

Light Waves and Data Highways: The Physics of Optical Communication Networks

V. Basil Hans

Abstract

Optical communication has revolutionised modern telecommunication, allowing for the quick transfer of information by light signals. This technology uses optical fibres as the transmission medium and offers higher bandwidth, lower signal loss and faster data transfer than typical electrical communication systems. Optical communication has become a key enabler of internet services, mobile networks, satellite communication and data centers which are all driving the increasing demand for high speed and dependable connectivity. Along with addressing major issues like fibre losses, installation costs, dispersion, and maintenance complexity, the study also explains how optical fibres work and emphasises the significance of light propagation in achieving long-distance communication with minimal loss. This article deals with the principles of optical communication, which covers the generation, transmission and receipt of optical signals. Recent developments in fibre optic technology and their role in supporting next-generation communication systems are also examined, highlighting the growing importance of optical communication in the digital era. It also discusses the advantages, applications, challenges and recent developments in the field of fibre optics technology. It also tackles important issues including dispersion, maintenance complexity, installation costs, and fibre losses. As the demand for worldwide communication keeps on rising, optical communication is a crucial technology that is pushing the future of digital connectivity and information exchange.

Keywords: Optical communications, optic fibre, data transferring, light waves, telecommunications networks

INTRODUCTION

Information traverses local, metropolitan and wide-area networks and connects billions of subscribers worldwide. The physical medium for propagating information is omnipresent light that exists as both a wave and a particle. Transmission technologies have progressed over the decades from copper wire to photonic systems, delivering unparalleled data transmission rates and distances of over 1.5 million km. The optical communication capacities in deployed long-haul networks are well beyond 100 terabits per single wavelength, and efforts towards petabit capacities and quantum enhanced optical communication are being investigated. This shows the considerable ongoing R&D in optical transmission, switching and networking. The volume of data communications traffic worldwide has grown tremendously, doubling every 2 years or so, spurred by the expansion of internet-connected gadgets, videos, data centres, cloud computing, electronic commerce, mobile platforms and social media.

*Author for Correspondence

V. Basil Hans
E-mail: vhans2011@gmail.com

Research Professor, Department of Commerce & Management and Humanities & Social Sciences, Srinivas University, Mangalore, Karnataka, India

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Photonic devices for information dissemination are also predicted to grow. Applications such as machine-to-machine communication, virtual reality, remote education and connected hospitals will propel the demand for data highways. The next generation of data highways will have to face many issues such as bandwidth and power efficiency, dependability (error monitoring/correction), upgrade flexibility, security and interoperability with existing systems [1, 2].

BASICS OF LIGHT WAVES

Light Waves and Data Highways: The Physics of Optical Communication Networks

The first step of an optical data highway is the recognition of ambient light and its manipulation by simple wave optics, materials and geometries. Optical communications are based on light waves that meet basic requirements of transmission, modulation and coding. High-capacity optical channels, fiber-optic systems and capacity-approaching codes provide efficient linkages for long-haul, high-capacity networks, and high-coherence optical systems approach the ultimate Shannon limit. Exploiting such channels necessitates compact, low-cost and low-power sources, modulators and detectors, and active or passive multiplexing methods to increase capacity and reach.

Free propagating light waves exist in the range from 1 nm to around 1 mm. Optical communications use spectral bands that transmit signals: ultraviolet, visible and near-infrared waves. Quantum theory says the light behaves as particles, even at the nano-scale. Photons quantise the free propagating light waves as individual energy carriers. With quantum theory, you can keep a wave description. But particle and wave descriptions are still inconsistent. For the previous century of optics, we have been working with coherent, steady-state light waves coming from a source with a single frequency and phase. Real sources do fluctuate, over a range that varies greatly, and in power. Data-highway communications need laser sources much smaller than a nanometre wide.

The spectral efficiency in bits per second per hertz is directly related to the needed breadth of the wavelength variation for frequency modulation. Stabilisation techniques are used to reduce first-order frequency modulation by fluctuations in coherent systems with radio-frequency modulation in the tens of gigahertz range, achieving a spectral efficiency of four bits per second per hertz, and within per-cent of capacity with a standard single-mode-fiber (SMF)-280 system. Fluctuations outside the unmodulated spectral width also should be less than the required information-carrying side-band envelope.

