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.

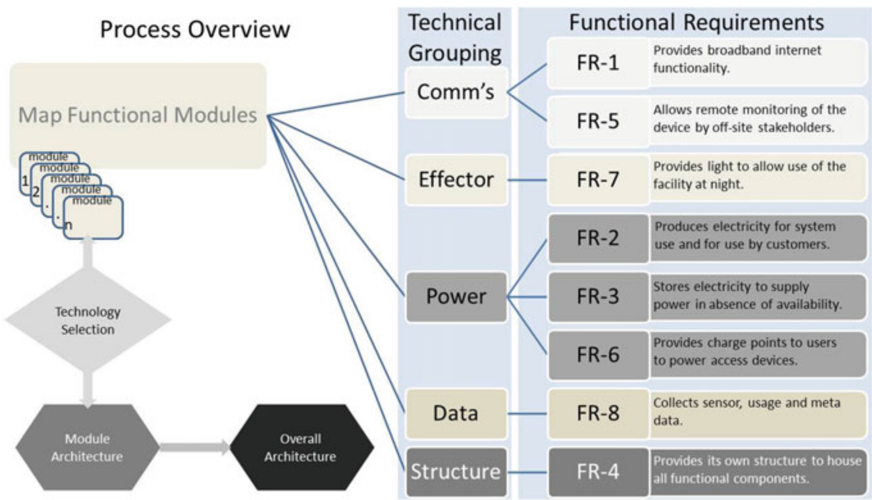

Fig. 1 High-level functional diagram for detailed product design

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,

[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.

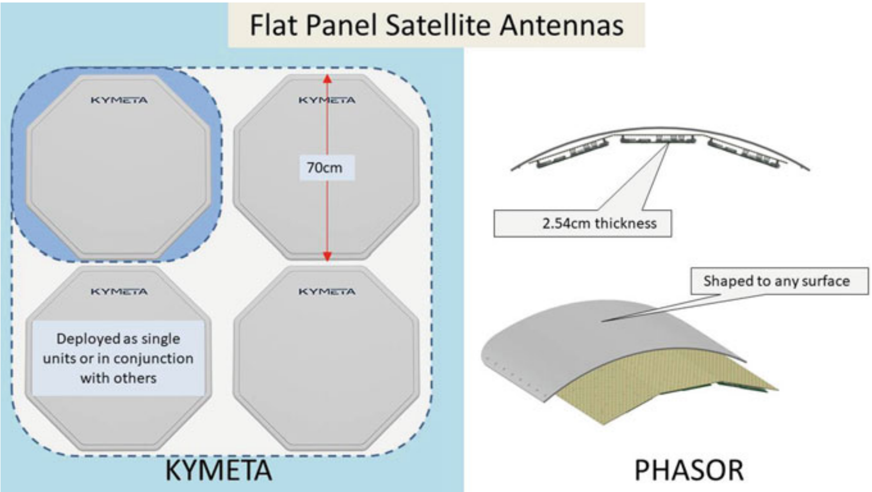

Fig. 2 Examples of new generation Flat Panel Antennas (see footnotes 7, 9)

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)

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[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.

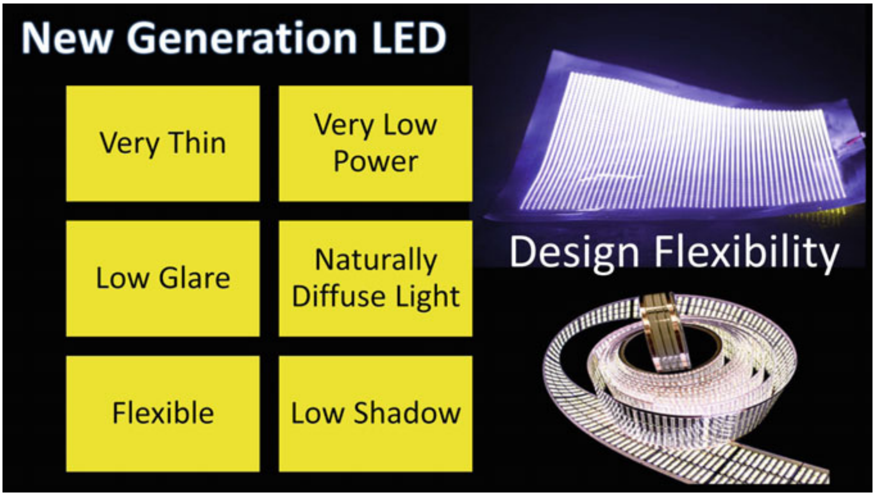

Fig. 4 New LED light technology (Nth-Light. 2018. *Printing the impossible* < *br* > . https://www.ndeg.com/. Accessed 28 April 2018

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.

