0.9%–1.5% impact on per capita GDP
Koutroumpis (2009)	15 EU 60 observations	2003–2006	0.3%–0.9% impact on GDP
García Zaballos and López-Rivas (2012)	26 LAC[a] 121 observations	2003–2009	3.2% impact on per capita GDP

[a]Latin America and the Caribbean

A General Purpose Technology (GPT) is defined in broad terms as a technology with the ability to expose new opportunities across the economic spectrum as opposed to simply addressing one particular aspect (Bresnahan and Trajtenberg 1995). Examples of GPTs include the steam engine, electricity, internal combustion engine, and railways. These technologies not only boost productivity across all sectors and different industries, they also it require a remake of infrastructure, leading to the reinvention of business models, even changing cultural norms. A GPT has three distinct characteristics (Bresnahan and Trajtenberg 1995):

1. Pervasive: Used in a wide range of sectors across different industries
2. Technological dynamism: It has the potential for continual technical improvements
3. General productivity: Evolution of the GPT produces productivity gains through the economy.

Broadband as a technology enabler of economic opportunity rather than as a "product" can therefore be seen as a GPT (Czernich et al. 2011). Broadband in conjunction with applications, contents, hardware and related services can satisfy the three GPT defining criteria:

- Criterion 1: Broadband is used as input in virtually every industry using ICT.
- Criterion 2; Broadband by nature is an evolving technology with constant improvements in speed and quality.
- Criterion 3: Broadband can enable and inspire new organizational methods resulting in marked productivity increases, e.g. GNSS devices using broadband to enable a new public transport system such as Uber.

The World Bank as one of the organisations actively promoting the economic benefits of broadband proliferation—in both developed and developing countries–has developed the Broadband Ecosystem model (Kelly and Rossotto 2012). The model assumes as a basic premise that broadband is available to users, secondly but importantly, recognizing the necessity of demand generation to justify the required network investment. Demand importantly needs to be driven by economic activities not primarily engaged in the direct ICT services and infrastructure sector, to create synergy to drive innovation and economic growth (Fig. 1).

Though the supply and demand components are essential to promote the need for broadband infrastructure and services, it cannot act as driver without capable users. Broadband can only reach its full economic potential as a GPT when driven by a user population—individuals, businesses and government—skilled in the ability to apply benefits and opportunities of the broadband ecosystem to economy and society. In organisations this is referred to as the “Absorptive Capacity” or the ability of the user-pool to recognize the value of new external information, assimilate said information and apply it in a way beneficial to the user-pool (Tsai 2001). An important consideration when considering the potential success of intra-organisation knowledge-transfer networks, is to determine the ability of the recipient of the “knowledge” to understand the knowledge received from the source (Tang 2011). This ability is critical to drive innovation in society through assimilation of new technologies by transformation of established processes, products or services. In the case of broadband, users have the ability to be content creators and, through user–led innovation, drive co-creation by fellow users of the broadband-enabled platform, provided the adsorptive capacity is present in the target population. Full cross-section economic benefit realisation of broadband will thus occur when the relevant role-players have the capacity to fully exploit the capabilities offered by the introduced platform. In terms of BARC the target community thus needs to find value in using the system to add value to the system.

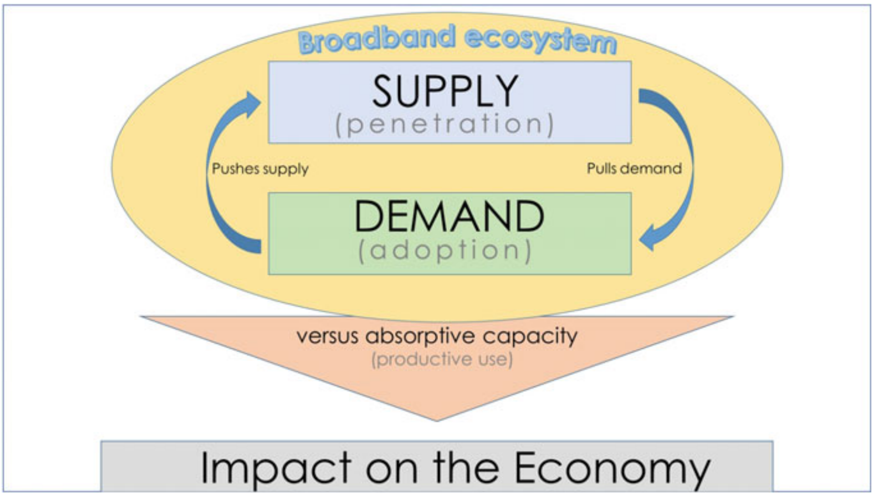

Fig. 1 The World Bank broadband ecosystem view (Kelly and Rossotto 2012)

In practical terms the impact of broadband internet has primarily been on the cost of production, the result of lower transaction costs enabled by the ability of users to acquire "cheap" information. It is estimated that the cost of computation has dropped by a factor of somewhere between "1.7 trillion and 73 trillion" times since the start of computational technology in the mid nineteenth century (Nordhaus 2007). The internet provides the means of distributing benefits of cheap transaction costs and the constant increasing volume of cheap information to an ever increasing diverse global user populace. The economic benefits provided by the broadband internet are threefold:

Inclusion

In its simplest form the availability of information creates awareness about the availability of a product or service, which in turn creates the potential for trade. The availability of e-commerce technology providing a safe environment for customer and supplier to trade makes trade possible using interfaces requiring little skill creating a more inclusive trading platform with a relatively low barrier of entry for example. Anou describes how Moroccan artisans are trading without middle men all over the world through their own dedicated trading portal.[16]

Efficiency

The internet has been introducing an accumulating stream of "micro" improvements to the efficiency of businesses processes, the cumulative impact of which has resulted in major economic benefits. Insights brought about by the use of data analysis of ERP systems have produced highly efficient supply chain management, enabling increasingly effective e-commerce, especially in combination with GNSS data. UPS[17], an American courier company used location data to create a very simplistic operational model for their drivers—"never turn through oncoming traffic at a traffic junction". This simple instruction has eliminated 37.8 million litres of fuel annually and yielded a number of additional knock-on benefits.[18]

Innovation

The introduction and convergence of increasingly powerful technology at increasingly lower pricing driven by Moore's law[19] has led to mass adoption of increasingly sophisticated technology by the general public. The modern smartphone is probably the most visible example of converged technology. In 1992 IBM introduced a product called the "Simon", the first functional "smartphone" of which around 50 000 units were sold. By the end of 2018 the global smartphone

[16] Anou. 2018. *Anou is a community of artisans working together to reshape Morocco's artisan economy so that it works for them rather than against them.* https://www.theanou.com/about accessed 28 February 2018.

[17] UPS, https://www.ups.com/us/en/global.page accessed 17 May 2019.

[18] Kendell, G. 2017. *UPS drivers don't turn left—and it saves them 10 million gallons of gas a year.* < *br* > . https://qz.com/895691/ups-drivers-dont-turn-left-and-it-saves-them-10-million-gallons-of-gas-a-year/ accessed 16 February 2018.

[19] Moore, G.E. 1995. Lithography and the future of Moore's law. *Integrated Circuit Metrology, Inspection, and Process Control IX.* International Society for Optics and Photonics. 2–18.

Table 2 Benefits of digital technology to key stakeholders[a]

	Digital technology		
	Inclusion	Efficiency	Innovation
Business	Trade	Capital utilization	Competition
People	Job opportunities	Labour productivity	Consumer welfare
Governments	Participation	Public sector capability	Voice

[a]World Bank Group. 2016. *World Development Report 2016: Digital Dividends*. World Bank Publications

population is estimated to exceed 2.5 billion.[20] The combination of smartphone technology, GNSS and cloud computing has created innovative products and services—many challenging existing traditional business models of which the Uber ride sharing service is probably one of the better known examples.

A summary of the effect that the three above-mentioned dynamics of internet introduction have on society is illustrated in Table 2.