Cross-phase modulation, four-wave mixing and other nonlinear interactions redistribute power between channels and must be carefully managed. Such power redistribution is insignificant in wavelength-division-multiplexing systems with channel spacing larger than 100-gigahertz, and in adequately spaced point-to-point channels with distributed amplification, as in the direct-detection coherent method.

Submicron-thick and micrometer-scale systems are defined by thin-wave and fiber-waveguides. The linear single-mode wavelengths of optical fibres, few micrometres in diameter, made out of glass or polymer gemstones seeded with tiny amounts of dopants are limited to many hundreds of gigahertz. At very high rate the transmitted information on slow moving solitons acts again like the ideal cable.

Wave-Particle Duality and the Electromagnetic Spectrum

Light generation, detection, modulation and demodulation in free space are very different from optical fibre links. Advances in these fields improve single-channel bit rate, channel number and transmission distance, which contribute to the development of optical data highway [1]. The high bit-rate and multi-channel optical data highways put strict constraints on the transmission of optical signals across terrestrial and submarine fibre links between data-centres and other network nodes. The power-efficient transmission of optical signals via fibre links following linear and nonlinear physical rules is a well-known research area of great interest.

In free space, the optical signal travels directly from the transmitter to the receiver in line-of-sight channels. However, fibre optics and integrated optics commonly employ multi-hop or multi-segment propagation, in which an optical signal propagates over at least a number of half-link segments. Thus, a high capacity single- data-rate line-of-sight (LOS) optical data highway can be followed without any violation of power efficiency and reach of transmission. On the other hand, the multi-hop multi-channel optical data highway with enormous channel bandwidth within the limits of channel count, power consumption and reach becomes more tempting and more demanding on channel-transmission physical layer design.

Optical fibre connects optical-data highway nodes in a point-to-point way. The multi-channel operation is compatible with dense wavelength-division multiplexing (DWDM) in the C-band and/or L-band, where the wide-band semiconductor-laser transmission approach guarantees the compatibility with either channel packing nature. The new solid-state multi-wavelength full-array optical sources and strong ultra-narrow-band filters free optical-data highways from channel-density constraints fundamentally. The need for large data resources stimulates the development of multi-channel, multi-hop or both optical-data highways. Hence, high-performance fibre optical transmission is required for any data-grade-acceptable link with compatible network traffic.

Optical Media

Now light-wave communications are employed over the world. They have large bandwidths and are important for the transfer of real time data over long distances. These communications use mainly the optical fibre as the medium, which increases the access to information and solves the growing needs of data in the society. Light-wave communications are deployed in worldwide high-capacity networks that make up most of the internet backbone, and in data center interconnects in supercomputers. The area is still growing with speed and this shows the necessity to adapt to the increasing needs of information transit and to pave way for future innovations. Photonic, communications, electronic, and signal-processing expertise in the optical communications arena come together at the industry, research, and university levels to improve capacity, reduce cost per bit, reduce energy consumption per transmitted bit, and adapt to emerging optical technologies and services [1].

Electromagnetic waves with frequencies higher than 3 terahertz (THz) exist in the optical domain and are usually referred to as light or light waves. The optical fibre is made of transparent materials such as silica gel or polymer, with a refractive index profile that confines the light in the fibre core. Optical fibres work in two different modes of transmission. There are single-mode fibres and multimode fibres. Single-mode fibres have a homogeneous core of around 10 micrometres in diameter, and support only one propagation mode. Multimode fibres feature greater core sizes (usually 50 to 62.5 micrometres) that may support a number of longitudinal propagation modes. These fibres are primarily employed for short distances, whereas single-mode fibres are used for virtually all long-distance light-wave communication applications.

Modulation and Coding Concepts

An optical fibre message is mathematically described as a light wave, and optical modulation techniques are classed according to the quantity of the wave that is modified to transport the code or audio signal.

