

Sustainable photonics that bridge the digital divide

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Introduction. Photonic technologies have become the work horse of our digitally connected world, where optical fibre communication systems are the driving force behind the digital revolution of the last 30 years. The immense impact of this optical cabling led to Charles Kao being awarded the Nobel Prize in 2009 for his groundbreaking achievements in the 1960s (1). Fibre optics allowed the formation of the modern digital communication sectors, accounting for a large proportion of Gross Domestic Product (GDP) of developed nations. Taking the United Kingdom as an example, this sector has over 5 times the share of the GDP compared to agriculture, valued at over £50 billion (\$70 billion). The digital technologies enabled by this sector have a broad impact across every industry, and are central to the current way of life in developed economies.

In contrast, the developing world is being stifled by the lack of a widely available internet connection, Fig. 1(a) and (b). This divide in availability of digital connected technologies severely inhibits economic potential of many of the world's least developed countries. To highlight the divide, the total GDP of Kenya (\$70 billion), an African nation with a population similar to that of the UK, is equivalent to the digital sector alone in the UK. While deploying a network infrastructure is expensive, the importance of bridging this divide cannot be overstated, where its benefit is particularly true in developing countries: in South Africa for example, Broadband has been estimated to contribute 1.38% to the GDP, a significant amount given the drive to reduce a 26% unemployment rate through accelerated economic expansion. South Africa plans a \$5 billion (R65 billion) broadband investment which is projected to create 400 000 jobs and raise annual GDP by \$10 billion (R130 billion).

The “divide” can be broken down into two parts: an economic gap due to low income and a geographical gap, due to lack of infrastructure, Fig. 1 (c) and (d) respectfully. Market driven infrastructure development has seen continental African fibre connectivity increase steadily, from the West Africa Submarine Cable link (SAT3) in 2001 to multiple optical connections interlinking many coastal nations across the continent today. This has provided specific local economic hubs with access, but continent wide access is still far from a reality: Africa accounts for 16% of the world's population but only 4% of the internet access. In South Africa, a relatively wealthy African nation, the market driven deployment has left much of the population unconnected. Bridging this divide would need some 160,000 km of fibre to provide network access comparable with developed nations. However, deploying optical fibre invokes a considerable capital costs, at upwards of \$100,000 per km (?), creating an impenetrable economic barrier to provided even basic network infrastructure for many countries. Even developed nations have struggled to achieve full photonics networks due to the costs, and complexity, to upgrade historical copper infrastructure. These hardwired electronic connections have begun to limit the data bandwidth growth potential across developed countries, where we are facing an impending “capacity crunch”.

In June 2017, a meeting was held in South Africa to develop a photonics enabled solution for the deployment of a communication network across Africa in a sustainable manner, hoping to “turn the digital divide into a digital opportunity”. A foundational objective was that developing nations should have network access that supports leadership in the globally digital economy,

rather than simply a consumer in it. While the scale of the challenge is daunting, it is nevertheless an opportunity: to identify and promote the next generation of photonics technologies that will support digital equality for developing nations over the next 100 years, much like copper has driven the successes of developed nations over the last 100 years. This rare green-field situation allows developing countries to leap-frog the constraints of legacy equipment and instead lead in sustainable photonics enabled technologies: installing the next generation optical network for the future, today.

Digital Divide: The technical challenge. Any network design will be required to be future-proofed with the ability to support a world class digital economy. Given the environmental and socio-economic challenges these nations face, sustainability must be ingrained into any solution. At this meeting the international group of participants worked to develop a holistic definition of sustainability for photonics technologies. This definition is designed to be applied more generally to much of the photonics community, with a reach beyond communications:

“Sustainable photonics solutions will aspire to provide technologies that are future focused in their social, economic and environmental impact. Materials, processing and implementation will be environmentally neutral, where infrastructure should be considered to have permanence beyond the initial financial recovery time. Sustainable photonics technologies should be based on an open, and fair-access platform to support long-term upgradability without commercial restrictions. Appropriate measures to provide adequate resilience is considered a core component of responsible system design.”

With our definition of sustainability in mind, we designed a network that could be deployed within developing nations, Fig. 2. The green field nature of many countries offers the opportunity to design a holistic network, embracing the best current and emerging technologies, to realise a network that is “future-proof”.