The definition for what technically constitutes broadband differs from country to country but principally it is about capacity and speed of access, i.e. the data transfer rate which defines ultimately which services the end user can connect to effectively over the internet. Developed countries normally have a higher minimum data rate to qualify as broadband than those in the developing world. The Broadband Strategies Handbook (Kelly and Rossotto 2012) sponsored by the World Bank was published in 2012 to assist policymakers—especially in the developing world–to acknowledge the economic importance of broadband, identify challenges, potential solutions and broadband as Universal Access and Service (UAS).

The ICT Regulation Toolkit[21] broadly defines the concepts of Universal Access and Universal Service as follows:

- **UA (Universal access)**—Everyone can access the service somewhere
- **US (Universal service)**—Everyone can have the service.

In addition the UA and US should be:

- **Available**—to all "inhabited parts of the country through public, community, shared or personal devices"
- **Accessible**—to all citizens regardless of "location, gender, disabilities and other personal characteristics"
- **Affordable**—to all citizens.

[20]Statista. 2018. *Number of smartphone users worldwide from 2014 to 2020 (in billions)*. https://www.statista.com/statistics/330695/number-of-smartphone-users-worldwide accessed 12 February 2018.

[21]ICT Regulation Toolkit. 2018. *A global resource for policy-makers, regulators, the telecom industry, and consumers*. http://www.ictregulationtoolkit.org/index accessed 16 February 2018.

Currently the full benefit of digital dividends still need to be realised globally. This is primarily the result of the failure to provide broadband as global UAS. The BARC can contribute by extending the digital dividend to the current demographic affected by the digital divide.

The final aspect that needs addressing to ensure adoption of BARC product by the intended demographic is to ensure it is affordable. Herein lies a problem; the intended demographic are typically one of the poorest in the world. Roughly 73% of the Sub-Saharan African population lives of less than 2 USD a day and an additional 5% on less than 1.25 USD per day. With not much of the small disposable income left after food expenditure to spend on anything else, new trade/earning opportunities are limited—an important driver of migration from rural areas to cities.[22] Though solutions such as BARC will be able to provide broadband as a universal service, affordability will be a major barrier for the successful introduction of such a technology platform into a market with very little expendable income.

What constitutes broadband affordability in a world with an ever increasing skewed income distribution? The UN Broadband Commission currently defines affordability as a 500 MB data plan available for less than 5% of average monthly income expressed as GNI/capita.[23] The A4AI (Alliance for Affordable Internet) argues that the formula does not take poverty and income inequality—including along gender lines—into account. A country with a high inequality distribution could therefore meet the UN's minimum ratio whilst a significant portion of the population could still be excluded from internet affordability. The A4AI has proposed the "1 for 2" ratio where 1 GB of data costs less than 2% of available income, which research shows will bring broadband within reach of most people.[24] One GB of data per month can provide the user with approximately 20 h of social media time, access to twenty 20-min educational videos at basic rate and 10 h of multimedia web-browsing. As it could be difficult to convince a population with very little disposable income to spend it on a service they may know little about, innovative funding models need to be considered.

2.1 Utilization and Partnership Opportunities

Bill Gates famously said "The internet is becoming the town square for the global village of tomorrow"—it is the very role intended for BARC, to include its community in the growing global broadband ecosystem. Introducing the product can forge mutually beneficial partnerships between the community and a diverse

[22]Global-Growing. 2018. *Fact-7: About three quarters of the African population live of less than $2, half of the population of less than $1.25 per day. People in rural areas are more often struck by poverty.*

[23]State Of Broadband, 2. 2017. *The State Of Broadband 2017: Broadband Catalyzing Sustainable Development.* Geneva: ITU.

[24]A4AI. 2016. *Redefining Broadband Affordability: Adopting a "1 for 2" Target to Enable Universal, Affordable Access.* https://a4ai.org/1for2-affordability-target/ accessed 1 May 2018.

stakeholder community e.g. commerce, scientific, government, individuals, NGO's. Though Education and Healthcare applications doubtless have a very high social impact, applications ensuring economic opportunity are the gateway to growth value. Though it is not possible to list, or even imagine the full utilization spectrum of the BARC, the following examples are deemed to be practical with a significant impact quantum.

Agri-Tech

In the developing world the agriculture sector is the largest employer. Sadly this sector does not contribute significantly to GDP, generally due to inefficient practices on relatively small lots and challenging access to the marketplace. Many young people therefore leave the rural areas in search of opportunity in the cities, which leads to abandoned land that becomes unproductive with nobody to work it. By introducing new productivity-boosting techniques and providing effective means to access to the marketplace the role of agriculture can be strengthened significantly.

A BARC system can leverage its utility of data collection and communication to successfully support "agri-tech"—the collective term used to describe the practice of technology use by farmers to increases efficiency and profitability. Though often associated with the more glamorous aspects of "precision agriculture"[25], featuring full automation using exotic robotic technologies, the real potential for the small farmer lies in data integration. This approach is characterised by the collection and processing of data to produce information systems which can be used to aid the farmer e.g. creating advanced prediction models and presenting it in plain useful way.

Prediction has always played an important role in farming, the further the farmer can peek into the future the greater the opportunity to mitigate risks. In addition to the well-known weather prediction (both long and short term) market and plague prediction systems are very important to farmers. Though there are already many systems available, most of them require the use of propriety hardware and software not in reach of many small-scale rural farmers, even if the communication technology is available. Farming with the aid of long-term prediction systems helps the farmer to plan and mitigate risk e.g. weather and plague prediction systems. More than 80% of agricultural production in the developing world is produced by small-scale farmers who typically do not have access to agricultural support services. Plant diseases thus often are not identified early on in the infection cycle, leading to devastating crop losses.

A research project using AI which can learn to recognize specific plant diseases very accurately, has been developed by researchers at Penn State and the Swiss Federal Institute of Technology.[26] This technology could be particularly beneficial to small-scale farmers in areas such as sub-Saharan Africa. Mobile devices can be

[25] Remi Schmaltz 'What is Precision Agriculture?', https://agfundernews.com/what-is-precision-agriculture.html accessed 9 April 2019.

[26] Gill, C. 2016. *Artificial intelligence could help farmers diagnose crop diseases.* https://news.psu.edu/story/429727/2016/10/04/research/artificial-intelligence-could-help-farmers-diagnose-crop-diseases accessed 22 May 2018.

used to gather data, which can be fed into the system to prescribe timely interventions. Communication again is key for such as service to be of any benefit. Insect swarms like green beetle, army worms, weevil, locusts and aphids cause severe crop damage over vast areas annually. Swarming can be predicted. FAO has devised a locust prediction system with a 70 day future-window using satellite data. Combining information from NASA's Aqua and Terra and SMOS from ESA create maps highlighting areas that favour locust swarming conditions.[27] Small-scale farmers could thus be warned using BARC if their area is going to be affected, as all BARCs are geo-located. Similar systems can be deployed based on intelligent software analysis done for plant disease prediction, soil management and other involved analytical tasks.

Getting products to market is another aspect where agri-tech can assist small-scale farmers. Product delivery is one of the areas where drones can be particularly well-suited providing an option to farmers where access to roads and lack of transport prevents practical access to larger markets. Though not all produce could be transported this way, it may be ideal for small-scale farmers of high-value produce like spices, often farmed in forest clearings which are difficult to reach conventionally. The BARC could act as a charge station and relay point for such drone activities.

Agri-tech holds vast potential especially in Africa where it is being adopted at a very rapid rate showing a 110% growth in start-ups since 2016.[28] However it is dependent on communication and data flow, making the BARC an ideal support platform. For skilled young people from rural areas who find themselves unemployed in the cities, introduction of this technology might serve as incentive to return to the rural land and apply their skills to integrate new technology into agriculture.

Banking

The Grameen Bank project in Bangladesh has proven that development can be driven by providing credit to "poorest of the poor" in rural areas, with no need for collateral. This bank targeted people who are often seen as "un-bankable" by conventional institutions.[29] Digitisation has brought new opportunities to bank the "un-bankable" population. According to the World Bank's Findex database, in 2017 as many as 1.7 billion adult people worldwide (mostly women) remained without any form of bank account or mobile money provider.[30] Digital payment systems provide various platforms to include even people without formal bank accounts into trading systems.

