TERABIT COMMUNICATIONS – TASKS, CHALLENGES, AND THE IMPACT OF DISRUPTIVE TECHNOLOGIES

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ABSTRACT

Throughout history, effective communication has been of THE most critical importance to all civilisations, the means employed being underpinned and enabled by the greatest scientific breakthroughs of the age. Today we live in an *information age* and consequently there is a growing need to send vast amounts of data both securely and at the shortest time possible across the globe. However, to keep pace with this demand it is critical that the capacity of future communication networks is able to perform accordingly. However it is an open secret that to achieve this is becoming an increasingly difficult task.

In this paper we explore key technological milestones and breakthroughs that have enabled to support rapidly the growing demand for data. This will be followed by a discussion of the drivers of this demand, the socio-political consequences of this development, and the technical challenges we must overcome if demand is to be met into the future. These technical challenges encompass issues of CMOS scalability, power consumption, and data centres & network switching abilities.

INTRODUCTION

Throughout history we have witnessed data transmission rates growing from less than one bit per second (bit/s) all the way up to tens of Terabits per second (Tbit/s). All started just one and half century ago by building communication networks using technologies based on copper wire. After discoveries leading to a laser, fibre optic prevailed. The combination of fibre optics, optical data multiplexing, and advanced signal processing has helped to realise data transmission capacities and levels of connectivity hitherto unimaginable only a decade ago.

Today there is a rapidly rising demand for ultra-high speed mobile data transmission spurred on by the increasing popularity of smart devices looking for social networking, and bandwidth hungry HD & 4K video streaming. This demand is placing data centres under pressure to provide ever increasing data transmission through their networks and at the same time improve the quality of data handling in terms of reduced latency, higher channel speed and improved scalability. The above becomes even more pressing with the current growing popularity of the 'cloud' concept.

An important consequence of instant mobile connectivity is its profound and irreversible effect on the global socio-political landscape. Just this month the Facebook membership exceeded 1.5 billion worldwide with one billion users accessing their account every single day. While there are undoubtedly many caveats, the general consensus on social networking is that it is a good thing, forcing governments and organisations to be more transparent and accountable for their actions [1]. Whether considered a positive or negative influence, social networking & multimedia media, has opened the floodgates to a global torrent of 'propaganda', both positive and negative, from individuals, organisations, various interest groups, and governments. The growth in demand for information and the influence on the socio-economic landscape is attributable to the rise of smart phones/tablets and e-services. The above is now outstripping the growth in fixed computing platforms. All these trends have resulted in network congestions (notably data centres) due to electronic bottleneck and the push for more cloud applications will compound this problem even more.

As data rates increase, it is becoming apparent that present electronic switching technology is becoming increasingly difficult to scale despite improvements in data management. The reasons for this inability to meet demand are twofold. Firstly, power consumption is rapidly increasing and becoming unsustainable. In fact, as of 2014, data centres alone globally consumed some 3% of the world's power generation capacity with ICT in general consuming a massive 10% of capacity [2]. Secondly, heat dissipation and cooling issues threaten to reduce device reliability. In the past CMOS scaling meant that faster data rates could be delivered at reduced power consumption. However since 2005 increasing CMOS leakage currents have meant a substantial increase in device power density. Providing adequate cooling is presenting an increasing problem with the increased the risk of thermal runaway and associated reduction in system reliability. In effect, device thermal density has become a limiting design criterion threatening to end Moore's law of scaling [3]. These power consumption considerations have spurred a move to parallel processing using multi-core central processing units (CPUs). However, there is a maximum speed-up beyond which adding more cores gives no additional advantage and the fastest CPUs in data centres today are limited to handling data at around 10Gb/s. It is apparent that the already significant power needs for data centres switching and cooling will grow more rapidly with growing network throughput resulting in sustainability problems in energy costs and carbon emissions compliance.

The fundamental limits of data centre switching reliant on bandwidth limited CMOS electronics is now perhaps being reached.