Digital modulation techniques employed for optical communication. 4. Optical Modulation Formats: Discusses in detail. Received signals are generally classed as analogue or digital. For example, binary levels are two amplitude levels into which the information to be communicated is encoded in digital transmission and they vary synchronously with time. Transmission without discrete levels is called analogue whereas transmission in such a circumstance is called digital.

As both amplitude variations and phase variations provide higher bandwidth efficiency than an on-off keying arrangement, digital optical modulation techniques alter the amplitude and/or phase of the light wave between two unique values. We study modulation formats like: amplitude modulation (AM), pulse-width modulation (PWM), frequency modulation (FM), phase modulation (PM) and amplitude phase modulation (APM).

Analogue modulation formats modulate the signal according to the audio signal to be transmitted - by means of amplitude modulation (AM) or frequency modulation (FM), etc. It will be shown in a similar manner, that if the structure is binary, then it can be considered as digital modulation with extended symbols/higher levels. Digital and analogue schemes require different error correcting codes depending on the level of control permitted [3].

OPTICAL COMMUNICATIONS PRINCIPLES

One of the main communication challenges is to generate and read signals as distance and capacity expand [2]. Like any transmission system, optical data highways generate signals to transmit and receive. The target across platforms for on-chip photonic circuitry integrates generation, modulation, detection, transmission, amplification and switching. Requirements and processes vary seamlessly throughout these roles. The millimeter-wave laser platform with cross-dimensional coverage at each level permits serious research of optical highway [1]. Core approaches of deploying optical highways on-chip minimise total equivalent optical journey by strict placement at integrated photonic circuits. Arbitrary-data signals are transmitted by illuminating mutually shifted broadband upconverted sidebands of a carrier. Huge on-chip signal-exploration is supported by off-chip pumps, but they rapidly converge toward tunable compact integration and multimode exploration.

Transmission Lines & Fibre Optics

Light conveys information through optical fibres over long distances. The fibre optical communication system can transmit information in the form of light pulses. The diameter of the core of the least bendable fibre is about 5 μm to maintain the single mode propagation. The numerical aperture of the outer core of the fibre controls the acceptance angle. The transmission length is limited by several pulse dispersion phenomena. When a pulse travels over the fibre, spectral components with differing velocities change the temporal pulse form. Light or a signal is emitted by an electrical or electronic equipment. A detector is used to convert optical signals to electrical signals [2].

Modulation is the transformation of an arbitrary continuous time function of time (t) into a finite number of discrete samples at even intervals of time (t). Modulation is the process of “placing” a digital message ($m(t)$) into a carrier signal ($c(t)$) of a higher frequency than $m(t)$. The analogue amplitude modulation (AM) and digital amplitude modulation are respectively continuous or digital changing of the amplitude of the carrier signal. There are various types of signals [1].

Core Technologies: Laser, Detector, Modulator

Optical networks use a transmission medium which supports propagation of discrete electromagnetic (EM) waves. In this part, three waveform reception components – lasers, photodetectors and modulators are essential aspects of basic optical data maintenance and critical technologies for future communication networks.

Lasers emit continuous light with one wavelength or monochromatic beams, while photodetectors are sensitive elements generating an output signal while receiving EM waves. Such minor processes are determining the overall performance of a network with respect to power consumption, cost and integration. The design of modern waveforms is directed towards efficiency and their use is widespread in novel stacked waves to elucidate a variety of signals [1].

There is a need to guarantee the compatibility of the constituent wavelength bands of the elements of each layer and the new multi-wavelength and multi-level interfaces in WDM technologies. For the special case of accommodating upward transmission capacity, one should consequently refrain from excessive repetition and instead increase extra wavelength bands or channel counts.

Methods of multiplexing and channel capacity

Wavelength Division Multiplexing (WDM) is the most popular technique for enhancing the bandwidth utilisation of optical fibre lines. This approach opens many optical channels utilising light of different wavelengths. This allows several hundred high capacity channels to be carried simultaneously in a single fibre, enabling several Terabits per second capacity in a single fibre [4]. The current WDM approach is Dense Wavelength Division Multiplexing (DWDM) using laser technology to provide narrow λ spacing. Standard ITU grid spacing is 50 GHz (0.4 nm Optical signals at discrete wavelengths can be created to carry data and/or control information.