[27]Phys.org. 2017. *Satellites forewarn of locust plagues. 2017.* https://phys.org/news/2017-06-satellites-forewarn-locust-plagues.html accessed 28 May 2018.

[28]ShapShak, T. 2018. *African Agri-tech Startups Boom With 110% Growth Since 2016.* https://www.forbes.com/sites/tobyshapshak/2018/05/09/african-agri-tech-startups-boom-with-110-growth-since-2016/#3d780b22433c accessed 27 May 2018.

[29]Yunus, M. 2008. *Grameen Bank At a Glance.* http://www.grameen-info.org/grameen-bank-at-a-glance/ accessed 18 February 2018.

[30]Demirgüç-Kunt, A., Klapper, L., Singer, D., Ansar, S. & Hess, J. 2018. *The Unbanked < br >* . Washington DC: World Bank Group.

Digital and mobile wallets are becoming an increasingly popular method for direct money transfer between people. Though initial systems like PayPal still required users to have a bank account, there are many digital wallets not requiring a bank account at all. The M-Pesa digital wallet has brought financial inclusion to thousands of customers initially in East-Africa and has since spread to many countries. The service involves the representation of physical currency in a mobile device, which can subsequently be used to effect transactions on which a small fee is paid.[31] The system requires a SIM-enabled mobile device. For customers not in a cell-phone reception area a crypto-currency based on the "Blockchain" system can be used. Blockchain technology is a digital decentralized ledger, which keeps record of all its transactions across a peer-to-peer network without the need of a centralised third party, making it an ideal platform for people without bank accounts (Scott 2016). PayToo is an example of a digital wallet using cryptocurrency, using advanced facial recognition technology for a very easy way of enrolment and transactional authentication.[32]

Internet connectivity has also brought about innovative ways to support the small merchant through provision of cheap easy-to-use point-of-sale systems not dependent on credit cards. The Quick Response (QR) code (an optical readable two-dimensional square featuring black and white "maps") was patented by Denso initially for use in the automotive parts industry.[33] The system is open for use to anyone adhering to the code standards. In 2011 Alipay was introduced in China deploying QR codes in an innovative way to act as point-of-sale system anywhere with an internet connection.[34] All systems described need internet connectivity to operate, which can be supported and provided by BARC.

Data as a Service

In 2001 the analyst Doug Laney coined the term "Big Data" to describe data in terms of a framework with three dimensions, namely volume, velocity and variety (Laney 2001). According to the IDC the monetization and consumption of third-party data are increasingly becoming strategic to organisations driving the creation of new services, such as Data as a Service (DaaS).[35] These new services utilise the latest analytical technology such as machine learning and compliment the traditional approach to in-house data analytics to create novel information artefacts.

The BARC has the ability to provide data sets from areas where it was not possible before and so support the "variety" dimension. Equipped with an extensive data acquisition capability, it can provide DaaS organisations with a standardised stream of data from remote sources which can be turned into revenue for the

[31] Joseph, M. 2017. *M-Pesa: the story of how the world's leading mobile money service was created in Kenya.* https://www.vodafone.com/content/index/what/technology-blog/m-pesa-created.html accessed 17 May 2018.

[32] Paytoo. 2018. *Why use Paytoo?* https://www.paytoo.com/ accessed 25 June 2018.

[33] QRcode. 2018. *History of QRcode.* https://www.qrcode.com/en/history/ accessed 12 May 2018.

[34] Li, S. & Kong, X. 2011. *System of Online Trading Through Intermediary Platform and Methods Thereof.* Google Patents.

[35] IDC. 2018. *Data as a Service.* https://www.idc.com/getdoc.jsp?containerId=IDC_P31301 accessed 12 November 2018.

community where BARC is based. Data provided by BARC will ultimately benefit the community in more indirect ways by receiving better prediction models for weather, for example.

Geo-Location

The remote asset management system of BARC—using the GNSS location beacon—can provide location meta-data for the deployed community. The geolocation data in turn can be used to bolster the accuracy of existing Geographical Information Systems (GIS) which could be beneficial to any number of parties. Government and NGOs can use these systems to aid interaction with the communities in question. Geolocation in conjunction with Blockchain technology can be used to provide a virtual address to community members which can be used for a variety of purposes. To engage in physical e-commerce transactions, a delivery address is a prerequisite. With "drone" delivery becoming a practical reality, the location beacon on the BARC can be used to determine an accurate release point for dropping the product using a parachute package. A virtual address can also effectively be used for regional governance purposes such as voting and census by linking an individual to a region.

Other

The BARC can be used as effector to communicate warnings about impending natural disasters such e.g. flooding.

Fairtrade (2009) in conjunction with the WTO adopted a Charter of Fair Trade Principles a single international reference point for stakeholders.[36] The idea behind the system is to allow primary producers to trade more directly with the end consumers to obtain a "fair deal". Consumers purchasing products with a Fairtrade logo help to reduce poverty through their power of selection. BARC could be used to inform and educate regarding Fairtrade, enabling direct communication between producer and consumer. It could also be used for credentialing based on location data and Blockchain technology.

3 Sustainability

Sustainable development is defined as "development which meets the needs of current generations without compromising the ability of future generations to meet their own needs" (Brundtland et al. 1987). To investigate future development in terms of growing environmental and societal deterioration, the UN held the first Earth Summit in Rio de Janeiro in 1992 which placed emphasis on actions at national and local level (UN Agenda 21, 1992). The UN Commission for Sustainable Development formally started to monitor the implementation of the Rio de Janeiro decisions at its annual meetings, leading to the introduction of UN Millennium Development Goals in 2000, which were followed by the Sustainable Development Goals (refer Appendix C). The BARC has particular relevance in

[36]Fairtrade. 2018. *About Fairtrade*. https://www.fairtrade.net/ accessed 30 May 2018.

terms of SDG Goal 9—“Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.” By providing broadband services into a community it opens up a number of opportunities for ICT to support sustainability commonly referred to as ICT4SDG.

3.1 ICT4SDG

The impact of ICT on society has been discussed formally as early as 1974 when Technical Committee 9 “ICT and Society” of the UN recognised IFIP (International Federation for Information Processing), an organisation representing IT associations from over 50 countries formally started a discussion on the role of information technology on society. In the OECD definition, the ICT sector is seen as a combination of manufacturing and services industries involved in the “capture, transmit and display data and information electronically”. This definition accommodate the highly integrated nature of modern ICT which can be found in virtually all sectors of any modern economy and is ideally suited as influencing agent to help reach the objectives of the SDG 2030 agenda.

ICT has a dichotomous environmental footprint though, both contributor and preventer of Green House Gas (GHG). Firstly ICT is a significant consumer of electrical energy needed to house the increasing mass of data, secondly its supply-chains annually consume a significant amount of basic resources whilst simultaneously producing vast amounts of e-waste annually. Currently the ICT sector contributes between 2% and 2.5% of total annual GHG.[37] Contrary to the harmful effect of ICT, it can be a significant environmental enabler with the ability under optimal conditions to reduce GHG by as much as 20% by 2030.[38] ICT is a development enabler on three levels; firstly it provides access to information services via hardware devices like cell phones to individuals globally. Secondly by creating connectivity between individuals communication is improved and networks created. Lastly the combination of access to information and interconnected networks of individuals leads to increased productivity and innovation. All three pillars of sustainable development—economic development, social inclusion and environmental protection—needs information flow as catalyst. With this in mind the ITU has launched the ICT4SDG[39] campaign. The main focal point of this campaign is to investigate which SDGs have particularly strong relationships to ICT and explore the respective possibilities. The study found a high level of correlation between country level performances of SDG’s 3, 4, 5, 6, 9, 11 and 13 and the level of ICT utilisation. In an increasingly information based economy the role of IS in solving global warming and related environmental issues has become very prominent. The enabling technology for such systems revolves around

[37]ITU. 2018. *ICT and Energy Efficiencies.*

[38]UNFCCC. 2016. *ICT Sector Helping to Tackle Climate Change.* https://unfccc.int/news/ict-sector-helping-to-tackle-climate-change accessed 17 February 2018.

