DAYANANDA SAGAR COLLEGE OF ENGINEERING

Shavige Malleshwara Hills, Kumaraswamy Layout, Bangalore-560078
(An Autonomous Institute affiliated to VTU, Accredited by NAAC with ‘A’ Grade, UGC & ISO 9001:2008 Certified)

VISVESVARAYA TECHNOLOGICAL UNIVERSITY

“JnanaSangama”, Belagavi-18, Karnataka, India.

An Internship report on

“QUANTUM COMMUNICATION AND CHANNEL CAPACITIES OF OPTICAL LINKS”

Internship report Submitted in partial fulfilment of the requirement for the degree of

Bachelor of Engineering

In

Telecommunication Engineering

By

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(1DS16TE024)

8th sem B.E

Under the guidance of

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Internship Certificate

This is to certify that Mr. Aravinda V, B.E. student of Dayananda Sagar College of Engineering, Bangalore, has undertaken Summer Internship in our laboratory under my supervision and completed successfully. The topic of the project is "Quantum comunication and channel capacites of optical links" and the duration is 10 June-20 July 2019. He has done a very good project work.

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DEPARTMENT OF TELECOMMUNICATION ENGINEERING

Accredited by National Board of Accreditation Council (NBA)

CERTIFICATE

This is to certify that the Internship report entitled **"Quantum Communication and Channel Capacities of Optical Links"** is a bonafide work carried out by **ARAVINDA V** (1DS16TE024) of VIII semester, Department of Telecommunication Engineering, DSCE an autonomous institute affiliated to **Visvesvaraya Technological University** in partial fulfillment for the Degree of **Bachelor of Engineering** during the year 2019-20. It is certified that all the suggestion indicated has been incorporated in the report.

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ABSTRACT

Indian Institute of Science (IISc) is a public deemed research university for higher education in science and engineering, located in Bangalore in the Indian state of Karnataka. The institute was established in 1909 with active support from Jamshedji Tata and Krishna Raja Wadiyar IV and thus is also locally known as the "Tata Institute" .It was granted the deemed to be university status in 1958 and the Institute of Eminence status in 2018.It is a premier Institute for advanced scientific and technological research and education in India. A visionary partnership between Jamshedji Tata, the Maharaja of Mysore, and the Government of India was instrumental in the establishment of IISc. The Institute was formed with an objective of providing advanced instruction and to conduct original investigations in all branches of knowledge to promote the material and industrial welfare of India. In the 107 years of its existence, IISc has laid equal emphasis on the pursuit of basic knowledge in science and engineering as well as on leveraging its research findings for the country's industrial and social welfare. IISc has more than 40 departments, centres or units, around 4000 students, and nearly 550 academic and scientific staff personnel.For the students with a keen sense of scientific inquiry, IISc offers advanced research opportunities in the areas of science, engineering, and technology.

The internship was done in the ECE department of IISc. The ECE Department is a Centre for Advanced Studies and has a rich heritage and a strong reputation for R&D activities of internationally acclaimed standards, predominantly in the areas of Communications, Signal Processing, Microelectronics and RF/Photonics. The internship was done the guidance of Dr. T Srinivas, Associate Professor, ECE department IISc. The domain of the internship was Quantum communication and Channel capacity of optical links.

The main objective of the internship was to learn and understand the Photonic Integrated Circuits, Optical channels and Quantum Communication topics through studying various research papers, publications etc. This internship also gave an exposure to various newly upcoming topics such Quantum Information Theory, Qubits, Quantum Key Distribution, Quantum Entanglement and their Security and Cryptographic advantages. The internship also focussed on how to calculate the channel capacity of an optical link. This internship also provided insights to various other topics related to the above-mentioned domains such as MEMS, Quantum computing etc.

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CHAPTER 1

ORGANIZATION OVERVIEW

1.1 Indian Institute of Science

The Indian Institute of Science, the brain child of Jamshedji Nusserwanji Tata, a successful businessman and philanthropist, was conceived in the late 1800s. To this end, Tata set up a provisional committee under the leadership of Burjorji Padshah, an educationist, to come up with a blueprint for the proposed university. The committee drafted a plan which went through several iterations before it was finalised. Tata also endowed a substantial part of his personal wealth for this ambitious project. The Institute which started with just two departments – General and Applied Chemistry and Electrical Technology – today has over 40 departments spread across six divisions: Biological Sciences, Chemical Sciences, Electrical Sciences, Interdisciplinary Research, Mechanical Sciences, and Physical and Mathematical Sciences. Today Indian Institute of Science (IISc) is a public institute deemed to be university for research and higher education in science and engineering.

The campus houses more than 40 departments and the Institute is fully residential and is spread over 400 acres of land in the heart of Bengaluru city. Research students constitute more than 70% of the students on the campus. Ph.D. degrees offered in 40 different disciplines, the two-year MTech. program is available in almost all engineering departments, also a new bachelor's degree program has begun recently with a four-year course. The departments and centres at IISc fall under the purview of either the Science Faculty or the Engineering Faculty. These departments/centres are divided into six divisions, each headed by a Chairperson.

The Indian Institute of Science collaborates with various government organisations like the Indian Ordnance Factories, DRDO, the ISRO, Bharat Electronics Limited, Aeronautical Development Agency, National Aerospace Laboratories, CSIR, Department of IT (Government of India), Centre for Development of Advanced Computing, etc. IISc also works in collaboration with private industry and research labs like the Google Inc, General Motors, Microsoft Research, IBM Research, Boeing, Robert Bosch Foundation, Pratt & Whitney and more.

QS World University rankings ranked IISc second in the world in terms of citations per faculty, IISc was ranked 251–300 in the world by the Times Higher Education World University Rankings of

2018, the top institute in India, as well as 21 in Asian the 2018 ranking and 14 among BRICS & Emerging Economies University Rankings in 2017. The QS World University Rankings of 2019 ranked IISc 170 in the world, as well as 51 in Asia and 10 among BRICS nations.

