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Fibre Optic Transmission Highways, Towards 5g Era - Information Superhighway Backbone - Networking: A Review

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Abstract:
Background:*New requirements in the era of Cloud and 5G are under evolution for information superhighways required for Digital economies. Corresponding to these new requirements, network optical backbones need to be laid for usage of various sectors in the economy.*
Materials and Methods: *These information highways are expected to connect enterprises, homes and entertainment, IoTs, Base stations via Front haul, Optical Distribution Network (ODN), Optical Network Unit (ONU), Optical Line Terminal (OLT), Edge Devices on Mid-haul/Backhaul, Metro Data Centres, ROADM/OXC, long haul and Core Data centres, for productive interaction in various sectors of Digital economies. These national productivity networks need to have features such as high availability, high speed, high bandwidth, low latency, accurate synchronization, network slicing and modularisation, with Intelligent Operation and Maintenance (O & M) and Transport Software Defined Networking, integrating high performance systems and Cloud based networks of the nation. So, every communication subsystem required isto be reviewed from existing systems indicated in the research publications.*
Results:*So, in this article reviewed, chronological order of scientific discoveries towards such Optical networks, Demand of 5G and Superhighway, various modulation and detection techniques for Fibre Optic Communications, Superhighway architectural subsystems and transport network design trade-off methods are discussed, to take up series of reviews, for building such transport network.*
Keywords:5G, Superhighway, Transport Network, ROADM, PAM, Fronthaul, Mid-haul/Backhaul, DWDM, WSS, QAM*

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I. Introduction

Globally, there has been projections, that the number of per capita networked devices connected to IP networks, raise from the present levels of 2.4 in 2018 to 3.6 networked devices per capita by 2023, up from 18.4 Billion to 29.3 Billion. There will be 5.3 billion total, Internet users (66 percent of global population) by 2023, up from 3.9 billion (51 percent of global population) in 2018. The share of Machine-To-Machine (M2M) connections will grow from 33 percent in 2018 to 50 percent by 2023 and shall be 14.7 billion M2M connections by 2023. Voice over IP with underlying cellular network integrated with Fibre optic back bones, under computer convergence communication has taken shape, to deliver services in digital economies for Industry 4.0.

Based on this explosive growth of inter connectivity requirement, every nation is looking for information superhighway. As this superhighway, along with edge devices need 24x7x365, high availability with high speed networking features, essential for per 5G handset or thin client connected to cloud network, the network with connected devices are always powered on with energy aware features. So, there is a requirement to reduce pico-joules per bit per hertz, in such designs and network connectivity. Out of all communication technologies both wire line and wireless, fibre optic communication has these features for front haul, mid haul and backhaul with wireless connectivity in the last stretch for the sake of mobility convenience. In-fact 5G has more wireline communication (Fibre optic) than the intended last mile wireless 5G connectivity.

II. Major Scientific discoveries and historical Over-View of Fibre Optic Transmissions and Networking

Over the period, the enabler inventions such as, Directly modulated laser, High Speed modulation, Hard Decision – Forward Error Correction, Differential Phase-shift-keying, Coherent detection with Optical Digital Signal Processing (oDSP), Soft Decision – Forward Error Correction(FEC), 100Gbaud-class Opto Electronic device and advanced Optical Digital Signal Processing. The overall, Fibre Optic transmission capacity is also increased, with the improvement in data rate per channel, the number of channels per fibre using Wavelength Division Multiplexing (WDM) or Dense Wavelength Division Multiplexing (DWDM). Flexible

Wavelength Management enabled by elements such as Reconfigurable optical add/drop multiplexers (ROADM) are utilised to make optical networks transparent and flexible [2]. The average single fibre transmission capacity increase over the last 30 years has been at a remarkable rate of over 30% per year, reaching 32 Tb/s in 2019, with a multiplication factor of 10,000. The following, ice breaking, scientific advancements in the history made this possible.

Key Technology Advances in Fibre-Optical Transmission

1880 - Invention of Photophone by Alexander Graham Bell

1948 - Formulation of communication Charles Townes channel limit by Shannon

1957 - Principle of Laser Operation by Charles Townes and Arther Schawlow

1966 - Pronouncement of fundamental limit of transmission is below, 20db/km, depending on purity of Fibre and paper proposing Fibre Communication by Charles Kao

1970 - Room temperature, semiconductor laser made first time in Russia, at Loffe Physical Institute in St Petersburg in May and on 1st June at Bell Labs

1980 - On Off Keying (Non Return to Zero) modulation up to the speeds 2.5Gb/s, per channel over 100 Kms single span, with directly modulated laser.

1987 - First Erbium Doped amplifier reported by Southampton.