[39]ITU ICT4SDG. 2018. *ICT4SDG ITU Committed to connecting the world.* https://www.itu.int/en/ITU-D/ICT-Applications/Pages/ICT4SDG.aspx accessed 14 November 2018.

data—autonomous data collection, fast ubiquitous communication networks to move the data and high-speed data processing. Air and water quality has a profound impact on the wellbeing of any community due to the fundamental role it plays in sustaining biological life. The following subsections explore these two aspects—which are key determinants in a number of the 2030 SDG's—in more detail.

3.2 Air Quality

According to WHO statistics annually 12.6 million people die due to environmental factors, the majority of which (seven million) are related to air pollution alone.[40] Good quality breathable air is essential to sustain human life, therefore a key determinant of attaining SDG3—"Ensure healthy lives and promote well-being for all at all ages". Air pollution is caused when pollutants which can cause damage to biological life are released in the air. Primarily caused by the burning of fossil fuels for electrical power generation, industrial emissions and vehicle exhaust, increased exposure to air pollution correlate with an increase of respiratory diseases and certain cancers in humans.

To measure air pollution the Air Quality Index (AQI) is used, a standardised way of measuring relative air quality for an indication of how "clean or polluted" the air in a particular area is. Different countries deploy different standards to calculate air quality. The US-EPA standard[41] is a good example to demonstrate the use of AQI. Five major air pollutant groupings are used to calculate the AQI namely; ground-level ozone, particulate matter, carbon monoxide, sulfer dioxide, and nitrogen dioxide. The AQI is represented as a colour scale to represent the health effect the measured air will have on the health of a person breathing it. Though pollution related issues are logically more concentrated in large urban and peri-urban areas, rural areas are also affected. The urban areas have the advantage that they are easier to be monitored. Most developed countries have high-tech air quality monitoring systems in place for data collection and analyses, which in turn is used to guide preventative policy and for generating alerts. Unfortunately air pollution data collection is very limited in the developing world, especially in rural areas refer (Fig. 2). Without adequate data collection it is almost impossible to implement effective air pollution management. The ability of BARC to measure and communicate real time data can help to create a picture of the extent of air pollution in the rural areas.[42]

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[40]UNEP. 2017. *Air Pollution: Africa's Invisible, Silent Killer*. https://www.unenvironment.org/news-and-stories/story/air-pollution-africas-invisible-silent-killer-1 accessed 29 December 2018.
[41]EPA. 2016. *Technical Assistance Document for the Reporting of Daily Air Quality the Air Quality Index (AQI)*. Research Triangle Park, NC: US EPA.
[42]AQICN. 2018. *Air Pollution in World: Real-time Air Quality Index Visual Map*. http://aqicn.org/map/world/ accessed 30 June 2018.

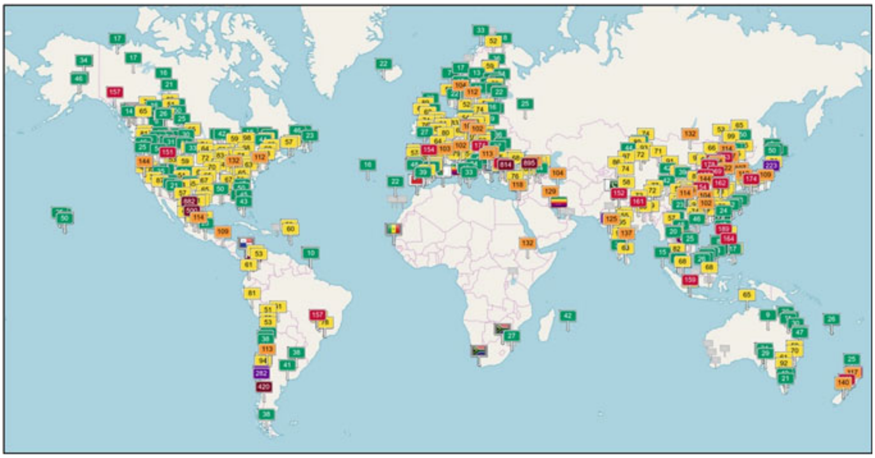

Fig. 2 Air Quality Index monitoring around the world

3.3 Water, Sanitation and Hygiene

Water, Sanitation and Hygiene (WASH) are all interlinked and together form the foundation of the health and wellbeing of any community. In the 2017 UN SDG 6 progress report it was noted that globally in excess of two billion people are exposed to water stress of some kind.[43] To foster better management of the global water resource a better understanding of consumption patterns will be required.

Water Stress Monitoring

The condition known as "water stress" occurs when water consumption by a community outstrips the available supply. This condition can be brought on by many factors but is essentially a function of quantity (how much water is available) and quality (potable or polluted). Such a condition can occur suddenly (catastrophic water source pollution, natural disaster, etc. gradually (population increase, climate change) and periodically (lower rainfall leading to droughts). Baseline water stress is expressed as a percentage of the total annual water withdrawals (agricultural, industrial, municipal/personal) of the total annual available flow for the measured area. Using additional sensors and sensitized devices in conjunction with BARC a valuable contribution can be made to a more in-depth knowledge of the state of water stress globally. To determine available water quantity, data can be collected regarding basic input i.e. rain and other sources of collection points:

- Rainfall—there are a number of different rainfall sensors on the market using different types of technology, e.g. mechanical. BARC could record local rainfall.

[43]UNSDG 6. 2017. *Goal 6: Ensure availability and sustainable management of water and sanitation for all.* https://unstats.un.org/sdgs/report/2017/goal-06/ accessed 2 December 2017.

- Storage—if water tanks are deployed in the vicinity of a BARCs their level can be measured remotely by a number of Wi-Fi enabled sensors available on the market.
- Estimation of quantities collected from rivers or wells. Hippo Roller, a popular device to move water in bulk from collection point to source, could for instance be sensitised.[44] By adding location and motion sensors data could be generated which can be transmitted automatically via BARC to a model used to estimate quantities collected.
- Pumps—groundwater pumps could be sensitised with a data collection device which could send its data to BARC if within range.
- A water harvesting tank equipped with submersible UV LED unit can be added.[45] Powered by BARC it could be used to minimise biological contamination of the stored water. Water quality could also be measured and communicated in real-time as affordable potable water sensors become available.[46] Monitoring of water sources for chemical or biological contamination could be an invaluable tool for the early detection and prevention of health hazards and to contain disease spread.

All water quantity data can be transmitted live to a cloud-based repository where it can be monitored and benchmarked against the indicators established by the regional or national water management authorities to monitor water stress.

Sanitation

Pit latrines are often deployed as a hygienic and low-cost sanitation solution for approximately 25% of the world population (Reid et al. 2014). Due to the anaerobic decomposition organic material, a significant amount of CH_4 (methane) is produced, one of the key greenhouse gasses. Methane detectors can for example be fitted to pit latrines in a community and the data relayed via BARC.

Hygiene

Poor hand hygiene practices in communities is a primary cause of the spread of various diseases. Proper hand hygiene is thus an easy way to prevent diseases. A number of initiatives worldwide exist to promote and aid the practice of good hand hygiene. Where these involve dispensing objects, it could easily be sensitised, the data collected and send via BARC to the program coordinators to communicate progress or advise on interventions.

A product like BARC equipped with the relevant sensors could therefore play a very valuable role to advance data collection surrounding WASH to aid policy and prevention.

[44]Hipporoller. 2018. *About us*. https://www.hipporoller.org/ accessed 22 May 2018.

[45]UV Sanitizer. 2018. *UV Sanitizer – Water Tanks*. https://selectech.co.za/product/uv-sanitizer-water-tanks/ accessed 11 March 2018.

[46]Cloete, N.A., Malekian, R. & Nair, L. 2016. Design of smart sensors for real-time water quality monitoring. *IEEE Access*. 4:3975–3990. https://ieeexplore.ieee.org/document/7516589.