A HISTORY OF COMMUNICATIONS

The Age of Copper Wire in Communications

Throughout history humans have required to relay messages and distribute important information. In the early days this was a difficult task particularly over long distances if the speed of delivery and data security was critical. This was about to change. Thanks to Samuel

Moor the telegraph was invented. The word telegraph is derived from Greek and means "to write far". With this invention the modern era of communication and data broadcasting began. This invention introduced electric current into the heart of data broadcasting and enabled data to be carried large distances over copper wire at high speed. The use of the telegraph in combination with Morse code helped to increase the data rate to around B ~ 10 bits/s, improve reliability and increase the distances L over which messages could be transmitted (see Fig. 1).

The first telegraph based trans-Atlantic cable was put into service in 1866. Interestingly enough, the telegraph was in some sense an early version of a *digital* transmission system using a combination of short and long electrical pulses to represent the alphabet.

In 1876, the invention of the telephone started the *analogue* era in communications. The development of telephone networks brought with it progressive changes in lifestyle that completely changed the way people interact with each other.

Moving forward, copper wire was replaced by the introduction of coaxial cable. This change substantially increased the capacity of transmission systems. The first communication system based on coaxial cable as the transmission medium was put into service in 1940. This was a 3 MHz system with a capacity of 300 audio or one television channels.

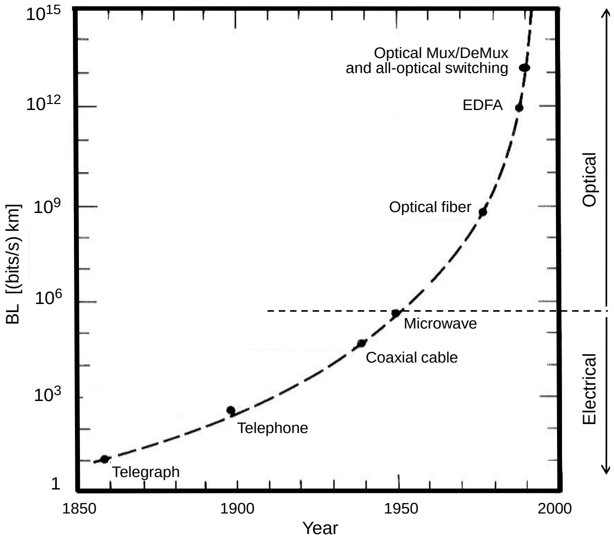

Fig. 1. The impact of disruptive technologies on communications

However, coaxial systems also have their limitations. Their transmission bandwidth is limited by the so-called *skin effect*, a frequency dependent loss of signal that rapidly incurs high signal losses at frequencies above 10 MHz. This effect decreases the distance required between the signal amplifiers used to maintain signal strength. In practice, the skin effect necessitates a very frequent use of signal amplifiers and/or regenerators which need to be placed a distance L apart of approximately 1 km. Coaxial based systems could be found in a variety of applications routinely transmitting data at a rate of B = 100 Mbit/s. One of the most advanced coaxial systems with a data rate of B = 274 Mbit/s was put into operation in 1975.

The skin effect impairments subsequently led to the development of transmission systems based on microwave technology. Here, the data carrier is an electromagnetic wave with a frequency of between 1and 10 GHz. The first microwave system with carrier frequency of 4 GHz was put into operation in 1948. The microwave systems helped to slightly increase the distance L between regenerators, but the data rate B remained at about the same level of around 100 Mbit/s. The microwave communication systems reached their practical physical limit BL = 100 (Mbit/s)•km in the early 1970. Fig. 1 illustrates the historical development of the parameter BL.

In the second half of the last century, scientists realised that the parameter BL can be increased by several orders of magnitude if optical waves could be used as the data carrier. Unfortunately, at the time there was neither a proper light source nor a suitable light guiding mechanism.

The Age of Fibre Optics

Broadcasting via optical fibre is rapidly growing field. Less than a half a century old, this field was enabled by two important but unrelated discoveries.