1.2 Electrical Communication Engineering Department

The ECE Department is recognized by UGC as a Centre for Advanced Studies and has a rich heritage and a strong reputation for R&D activities of internationally acclaimed standards, predominantly in the areas of Communications, Signal Processing, Microelectronics and RF/Photonics. Presently, with 128 Ph.D. students, over 84 ME students, 11 M.Sc. students and 31 faculty members, the department does cutting edge research in areas such as sensor networks, wireless networks, QOS Architectures, Wireless Communications, MIMO Technologies, Coding Theory, Information Theory, Cognitive Radio, Speech/Audio, Video, Biomedical, SP for Communication, Compressive Sensing, Low Power Circuits, CMOS for RF, Nano Devices, MEMS and Sensors, RF MEMS, Antennas, Imaging, Optical communication, Biosensors.

1.3 About my Internship Guide Professor:

Dr. T. Srinivas is an Associate Professor in ECE department of IISc. His main area of research interest is Photonics integrated Circuits, both theoretical and experimental, with application to optical communications and optical sensors. He graduated from New Science College, Hyderabad, with B Sc(Hons) in physics and did his ME (Integrated) from ECE Dept, IISc, and PhD also from IISc in the faculty of Engineering on Application of coupled mode theory to fiber and integrated optic waveguide structures, under Prof A Selvarajan. He has done his Post-Doctoral Research in Toyohashi University of Technology, Japan, during 1992-98. There his work was on tapered optical waveguide couplers and integrated optical amplifiers.

He has involved in several academic and professional activities. Recently he has been the Chairman GATE, IISc Zone (2011-13), member of NBA (2010-present), besides acting as reviewer to several journal and conferences, notably IEEE PTL, J of modern optics, JOSA, Sadhana, current science, etc. He has taken part in many national and international conferences, notably, bi-annual Photonics conference in India, ICUMT, IEEE Sensors, OFC, etc Recently, he was the General chair to International conference on optical engineering (ICOE) organized under IEEE Photonics society with the support of VTU Belgaum.

CHAPTER 2

INTRODUCTION

Quantum mechanics is the branch of physics relating to the very small. It results in what may appear to be some very strange conclusions about the physical world. At the scale of atoms and electrons, many of the equations of classical mechanics, which describe how things move at everyday sizes and speeds, cease to be useful. In classical mechanics, objects exist in a specific place at a specific time. However, in quantum mechanics, objects instead exist in a haze of probability; they have a certain chance of being at point A, another chance of being at point B and so on.

Light can sometimes behave as a particle. This was initially met with harsh criticism, as it ran contrary to 200 years of experiments showing that light behaved as a wave; much like ripples on the surface of a calm lake. Light behaves similarly in that it bounces off walls and bends around corners, and that the crests and troughs of the wave can add up or cancel out. Added wave crests result in brighter light, while waves that cancel out produce darkness. A light source can be thought of as a ball on a stick being rhythmically dipped in the centre of a lake. The colour emitted corresponds to the distance between the crests, which is determined by the speed of the ball's rhythm.

In 1905, Einstein published a paper, "Concerning an Heuristic Point of View Toward the Emission and Transformation of Light," in which he envisioned light traveling not as a wave, but as some manner of "energy quanta." This packet of energy, Einstein suggested, could "be absorbed or generated only as a whole," specifically when an atom "jumps" between quantized vibration rates. This would also apply, as would be shown a few years later, when an electron "jumps" between quantized orbits. Under this model, Einstein's "energy quanta" contained the energy difference of the jump; when divided by Planck's constant, that energy difference determined the colour of light carried by those quanta. So, these small particles of light were called as photons, they are technically described as the quantum particle of the electromagnetic field.

So now we use these photons as a medium of communication by transmitting them in particular sequences and time intervals. We also encode them with data in terms of their spin, polarization etc. This gives rise to a new domain called as optical communication. Optical communication, also known as optical telecommunication, is communication at a distance using light to carry information. It can be performed visually or by using electronic devices. The earliest basic forms of optical communication date back several millennia, while the earliest electrical device created to do so was the photophone, invented in 1880.

An optical communication system uses a transmitter, which encodes a message into an optical signal, a channel, which carries the signal to its destination, and a receiver, which reproduces the message from the received optical signal. When electronic equipment is not employed the 'receiver' is a person visually observing and interpreting a signal, which may be either simple (such as the presence of a beacon fire) or complex (such as lights using colour codes or flashed in a code sequence). Free-space optical communication has been deployed in space, while terrestrial forms are naturally limited by geography, weather and the availability of light. Fiber-optic communication is a method of transmitting information from one place to another by sending pulses of light through an optical fiber. The light forms an electromagnetic carrier wave that is modulated to carry information.

CHAPTER 3

QUANTUM COMMUNICATION

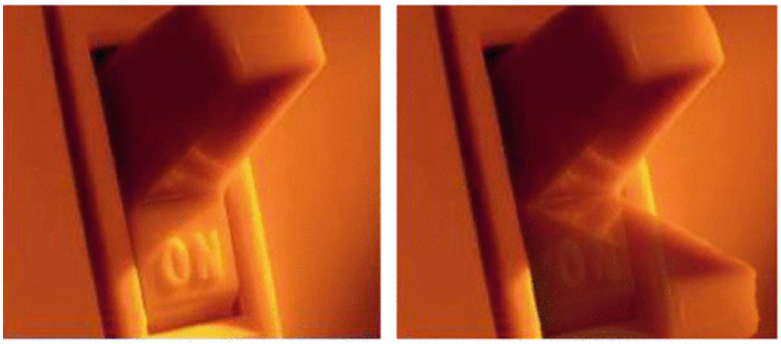
3.1 INTRODUCTION TO QUANTUM COMMUNICATION

Quantum communication is a field of applied quantum physics closely related to quantum information processing and quantum teleportation. Its most interesting application is protecting information channels against eavesdropping by means of quantum cryptography.