Engineering analysis shows that Optimum Transmission Length for amplified links, is given by the ratio of amplification bandwidth to the effective bandwidth of the data and the number of channels carried per dense WDM signal. However, if time/length product is more than unity, the probability of having an undetected error increase. Moreover, over-utilization of the spectrum results in a higher degree of cross-talk between channels. From these assessments it can be said that Dense wavelength division multiplexing has huge promise for high-bandwidth transmissions. It involves a careful consideration of various signal-processing techniques vary at different levels of the network [5].

Another factor to consider is complexity and there are two main possibilities in the dense wavelength division multiplexing ports field, namely Separate and Monolithic, existing now. Critical Dimensions tools are variable in magnitude in the design and control of Gain Flattening Filters to ensure adequate dependency, hence the need to establish distance monitoring. Further complication is introduced when Polarisation Division Multiplexing is used as the system is believed to operate on one Polarisation and so additional monitoring is necessary for the individual polarisation axis along the routes [6].

Signal Integrity & Noise Considerations

The main limiting factors in ultralong-distance optical communications are chromatic dispersion, polarization-mode dispersion or nonlinear interactions, which continuously alter the signal. This type of distortion usually increases the bit-error-rate (BER) above the tolerable limit and the signal-to-noise ratio (SNR) is usually used to measure and anticipate this impairment [1].

DATA HIGHWAYS NETWORK ARCHITECTURES AND PROTOCOLS

Roadmap documents are often found in the scientific literature, providing a guide for research directions towards long-term goals. The seminal ideas for lightwave communications by Kao and Hockham were conceived in 1966 and since that time there has been much evolution in optical systems. Four decades of evolution in materials, components and subsystems have built up to enable record transmission capacities in excess of 1 terabit per second over long-haul links. Building on this momentum, a recent roadmap on optical communication highlights the various tactics, accompanying difficulties, and developing technologies that are projected to define next-generation optical systems and networks. One basic change that is affecting the design of optical networks is the change of files from analogue to digital in multimedia and IT applications. This phenomena of digitalisation has produced new kinds of applications. Next generation networks are to suit the changing requirements of applications and current networks deployed for information transportation are thoroughly investigated to build them. Therefore, a recurrent challenge since the beginning of optical networks has been to introduce new network architectures fitted to conduct topology and routing layouts based on new requirements [7]. The layered model of the telecommunication network is a fundamental guide for the optical infrastructures. Parallel to the evolution of new architectures, another stream of research is the research on new protocols or the extension of current ones. The fast pace of evolution and the need to move on the mass scale meant that the challenges kept changing to the Wavelength Division Multiplexing (WDM) span, routing and topological matters, whenever a new technology became available for the deployment and when bandwidth more and more started to expect not only transmission but accommodation of the control plane, an equally critical part of a successful optical network.

Responsibilities of Physical Layer & Layered Models

The International Telecommunication Union (ITU) standard G.805 defines a multi-layer, multi-domain network design, emphasising layering and abstraction [8]. The layered structure consists of a transport layer including wavelength, time-division multiplexing (TDM) and byte-oriented time-slot interchange, a connection control layer establishing, adapting, releasing and monitoring end-to-end multi-domain Transport Layer connections and a control plane establishing, modifying and releasing connections and offering management functions. Layering isolates the complexity of higher functions, resulting in a simplified interface that supports interoperation on a multi-vendor basis.

Network layers and their links are presented in layer dependent techniques. A customer Ethernet signal is received at the customer edge and signalling and framing is performed to build an Optical Ethernet frame. Framed signals enter Optical Channel layer. Provides signals for Ethernet over Optical Media Module Transport Unit (OMTU), Time Division Multiplexed Optical Multi-Channel Transport Unit (OTU) and Rings. The management and monitoring functions over these levels are the management plane related to the optical channel.