Charles Kao demonstrated that light can be transmitted using an optical ‘waveguide’ and, at about the same time, the semiconductor GaAs laser was demonstrated. Over the 1960’s and early 1970’s, optical fibre exhibited losses of more than 1,000 dB/km. Breakthroughs came in the 1970’s with the development of optical fibre with losses acceptable for use in telecom (~20 dB/km in the 1 µm wavelength region) [4]. Furthermore, a 0.8 µm GaAs semiconductor laser was demonstrated capable of continuous operation at room temperature and operating in the first transmission window where light suffers low attenuation.

In 1977, General Telephone and Electronics (GTE) sent the first live telephone traffic using optical fibre at 6 Mbit/s and the first generation of fibre optic communication systems was put into operation in 1978. These systems operated in the first window and were based on using the aforementioned GaAs lasers as optical carrier generators. They were able to carry up to ~50 Mbit/s of data traffic. No signal regeneration was required for distances L up to around 10 km. This first generation of optical communication systems helped to increase the previous value of the parameter BL achieved by RF systems to approximately 500 (Mbit/s)•km.

The development of the second generation of fibre optic systems tackled the signal losses of the first generation. These losses presented a serious problem since back then there were no optical amplifiers available. To overcome these losses, the signal had to be re-amplified by means of regeneration. This meant the following: The weak incoming signal was converted back to its RF form using a photo-detector and the resulting RF signal was then used again to modulate a laser transmitter. The resulted optical signal was then fed back into the optical fibre link. This approach proved expensive for system providers.

By close examination of the light absorption characteristics of glass, scientists realised that the parameter L can be increased by transmitting at around 1.3 µm where the optical fibre should exhibit much lower loss and in addition also exhibit minimal chromatic dispersion thus reducing data spreading. This became known as the second transmission window.

The development of a laser and detector for operation in the second window of optical fibre succeeded in 1977 with the demonstration of the InGaAsP semiconductor laser. Three years later in 1980 this technology was used to put the first 1.3 µm based fibre optics communication system into service. This increased the distance L between repeaters to 20 km with the number of transmitted bits remaining at the B approximately 50 Mbit/s. This was due to *modal* dispersion in the multi mode optical fibres used.

The problem of modal dispersion was solved when multimode fibre was replaced by single mode fibre. This was first demonstrated in the laboratory and six years later, in 1981 was used in the field. The installed system supported a data bit rate of B = 1.7 Gbit/s, L = 50 km and BL = 80.5 (Gbit/s)•km. Although the installation cost was high, the long term running cost for the system providers was lower than it would have been using other technologies including coaxial cable or microwave systems. Further improvements in 1979 led to development of optical fibre that supports transmission in the second window with losses of about 0.5 dB/km [5].

Quartz glass offers the lowest loss at around 1.55 µm, the third transmission window, however this third generation of fibre optic systems could not be put into operation immediately due to fibre dispersion. While attenuation of optical fibre around 1.55 µm is minimal (0.2 dB/km), the dispersion is not. To prevent optical data pulses time spreading due to fibre dispersion, a conventional 1.55 µm InGaAsP semiconductor laser could not be used (a specially for higher data rates transmissions). This very serious limitation could be solved either by using a specially designed optical fibre engineered to have minimum chromatic dispersion at 1.55 µm (dispersion-shifted fibre, DSF) and/or by using lasers with a much narrower linewidth. Therefore distributed feedback lasers (DFB lasers) were developed.

In order to achieve the best outcome, both approaches were applied and tested in in 1985 and in 1990 were introduced commercially. The system had the following parameters: B = 10 Gbit/s, L > 100 km, and BL = 1 (Tbit/s)•km. The BL parameter for the third generation of communication systems is about 125 times larger than the value reported for the second generation systems.

Optical fibre's each transmission band (0.85; 1.3 or 1.55 µm) can offer the spectral width approximately of 20-25 Terra Hertz (THz). The transmission capacity of any one of these bands would have been sufficient to carry the transmission of all "wireline" based telephone conversations in the United States during the peak time before the end of millennium and was roughly one thousand times greater than the entire radio frequency spectrum allocated for broadcasting in the atmosphere.