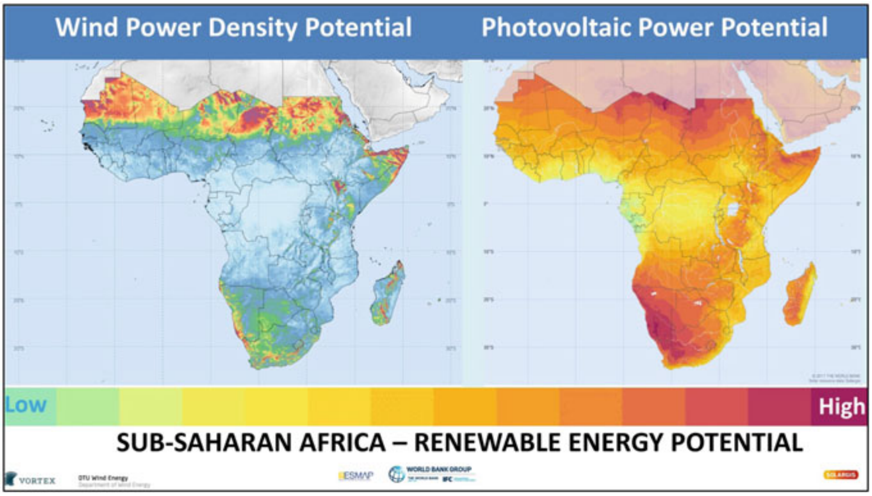

Fig. 5 Wind and photovoltaic potential of sub-Saharan Africa

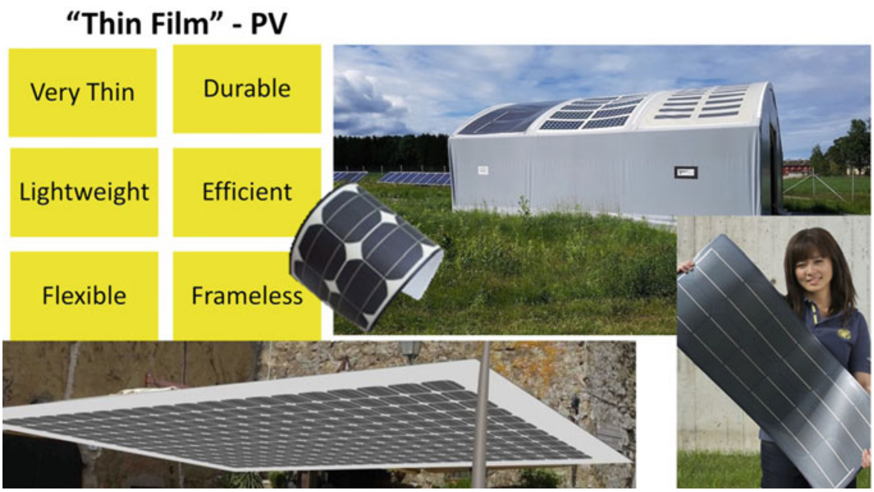

Fig. 6 Examples of new PV technology

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.

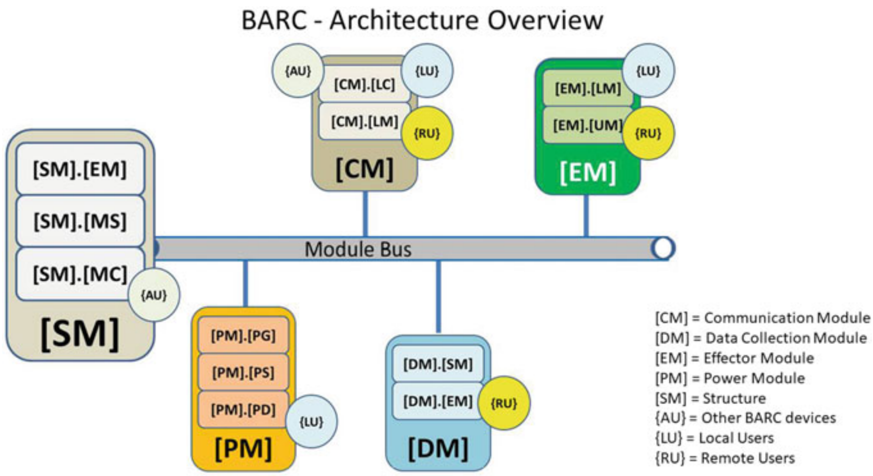

Fig. 7 BARC System Architecture Overview

- 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.