Based on projected trends of data usage, driven by e-commerce and cloud services, we have identified that an average of 1 Gbps household download speed is required. Clearly, the network will need to be constructed to allow for staged upgrades as initial internet provision stimulates local economic growth. Our projection indicates that inner city areas will require 100 Gbps to support globally competitive digital enterprise. Communities within a few km of these high speed network nodes could be initially connected with 10 Gbps free-space optical, or radio backhaul, with future fibre upgrades as the fibre network naturally grows to meet demand. These rural communities network exchanges could be solar powered, removing the requirement for connection to a power grid. Very rural communities will be a particular challenge, where 10Mbps aerial drop solutions maybe required to give these communities access to internet services capable of supporting video conferencing, which is a core requirement for the provision of remote medical diagnosis. As economic growth will change a community’s architecture, we believe the much of the “last-mile” will likely be provided by photonics driven wireless connectivity to reduce increased infrastructure costs in the future. With this in mind we consider the current and future technologies that can support such an ambitious plan for universal digital access (Fig. 3).

Connecting to the World

As the carrier for the majority of our digital services is optical fibre, any practical solution would require connecting into that existing infrastructure. Although challenging, the undersea cables are actually one of the more conventional parts of bridging the digital divide as many coastal cities already have fibre connection. Linking the cities and communities further from the coasts, and away from local economic hubs of developing nations is where many of the technological hurdles are exposed. Sustainability is key to supporting economic development, and therefore the installation of subsea cables should be designed to support network access for everyone. Technological compatibility with rest of world is vitally important in this part of the network. Bundles of single mode optical fibre laid on the seabed is the standard. These links utilise advanced coherent optical encoding to transmit the huge bandwidth required in these links, where embracing these technologies will be required for new network deployments.

Although powerful, these cabled links may be a thing of the past as a space based communication revolution is underway. Space-X's Elon Musk has voiced this ambitions to deploy an army of micro satellite to move our terrestrial networks into space, where in-space laser links would likely provide the connection between these satellites. The lack of air in space means turbulence, hence optical aberrations, are virtually non existent, but this is not the case when connecting down to earth. Several international teams are making exciting strides in this area, demonstrating both single channel and multi-channel space to ground links (?).

QKD systems are a good example of a strategically crucial technology that has to be considered when planning future communication networks that should be sustainable for decades. Quantum security technologies are moving steadily from the laboratory to real-world demonstrations, with fibre-based quantum key distribution (QKD) systems commercially available over distances of approximately 100 km. A fundamental issue with long distance quantum systems is the no-cloning theorem, which effectively prevents the optical power amplification required to overcome the attenuation in subsea optical fibre networks (5). Quantum repeater technologies have seen some early progress, however cable-free space to ground systems could be a solution for end to end quantum encryption. Recently Quantum FSO solutions have been demonstrated to connect cities 1200 km apart by ground to satellite link with propagation lengths exceeding 2000 km (6). A core theme to many state-of-the-art QKD systems is compatibility with standard telecoms equipment, which have led to secret key rates increasing from Mb/s using conventional QKD protocols (such as decoy-state BB84 and continuous variables) to many Gb/s rates with technologies such as "floodlight QKD" that transmit many photons per bits [5]. Multiplexing (HD-QKD) techniques such as spatial modes of light offer further potential increases, but will require changes to deployed optical interconnects. Holistic approaches to quantum security will mean hybrid classical-quantum links are likely to support technologies such as quantum error correction (7).

Photonics solutions will be at the heart of a quantum secured sustainable network. This need for fast and secure access is a focus of the International Telecommunication Union, whose two main objectives are: eliminating the digital divide, and ensuring a more secure cyberspace.

Space based optical communications are becoming ever closer to a commercial reality. While such ambitious projects capture the imagination, for the foreseeable future fibre optical connections will likely be the way the world is linked.

Connecting cities

A clearly recognisable component of sustainability is the energy requirements for digital infrastructure, where much of the energy usage arises in the "last-mile" of the network that connects the inhabitants of our cities. The current total energy consumption used for communications equates to 3% of global power usage, and 3% of our greenhouse emission. A staggering increase from only 10 years ago, where the usage was considerably less than 1%. One driver for this increased consumption has been growth in capacity, which has been rising at 40% per annum. Switching off legacy technology, and current advances in energy efficiency have been able to reduce consumption at a rate of 20% per bit every year, but with ever increasing capacity these reductions are leading us into an internet energy crisis unless novel technologies are deployed. The current 3% energy consumption is equivalent to the electrical power used in the United Kingdom, and is projected to exceed the usage of the entire African continent by 2035.

Many novel solutions are being developed to specifically address issues with energy consumption. One example is passive optical networks (PON), which are an ideal technology for achieving our green communication goals (9, 10, 16). Combining technologies such as fibre and millimetre wave communications (12), or PON with wireless local area networks (13) are offering the potential to lower power consumption. The gain in these systems arises from designing both the access and backhaul network as a single entity, and is a core inspiration for our proposed system design. Improved power efficiency through the use of transparent optical switching technologies, optical integration of transceivers, and novel data management will be core to sustainable network designs (14).