A novel physical-layer paradigm for multi-domain Optical Transport Network (OTN) systems using hybrid Wavelength Division Multiplexing (WDM)/Ethernet. Multi-service OTN/WDM metropolitan and regional systems circuit-switch wavelengths to the edge for client service and routing forwarding. Wavelengths can pass through one or two domains without allocation on full crossconnectivity Many OTN/WDM links span across several administrative domains, which forces the top layer to differentiate route-dependent control-plane optical channels and set up parameter-controlled channels. Hybrid control-plane techniques centralise route-dependent control information in a particular layer in a dedicated or integrated manner.

WDM and Dense Wavelength Division Multiplexing

In an optical network, Wavelength Division Multiplexing (WDM) enables the transmission of many optical signals at the same time over the same fibre; each signal operates at a distinct wavelength and carries an independent stream of information [9]. Different wavelengths enable each channel to have its own modulation technique, format and performance optimisation. Moreover, WDM provides a means to generate a wide bandwidth aggregate optical signal from a small number of input data streams.

With DWDM, the idea is taken further by using closely spaced wavelengths, which increases spectral efficiency. Channel separations below 1 nm have been demonstrated leading to a potential capacity exceeding a terabit per second over a single fibre. Such systems demand very strict control of the quality of the optical signal, in order to prevent degradation caused by limited bandwidth and the wealth of nonlinear phenomena that occur at such high data rates.

Paradigms for Optical Switching and Routing

In an optical network, signal propagation generally requires switching through an intermediate stage between a source and destination. Optical switching combines WDM with time-division multiplexing; WDM increases channel capacity, and switching routes individual channels to specific destinations. We show that in a WDM-based signal path a time-varying signal can route multiplexed optical traffic through a switch fabric that contains nonlinear regenerators. All-optical switching in wavelength-routing optical interconnection networks can be realised by exploiting a parallel processing capacity for demultiplexing WDM signals. A switching fabric interconnects a number of inputs and outputs . Integration of optical modulation, demodulation and time-compression enables a range of switching operations to facilitate wavelength routing. Many designs of switching fabrics try to reduce the network congestion and conflict. Contention happens when more than one input attempts to reach the same output at the same time. One way is to have a storage buffer in the intermediate switch to resolve the contention. So, if contention occurs, the switch selects a different path. Handoff can be illustrated using an optical switch that emulates a telephone switchboard, where each link from an input channel to an output channel is switched to a new channel when it receives a second request for the same channel. Quality-of-service (QoS) parameters provide a threshold for acceptable contention and delay in signal transit through individual switches and help in designing loss-free, nonblocking optical switching arrays.

Backbone Design and Network Topologies

Conventional Wide Area Network (WAN) architectures are limited in their ability to fully exploit the bandwidth provided by Wavelength Division Multiplexing (WDM) since, while the optical transmission rates are on the order of gigahertz, the speed of the electronic processing, switching,

buffering and error checking, remains roughly an order of magnitude slower [7]. Packet switching, a popular solution for throughput increase, suffers from node bottlenecks due to long queuing and processing times (both constant and variable). Even in “fast packet switching” cases considerable uncertainty and average waiting times exist and this makes expensive buffering necessary. Lightnet is an architectural approach specifically intended for all optical networks to boost the effective throughput and to get rid of the bottlenecks faced in the contemporary node designs.

Sacrificing some of the transmission bandwidth can raise the effective bandwidth per packet, without increasing the number of switching stages. Such a tradeoff not only improves performance but simplifies switching decisions by allowing the design of topology-dependent “virtual” packet switching techniques based on the path information. With optical throughputs approaching one hundred gigaHertz, the most critical hurdle to implementing all-optical WDM communications from end to end is conventional electrical buffering, path-setup, processing and switching speeds. Lightnet designs can be implemented with state-of-the-art high-speed photonic routers and a regular connectivity structure that is easy to design and build. Packet paths are independent of data paths. This enables the building of high-throughput routers, stages and node designs with a lower level of interconnect complexity than is generally associated with high connectivity.