4 Governance

The concept of e-Government is to harness the potential of ICTs to introduce "citizen-centred" governance by contributing to the accessibility, accountability, efficiency and transparency of government through the implementation of ICT-based services. e-Services are the tangible output of e-government, which can assist to effectively manage the interaction between the state and its citizens. Interacting with citizens through provision of critical online information and automating administrative processes can help local, regional and national governments to gain goodwill from their constituents.

Most developed countries have some form of e-Government in place; Estonia has arguably on of the most advanced programs, as the first country in the world to offer e-Residency—"a transnational digital identity"—Estonia embarked on a program to introduce electronic ID's in 2002.[47] In the process the country had to overcome its digital divide, solved through effective public-private partnerships. The Estonian e-Services portal currently allows access to more than 1600 services. Using a smart e-ID verification, citizens can engage in vital services including the registration of a new businesses, tax submissions and voting amongst others.[48] Though many developing countries have also adopted policies to embrace e-Government, opportunities offered by these new technologies remain largely unexploited due to a number of reasons. Barriers to the success of e-government have been identified in a study of three African countries to include (Kitaw 2006):

- Underdeveloped telecommunication infrastructure
- Low literacy
- Lack of government commitment to citizen-centred governance.

The UN measures as country's e-Governance ranking by determining the e-Government Development Index (EGDI)[49] which is made up of the weighted average of the following three normalized scores:

- OSI—Online Service Index, representing the scope and quality of online services.
- TII—Telecommunication Infrastructure Index, which represents the development status of the telecommunication infrastructure.
- HCI—Human Capital Index, a measure of how well a country is developing its inherent human capital.

[47]e-Estonia. 2018. *We have built a digital society and so can you.* https://e-estonia.com/ accessed 7 June 2018.

[48]Jaffe, E. 2016. *How Estonia became a global model for e-government.* https://medium.com/sidewalk-talk/how-estonia-became-a-global-model-for-e-government-c12e5002d818 accessed 5 June 2018.

[49]UN E-Government Knowledgebase, 'UN E-Government Survey 2018' https://publicadministration.un.org/egovkb/en-us/Reports/UN-E-Government-Survey-2018 accessed 17 April 2018.

With an EGDI score of 0.7241 Europe is above the global average of 0.4922. Africa has a low average EGDI score of 0.2882, mostly generally ascribed to a lower TII.[50] By providing the enabling infrastructure and education services BARC will stimulate e-literacy amongst users which can in turn aid the efforts of subsequent e-Governance initiatives by local or national government.

[50]EGOVKB. 2018. *Regional data.* https://publicadministration.un.org/egovkb/en-us/Data/Region-Information accessed 10 June 2018.

Financing the Construction and Operation of the BARC

Abstract

Any system such as BARC needs to be funded in one way or the other to make it a reality. This section conducted a high-level investigation with regards to potential funding approaches for such a project.

1 Funding Models

Though there is a multitude of ways to fund a project such as BARC, three basic popular models were considered.

Purely-For-Profit model, where investors invest in the project with the purpose of realising a positive return on investment. Are investors willing to invest in a technology that has the potential to generate revenue but gives very little indication of the quantum and therefore what the return on investment will be? Venture Capital investors typically are interested in products targeting large lucrative markets and/or unique market opportunities with the capability to grow revenue well beyond 100 million USD to produce maximum return on investment.[1] Though a product like BARC does address a unique market opportunity targeting a large market (the rural unconnected) it will be extremely difficult to entice for-profit investors looking for a quick return.

Public-Private-Partnerships, where the public sector partners with private sector entities to meet a growing demand for infrastructure development such as BARC. The private portion in the partnership is still profit focussed and will more than likely only finance the portions where profit could be extracted leading to

[1]Stengel, G. 2013. *Want Venture Capital? Here Are 10 Must-Haves*. https://www.forbes.com/sites/geristengel/2013/11/20/want-venture-capital-here-are-10-must-haves/#61906c3d9489. Accessed 23 November 2017.

C. Kotze, *A Broadband Apparatus for Underserviced Remote Communities*, Southern Space Studies, https://doi.org/10.1007/978-3-030-15766-1_6

asymmetrical risk exposure.[2] Political motives can be detrimental to project continuity should a change in regime take place.

Social Entrepreneurship, which is about applying "practical, innovative and sustainable approaches to benefit society in general, with an emphasis on those who are marginalized and poor."[3] This model is typified by projects driven by independent social entrepreneurs that focus on using innovation to deliver social impact in areas such as agriculture, education, health, sustainability etc. The model allows for the creation of for profit and non-profit entities. Andela is an example of such a for-profit organisation, supplying first-class education to software developers from Africa in an innovative way, involving no tuition fees.[4] It recovers the cost of education and a profit by providing remote software development services to international companies. A project such as the BARC, where effective social impact will be dependent on its long-term survival, will be more suited to a for-profit model than a non-profit model to ensure future technology reinvestment.

Convincing the community to buy into a product with not yet proven value will require a funding model allowing the product to demonstrate how its use will translate into practical benefit for the community. In his book "Diffusion of Innovations" Rogers (1995) defined the "rate of adoption" as the time it takes for a user population to adopt an innovation. The rate of adoption follows a curve with a few early adopters paving the way for increasing adoption to a point where a critical adoption mass is reached, or not entrenching the innovation or leading to failure. A funding model thus has to take into account an initial period of "free" use by the community to support an adequate adoption period. Davis (1985) proposed the Technology Acceptance Model (TAM) originally to identify predictors of user acceptance of the use of Information Systems (IS) technology in organisations. The initial model predicted a positive technology acceptance if users have a positive inclination to use the system, which in turn will be influenced by the user's perception of the product's usefulness and ease of use (Davis 1985).

Various amended models of TAM have been put forward subsequently in an attempt to understand scenarios characterised by lower levels of education and income that the initial version did not account for. Musa (2006) made a case for modifying TAM to account for limited accessibility in developing countries and argues that the true benefit of technology adoption comes from "meaningful applications that enhance standards of living"—i.e. value. To ensure BARC has the intended long-term social impact it needs to increase in value with an increase in use: the principal behind the "freemium" funding model popular with internet start-ups. In the case of the BARC the introduction of social services such as healthcare and education can serve the purpose to anchor the system initially, followed by the introduction of commercial services. Services with the ability to

[2]PPPLRC. 2018. *Government Objectives: Benefits and Risks of PPPs*. https://ppp.worldbank.org/public-private-partnership/overview/ppp-objectives. Accessed 1 May 2018.
[3]Schwab Foundation. 2018. *What is social entrepreneurship?* https://www.schwabfound.org/what-is-social-entrepreneurship. Accessed 22 May 2018.
[4]Andela. 2018. *Andela builds distributed engineering teams with Africa's most talented software developers*. https://andela.com/about/. Accessed 13 May 2018.

generate revenue for the community will ultimately increase the tangible value of the product with use. Communities benefiting commercially from such a product will be more likely to increase usage of the system, which will in turn promote user retention and participation.

2 Proposed Funding and Revenue

In this model each BARC can be seen as a single business with a cost and profit centre reporting into a central control model. Each BARC will be represented by a certain number of shares issued against the unit, which when allocated to investors, will cover the costs represented by:

- **CAPEX**—Acquisition and Installation
- **OPEX**—All operational monthly costs for a period of three years, i.e. broadband satellite subscription, remote monitoring, maintenance, etc. Each BARC will have an initial allocated broadband data quota per month. Communities can request an increase in the total data allocation per month, which will be charged additionally.

Shares will be allocated in three blocks as follows:

1. 25%—to the community in the form of an interest-free loan payable after the initial 3-year induction period is complete.
2. 60%—to a primary sponsor investor for the first 3 years.
3. 15%—retained by the BARC holding company to be sold to independent investors.