However, there is an absorption peak separating the second and the third window caused by OH- absorption. Since 1998, AllWave® Zero Water Peak single mode optical fibre was the first 'full-spectrum' fibre shipped for use in optical transmission systems enabling operation over the entire wavelength range from 1260 to 1625 nm. The OH- peak removal further increased the transmission bandwidth of optical fibre.

The next major breakthrough is associated with discovery of optical fibre amplifiers and the introduction of optical data multiplexing techniques. The first aimed at increasing the distance L in the third transmission window of optical fibre (1.55 µm) by using the newly developed Erbium doped fibre amplifiers (EDFAs) rather than employing optical regeneration methods to overcome signal losses. First demonstrated in 1987, their unique properties were, high gain, high saturation power, good cascadability relatively large bandwidth of operation, and importantly low cost [6,7].

The introduction of optical data multiplexing techniques such as Dense Wavelength Division Multiplexing, Optical Time Division Multiplexing, and Optical Code Division Multiplexing helped to increase transmission capacity (aggregate throughput) while maintaining data rates per single data channel. The deployment of optical multiplexing techniques required to develop new optical technologies and devices such as narrow band DFB lasers and fibre compatible wavelength filters, add/drop multiplexers and demultiplexers, just to name a few. These technological advancements enabled the current generation of fibre optic communication systems to exceed aggregate transmission rates well over 10 Tbit/s.

It is fair to say that the fibre optics became the backbone infrastructure for the so called Information Super Highway. Today, a rapidly expanding Internet leaves no doubt for the need of even faster data communications.

UNPRECEDENTED DEMAND

The Rapid Growth

What's driving today's rapid increase in the demand for data traffic? The key to this question can be found in the past. The 19th Century English economist William Stanley Jevons recognised that when the efficiency of a resource is improved, then increased consumption will occur rather than merely a satisfaction of current demand. In other words, improved resource efficiency *drives* demand. Attempts to satisfy current demand through, for example, cheaper, faster mobile devices with improved content and functionality will, in fact, spur an even greater demand. This is particularly true of the Asia Pacific markets where improved living standards combined with increasing affordability of smart-phones and tablets, and a thirst for information is driving the fastest growing demand for data in the world.

In fact, global demand for data has been increasing year on year at a phenomenal rate. Cisco predicts that annual global IP traffic will pass the 1 Zettabyte/year, (1 ZByte = 10^{21} Bytes) mark by the end of 2016, reaching 2 ZBytes/yr or 168 Exabytes/month, (1 EByte = 10^{18} Bytes) by the end of 2019. This is almost 3 times its 2014 level and represents a compound annual growth rate (CAGR) of 23% from 2014 to 2019. This figure includes all traffic up to the boundary of the data centre and excludes traffic between data centres.

Similarly, *global data centre IP traffic* (which includes traffic between data centres) is forecast to undergo a 3 fold increase over its 2013 level of 3.1 ZBytes/yr in 2013, reaching 8.6 ZBytes/yr by the end of 2018 (Fig. 2). This is also a CAGR of 23% [8].

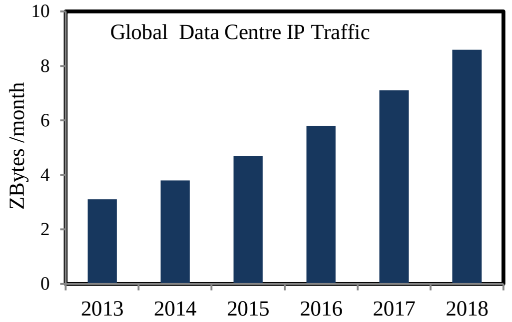

Fig. 2. Global Data Centre IP demand forecast 2013-2018

It is remarkable that by 2018 78% of this traffic is forecast to be cloud traffic and that presently around 75% of all IP traffic exists *between* data centres. The emergence of the 'cloud' is therefore fast becoming THE prime consumer of bandwidth. Most strikingly, *global mobile data traffic* will increase 10-fold between 2014 and 2019 as shown in Fig. 3 and, in particular, mobile data traffic from devices such as smart phones and tablets will grow at a CAGR of 57% between 2014 and 2019, reaching 24.3 Exabytes/month by 2019 [9]. Global mobile data traffic demand is therefore showing the most rapid increase and is forecast to grow three times faster than fixed device IP traffic from 2014 to 2019.