RELIABILITY, STANDARDS AND PERFORMANCE

The exponential expansion of data traffic generated by internet-connected gadgets has made optical communication increasingly important. Significant progress has been made in optical fibres, notably the shift from multimode to singlemode construction, which has cut both dispersion and loss, allowing for longer distances and greater data speeds. Optical channels development is still in progress to accommodate the bandwidth requirements [1], although the optical loss, dispersion and non-linearity are the limiting variables and are kept constant. With the increasing importance of optical data transmission, the efficient and reliable transfer between networks is a necessity.

This surge in data traffic will continue to push the demand for higher broadband capacity at reduced cost. The number of channels is controlled by the wavelength spacing used. Non-linear effects on some channels limit the transmission capacity. These parameters determine the overall broadband capacity provided to the network. Another requirement is round-the-clock, reliable service. Networking architecture includes connection and flow control, routing, signalling and network management

Attenuation, Dispersion and Non-linearities

The propagation of light in optical fibres is sometimes theoretically modelled by a properly formulated model of bandwidth-limited propagation of statistical signals down a linear constant-coefficient noisy transmission line to describe the attenuation and dispersion of light. The nonlinear Schrödinger equation, incorporating the most important nonlinear effects in the fibre, can be used to study the effect of fibre nonlinearity on transmission and also the performance limitations due to the combined effect of chromatic dispersion and fibre nonlinearity.

An instance is the joint effect of chromatic dispersion and fibre nonlinearity . This effect is well represented by an integrated area of the fibre signal spectrum, generally known as the chirp parameter . A regular perturbation theory to the combined fibre parameter gives an approximate model for the fibre in the weak-dispersion, noiseless regime and a pure-quadratic description, which is associated with the first-order symmetric phase modulation, improves the model accuracy in the high nonlinearity, low-dispersion domain [10].

Methods of Error Detection and Correction

An optical communication system can work well and match the performance requirements, provided the bits are on time and the transitions are in the appropriate position [11]. Receiver design

appropriateness is determined by bit error rate (BER) and eye pattern. The most significant achievement is the development of error detection and repair systems since modulation has Channel coding allows for higher order modulation forms while meeting rigorous BER criteria. Typical raw BER of 10^{-3} or 10^{-4} is usual, without error detection. The signal can be regenerated to recover the original input or error detection/correction can be performed.

Forward error correction (FEC) enhances the network scalability and the distance of transmission by reducing the necessary sensitivity of the receiver. The additional FEC overhead in the form of G.976_1, G.975.1, G.975.3, G-709_3 is more than enough to the optical link margin at the moment. There is no way to improve it. An all-optical error detection based on the 3R (re-shaping, re-amplifying, re-timing) approach was presented with a reach of 80 km in 2010 [12]. Regeneration of eye diagrams is not possible using EDFA or OEDFA or phase preserving amplification . In the last 5 years, various error-detection systems have received interest to reduce finite amplification resources.

Standards and Compliance Interoperability

Standards bodies and regulatory organisations have major impact on the physical layer architecture of communication networks. These organisations set standards for expressiveness and implement and guarantee interoperability to such standards. However, there are several key features of the connection among standards, interoperability, compliance and optical communication networks that need clarification and exposition. The processing bandwidth and the rate of information encapsulated in a transmitted signal are timeless metrics of communication systems more generally. Similar statements apply to optical transmission, despite the progressive development and proliferation of optical-electronic equipment, networks and fiber-waveguiding technologies [1].

Standards obviously play a role in providing a consistent and widely used metric for the comparative evaluation of novel transmission concepts, and optical-equivalent gain is similarly instructive for evaluating the relevance or appropriateness of amplitude modulation or complex modulation formats for dense-wave-division-multiplexed transmission over links that might well carry few, if any, wavelengths. The difference between digital and analogue communication systems is universal as discussed at great length in the prior sections, whether the nature of the processes conducted, and the dominating noise characteristics involved, are purely electrical, purely optical, or partly electrical and partly optical [2]. crucial components using electrical processing in the optical domain are seen as suitable platforms for digital transmission and bring into play crucial interoperability aspects.

EMERGING TRENDS AND FUTURE OUTLOOK

The creation of quantum communications networks is occurring with the advent of quantum communications -- an inviolable alternative to long-standing secrecy protocols based on computational complexity [1]. Such networks are projected to constitute a substantial part of the commerce that future optical networks will transport. The most prevalent application in today's quantum networks is the distribution of quantum keys, usually called quantum key distribution (QKD). Implementation on optical fibres or free-space links is pursued in parallel; both implementations assure the same principles and give identical building blocks to the networking layer.