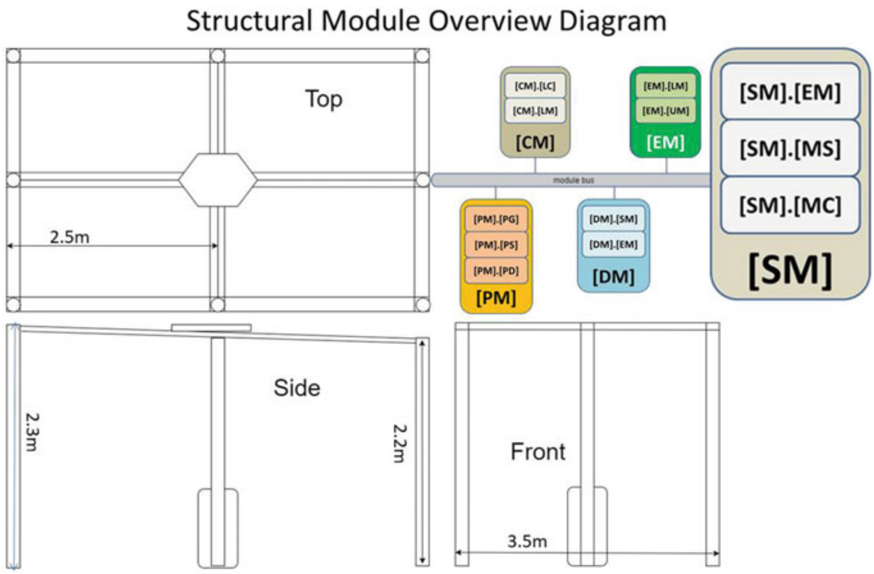

Fig. 8 Structural module overview

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.