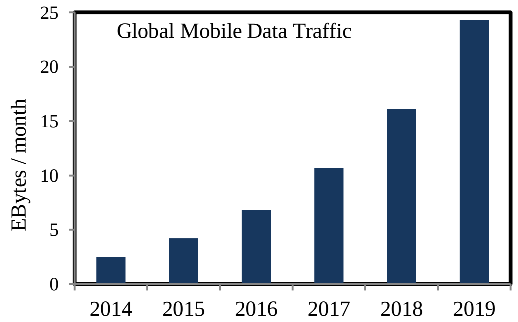

Fig. 3. Global Mobile data traffic forecast 2014-2019

To put these figures into perspective, while global mobile data traffic was 4 percent of total IP traffic in 2014, it will be 14% of total IP traffic by 2019. It is therefore clear that not only is the demand for 'cloud' services such as social network sites growing rapidly, but accessing the cloud using mobile internet devices is consuming a significantly greater proportion of available bandwidth year on year. It is interesting to note that this move to the 'cloud' bears a striking resemblance to the development of mainframe computing in the 1960's. Access to online services has, in a way, come full circle via 'personal computing' and 'mobile computing' with the development of 'cloud computing' where processing and content such as video or music is accessed from remote servers rather than from the device hard-drive. The device, increasingly a smart-phone or tablet, has effectively been demoted to the modern equivalent of a 'terminal'. This presents an enormous pressure to improve network security.

Socio-Political Consequences

As the most pervasive technology of the information age, the internet has connected almost every human on the planet. The internet has increased sociability and reduced isolation amongst the world population. This connectivity has 'democratised' the flow of information where attempts by websites to stifle free communication are easily thwarted by users who 'vote with their keyboards' and move their dialogue to more open networking sites. Furthermore, rather than information or 'propaganda' going one way from the top down to the people, information can now be passed from person to person or community to community. This democratising effect of social networking has allowed the hitherto impossible coming together of like-minded people to form communities whose members are geographically spread across vast areas. Who would predict just a few years ago that Facebook will exceed 1.5 billion members of which 1 billion visit their account daily? Various internet communities are being formed according to for example, common interests, causes or political persuasions. While interaction on internet sites is virtual, the effects are anything but. A prime example is the so-called 'Arab Spring' uprisings of 2010 against establishments across North Africa and the Middle East. Here, social networking using smart mobile devices in particular allowed political movements to organise more effectively and successfully challenge existing power establishments.

Whether the above outcome is deemed positive or negative, it is arguably desirable that both greater access to the internet and the demand for data continues to be satisfied. However, there are technical challenges in sustaining the required growth that are looming on the horizon.

Current Challenges

To sustain the rapid growth of data traffic and increasing use of '*cloud*' based applications in particular data centres must scale to provide higher bandwidths while maintaining low latency and improved scalability. However current data centres performing all data processing based on electronic switching are incapable of sustaining demand into the future [10] and it has been suggested that the fundamental limits of data centre switching is now perhaps being reached [11]. The reason for this inability to meet demand is twofold. Firstly, the scaling of copper interconnects has resulted in increasing switching delays with an associated increased contribution to chip power density. Secondly, the scaling of CMOS electronics has resulted in significant leakage currents that incur an increase in static power consumption resulting in reduced speed.

Fig. 4 shows the historical development of data rates over one single WDM data channel between year 1980 and today and illustrates the consequences on data rates imposed by CMOS electronics. It also illustrates the deployment of 100 Gigabit Ethernet, GbE.