Richard Feynman was among the first to note that if binary information can be represented physically, for example, by a burst of photons or the aggregated charge of a collection of electrons, quantum mechanical properties such as the polarization of a photon or the spin of an electron might also be exploited to encode and transmit information. If we are able to utilize quantum mechanics for communication and computing purposes, we would have the opportunity to construct more efficient algorithms than their best classical counterparts, thanks to physical phenomena available only in the quantum world. The path is open to exceed the classical capacity of communication channels, and the potential exists to improve communication protocols; for example, questions and risks regarding the security of public key cryptography can be eliminated in global-scale networks. Whether classical or quantum, computing and communications have many overlapping areas. For example, signal processing is critical for efficient high-quality communication between parties, but it can also be classified as a computing topic. Quantum computing can be exploited to provide computationally more efficient solutions to classical signal processing problems. Quantum-assisted communications combines quantum signal processing with classical communication channels. Quantum-based communications is identified with the case of the channel itself obeying quantum rules. Quantum communication takes advantage of the laws of quantum physics to protect data. These laws allow particles—typically photons of light for transmitting data along optical cables to take on a state of superposition, which means they can represent multiple combinations of 1 and 0 simultaneously. The particles are known as quantum bits, or qubits.

3.2 QUBITS

In classical information and computation science, information is encoded in the most fundamental entity, the bit. Its two possible values 0 and 1 are physically realized in many ways, be it simply by mechanical means (as a switch), in solids by magnetic or ferroelectric domains (hard drives), or by light pulses (optical digital media). All of these methods have one thing in common—one state of the device mutually excludes the simultaneous presence of the other—the switch is either on or off as shown in the figure below-



classical bit qubit

Figure 1: An illustration of the difference between a classical bit and a qubit

The superposition principle entails one of the most fundamental aspects of quantum physics, namely to allow the description of a physical system as being in a probabilistic combination of its alternative states. This so-called superposition of states not only provides all predictions for the outcome of a physical measurement, but it also has drastic consequences for the nature of the physical state that we ascribe to a system. Its most important direct implication is the so-called *no-cloning theorem*, which states that it is impossible to obtain a perfect copy of a qubit in an unknown state without destroying the information content of the original. The no-cloning theorem is the basis for the security of all quantum communication. Thanks to entanglement, qubits can hold up to two bits of data and transmit data between qubits up to 1400 meters apart.

The concept of superposition is important because this is what qubits about, so let’s start developing a mathematical model for the spin-

When we say the spin of a particle is in a superposition of states, it simply means it is in a linear combination of up spin and down spin. The coefficient α is called the amplitude. Here is the equation in the Dirac notation-

$$\overbrace{\alpha_0 \underbrace{|0\rangle}_{\text{up spin}} + \alpha_1 \underbrace{|1\rangle}_{\text{down spin}}}^{\text{linear combination}}$$

Here, the up spin and the down spin states are just the basis vectors. The concept is similar to the x, y basis vectors in the law of motion in Physics.

$$\vec{p} = \alpha_0 \vec{x} + \alpha_1 \vec{y}$$

$$\underbrace{|\Psi\rangle}_{\text{quantum state}} = \underbrace{\alpha_0|0\rangle + \alpha_1|1\rangle}_{\text{superposition}}$$

The Dirac notation $|\psi\rangle$ is just a short form for a matrix.

$$|\Psi\rangle = \underbrace{\alpha_0|0\rangle + \alpha_1|1\rangle}_{\text{superposition}} = \begin{bmatrix} \alpha_0 \\ \alpha_1 \end{bmatrix}$$

$|0\rangle$ and $|1\rangle$ are the two orthogonal basis vectors that are encoded as:

$$|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \quad |1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

0: not spin up

1: spin down

It also has a dual form written as:

$$\langle 0| = \begin{bmatrix} 1 & 0 \end{bmatrix}, \quad \langle 1| = \begin{bmatrix} 0 & 1 \end{bmatrix}$$

The math is simply matrix multiplication and linear algebra. We just shorten it with Dirac notation.

Between measurements, we can manipulate the superpositions. But when we measure the up spin, the superposition collapses to one of the possible states, i.e. either $|0\rangle$ or $|1\rangle$. This is the core principle of quantum dynamics, and how nature works. Let's say a particle is in:

$$\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$$

The chance that it collapses to a particular state equals the square of the corresponding amplitude. It turns out this method models the experimental results very well. In our example, the chance of measuring the particle in up spin is therefore 1/2.

square the coeff. to find the chance to be measured as up spin

$$\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$$

up spin

There is one obvious rule we need to follow. The probabilities of measuring all possible states add up to 1 (⟨ψ|ψ⟩=1). To enforce this, we make

$$|\alpha_0|^2 + |\alpha_1|^2 = 1$$

We can visualize the superposition as a point lying on the surface of a unit sphere. The up and down spin is just the north and south pole of the sphere respectively. So, the red dot below is another example of a superposition state. When it is measured, nature forces it to take a side, either up or down.