Accessibility, scalability and resilience to rapid demographic changes have been core drivers for the prevalence of wireless linkage, largely in the form of cellular networks that have been deployed across Africa (15, 16). The number of connected handheld devices closely mirrors that of developed nations, albeit at considerably lower data usage levels due to cost. Radio wireless communication schemes although necessary, are notoriously energy inefficient and bandwidth limited. To enable the high capacity required within the wireless portions of the network novel photonics driven cable free solutions will need to be implemented. The push to millimetre wave radio carriers is blurring the line between radio and optical communications, where high capacity mm-wave wireless links have been achieved at beyond 70 Gbps driven seamlessly from an optically modulated signal. Even though the final form of 5G is yet to be realised, the modulators and MIMO techniques used will closely mirror those used in optical networks (17).

As a holistically designed network is key to sustainability, we envisage cable free photonics solutions playing strategic roles in how cities connect. Free Space Optical (FSO) for last-mile, and visible light communication (VLC) for indoor applications are exciting potential approaches (18). The dual-use nature of imbuing one's room lighting with information makes

VLC a particularly attractive proposition for indoor data communication where data rates can reach beyond 100 Gbps (19, 20). Challenges facing wide scale deployment of point-to-point FSO links are rapidly being resolved by a burgeoning field of engineering and physics research, where systems employing Space Division Multiplexing have been demonstrated at 100 Tbps with systems working over km distances in urban environments (21, 22). FSO links offer the opportunity to radically rethink the structure of last mile networks, where a physically adaptive network could be deployed that dynamically restructures the optical links as required on a city scale. These smart, optically connected cities could be resilient and sustainable given the developments of the correct technologies.

Connecting Communities

This is the greatest challenge, requiring some of the most innovative and novel solutions. As many rural communities are off grid and in difficult economic situations, ample access to power is not guaranteed. Digital links can lead to economic growth, which is usually a driver for infrastructure development. To reach our ambition of sustainable networks, we must deliver off grid communications technologies.

Integrating solar power and optical links can provide a method to connect off grid rural communities. Energy efficient network hardware can be powered with a small number of solar panels, providing important energy independence. However, such solutions will not scale with growth of communities it connects and careful selection of the optical linkage is vital. Advanced deep reach PON architectures provide outstanding energy efficiency per bit, and are technologies that will be central to future network designs (11). Integration of these low energy green PON networks with solar optical relay stations will provide an opportunity for off grid network access that can drive the developments of rural communities. Integration of SDM can further decrease the energy per bit in fibre linkages for both PON, and long-distance, where amplifiers, multiplexers and relays can be shared instead of duplicated for every channel in a system providing potential for greater system efficiency (?).

Terrain, land-ownership, and infrastructure security risk can limit the applicability of cabled connections. As such cable free access systems will be required. High capacity Free-space optical linkage at a minimum of 10 Gbps operating over a few km's in distance could provide this much needed hop to bridge the gap between cable and off-grid local PON networks. However, for even more remote communities more advanced solutions will be required. To address this challenge, Facebook and Google have a vision to connect communities with composite terrestrial, high-altitude and satellite system to cover both medium- and low-density populations. These prospective technologies will use balloons, solar powered unmanned aerial vehicles (UAVs) and blimps cruising at an altitude of 20 – 25 km, interconnected by fast FSO links in relatively "turbulent free" horizontal paths. These would provide blanket wireless coverage of at least 25 Mbps over a large area, and could provide low speed service to very rural communities.

Low-speed connections for rural communities provide enough bandwidth for consumption of the digital world, access to vital services and support, but these speeds are not adequate for the

leading it. It will be important that these communities are connected on an open, and fare-access platforms that allow them to grow independently. We expect the high speeds networks will branch out from the cities and fully connect even the most remote communities as economies grow and the network will grow sustainability into the future.

A wide range of advanced photonics technologies will play a crucial role in the development of a sustainable solution to the digital divide. A broad more holistic approach to sustainability is needed to allow photonics technologies to truly enable growth within the developing world. Our principles of sustainable photonics endeavour to fully encompass these challenges, and identify fully sustainable technological approaches. We hope our network design will inspire sustainable solutions for the future of the optical networks we rely on everyday.