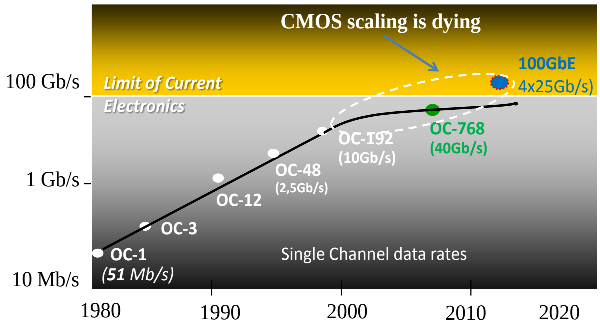

Fig. 4. Historical development of single channel data rates

This dramatic increase in power consumption is rooted in CMOS transistor scaling that has until now delivered progressively smaller, cheaper, faster and lower power consumption devices. In 1974 Robert Dennard described the MOSFET scaling rules crucial to reducing transistor size while at the same time increasing switching speed and reducing power consumption [12]. These scaling principles were adopted by the semiconductor industry to develop and improve silicon devices and the terms ‘Dennard Scaling’ and ‘Dennard’s Law’ were coined. Dennard scaling states that as transistor size reduces, power consumption will reduce while maximum switching speed can be increased. An important observation of Dennard scaling is that power density (Watts/unit chip area) has remained approximately constant as transistor density has increased. In addition, the density of transistors has been increasing by a factor of about two every 18 months for over 40 years. Gordon Moore first suggested such an exponential improvement in transistor density back in 1965 with an estimated doubling of transistor density every two years [3]. What has actually happened to date has validated what became known as ‘Moore’s law’ despite increasing technical challenges in integration. This trend is forecast by Intel to continue until around 2020 [13].

However, despite the continuation of Moore’s law, Dennard scaling came to an end in 2005 with the development of 90nm lithography. At this level, transistor gates become too thin to prevent current from leaking into the substrate, resulting in a rise in power density. The well-known relationship $P_d = C\,V^2 f$ illustrates the relationship between clock speed and power consumption where P_d is the transistor dynamic switching power consumption; C is the CMOS switch lumped capacitance which is the sum of the junction capacitances and gate capacitances; V is the supply voltage; and f is the clock frequency. The above expression for P_d can be justified by considering a CMOS inverter for example. Here a 1-0 transition charges the equivalent capacitance through the source-drain of the PMOS type transistor, dissipating half the energy and in the 0-1 transition the capacitor dumps the stored charge through the source-drain of the NMOS transistor resulting in an approximate total energy dissipation of $2 * \frac{1}{2} C\,V^2$ over one cycle.

There is also a brief short-circuit dynamic power consumption due to both transistors conducting simultaneously for a short time. This is due to the finite rise and fall time during a state transition which results in an input gate voltage range where both NMOS and PMOS transistors are open simultaneously.

Before leakage current became a problem at around 90 nm, as transistor dimensions reduced, C reduced allowing f to be increased and V to be reduced while at the same time reducing the power consumption P_d and maintaining the overall power density of the chip about constant. This power scaling is also true of the short-circuit power. Performance per watt rose as transistor density increased and therefore the energy per bit reduced. However, leakage current due to gate oxide tunnelling has become an issue due to the scaling of the gate oxide thickness. In addition, a reduction in the threshold voltage has resulted in increasing sub-threshold leakage currents. This has in part been mitigated by the end of supply voltage scaling. However as described above, the dynamic switching power of CMOS equipment is proportional to the square of the supply voltage and therefore the maximum switching speed must be restricted to maintain total power dissipation at a sustainable level. If device power density is not controlled, providing adequate cooling will present an intractable problem and result in an increased risk of thermal runaway and reduced system reliability.