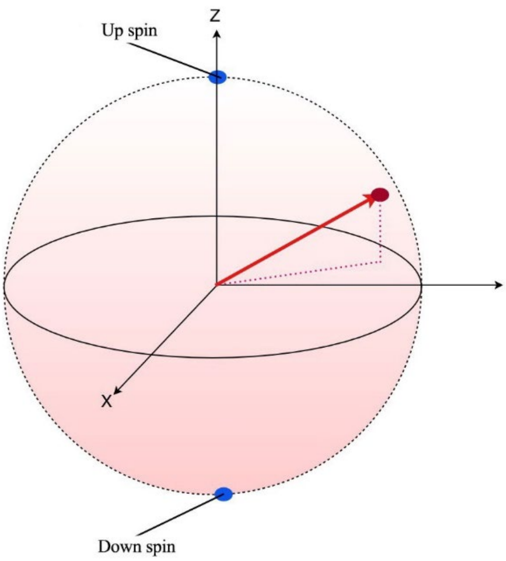


Figure 2: Superposition represented as the Bloch sphere

3.3 QUANTUM COMMUNICATION SCHEMES

Quantum information science and quantum communication are important ingredients in future quantum information processing technologies. They enable the transfer of a quantum state from one location to another. All quantum communication schemes have in common that two or more parties are connected via both a classical communication channel and a quantum channel (i.e., a channel over which quantum systems are transmitted). Typically, measurements are performed on the individual quantum (sub-) systems and the measurement bases used for every measurement are communicated via the classical channel. Here, we focus on quantum communication with discrete variables. However, we should mention that there exists a parallel branch of quantum communication that is based on continuous variables, where extensive theoretical and experimental work has been performed. There are a few quantum communications schemes out of which two are studied and understood in the internship-

A) QUANTUM KEY DISTRIBUTION

The most well-known and developed application of quantum cryptography is quantum key distribution (QKD). QKD describes the use of quantum mechanical effects to perform cryptographic tasks or to break cryptographic systems.

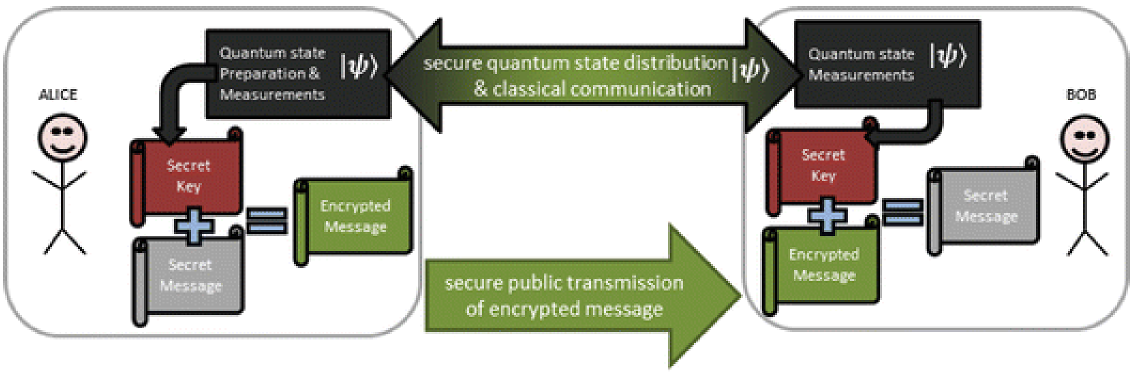


Figure 3: Quantum Key Distribution

The principle of operation of a QKD system is quite straightforward: two parties (Alice and Bob) use single photons that are randomly polarized to states representing ones and zeroes to transmit a series of random number sequences that are used as keys in cryptographic communications. Both stations are linked together with a quantum channel and a classical channel. Alice generates a random stream of qubits that are sent over the quantum channel. Upon reception of the stream Bob and Alice — using the classical channel — perform classical operations to check if an eavesdropper has tried to extract information on the qubits stream. The presence of an eavesdropper is revealed by the imperfect correlation between the two lists of bits obtained after the transmission of qubits between the emitter and the receiver. One important component of virtually all proper encryption schemes is true randomness which can elegantly be generated by means of quantum optics.

In contrast to classical cryptography, QKD does not simply rely on the difficulty of solving a mathematical problem (such as finding the prime powers of a large number). Therefore, even a quantum computer could not break the key. QKD consists of two phases. In the first phase the two communicating parties (Alice and Bob) exchange quantum signals over the quantum channel and perform measurements, obtaining a raw key (i.e., two strongly correlated but nonidentical and only partly secret strings). In the second phase, Alice and Bob use the classical channel to perform an interactive post-processing protocol, which allows them to distil two identical and completely secret (known only to themselves) strings, which are two identical copies of the generated secret key. The classical channel in this protocol needs to be authenticated: this means that Alice and Bob identify themselves; a third person can listen to the conversation but cannot participate in it. The quantum channel, however, is open to any possible manipulation from a third person. Eavesdropping attempts during the key transmission appear as errors in the measurement results, allowing the presence of an eavesdropper to be detected.

The security of the key distribution is based on the fact that a measurement of an unknown quantum system will (in most cases) disturb the system: If Alice's and Bob's sifted keys are perfectly correlated (which can be proven by comparing a small subset of the whole sifted key via classical communication), no eavesdropper tried to listen to the transmission and the key can be used for encoding a confidential message using the one-time pad (i.e., a specific key is exactly as long as the message to be encrypted and this key is only used once). In practical systems, however, there will always be some inherent noise due to dark counts in the detectors and transmission errors. As it cannot be distinguished whether the errors in the sifted key come from noise in the quantum channel or from eavesdropping activity, they all must be attributed to an eavesdropping attack. If the error is below a certain threshold, Alice and Bob can still distil a final secret key using classical protocols for error correction and privacy amplification. If the error is above the threshold, the key is discarded and a new distribution has to be started.