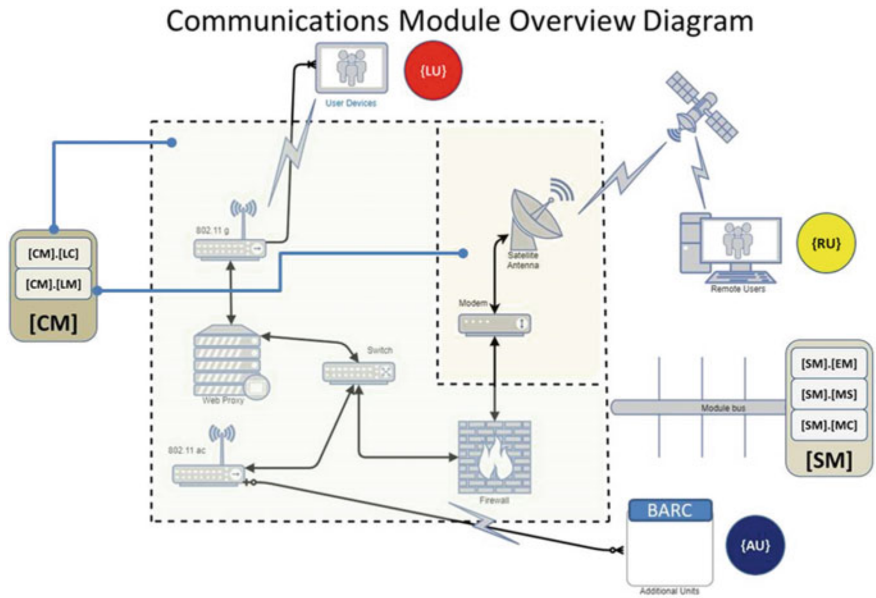

Fig. 9 Communications module overview

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

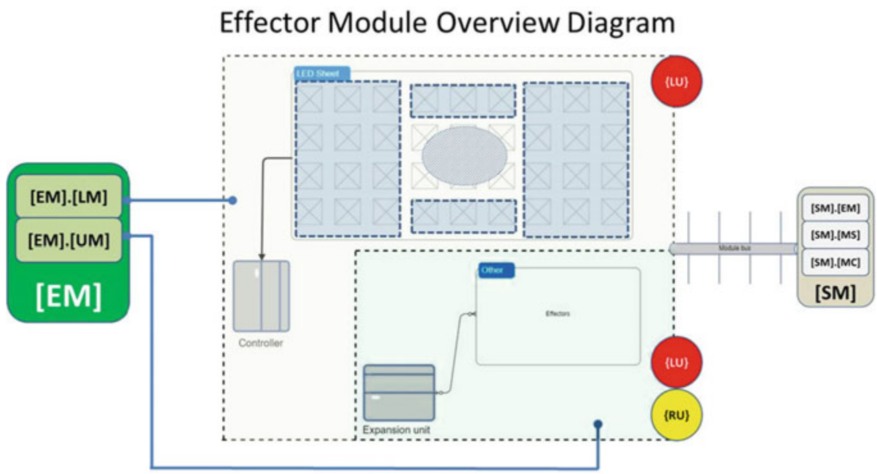

Fig. 10 Effector module overview

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,

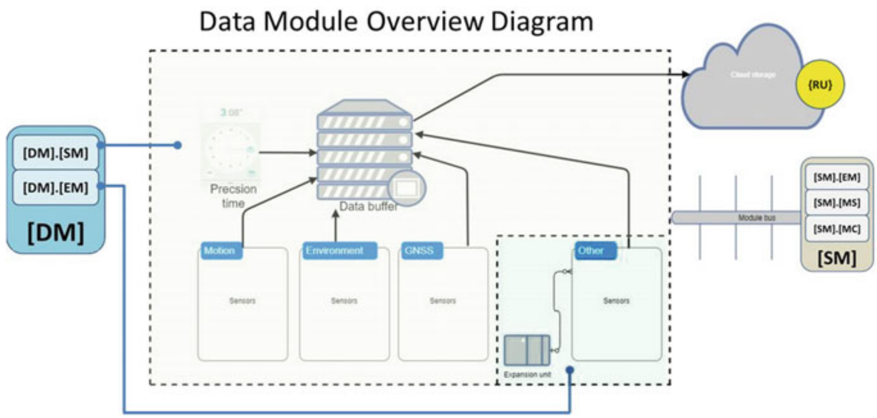

Fig. 11 Data module overview

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.

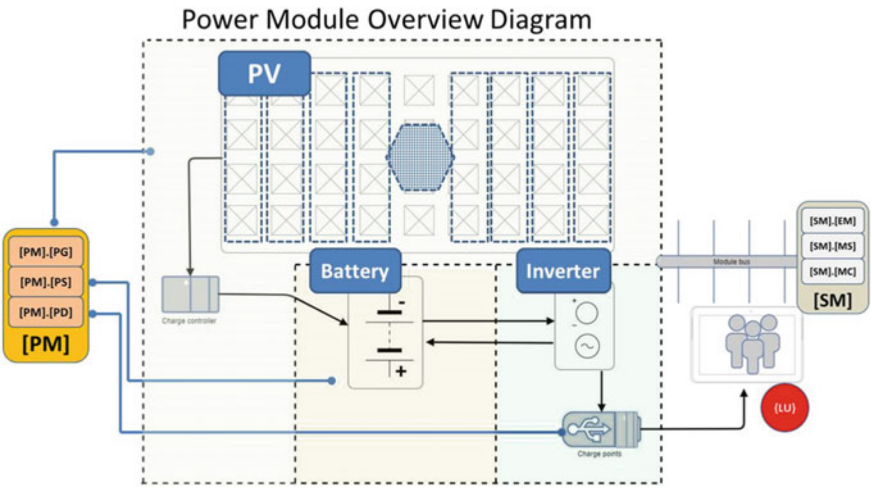

Fig. 12 Power module overview

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

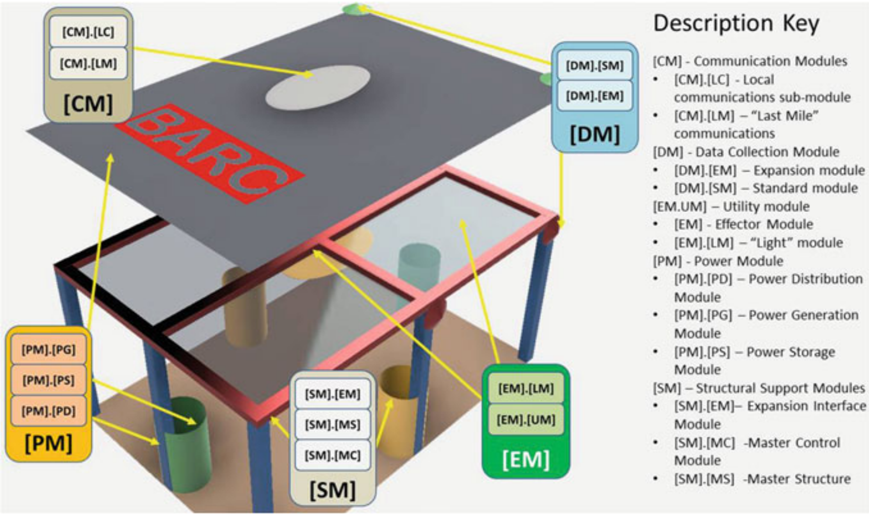

Fig. 13 BARC architecture overlay on 3D model

- 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.