In the absence of a mature alternative technology to overcome the leakage current problem it is necessary to reduce power consumption by reducing the clock frequency and therefore the processing speed. Consequently the fastest CPUs in data centres today are limited to handling data at around 10Gb/s. Research into reducing CMOS leakage currents has demonstrated improvements in data handling capacity and power efficiency [14]. However, these improvements have been slow with only modest gains in reduced leakage current achieved. Consequently since 2005 chip manufacturers Intel and AMD have concentrated on introducing parallel processing CPUs using multicore processors to increase processing power. While parallel processing can, to a degree compensate for limited clock frequencies, it clearly results in at least a linear increase in power consumption since an effective doubling in performance requires at least two processors. Also, Amdahl’s parallelism law states that ‘If a computation has a serial component *S*% and a parallel component *P*%, then the maximum speed-up given an infinite number of processors is *(S+P)/S’*. Clearly, the greater the parallel portion *P*, the higher the speed-up. Amdahl’s law says that *there is a fundamental maximum improvement in computational speed that is dependent upon the proportion of serial computation, beyond which further additional parallel processors will contribute a rapidly diminishing improvement in processing speed.* Consequently the performance per watt which is initially constant will eventually decrease rapidly as the number of processors is increased beyond the optimum number. As demand grows, a data bottleneck will result with increases in contention and an associated increase in latency.

It is therefore expected that data centres will become unable to comply with the minimum quality of service they are contracted to provide. In the longer term, the answer to satisfying the rapid increase in demand for processing power in data centres will therefore not be found using present CMOS electronic technology. The fundamental limits of data switching in this bandwidth limited technology may be reached sooner rather than later. In the short term, while Moore's law holds and effective cooling can be achieved, processing speeds can continue to rise. However power density will no longer be constant or slowly increasing as previously predicted by Dennard's Law but will increase with processor chip density. However, the energy consumed per bit will continue to reduce, albeit at a slower rate than before.

The fundamental limits to parallelism indicated by Amdahl's law (assuming that there will always be a serial computation portion) and limits to the sustainable power density in CMOS based processors dictated by thermal runaway and electronics/cooling power consumption concerns lead to a fundamental limit on the processing power of present electronic data centres.

In the short term, increasing clock speeds to satisfy demand is therefore not a realistic solution. As a mature technology, photonics may hold the key to enable data networks to meet growing demand in the long term.

It is believed that all-optical systems using photonic integrated circuits and highly scalable optical interconnects may provide the answer with the promise of signal processing data rates exceeding Tbit/s.

One example of the realization of the all-optical terabit switching device is shown in Fig. 5 [15,16]. The

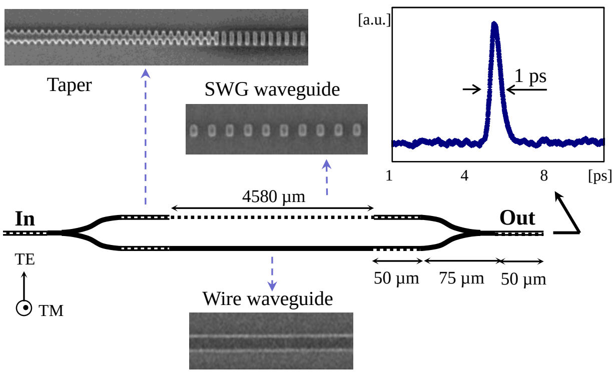

Fig. 5. A terabit all-optical self-switching device based on the Mach-Zehnder interferometer. The inset ilustrates1Tbit/s switching capabilities of this device; SWG is subwavelength waveguide grating structure

integrated chip is only 6.1 mm long and is based on an unbalanced Mach-Zehnder interferometer [15]. One MZI's arm is comprised of a 50 μm SWG taper followed by an SWG waveguide and again by an SWG taper to transition back to a wire waveguide. The reference arm is a wire waveguide with SWG taper-to-taper structure realized to equalize the loss of both arms.

CONCLUSIONS

Over the years data rates have grown from less than 1 bit/s well beyond 10 Tbit/s of aggregate throughput. This progression has been accomplished thanks to new disruptive technologies. They enabled the realization of network transmission capacities that just a few years ago would have been unimaginable. However today the further grows of the information and communication sector is being hampered by the speed limitations of the current CMOS electronic technology (the speed-up using the parallel signal processing in part helps to overcome this bottleneck but only temporarily). However, much more serious issue has resulted from this bottleneck – the power consumption grows. This grows is not only affecting the CMOS but is also trickling down into data centres where as a result power demands have been growing so dramatically that the current rate is not sustainable [17]. These power consumption grows will soon hinder the ability of data networks to further scale up to satisfy future demands.

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