Integrated photonics is developing fast and has the potential to provide large reduction in size and power consumption. Many large capacity applications require low-cost bandwidth sharing. Integrated photonics enables advanced multiplexing formats for higher level integrations. The notions have been demonstrated by simple experimental demonstrations and a great variety of practical materials and devices are accessible. The challenges include the development of low-traffic-demand applications which motivate the required large-scale integration and the last distance and capacity need to have compatible expansion.

One of the major goals of research in optical networks is terabit-scale with the potential to exceed 1 Tb/s in long-haul optical lines. Challenges ahead are high-capacity links and data highways, low-latency

transport in elastic-data networks, large-bandwidth time-division multiplexing, high-scale WDM in core links and last-mile delivery in communication networks. The terahertz spectrum--wavelength bands that are now untapped--presents great new prospects. Mixed-capacity systems are possible by considering both individual components and the whole system. "There are challenges in materials, devices and concepts, but there are broad and abundant opportunities across the entire spectrum."

Quantum Networking and Secure Optical Connections

Quantum networks are networks of nodes linked by quantum communication lines that transport quantum states without transferring the carriers from node to node. The ultimate goal is to build a large-scale quantum internet that enables the sharing of quantum states of light between any two nodes of a network. Such a quantum internet is envisaged to give rise to novel communication capabilities, e.g. secure message transfer or distributed quantum processing [13]. To execute this we need essential building blocks: production of quantum states at the source, transmission of these states over optical lines, and measurement of the states at the destination, without impairing the quantum character of the state.

Long distance quantum communication is best done by light, but the very nature of light makes it challenging to transport it from one source to another in a network. Photon sources emit indistinguishable photons at different wavelengths, and several couplers are introduced along the link. Hybrid systems that combine different platforms to use each other's benefits and quantum interface guiding photons to cavity-enhanced sources create a foundation for an extensible quantum network that may be scaled up indefinitely. Now, several sources inject indistinguishable photons into two nodes via telecommunications wavelengths to solve the intermittent transmission-blocking networks, which is still a research difficulty [14].

Integrated Photonics and Photonic Integration Circuits

Integrated optics developed in the 1970s with the waveguide technology for communications, and was followed by the creation of photonic integrated circuits. These circuits can integrate many photonic components and functions in a single substrate, customising different microstructures for functionalisation. Photonic integrated circuits offer numerous advantages over conventional discrete photonic components. They increase reliability by eliminating the need for optical coupling between components, reduce fabrication costs through batch production, decrease the footprint and volume to save space, and allow for more sophisticated architectures with greater flexibility in system design [1].

Fabrication issues include creating acceptable materials, realising low-loss, high quality waveguides, integrating active components, and designing fabrication platforms compatible with complementary metal-oxide-semiconductors. photonic integrated circuits combining most essential components on one chip enable system-level integration at chip-level. This allows the specified integrated photonics in phy-layer protocols to be directly incorporated on the optical transmitter or receiver chip circuit to reduce packaging, power and delay. However, ha-design tools for photonic components and circuit integration are still in a primitive stage as compared to the sophisticated electronic design automation tools for electrical circuits [15].

Terabits and Beyond: Challenges and Opportunities

The ever growing data generation by smartphones, sensors, internet of things, smart cities, smart homes, telecreaming, health monitoring, digital twins, virtual reality etc. has increased the need for high capacity optical links for long distance transmission. New materials (standard silica or speciality fibre), devices (lasers, detectors, MODs, MEMS switches) and topologies (beam steering cross connect) may be involved in terabit scale research on data transmission.

TECHNIQUES OF EVALUATION OF OPTICAL DATA HIGHWAY

The following methods for evaluation of optical data highways complement the experimental procedures by modelling, simulation and benchmarking methodologies. These tasks are readily

supported by a number of instrumentation tools, numerical platforms and representational packages.