1988 - Bell Labs demonstrated soliton transmission through 4000 Km of single mode fibre

1990 - On Off Keying (Return to Zero) modulation up to the speeds 10 Gb/s, per channel, 40 Gb/s over 40 Wavelength Division Multiplexing (WDM) for 400 Gb/s and 1000 Kms Multi Span with Hard Detection Forward Error Correction.

1993 - Andrew Chraplyvy et al. at Bell labs transmitted at 10 Gb/s on each of eight wavelengths through 280 km of dispersion managed fibre

1996 - Wavelength Division Multiplexing Systems commercially made available

2000 - DPSK/DQPSK modulation up to the speeds 40 Gb/s per channel, over 40 DWDM for 1.6 Tb/s and 1000 km@40G, 3000 km@10G, with Raman amplifier, ROADMs

2002 - Compensation for Nonlinearity for phase-modulated signals by Bell Labs

2003 - Gigabit Passive Optical Network (GPON) standardised by ITU implementation

2004 - DSP based coherent optical detection concept by University College of London

2009 – Super-channel introduced and demonstrated at 1.2 Tb/s by Bell Labs

2010 - PDM-QPSK 100 Gb/s modulation, 1xN Wavelength Selective Switching, over 80 DWDM with Colourless-Directionless-Contention less – ROADMs, over 4000kms @100G with Coherent Detection, oDSP, Soft Detection Forward Error Correction.

2011 - Bell Labs researched on spatial multiplexing for scaling of optical transport capacity

2012 - Standardization of Flexible-grid WDM by ITU-T G.694.1.2012

2016- Specification of low loss low-nonlinearity optical fibres were specified by ITU-T

2018 - Colour less, Directionless, Contention less, low loss Wavelength Selective Switch (WSS) developed by Lumentum

2019 – Huawei Technologies demonstrated Super C-band transmission with 6 THz optical bandwidth

2020 - PDM-nQAM, CS, PAM8, Discrete Multitone Transponder, MxN Wave length Selective Switching, Flexible Grid, Super Channel Erbium Doped Fibre Amplifier, over 2000 (1000) km @ 200(400)G for 16-32 Tb/s Flex-Grid.

III. DEMANDS OF 5G AND SUPERHIGHWAY

In order to enhance Fibre Transmission capacity to meet the enhanced Mobile Broadband requirement arised, due to 5G connectivity, four physical dimensions of a light wave travelling along a fibre transmission link need to be exploited.

1. Multiple single mode fibres in a same fibre cable – Space Division Multiplexing
2. Amplitude and Phase modulation of an Optical Carrier via. Quadrature Amplitude modulation (QAM), Quadrature Phase Shift Keying (QPSK), Pulse Amplitude Modulation
3. Wavelength Division Multiplexing (WDM), over all Optical Window Bands E, S, C, L Bands - 1360 – 1460 nm, 1460 -1530 nm, 1530-1565 nm, and 1565-1625 nm respectively
4. Polarization Division Multiplexing (PDM), via. Dual Polarization and Polarisation Division Multiplexing.

In a 5G oriented Optical Transport Network, requirements of Front haul, Mid haul and Backhaul and ideally connectivity to Data Centres is a requirement. Mobile network applications have a diverse set of demands such as ultralow latency, ultrahigh availability, ultra large bandwidth and overall optimization of the entire network. Based on the welldefined time-division multiplexing (TDM) and switching in Optical Transport Network (OTN), guaranteed low latency can be achieved to effectively meet the 5G network latency requirement. C-RAN is playing an important role in mobile networks by improving network performance via. Coordinated Multipoint Transmission/Reception.

In addition to 5G Fibre Optics, any region/geography also need computer interconnectivity, over it's all pervading IP/network nodes with high availability(99.999%) and high speed (400 Gbit/sec per channel) features, at lowest technology costs. The developments globally are advancing for interconnectivity of these client computer nodes to cloud servers on which Application Servers in various sectors and Enterprise Architecture are residing. It is not only computer connectivity but also Households for HDTV, internet, based devices, Processes and Monitoring points are getting connected via. IP based IoT devices for Industry 4.0 readiness of Manufacturing, Services and Trade processes, for their productivity and cost competitiveness. Billions of IP based IoT devices are expected by 2025. Moreover, it is expected highest security is in Fibre Optic communication and associated quantum communication. These essential requirements are in general are made possible only through high end Fibre Optic communication technologies and associated subsystems.