The primary long-term value proposition of a product like BARC stems from its ability to increase the value of a network by increasing its user base, i.e. the "Network Effect (Swann 2002)." David Sarnoff was an American broadcast radio pioneer and one of the first people who attempted to create a "law" to predict the value of a network, in his case an analogue radio broadcast network. He suggested a linear relationship between the number of listeners and value of the radio network, which came to be known as Sarnoff's Law (Swann 2002). Through the years as digital networks started penetrating the market, new laws were established to predict the value of digital networks, based on the number of users. Each of these laws were derived under different conditions and/or assumptions. The following are four examples of these laws, (V = network value, a = monetary unit and n = number of network users):

- Sarnoff's Law—$V = a \times n$, mostly applicable to broadcast services and dictates the network value to be proportional to the number of radio listeners or television viewers, typically applicable to advertising revenue (Swann 2002).

- Metcalfe's Law—$V = a \times n^2$, applicable to communication networks, as opposed to a broadcast network, values the network as proportional to the square of the number of connected users (Metcalfe 1995).
- Reed's Law—$V = a \times (2^n - 1)$, expanding on Metcalfe's law by taking into account the value increase of a network ascribed to the effect of collaboration between subgroups within a network (Reed 1999).
- Odlyzko's Law—$V = a \times n \log(n)$, arguing that, though connectivity between network users offers a value advantage over broadcast networks, not all connections in the network have an equal value, therefore network effects are not as strong as proposed by Metcalfe and Reed (Briscoe et al. 2006).

Though both laws of Metcalfe and Reed have been criticised for not being applicable in all situations they still support the concept that user growth ultimately drives increased network value. In a 2015 study of social networks Facebook and Tencent, Metcalfe's Law was validated even though the two companies have major differences in business model and technology (Zhang et al. 2015). The goal of BARC is to add new users to the internet and therefore does have a value that could be monetised to an extent. But what are the ways to fund a product of which the eventual success is very difficult to predict, where the initial two years of installation are almost guaranteed to show no direct return?

The potential revenue opportunity in terms of the network effect of BARC can be viewed as analogous to the introduction of the web browser in the early 1990's—an unknown product allowing the user access to an unknown concept (the internet). In the early 1990's, Mosaic—the first user-friendly web browser that made it possible for anyone to use the internet without the need for special knowledge—was given away for free. The principle was to spark interest in the internet, which was largely unknown to the public at large. Mosaic's uptake was so successful that it was credited with a three-fold increase of web users, which in turn sparked a factor of 100 growth in web sites. This prompted a commercial opportunity for Netscape Corporation to produce a commercial version of Mosaic in the form of Netscape Navigator. Since the product was initially given away for free, the revenue had to be recovered indirectly from the user via nodes in the value chain. Firstly users had to download the product providing information such as en e-mail address, creating value by forming the first database of potential on-line shoppers which could be monetised.[5] The company subsequently created direct revenue by selling webserver software to service provider companies, a service needed to create additional demand for the browser software, rapidly driving user numbers—by 1996 the USA already had an internet user population of 20 million.[6] A further revenue stream came through the selling of the software "indirectly" to users

[5]Cooper, S. 2014. *Whatever happened to Netscape?* https://www.engadget.com/2014/05/10/history-of-netscape/. Accessed 29 May 2018.

[6]Manjoo, F. 2009. *Jurassic Web, The Internet of 1996 is almost unrecognizable compared with what we have today*. https://slate.com/technology/2009/02/the-unrecognizable-internet-of-1996.html. Accessed 18 November 2018.

through reseller agreements with internet service providers and hardware manufacturers. An IBM PC could be shipped with a Netscape bundle included; the user paid for the PC but the software was perceived to be free, the software enhanced the usability of the PC in the user's eyes and was seen as a purchase decider in the eyes of the vendor.

This model was used as a base to develop a funding model for BARC as the product will need an adequate period for the community to accept the technology initially. The first step to consider was to isolate potential revenue streams from the product which could be used to sell the value of the product to investors in order to fund the initial adoption period of the product. A number of potential revenue streams were identified:

- Communications—The availability of the product in a remote areas can enable for-profit organisations such as banks to reach these communities previously excluded from the market. A bank could act as an initial sponsor, and could subsequently recover the investment through micro-transactions from payment systems. Micro-transactions are transactions with a very small value, e.g. the purchase of tokens within mobile apps and games.[7]
- Data Network Effect—The ability of a product to increase its value as more data is collected which in turn prompts additional use and yields more data, is known as the Data Network Effect (Mitomo 2017). By placing the product in remote areas, the aggregation of collected sensor data can be marketed to interested parties.
- Infrastructure as a Service—Taking a leaf out of the "cloud" provider book, the product could be used to provide occasional power and communication services for visitors. Aid organisations supplying community services like teaching and healthcare during occasional "in situ" visits could "lease" services during their stay.
- Geo Location information in conjunction with Blockchain technology can be monetized through commercial transactions. One way of achieving this would be to issue a "Geo Tag" for the location from a certification portal. Such a tag could be used for location validation as a security feature during e-commerce transactions, using micro transactions to generate revenue which could be deposited into the specific BARC's account.

The product through its use will potentially open new sources of revenue to encourage stakeholder investment both from existing as well as attracting new shareholders.

[7]Anderton, K. 2018. *The Ongoing Controversy Of Microtransactions In Gaming*. *Accessed Infographic.* https://www.forbes.com/sites/kevinanderton/2018/03/07/the-on-going-controversy-of-microtransactions-in-gaming-infographic/#5e5a0e01d9c5. Accessed 22 May 2018.

Conclusions and Further Work

The aim of this study has been to answer this basic question: How can the "Last-Mile" challenge be addressed to supply broadband to underserviced communities by combining existing and emerging technology? In the process, a substantial body of multi-disciplinary technical literature was reviewed over a period of 2 years (with a special focus on recent publications) in order to create a forward-thinking body of knowledge.

The first chapter attempted to set the scene by providing background information and introducing key concepts, including the "Digital Divide" and addressing why it is necessary to bridge the "Last-Mile" to connect the un-connected. Secondly, it explored the barriers to internet adoption that are preventing connection of under-serviced remote communities—most of which are poor and lacking infrastructure. Key to the connectivity problem is solving the infrastructure problem in terms of "Last-Mile" availability of electricity and communication. A technology overview was done to investigate how current rapid simultaneous technological development in a number of fields could be harnessed to "connect the unconnected"—including renewable power and broadband satellite technology. Currently the satellite broadband segment is well poised for growth having already recorded a significant (50%) revenue growth over the initial 5 year period since introduction of High Throughput Satellite technology in 2010, with an average subscriber growth rate of 11%.[1] With a number of very large constellations planned from various operators, the available bandwidth is expected to grow significantly, and the increased competition is expected to put downward pressure on subscription rates. The chapter put forward the idea of a self-contained, infrastructure independent, apparatus to supply broadband internet and ancillary enabling services to remote underserviced communities. The proposed concept was named BARC (**B**roadband **A**pparatus for Underserviced **R**emote **C**ommunities).

The second chapter had it as goal to produce a requirements definition for the BARC product concept. It introduces the reader to a number of basic considerations

[1]State of the Satellite Industry Report. 2017. *State of the Satellite Industry Report*. Washington DC: SIA.

C. Kotze, *A Broadband Apparatus for Underserviced Remote Communities*,
Southern Space Studies, https://doi.org/10.1007/978-3-030-15766-1_7

surrounding new product development: defining the concepts, delineating functional and non-functional requirements for the rest of the study. A "FURPS+" model was used as framework to develop the requirement set. A product story was used to position the product in terms of the "what, how & why" with regards to its intended audience to unmask the requirements and in the process conducting a FAB (Features, Advantages and Benefits) analysis. The process involved defining all the key actors and imagining scenarios involving their expected interactions with the BARC product. In total, nine of these use-case scenarios were identified and explored in a template format detailing the interactions between the actors and BARC: including pre/post-conditions and any expectations impacting the use-case scenario. From the use-case analysis, eight Functional Requirements, nine Acceptance Requirements and seventeen Performance Requirements were defined—they set the stage for the concept development.