Experimental methods include performance based methods, such as refractive index, distance, optimisation and structure and delay, nonlinearity, passiveness and demodulation. Performance measures include: skew, jitter, bit error rate, visual signal-to-noise ratio, spectrum and eye-diagram analysis [1]. Statistical analysis includes time domain storage and spectrum diversity with wideband equalisation, on line sampling via temporal archiving, and noise leading to signal and parameter identification, time resolution, and link budget metrics.

Simulation workflow traces signal evolution in a fibre considering domains, models, orders and time affecting propagation. The modelling aspects that are relevant are link parameters, neighbouring channels, topologies, partitioning, performance metric extraction. Numerical construction: approach, structure, statistics. Usually permits postprocessing. Representative tools: VPIphotonics | MultiComp, OptiSystem, Chysalis MRL, OptiFDTD, simplified MATLAB applications with stochastic testing. Typical problems include lab-to-model pattern matching, setup dependency, nonlinear-link reconfiguration, noise density and initial-signal perturbation.

Experimental methods and performance measures

Light-wave communications are the core of the information age, delivering the huge capacity needed to carry data over vast distances. The Internet backbone – the worldwide high-capacity networks – and the intra-datacenter interconnects of supercomputers are made up of light-wave technology. The field remains one of high diversity and quick change where the scientific community is targeting higher capacity and cheaper prices while reducing energy consumption and adapting to new services and technology [1].

Optical links, networks and systems are evaluated using different experimental methodologies, measurement metrics, data analysis methods, transmission modelling approaches and simulation tools. These strategies give an insight into the link performance, latency and dependability. Optical-link performance estimates are typically based on measurements of the average power available at the receiver, the quality of the received signal, the error ratio of a test bit stream, and the receiver sensitivity for a certain error ratio and defined overhead. Measurements can also measure the network latency incurred from an unencoded bit stream routed through one or more nodes.

A pseudo-random bit stream can be used to evaluate the reliability of time division multiplexed (TDM) channels to check the independence of the channels, measure the combined performance, and establish the maximum number of TDM channels that can be used while maintaining a specified minimum performance per channel [2].

Modelling, Simulation and Benchmarking

Optical data highways connect data centers from hundreds of meters up to twenty thousand km away for global connection. Accurate measurements of link performance, latency, and reliability are critical criteria for judging the operational quality of an optical data highway and form the basis for business and science efforts to construct and upgrade optical networks. A wide variety of experimental methodologies, measurements, and data processing approaches offer insight into the capacity, coverage, and accuracy of deployed roadway systems. The extremities of links are extended with emerging components, materials, and processes. Experiments are based on several aspects of performance, architectural evaluation and technology analysis Experiments give a framework for modelling, simulation and benchmarking typical of distributed networks.

The constraints of transmission at optical wavelengths with regard to link and network performance have been intensively investigated during the last half-century due to the practical and theoretical importance of long-haul communications. These optical linkages have amplification, routing, and signal

management properties not present in their electronic and transport-layer equivalents. An early experimental demonstration of artificial and statistical time-division multiplexing (TDM) has pointed out the special optical properties that determine the possible range and coverage of data highways. Extensions were tested in such a preparation stage by testing a long distance optical TDM substrate that shows traffic size independence. A transport-layer model developed analytical link-performance formulas showing consistency across element-type combinations and change in conventional physical-system characteristics [1].

CONCLUSION

Communications with light waves have become the cornerstone of the information age, with huge bandwidths that continue to grow into the terabit, petabit, and exabit scales. Long distance mass-data transmission using optical fibres is the basis for the global high capacity networks, internet backbones, datacenter interconnects and supercomputing. The full potential of optical communication systems still remains an open issue, with lower cost, lower energy consumption and better adaptation to new services and technologies as major objectives.

The need for optical data highways is increasing for developing applications such as next generation metro networks and radio-over-fiber systems, in addition to sustaining high capacity long-haul and datacenter operations. Applications include optical wide area and metropolitan area networks, high speed computing and optical access. The identification of fundamental performance limits also guides optical-data-highway technologies. This provides a baseline against which new technologies can be evaluated.

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