IV. Optical Modulation and Detection Technologies

Continuous improvements in modulation and detection techniques increase spectral efficiency in Wavelength-Division-Multiplexed systems, with robustness against transmission impairments and facilitate electrical compensation to some extent. The basic physical attributes of a light wave that can be modulated to carry information are amplitude, phase and polarization. Based on these attributes, the popular modulation and detection schemes are around

Modulation:

- Intensity modulation
- Wavelength/frequency modulation
- Temporal modulation
- Phase modulation
- Polarization modulation

Classification of Detection Systems:

Asynchronous: There are two Detection techniques under Asynchronous classification, Non-coherent and Differentially coherent.

- PAM
- Direct Detection
- Envelope Detection
- Non-coherent
- DPSK
- Interferometric Detection
- Differentially Coherent
- Delay and Multiply Detection

Synchronous:

- PSK, QAM
- Coherent Detection
- Coherent

Digitally modulated optical signal detection methods are classified logically based on traditional distinctions. The traditional distinctions are Coherent, Non-coherent, Differentially coherent detections. In non-coherent detection, only the presence or absence of energy is ascertained and no phase information is recovered.

In any Fibre Optic communication receiver, sensitivity n_b/n_{eq} is the average number of photons per bit $n_{b,}$ divided by the equivalent Amplified Spontaneous Emission (ASE) noise factor of the optical amplifier, effecting dispersion. Binary modulation achieves a minimum spectral efficiency of 1b/s/Hz per polarization. 2-Differential Phase Shift Keying with interferometric detection and low implementation complexity is an attractive scheme for its excellent sensitivity. Quaternary modulation doubles spectral efficiency, while achieving higher tolerance to impairments, such as chromatic dispersion (CD) and polarization mode dispersion (PMD). 4- Differential Phase Shift Keying with interferometric detection is better in-spite of additional, for its reasonable sensitivity, while 4-Phase Shift Keying with coherent detection offers better sensitivity.

If, higher spectral efficiency are required higher degree of freedom in the scheme and design need to be incorporated. Quadrature Amplitude Modulation (QAM) with coherent detection offers the best sensitivity among the various detection schemes. The superior performance of QAM is due to the fact that QAM encodes information in two degrees of freedom (two quadrature phases). Whereas PSK, DPSK or PAM encode information in only one degree of freedom, i.e phase, phase or magnitude respectively. Noncoherent or differentially coherent detection is implemented using direct detection, avoiding the need for a Local Oscillator laser and polarization control or diversity. Any of the 3 techniques are implemented using heterodyne or homodyne down conversion, yielding two potential advantages. These advantages allow, design of a frequency agile receiver to enable wavelength routed switching or frequency hopped transmission and Chromatic Dispersion appear as a linear distortion, facilitating its effective, low-complexity compensation in the electrical domain within some limits.

HOMODYNE AND HETRODYNE DESIGN ISSUES

Homodyne requires the optical receiver to have an electrical bandwidth of the order of the symbol rate R_s, while heterodyne requires a bandwidth of about $2R_{s,}$ which is prohibitive at high symbol rates. In cases, where it is necessary to down convert two quadrature phases of an optical signal such as 1) electrical compensation of nonlinear phase noise in fibre 2) demodulation of quadrature modulation 3) synchronous demodulation in the electrical domain in place of using an optical PLL 4) synchronous demodulation in the electrical domain 5) electrical compensation of Chrominance Dispersion, homodyne requires two balanced optical receivers, while heterodyne requires only one.

DPSK and PSK is implemented using typical distributed-feedback lasers, whereas other modulation/detection techniques require narrower-line width lasers. Some of the Laser linewidths indicated in the literature by researchers, for various detection techniques under various modulation schemes are indicated in terms of $\Delta v/R_b$ for R_b = 10 Gb/s. These are 1) DPSK (Differentially coherent detection) need 5 Mhz [7] 2) 16-PSK (Coherent detection) need 2.4 Khz need 2.4 kHz [9] 3) 16 QAM (Coherent detection) need 6.9 kHz [10]

V. Superhighway Architectural Subsystems

OPTICAL SUPER CHANNELS

Higher optical line rates of the order of 400G, 500G per fibre and Multi terabit through the use, of super channels have been advanced by the research community. These advancements are changing the way how long-haul networks are designed, with higher spectral efficiency. The increased disparity between client and super-channel line rates drives a switch, based architecture rather than mux-ponders/transponders, in order to aggregate multiple client interfaces onto an optical line. Even though, super channel, based architecture may have shorter optical reach with less sub carrier separation to symbol rate ratio, the North American long haul reference network model, the CORONET of United States topology with 75 nodes, 99 fibres already reached 1221 Kms way back. This architecture assumed an Optical Transport Network (OTN) digital switch and an Optical Add-Drop Multiplexer (OADM) at every node. Super channel lines will necessitate more traffic regulation at intermediate sites without wavelength switching, to be able to have reasonable wavelengths. If, wavelengths chosen are less, naturally it will increase, costly optical-electrical-optical (OEO) conversions and nodal digital switch size requirements