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Acronyms

Wavelength Division Multiplexing in Single Mode Fibre (WDM-SMF), Coherent Optical Communications (Coherent), Single Mode within Free Space Optics (SM - FSO), Passive Optical Networking incorporating Wavelength Division Multiplexing (PON - WDM), Single Wavelength Passive Optical Networking (PON), Wireless Sensor Network Architectures (WSN), Wireless Radio 5G (5G), Space Based Free Space Optical Links to earth (Space Based FSO), Visible Light Communications (VLC), Mid Infrared Free Space Optical Communications (MidIR-FSO), Wavelength Division Multiplexing within a Free Space Optical system (WDM - FSO), Wideband Optical Amplifiers for Long haul communications (Wideband Amps), weather balloon platforms for access (Ballon), Quantum Key Distribution incorporating high dimensional spatial modes (QKD - HD), Light Fidelity (LiFi), Radio Frequency channel incorporating Mode Division Multiplexing (RF - MDM), Drone areal drop access technologies (Drone), Millimetre wave Access schemes (MMw Access) and Space Division Multiplexing within Passive Optical Networking (SDM - PON).

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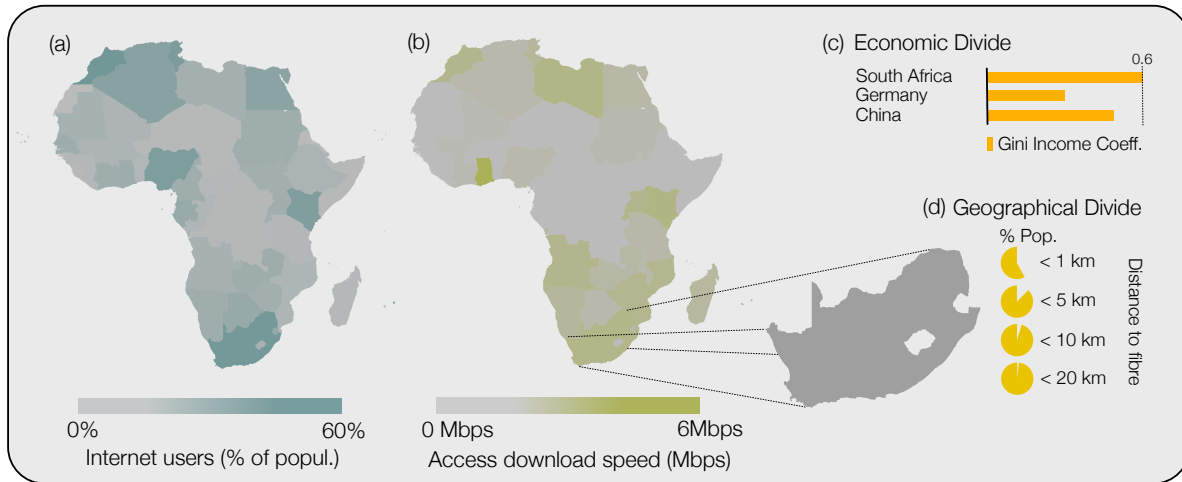


Figure 1: **The digital divide.** (a) Internet users as a percentage of the population mapped across the African continent. The average for developed nations is 84%. (b) Download speeds for internet users mapped across Africa, where the average for developed nations is $> 12\text{Mbps}$ (2). (c) Economical divides within a nation present core challenges to resolving the issues surrounding digital access. The Gini Coefficient, a measure of statistical dispersion intended to represent the income or wealth distribution of a nation's residents, for South Africa is compared to Germany and China (3). (d) Geographical divide presents issues with the deployment of infrastructure to rural areas.