B) QUANTUM TELEPORTATION AND ENTANGLEMENT

Quantum teleportation is a process by which the state of a quantum system is transferred onto another distant quantum system without ever existing at any location in between. In contrast to what is often wrongly stated, this does not even in principle allow for faster-than-light communication or transport of matter. This becomes clearer when considering the entire three-step protocol of quantum teleportation as shown in figure below-

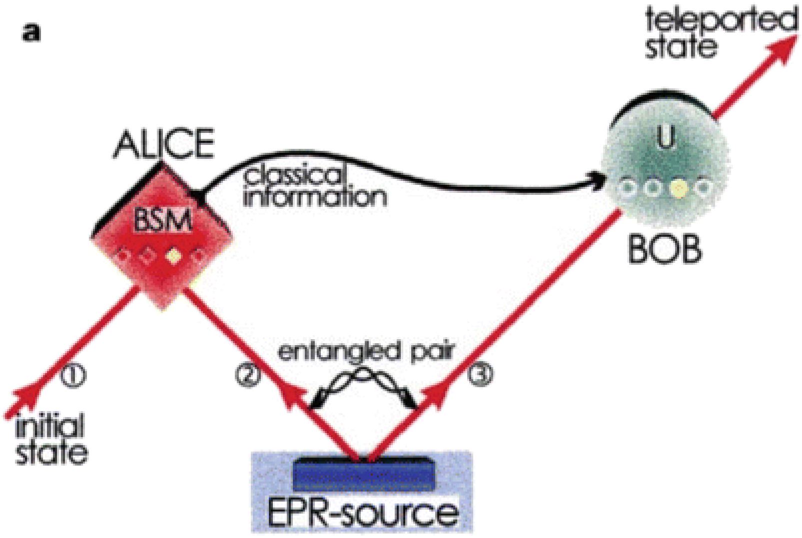


Figure 4: Quantum teleportation scheme

Quantum entanglement is a label for the observed physical phenomenon that occurs when a pair or group of particles is generated, interact, or share spatial proximity in a way such that the quantum state of each particle of the pair or group cannot be described independently of the state of the others, even when the particles are separated by a large distance Quantum entanglement occurs when two particles become inextricably linked, and whatever happens to one immediately affects the other, regardless of how far apart they are. Hence the 'spooky action at a distance' description.

In this scheme first it is necessary that Alice (the sender) and Bob (the receiver) share a pair of entangled qubits (qubits 2 and 3 in the figure). Next, Alice is provided with a third qubit (qubit 1), the state of which she wants to teleport and which is unknown to her. In the last step, Alice destroys any information about the state of qubit 1 by performing a so-called Bell-state measurement (BSM) between qubits 1 and 2. As a consequence of this measurement and due to the initial entanglement between qubit 2 and 3, qubit 3 is instantaneously projected onto the same state as qubit 1. However, the teleportation protocol only works in cases, where the BSM resulted in exactly one out of four possible random outcomes. As a consequence, Bob needs to be notified by Alice about the outcome of the BSM in order to being able to identify the successful teleportation events. This requires classical communication between Alice and Bob and essentially limits the speed of information transfer within the teleportation protocol to the speed of the classical communication channel.

Quantum teleportation is an essential prerequisite for a so-called quantum repeater. A quantum repeater will be an important building block in a future network, since it allows to interconnect different network nodes. In a quantum repeater, two particles of independent entangled pairs are combined within a BSM, such that the entanglement is relayed onto the remaining two particles. This process is called entanglement swapping and will eventually allow to overcome any distance limitations in a global-scale network. However, in order to efficiently execute entanglement swapping, it has to be supplemented with an entanglement purification step requiring quantum memories.

We can also use these quantum communication schemes for long distance communication either in line of sight or no line of sight, free space or via fiber etc. It can also be used for Space communication using the same entanglement concept. Also, quantum communication provides better security and also can actually carry higher amounts of data. In future we would also have a concept of high-speed quantum internet.

CHAPTER 4

OPTICAL INTEGRATED CIRCUITS

An optical integrated circuit (OIC) is a thin-film-type optical circuit designed to perform a function by integrating a laser diode light source, functional components such as switches/ modulators, interconnecting waveguides, and photodiode detectors, all on a single substrate. Through integration, a more compact, stable, and functional optical system can be produced. The key components are slab [two-dimensional (2-D)] or channel [three dimensional (3-D)] waveguides. Therefore, the important point is how to design and fabricate good waveguides using the right materials and processes. The features of OIC's are-

- Single-mode structure: waveguide widths are on the order of micrometres and are such that a single-mode optical wave propagates.
- Stable alignment by integration: the device can withstand vibration and temperature change; that is the greatest advantage of OICs.
- Easy control of the guided wave.
- Low operating voltage and short interaction length.
- Faster operation due to shorter electrodes and less capacitance.
- Larger optical power density.
- Compactness and light weight.

Photonic integrated circuits (also called planar light wave circuits = PLC or integrated optoelectronic devices) are devices on which several or even many optical (and often also electronic) components are integrated. The technology of such devices is called integrated optics. Photonic integrated circuits are usually fabricated with a wafer-scale technology (involving lithography) on substrates (often called chips) of silicon, silica, or a nonlinear crystal material such as lithium niobate ($LiNbO_3$). The substrate material already determines a number of features and limitations of the technology:

- Silica-on-silicon integrated optics builds on silicon wafers, for which many aspects of the powerful microelectronics technology can be used. Silica waveguides allow the realization of couplers, filters(e.g. for multiplexers and demultiplexers in wavelength division multiplexing technology), power splitters and combiners, and even active elements with optical gain. They can also be connected to optical fibres.

- An area of strong current interest is silicon photonics, where photonic functions are implemented directly on silicon chips.
- An already commercialized photonic integrated circuits technology is based on indium phosphide (InP); it is used mainly in optical fiber communications.
- Waveguides can be fabricated on silica glass (fused silica) e.g. with lithographic techniques involving chemical processing or indiffusion of dopants, or with laser micromachining. The latter techniques can be used for fabricating waveguides far below the surface (embedded waveguides), so that three-dimensional circuit designs become possible. Amplifiers and lasers can be made by using rare-earth-doped glasses.
- Lithium niobate ($LiNbO_3$) as a nonlinear crystal material is suitable for devices performing nonlinear functions, for example electro-optic modulators or acousto-optic transducers. Waveguides can be fabricated on lithium niobate substrates e.g. via proton exchange or by in diffusion of titanium, in any case controlled by a lithographic method. Doping with rare earth ions makes possible amplifiers and lasers. The birefringence of this material creates opportunities for polarization control, which may then be used e.g. for filtering purposes. On the other hand, the birefringence makes it more difficult to obtain polarization-independent devices, as are often required for optical fiber communications.