In Chap. 3 the reader was introduced to the design philosophy which revolves around the idea of creating a product that will not only satisfy all requirements technically, but to do it in such a way as to encourage the intended user to want to use the product. The goal was to create a familiar form to blend into any environment with the ability to add function over and above the technical performance to serve the community in a larger way. A product design was chosen that can provide shade in the day and supply light at night and in so doing combat "light poverty"—a condition affecting many people in infrastructure-deprived areas.

The first artefact produced by the process was a rough basic design concept outlining additional design requirements: a modular approach and the desire to have a smooth design featuring flat surface areas. The master design concept identified a number of essential modules which were applied to common forms typically associated with people gathering to come up with a shortlist of three design concepts. The three designs were evaluated against a reference-design using an adapted Pugh Matrix to come up with a very basic design resembling a car port featuring symmetrical flat faces.

Chapter 4 took the reader through the steps of refining the chosen concept design introducing an overall design-statement; identifying the primary component set and producing architecture overviews of all identified modules to ensure conformance to the initial requirements definition. A formal technology review was conducted as a substantial part of the study—to identify applicable technology which could be used to satisfy the design statement. The flat structure necessitated the use of FPA, as opposed to the more traditional parabolic dish. A FPA not only suits the design very well, but since it features tracking ability, importantly, will be able to utilise the new planned mega-constellations in a variety of orbits. On the down side, these are very new products currently directed at the high-end of the application market such as aviation and super yachts and are still very expensive for an application such as BARC. Market observers are not optimistic that the technology will be any serious mass commercial competition for traditional parabolic antennas for a number of years due to scalability and cost concerns.[2]

Market predictions are however not a reason to ignore the technology in the design. In 1980 McKinsey predicted the cell-phone market in the USA will be worth only 900,000 units by 2000 (less than one 1% of the actual market), convincing AT&T, who commissioned the report, not to invest in the market.[3] With more than 21 companies actively developing the technology, the adoption curve will more than likely be significantly faster than currently predicted, primarily driven by the "in-flight" connectivity market. Other current technological developments might prompt an even quicker adoption than anticipated, such as the possibility of mass adoption of autonomous vehicles. This scenario will open up a very big market with the expected benefits of rapid cost reduction due to scale-up of production.[4] Therefore, though FPA technology is in a starting phase it does hold promise for a number of markets currently excluded from satellite applications due to antenna constraints.

The design statement emphasises the use of environmentally safe and energy-efficient technology. Responsible technology selection is crucial to ethical environmental design, not only regarding disposal, but also importantly, responsible sourcing, free of damaging mining practices involving child labour and conflict resources. From an environmental perspective especially, the negative aspects of battery technology, have become the focus of public attention as the adoption of electric and hybrid cars are increasingly moving into the mainstream.[5] To counter the very real concerns regarding the environmental impact of sourcing metals such as Nickel, the Global Battery Alliance[6] was created. This initiative of the World Economic Forum (created in 2017) as a public-private collaboration effort to ensure an ethical "inclusive, innovative and sustainable battery value chain" in support of the UN 2030 SDG. A fast-growing niche segment in the PV market is the manufacturing of stable cost-effective, high efficiency (16–22%) CIGS (Copper, Indium, Gallium & Selenide) "thin-film" PV cells—a technology which opens up new design opportunities ideally suited for the BARC design.[7] Though

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[2]Pultarova, T. 2017. *Kymeta ships first 400 flat-panel antennas, confirms talks with OneWeb.* https://spacenews.com/kymeta-ships-first-400-flat-panel-antennas-confirms-talks-with-oneweb accessed 23 November 2018.

[3]Lozano, A. 2018. *The Hall of Innovation - Cellular telephony: just a niche market.* https://www.dtic.upf.edu/~alozano/innovation/index.html#mckinsey accessed 12 May 2018.

[4]Erwin, S. 2018. *U.S. military a potential big customer for satellite industry's new low-cost terminals.* https://spacenews.com/u-s-military-a-potential-big-customer-for-satellite-industrys-new-low-cost-terminals/ accessed 19 November 2018.

[5]Eckart, J. 2017. *Batteries can be part of the fight against climate change—if we do these five things.* https://www.weforum.org/agenda/2017/11/battery-batteries-electric-cars-carbon-sustainable-power-energy/ accessed 27 December 2018.

[6]Global Battery Alliance. 2018. *Global Battery Alliance.* https://www.weforum.org/projects/global-battery-alliance accessed 27 December 2018.

[7]NREL. 2018. *Copper Indium Gallium Diselenide Solar Cells.*

the toxic material cadmium is often associated with the manufacture of thin-film PV, there are manufacturers producing cadmium-free thin film CIGS.[8]

Another consideration of technology selection was to consider the impact of the intended function of the technology on the ambient implementation environment. New generation LED technology offers an environmentally friendly option with no equivalent in traditional lighting technology, especially in the form of super thin ultra-efficient printable LED sheets which are ideally suited to a novel application such as BARC. However, implementation of broad-spectrum blue-white LED lighting into previously unlit areas does have a potential environmental concern. Firstly, according to the International Dark-Sky Association—a critic of the roll-out of LED citing perceived light-pollution—it can create "sky glow", which might lead to loss of celestial detail at night which could be culturally significant for the community.[9] From a health point of view, LED's with very high Kelvin ("blue") values can influence circadian rhythms causing sleep disturbances (Hatori 2017). Even though these problems can be countered by using shielding and lowering of the Correlated Colour Temperature (CCT) to less than 3000 K, it is important to take note of the challenges posed. Collection of data is a primary function of BARC, which is driven by sensors. One of the emerging technologies identified from a design point of view is printable thin-layer sensors using materials like graphene that are opening up many new opportunities such as direct integration of sensors into the frame and roof surfaces (Banerjee 2016).

A substantial contribution to the body of knowledge of the study came from investigating the impact on society, economics, sustainability and government of "connecting the unconnected"—as described in Chap. 5. Education and health are cornerstones of the social wellbeing of any community. The study emphasised through examples the potential gains which could be obtained through broadband connectivity of underserviced communities. The economic impact was approached in a similar fashion, framed against broadband internet as a General Purpose Technology. The chapter introduced the reader to the importance of sustainable development as a key component in ensuring a fair dispensation for future generations. Broadband connectivity has a crucial role to play in supporting sustainability. The chapter also presented the advantages of e-Governance which could be enabled by the availability of pervasive broadband connectivity.

Though the scope of the study did not include a formal costing study, it does acknowledge the importance of sustainable funding. In Chap. 6 a funding model was explored in terms of the value proposition presented by the Network Effect and revenue streams available to the BARC product, primarily based on the increasing monetary value of data.

According the UN's Department of Economic and Social affairs, the global population passed the 7 billion mark in 2011 already and by the time the SDG reach

[8]Midsummer. 2018. *Environment.* http://midsummer.se/technology/environment accessed 1 May 2018.

[9]IDA. 2018. *LED Practical Guide.* http://darksky.org/lighting/led-guide/ accessed 28 April 2018.

the 2030 deadline, the global population will surpass 8.5 billion.[10] Africa is expected to have the highest population growth, with Sub-Saharan countries expected to experience rapid growth and account for 50% of global population growth between 2015 and 2050. Ironically, according to data from the World Bank, this region is also home to the largest population—41% in 2013—affected by poverty.[11] The greatest percentage of people with no connection to the internet is also to be found in Sub-Saharan Africa. Adoption of connected technology is increasingly crucial to participate in the modern economy to enable economic growth, which in turn is the key to poverty reduction, as is managing and understanding the implications of the effects of rapid population growth to ensure sustainable development.

Finally, some thoughts on future work. The study has identified that creation of a device like BARC is technically possible, but its scope did not include proving the feasibility of such a project. Future work on the topic could include the following:

- Financial—conduct a study to test the financial viability of the device in terms of the target demographic and the proposed funding model.
- Users—a detailed user interface study should be conducted to provide insight into challenges resulting from the placement of such a product in areas dominated by a target demographic with little to no digital skills. Such a study should also take into consideration how emerging technologies such as natural language processing and AI can be integrated to bridge the skills gap.