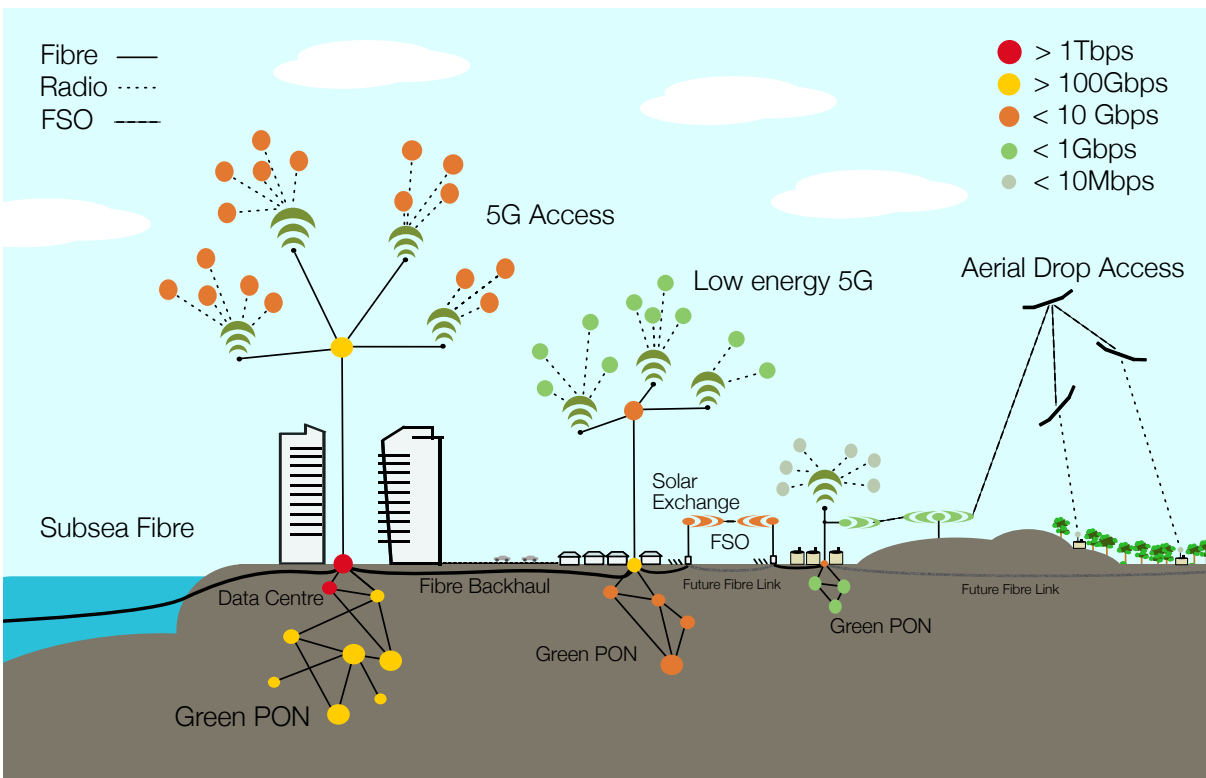


Figure 2: A network design that bridges the digital divide, where sustainability must be central to it's deployment.

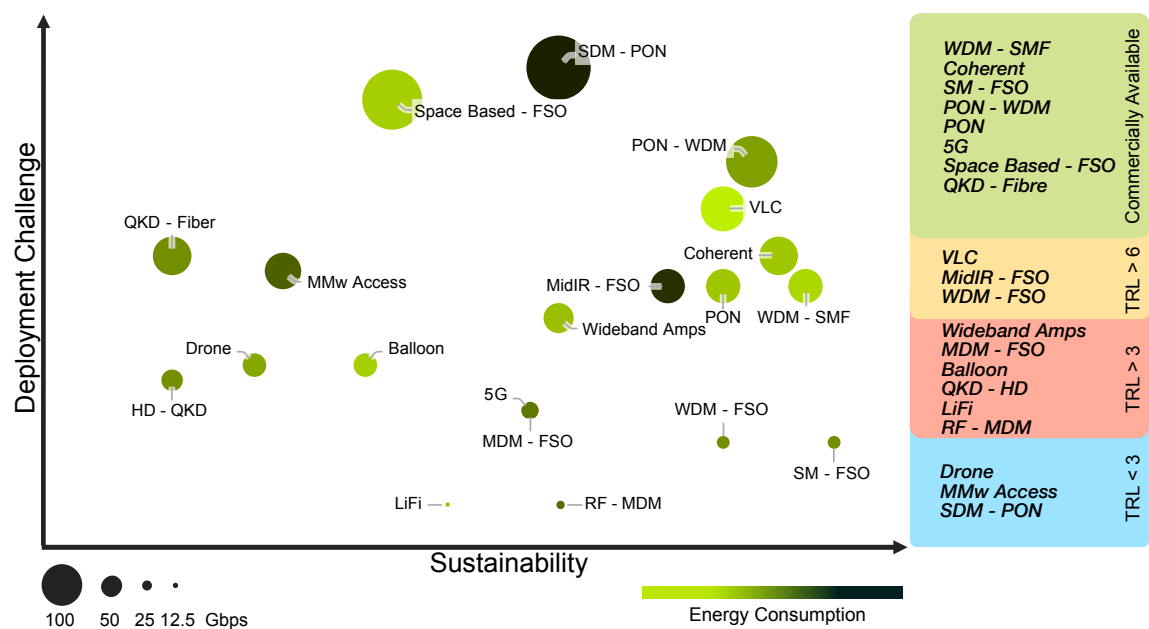


Figure 3: **Comparative sustainability.** Commercial and emerging technologies are evaluated against, bandwidth potential (circle size), energy consumption per Gb (color scale), deployment challenge and match to the sustainable photonics definition. Full acronym descriptions can be found in the supplementary information.