Photonic integrated circuits can either host large arrays of identical components, or contain complex circuit configurations. However, for various reasons the complexity achievable is not nearly as high as for electronic integrated circuits. Their main application is in the area of optical fiber communications, particularly in fiber-optic networks, but they can also be used for, e.g., optical sensors and in metrology.

An important distinction is that between devices with smaller or larger mode areas:

- Some waveguides (e.g. made in silicon-on-insulator technology) exhibit strong confinement, leading to small effective mode areas and allowing for tight bends without excessive bend losses. They are therefore potentially suitable for chips with a very high level of integration. However, such devices are essentially always polarization dependent, having a strong built-it birefringence. Polarization-insensitive designs would be possible in principle, but would introduce unrealistic fabrication tolerances.
- Other waveguides exhibit much weaker guidance and can be made in polarization-insensitive form. However, such waveguides do not allow tight bends and thus prevent a high level of integration.

In OIC we basically have two types of waveguides- 2 Dimensional and 3 Dimensional waveguides. The cross-sectional structure of the 2D waveguide is as shown below-

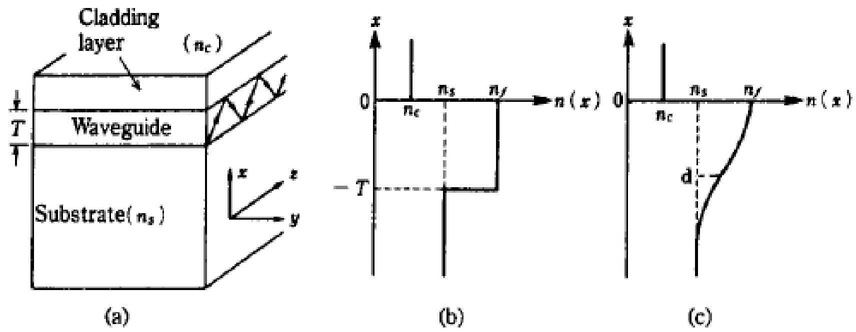


Figure 5: Cross Section of 2D waveguide

(a) Basic Optical waveguide Structure (b) The step index type (c) The graded index type

The basic structure of a 2-D (or slab) waveguide is shown in Figure above with the index profiles along the depth, where the indices of the cladding layer, guiding layer, and substrate are nc, nf, and ns, respectively. In the case that nf> ns > nc, the light is confined in the guiding layer by the total internal reflections at two interfaces and propagates along a zigzag path, as shown in Fig.(a).Such a confined light wave is called a guided mode whose propagation constant β along the z direction exists in the range of $k_o$ns < β < k_onf, where $k_o=2\pi/\lambda$.

The 2-D wave analysis indicates that pure TE and TM modes can propagate in the waveguide. The TE mode consists of field components, Ey, Hx, and Hz, while the TM mode has Ex, Hy, and Ez. A unified treatment of the TE modes is made possible by introducing the normalized frequency V and the normalized guide index b_E, defined as-

$$V = k_o \mathrm{T}\sqrt{nf^2 - ns^2} \;\; ; \quad b_E = \frac{N_{eff}^2 - nf^2}{nf^2 - ns^2}$$

Usually, the guided mode is characterized by the effective index denoted as shown in above equation, N_{eff} and is given by relation, $\beta = k_o N_{eff}$ and ns <N_{eff} < nf. N_{eff} must have discrete values in this range because only zigzag rays with certain incident angles can propagate as the guided modes along the guiding layer.

However, the 2-D waveguides are generally asymmetric (ns≠nc). By using the above definitions, the dispersion equation of the TE_m modes can be expressed in the normalized form-

$$V\sqrt{1-b_E} = (m+1)\pi - \tan^{-1}\sqrt{\frac{1-b_E}{b_E}} - \tan^{-1}\sqrt{\frac{1-b_E}{b_E+a_E}}$$

Where a_E is the asymmetric measure of the waveguide and it is given by-

$$a_E = \frac{(ns^2 - nc^2)}{(nf^2 - ns^2)}$$

The normalised Dispersion curve can be plotted as show in the below figure where m=0,1,2, 3, ... the mode number corresponding to the number of modes of the electric field distribution. When the waveguide parameters, such as the material indices and the guide thickness, are given, the effective index N_{eff} of the TE mode is obtained graphically. The waveguide parameters are usually defined on the basis of cut-off of the guided mode, in which N_{eff} =ns (bE=0), the value of V_m at the cut off is given by,

