COMMENT

Tackling Africa's digital divide

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Innovations in "sustainable" photonics technologies such as free-space optical links and solar-powered equipment provide developing countries with new cost-effective opportunities for deploying future-proof telecommunication networks.

Photonic technologies are the work horse of our digitally connected world, with optical fibre communication systems driving the digital revolution of the past 30 years. The immense impact of the invention of the optical cabling led to Charles Kao being awarded the Nobel Prize in 2009 for his ground-breaking research into low-loss silica fibre in the 1960s [1]. In the decades since, the deployment of fibre optic cables has empowered the formation of the modern IT sector which accounts 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, Africa 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 in developing countries cannot be overstated: 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) [2].

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. Over the past 20 years, continental African fibre connectivity has increased steadily, from the West Africa Submarine Cable link (SAT3) installed in 2001 to the multiple optical connections interlinking many costal nations across the continent today. This infrastructure development has provided specific local economic hubs with broadband 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. Even in South Africa, a relatively wealthy African nation, much of the population remains unconnected. Bridging this divide to provide network access comparable with developed nations would need the deployment of around 160,000 km of fibre. However, deploying optical fibre invokes a considerable capital costs, at upwards of $100,000 per km [3], 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 involved, to upgrade historical copper infrastructure. These electronic connections have begun to limit the data bandwidth growth potential across developed countries, where we are facing an impending "capacity crunch".

Recently, an EPSRC Global Challenges funded workshop on "Resolving the digital divide with sustainable photonics" was held in South Africa to discuss how photonics can provide a communication network across Africa in a sustainable manner, hoping to "turn the digital divide into a digital opportunity". 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 potentially allows developing countries to leap-frog the constraints of legacy equipment and instead lead in deploying new sustainable photonics enabled technologies.

Digital Divide: The technical challenge

Any network design should be future-proof with the ability to support a world-class digital economy. Given the environmental and socio-economic challenges many developing 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, as follows:

"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 fiscal 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 are considered a core component of responsible system design."

With this definition of sustainability in mind, we designed a network for developing nations, as depicted in Fig. 2. Based on projected trends of data usage, driven by e-commerce and cloud services, we believe that an average of 1 Gbps household download speed is required. 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.

Rural community network exchanges could be solar powered, removing the requirement for connection to a power grid. Remote locations will be a particular challenge and 10 Mbps aerial drop solutions may be the answer to provide internet services capable of supporting video conferencing, which is necessary for remote medical diagnosis. As economic growth will change a community's architecture, we believe that 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

Undersea cables consisting of bundles of single mode optical fibre laid on the seabed significantly help to bridge the digital divide in Africa by providing coastal cities with a fast, international fibre connection. These links utilise advanced coherent optical encoding to transmit with a huge bandwidth. Although powerful, these cabled links may actually become a thing of the past due to the arrival of the space based communication revolution which may provide a new opportunity for international connectivity. Space-X's Elon Musk has voiced his ambitions to deploy an army of micro satellites connected by in-space laser links. The lack of air in space means turbulence, hence optical aberrations, are virtually non-existent, something that is not the case for space-Earth connections. Several international teams are making exciting strides in the area of ground-satellite optical communications, demonstrating both single mode (SM-FSO) and multi-channel space to ground links (Space Based -FSO) in the mid infrared part of the optical spectrum (MidIR-FSO).

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-Fibre) 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. Quantum repeater technologies have seen some early progress [4], however cable-free space to ground systems could be a solution for end to end quantum encryption. Recently, Quantum Free Space Optical (FSO) solutions have been demonstrated to connect cities 1200 km apart by a ground to satellite link with propagation lengths exceeding 2000 km [5]. A core theme to many state-of-the-art QKD systems is compatibility with standard telecoms equipment, which have led to secret key transfer rates increasing from Mbps using conventional QKD protocols (such as decoy-state BB84 and continuous variables) to many Gbps rates with technologies such as "floodlight QKD" that transmit many photons per bits. 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 [6].

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.

Connecting cities

An important consideration for sustainability is the energy requirement for operating a digital infrastructure. At present, much of the energy usage arises in the "last-mile" of the network within cities. The current total energy consumption used for communication network infrastructure and data centres equates to 3% of global power usage, and 3% of our greenhouse emission. This is 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 [7]. Switching off legacy technology and current advances in energy efficiency have resulted in the energy associated with transmitting a data-bit falling at a rate of 20% per bit every year, but with ever increasing capacity we are facing an internet energy crisis unless novel technologies are deployed. The current 3% world-wide energy consumption is equivalent to the entire 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 [8]. One example is the passive optical network (PON), which is an ideal technology for achieving our green communication goals [9, 10, 11]. Combining technologies such as fibre and millimetre wave communications [12], or PON with wireless local area networks [13] brings the potential to further lower power consumption. The benefit arises form 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 manage 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 technology, 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 and high capacity millimetre-wave wireless links have been achieved at beyond 70 Gbps driven seamlessly form an optically modulated signal (MMw Access). Even through the final form of 5G is yet to be realised, the modulators and MIMO techniques (RF -MDM) used will closely mirrored to 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 communications (FSO) or the last-mile and visible light communication (VLC) for indoor applications are exciting potential approaches [18]. The dual-functionality of VLC where energy-efficient LEDs are used to perform tasks of both illumination and data communications is a particularly attractive proposition for indoor data communication at rates of 100 Gbps and beyond [19, 20]. Challenges facing widescale deployment of point-to-point FSO links are rapidly being resolved by a burgeoning field of engineering and physics research, where systems employing a combination of Mode Division Multiplexing (MDM-FSO) and wavelength division multiplexing (MDM -FSO) 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.

Connecting Communities

This is the greatest challenge, requiring some of the most innovative and novel solutions. As many rural communities are off the electrical grid and in difficult economic situations, ample access to power is not guaranteed. The answer may lie with integrating solar power with optical links. Energy efficient network hardware can be powered by a small number of solar panels, providing energy independence which is important. However, such solutions will not scale with the growth of the communities it connects and the use of energy efficient photonic technology is vital. Advanced deep reach passive optical network (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 could provide an opportunity for off grid network access for rural communities. The use of Space Division Multiplexing (SDM-PON) can further decrease the energy per bit in fibre links by allowing optical amplifiers, multiplexers and relays to be shared instead of duplicated for every channel in a system [23].

Issues related to terrain, land-ownership and security risks to infrastructure can all limit the applicability of cabled connections. As such cable free access systems will be required. High capacity FSO linkage at a minimum of 10 Gbps operating over a few kilometres in distance could provide this much needed hop to bridge the gap between cable and off-grid local PON networks. However, for 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 (drones) 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 leading it. It will be important that these communities are connected on open and fair-access platforms that allow them to grow independently. We expect the high speed 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.

In summary, a wide range of advanced photonics technologies will play a crucial role in the development of a sustainable solution to the digital divide. We hope that our network design ideas will inspire sustainable solutions for the future of the optical networks we rely on every day.

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Figure captions

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 >

12Mbps [24]. (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 [25]. (d) Geographical divide presents issues with the deployment of infrastructure to rural areas. Data courtesy of the Council for Scientific and Industrial Research (CSIR) South Africa.

Figure 2: A proposed sustainable network. A network design that bridges the digital divide and uses technologies selected to minimize the energy consumption and cost of deployment.

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

Supplementary Information

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 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), Multimode Optical Amplifiers (MM Amps), weather ballon 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).