TRANSPORT NETWORKS

Optical line capacity required to carry a given set of service demands is characterized by Transport Network efficiency. While designing a national network, improving network efficiency is critical to network providers, since it leads to lower networking costs. In such an efficient network design, an approach with right balance between the digital switching i.e Optical- Electrical-Optical (OEO) and the Wavelength Switching i.e Optical-Optical-Optical. In this approach, the digital switching is expected to improve network efficiency by combining partially filled wavelengths into few, fully occupied wavelengths, but also ensures, higher transit traffic in switches, thus increases digital switching capacity requirements and OEO conversion costs. In contrast wavelength switching reduces OEO costs by optically bypassing intermediate switching points, which may lead to, network capacity underutilization, if alone used.

Ultimately, it is the optical line rate, which highly influence the network design trade- off between Optical-Electrical-Optical and Optical-Optical-Optical switching, to provide optimal design balance between the two switching systems, thus the network design trade off differs for 100 Gbps and 500 Gbps super-channels [11]. Higher optical line rates of super channels drive the need for more digital switching diversions of traffic and yield less opportunities for wavelength expressions. In fact, the design is optimized using a capacity. In general, Optical line capacity is decided based on the extent of broadband usage and it's integration with the economy through various economic sectors. It also depends on, targets of the nation on how on-line and digital, itwant's to be, during the network configuration life. In the research domain, there are results published on required optical line capacity, before 5G era. The results indicated the following, three inefficiencies with 500G Optical Transport Network (OTN) model's link usage, when applied on CORONET of USA:

- 3 x more transit traffic in the 500 Gb/s case: This line rate gives, less opportunities for efficient wavelength expressing, as more Optical-Electrical-Optical traffic is required to approach a full wavelength utilisation. This drives additional transit traffic and inclusion of associated latency, but with advantage of increased optical line capacity between switches.

➢ 5x more regen capacity for 500Gb/s: As traffic bandwidth between end points increases and more opportunities exist to express wavelengths with longer distances. Reach is very important, year over year, due to less reach capability of a 500Gb/s line.

➢ 7x more unused capacity for 500Gb/s: Despite the large traffic levels placed on the whole network, a line rate of 500 Gb/s is excessive at some smaller sites, resulting in 26% of the deployed capacity

In any large network design consideration, some large geographical sites are identified, network scalability of the design is predicted in part by the switching capacity requirements of these large geographical sites. So, provision to network operators is to resort to multi-chassis hot plug and play solutions or switch clusters, both the options are costly and difficult to engineer and manage.

So, the range of required Optical Transport Network (OTN) digital switching capacities for the identified large geographical sites of the network under design is required to be estimated, which includes both client capacity and network side, optical line capacity. In the research studies undertaken, 100 Gb/s OTN offers a moderate improvement in scalability compared to 500 Gb/s OTN, however both architectures still require very large switches at the identified large geographical sites, often exceeding the capacity of commercially available OTN switches. Hybrid network architectures consists of mux-ponders/transponders and OTN switching. In this hybrid architectures, larger demands are offloaded onto mux-ponders/transponders, freeing up the OTN switching infrastructure to focus on what it does best, i.e aggregating and transport of smaller demands. In the research, there have been indications of significant reduction up to 87% in the required Optical Transport Network (OTN) switch capacity with hybrid architecture of combination of 100 Gb/s and 500 Gb/s.

It may be noted, an entirely super-channel based network architecture can have a significant negative impact on network efficiency compared to a finer granularity line rate network architecture, requiring more than double optical line capacity to meet the same service demands across a network. Super-channels do not provide sufficient granularity to be used exclusively in the design of the long-haul networks. A network based, exclusively on digital switching can create significant scalability challenges, requiring very large capacity switches. This is eliminated in the design, using hybrid architecture that utilizes both mux-ponders/transponders and digital switching.ThusSuper channels are for providing a cost effective way to increase optical capacity between the busiest core locations. Still, the most efficient networks will continue to use a blend of optical line rates and technologies, also involving present 40/100G hybrid architectures.

VI. Conclusion

A review is undertaken to assess general demand and importance of superhighways for Digital economies and chronological scientific discoveries to build such national superhighways. Optical Modulation, Detection techniques and associated Laser line widths, as we move up the ladder for higher spectral efficiency i.e more bits/s/Hz per picowatt, possible in Fibre Communication with a view to identify subsystem designs of the superhighway, for various subsystem design trade off and usage in Transport Network, of the over Fibre Optic Communications Network that support 5G and Cloud network architectures.

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