$$V_m = V_o + m\pi \quad ; \; V_o = \tan^{-1}\sqrt{a_E}$$

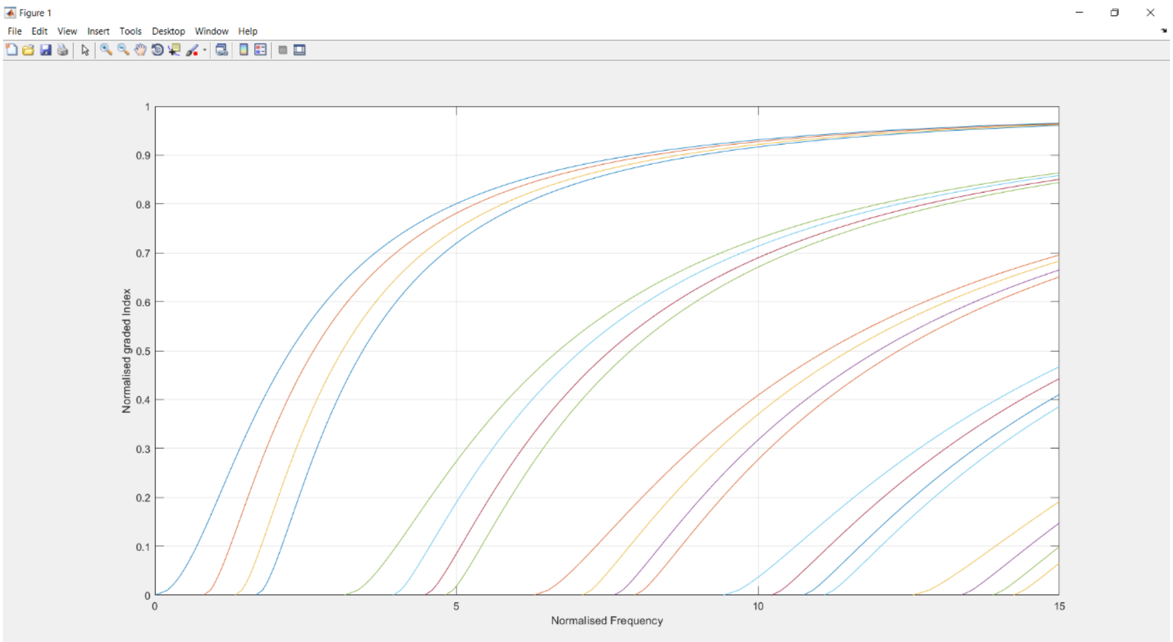


Figure 6: **Dispersion Curve**

Optical waveguide devices having functions of light modulation/switching require 3-D (or channel) waveguides in which the light is transversely confined in the y direction in addition to confinement along the depth. In 3-D waveguides, a guided mode is effectively controlled without light spreading due to diffraction on the guide surface. The 3-D waveguides are divided into four different types, as shown in Figure below. Among them, the buried type of 3-D waveguides, including Ti-diffused LiNbO3 and ion-exchanged waveguides, are more suitable for optical waveguide devices. The reasons why this type of waveguide has advantages are that the propagation loss is usually lower than 1 dB/cm even for visible light and that planar electrodes are easily placed on the guide surface to achieve light modulation/switching. On the contrary, ridge waveguides are formed by removing undesired higher-index film with dry etching and lift-off of deposited film. These waveguides tend to suffer a significant scattering loss due to waveguide wall roughness. This shortcoming, however, is overcome by deposition of rather thick lower-index material as a cladding layer on the waveguides.

In the 3-D waveguides consisting of dielectric materials, pure TE and TM modes are not supported, and two families of hybrid modes exist. The hybrid modes are classified according to whether the main electric field component lies in the x or y direction. The mode having the main electric field E_x is called the E_x mode. This mode resembles the TM_{pq} mode in a slab waveguide; hence the E_x mode is sometimes called the TM-like mode. The subscripts p and q denote the number of nodes of the electric field E_x in the x and y directions, respectively. Similarly, the E_y mode (that is the TE-like mode) has the main electric field E_y.

CHAPTER 5

OPTICAL CHANNELS AND THEIR CAPACITIES

5.1 CLASSICAL OPTICAL CHANNEL AND ITS CAPACITY

Optical communication, also known as optical telecommunication, is communication at a distance using light to carry information. It can be performed visually or by using electronic devices. The earliest basic forms of optical communication date back several millennia, while the earliest electrical device created to do so was the photophone, invented in 1880.

An optical communication system uses a transmitter, which encodes a message into an optical signal, a channel, which carries the signal to its destination, and a receiver, which reproduces the message from the received optical signal. When electronic equipment is not employed the 'receiver' is a person visually observing and interpreting a signal, which may be either simple (such as the presence of a beacon fire) or complex (such as lights using colour codes or flashed in a Morse code sequence). Free-space optical communication has been deployed in space, while terrestrial forms are naturally limited by geography, weather and the availability of light.

Optical communication uses mainly two types of channels – optical fibers and free space. Optical fiber is the most common type of channel for optical communications. The transmitters in optical fiber links are generally light-emitting diodes (LEDs) or laser diodes. Infrared light, rather than visible light is used more commonly, because optical fibers transmit infrared wavelengths with less attenuation and dispersion. The signal encoding is typically simple intensity modulation, although historically optical phase and frequency modulation have been demonstrated in the lab. The need for periodic signal regeneration was largely superseded by the introduction of the erbium-doped fiber amplifier, which extended link distances at significantly lower cost.

Channel capacity, in electrical engineering, computer science, and information theory, is the tight upper bound on the rate at which information can be reliably transmitted over a channel. Following the terms of the noisy-channel coding theorem, the channel capacity of a given channel is the highest information rate (in units of information per unit time) that can be achieved with arbitrarily small error probability.

Information theory, developed by Claude E. Shannon in 1948, defines the notion of channel capacity and provides a mathematical model by which one can compute it. The key result states that the capacity of the channel, as defined above, is given by the maximum of the mutual information between the input and output of the channel, where the maximization is with respect to the input distribution. Information theory studies the quantification, storage, and communication of information. It was originally proposed by Claude Shannon in 1948 to find fundamental limits on signal processing and communication operations such as data compression, in a landmark paper titled "A Mathematical Theory of Communication".