Some final thoughts: working through this project has left the researcher with a profound appreciation for the need to create the opportunity to hand the nearly four billion currently "un-connected" entry into the "broadband ecosystem". The research also indicated a sense of urgency in dealing with this problem as there are already very strong indicators that the digitally "rich" economies are accelerating ahead of economies with a low digital penetration. Failing to intervene timeously will increasingly relegate a substantial portion of the global population to the digital equivalent of the Medieval Period—excluding them from partaking in the spoils of the Fourth Industrial Revolution. Such a situation will amplify existing inequalities to significant new levels, to the point where the "unconnected" will have no way to trade with the "connected." This is a scenario which should be avoided at all costs.

[10]UNDESA. 2017. *World Population Prospects The 2017 Revision.* New York: United Nations Department of Economic and Social Affairs.

[11]Wadhwa, D. 2018. *The number of extremely poor people continues to rise in Sub-Saharan Africa.* https://blogs.worldbank.org/opendata/number-extremely-poor-people-continues-rise-sub-saharan-africa accessed 29 November 2018.

Appendix A
Battery Comparison Table

Specifications	Battery type					
	Lead Acid	NiCd	NiMH	Li-ion		
				Cobalt	Manganese	Phosphate
Specific energy (Wh/kg)	30–50	45–80	60–120	150–250	100–150	90–120
Internal resistance	Very low	Very low	Low	Moderate	Low	Very low
Cycle life (80% DoD)	200–300	1000	300–500	500–1000	500–1000	1000–2000
Charge time (h)	8–16	1–2	2–4	2–4	1–2	1–2
Overcharge tolerance	High	Moderate	Low	Low. No trickle charge		
Self-discharge/month at room temp	5%	20%	30%	<5% Protection circuit consumes 3%		
Nominal cell voltage (V)	2	1.2	1.2	3.6	3.7	3.2–3.3
Charge temperature (°C)	−20–50	0–45		0–45		
Discharge temperature (°C)	−20–50	−20–65		−20–60		
Maintenance requirement	3–6 months (topping charge)	Full discharge every 90 days during full use		Maintenance free		
Safety requirement	Thermally stable	Thermally stable, fuse protection		Protection circuit mandatory		
In use since	Late 1800s	1950	1990	1991	1996	1999
Toxicity	Very high	Very high	Low	Low		
Coulombic efficiency	~90%	~70% slow charge ~90% fast charge		99%		
Cost	Low	Moderate		High		

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Appendix B
Structural Module Bill of Material

Bill of material	Module	Sub-module			Count	External modules connector	Part number	
	[SM]	[SM].[MS]						
Vertical support poles	Bottom halve	Front	Left	VBFL	1		[SM].[MS]	VBFL
			Centre	VBFC	1	Yes	[SM].[MS]	VBFC
			Right	VBFR	1		[SM].[MS]	VBFR
		Back	Left	VBBL	1		[SM].[MS]	VBBL
			Centre	VBBC	1	Yes	[SM].[MS]	VBBC
			Right	VBBR	1		[SM].[MS]	VBBR
		Centre	Left	VBCL	1	Yes	[SM].[MS]	VBCL
			Right	VBCR	1	Yes	[SM].[MS]	VBCR
	Top halve	Front	Left	VTFL	1		[SM].[MS]	VTFL
			Centre	VTFC	1		[SM].[MS]	VTFC
			Right	VTFR	1		[SM].[MS]	VTFR
		Back	Left	VTBL	1		[SM].[MS]	VTBL
			Centre	VTBC	1		[SM].[MS]	VTBC
			Right	VTBR	1		[SM].[MS]	VTBR

(continued)

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(continued)

Bill of material	Module [SM]	Sub-module [SM].[MS]			Count	External modules connector	Part number	
		Centre	Left	VTCL	1		[SM].[MS]	VTCL
			Right	VTCR	1		[SM].[MS]	VTCR
Horizonatl support beams	Top	Front	Left	HTFL	1		[SM].[MS]	HTFL
			Centre	HTFC	1		[SM].[MS]	HTFC
			Right	HTFR	1		[SM].[MS]	HTFR
		Back	Left	HTBL	1		[SM].[MS]	HTBL
			Centre	HTBC	1		[SM].[MS]	HTBC
			Right	HTFR	1		[SM].[MS]	HTFR
Cross beams	Top	Front	Left	XTFL	1		[SM].[MS]	XTFL
			Right	XTFR	1		[SM].[MS]	XTFR
		Back	Left	XTBL	1		[SM].[MS]	XTBL
			Right	XTFR	1		[SM].[MS]	XTFR
		Centre	Left	XTBL	1		[SM].[MS]	XTBL
			Right	XTFR	1		[SM].[MS]	XTFR
Connectors	Corner	Front	Left	CCFL	1	Yes	[SM].[MS]	CCFL
			Right	CCFR	1	Yes	[SM].[MS]	CCFR
		Back	Left	CCBL	1	Yes	[SM].[MS]	CCBL
			Right	CCFR	1	Yes	[SM].[MS]	CCFR
	T-pieces	Front	Left	CTFL	1		[SM].[MS]	CTFL
			Right	CTFR	1		[SM].[MS]	CTFR
		Back	Left	CTBL	1		[SM].[MS]	CTBL
			Right	CTFR	1		[SM].[MS]	CTFR
	Cross	Centre	Centre	CCCC	1	Yes	[SM].[MS]	CCCC

(continued)

(continued)

Bill of material	Module	Sub-module			Count	External modules connector	Part number	
	[SM]	[SM].[MS]						
Terminators	Foot pieces	Front	Left	TFFL	1		[SM].[MS]	TFFL
			Centre	TFFC	1		[SM].[MS]	TFFC
			Right	TFFR	1		[SM].[MS]	TFFR
		Back	Left	TFBL	1		[SM].[MS]	TFBL
			Centre	TFBC	1		[SM].[MS]	TFBC
			Right	TFBR	1		[SM].[MS]	TFBR
		Centre	Left	TFCL	1		[SM].[MS]	TFCL
			Right	TFCR	1		[SM].[MS]	TFCR
Roof utility mount		Centre	Top	RUTM	1		[SM].[MS]	RUTM
			Bottom	RUBM	1		[SM].[MS]	RUBM
Effector expansion		Top	Front	EFTF	1	Yes	[SM].[MS]	EFTF
			Back	EFTB	1	Yes	[SM].[MS]	EFTB
			Right	EFTR	1	Yes	[SM].[MS]	EFTR
			Left	EFTL	1	Yes	[SM].[MS]	EFTL
Data expansion		Foot	Left	DEFL	1	Yes	[SM].[MS]	DEFL
			Right	DEFR	1	Yes	[SM].[MS]	DEFR
		Top	Front	DETF	1	Yes	[SM].[MS]	DETF
			Back	DETB	1	Yes	[SM].[MS]	DETB
Total		55						

Appendix C
United Nations Sustainable Development Goals

SDG	SDG description
SDG 1	End poverty in all its forms everywhere
SDG 2	End hunger, achieve food security and improved nutrition, and promote sustainable agriculture
SDG 3	Ensure healthy lives and promote well-being for all at all ages
SDG 4	Ensure inclusive and equitable quality education and promote life-long learning opportunities for all
SDG 5	Achieve gender equality and empower all women and girls
SDG 6	Ensure availability and sustainable management of water and sanitation for all
SDG 7	Ensure access to affordable, reliable, sustainable, and modern energy for all
SDG 8	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
SDG 9	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation
SDG 10	Reduce inequality within and among countries
SDG 11	Make cities and human settlements inclusive, safe, resilient and sustainable
SDG 12	Ensure sustainable consumption and production patterns
SDG 13	Take urgent action to combat climate change and its impacts (in line with the United Nations Framework Convention on Climate Change)
SDG 14	Conserve and sustainably use the oceans, seas and marine resources for sustainable development
SDG 15	Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
SDG 16	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
SDG 17	Strengthen the means of implementation and revitalize the global partnership for sustainable development

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