A key measure in information theory is "entropy". Entropy quantifies the amount of uncertainty involved in the value of a random variable or the outcome of a random process. For example, identifying the outcome of a fair coin flip (with two equally likely outcomes) provides less information (lower entropy) than specifying the outcome from a roll of a die (with six equally likely outcomes). Some other important measures in information theory are mutual information, channel capacity, error exponents, and relative entropy. Based on the probability mass function of each source symbol to be communicated, the Shannon entropy H, in units of bits (per symbol), is given by-

$$H = -\sum_{i} p_i \log_2(p_i)$$

where p_i is the probability of occurrence of the i-th possible value of the source symbol. This equation gives the entropy in the units of "bits" (per symbol) because it uses a logarithm of base 2, and this base-2 measure of entropy has sometimes been called the "Shannon" in his honour. Entropy is also commonly computed using the natural logarithm which produces a measurement of entropy in "nats" per symbol and sometimes simplifies the analysis by avoiding the need to include extra constants in the formulas.

Mutual information measures the amount of information that can be obtained about one random variable by observing another. It is important in communication where it can be used to maximize the amount of information shared between sent and received signals.

The mutual information of X relative to Y is given by:

$$I(X;Y) = E_{X,Y}[SI(x,y)] = \sum_{x,y} p(x,y) \log \frac{p(x,y)}{p(x)p(y)}$$

where SI (Specific mutual Information) is the pointwise mutual information.

The appropriate measure for this is the mutual information, and this maximum mutual information is called the channel capacity and is given by:

$$C=\max_f I(X;\, Y)$$

An application of the channel capacity concept to an additive white Gaussian noise (AWGN) channel with B Hz bandwidth and signal-to-noise ratio S/N is the Shannon–Hartley theorem:

$$C = Blog_2(\frac{S}{N} + 1)$$

C is measured in bits per second if the logarithm is taken in base 2, or nats per second if the natural logarithm is used, assuming B is in hertz; the signal and noise powers S and N are expressed in a linear power unit.

5.2 OPTICAL COMMUNICATION CHANNEL CAPACITY TRENDS

Optical communication is unchallenged for the transmission of large amounts of data over long distances with low latency and it underlies modern communications networks, in particular the internet. Since the first deployments of fiber-optic communication systems three decades ago, the capacity carried by a single-mode optical fiber has increased by a staggering 10000 times. Most of the growth occurred in the first two decades with growth slowing to ten times in the last decade. Over the same three decades, network traffic has increased by a much smaller factor of 100, but with most of the growth occurring in the last few years, when data started dominating network traffic. At the current growth rate, the next factor of 100 in network traffic growth will occur within a decade. The large difference in growth rates between the delivered fiber capacity and the traffic demand is expected to create a capacity shortage within a decade.

Optical communications underwent a revolution in the 1990s as optical amplifiers and WDM enabled the information carried on a single fiber to move from a few gigabits per second to over one terabit per second. This rapid expansion of system capacity is visible in Figure below. The points on the figure are total capacities for a single fiber in laboratory/research demonstrations. Points are also distinguished by whether WDM is employed. Generally, only points which represent a new record of capacity are plotted. Various time periods exhibit relatively stable growth rates with relatively sharp demarcations between them. We see an initial rapid rise in capacity for single channel time division multiplexing (TDM) demonstrations as researchers employed available microwave components in digital circuits.

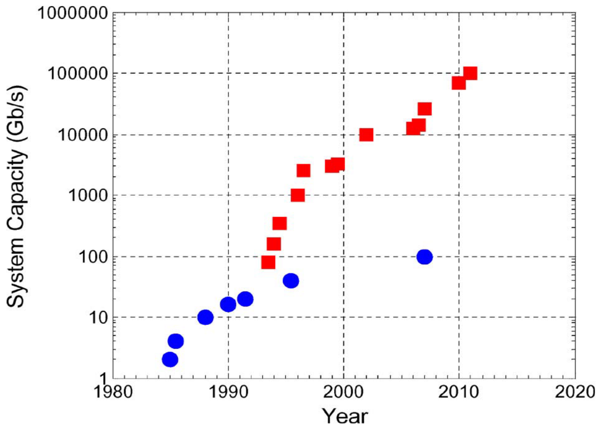


Figure 7: Demonstrated Graph of system capacities

5.3 BRIEF INTRODUCTION TO QUANTUM CHANNEL CAPACITY

In the field of Quantum Communication, Quantum information processing exploits the quantum nature of information. It offers fundamentally new solutions in the field of computer science and extends the possibilities to a level that cannot be imagined in classical communication systems. On the other hand, it requires the generalization of classical information theory through a quantum perception of the world. As Shannon entropy plays fundamental role in classical information theory, the von Neumann entropy does the same for quantum information. The von Neumann entropy S(ρ) of quantum state ρ can be viewed as an extension of classical entropy for quantum systems. It measures the information of the quantum states in the form of the uncertainty of a quantum state. The classical Shannon entropy H(X) of a variable X with probability distribution p(x) can be defined as-

$$\mathrm{H(X)} = -\sum_{\mathrm{x}\in\mathrm{X}} \mathrm{p(x)log_2(p(x))}$$

The von Neumann entropy measures the information contained in the quantum system ρ is defined as-

$$\mathrm{S}(\rho) = -\mathrm{Tr}(\rho\log(\rho))$$

The Holevo bound determines the amount of information that can be extracted from a single qubit state. If Alice sends a quantum state ρi with probability pi over an ideal quantum channel, then at Bob's receiver a mixed state appears.

$$\rho\mathrm{A} = \rho\mathrm{B} = \sum_{i} pi\rho\mathrm{i}$$

Bob constructs a measurement {Mi} to extract the information encoded in the quantum states. If he applies the measurement to ρA, the probability distribution of Bob's classical symbol B will be $\Pr[b|\rho A] = \mathrm{Tr}(M^{\dagger}{}_{b}M_{b}\rho A)$. As had been shown by Holevo, the bound for the maximal classical mutual information between Alice and Bob is the bound for the maximal classical mutual information between Alice and Bob is-

$$I(A:B) \leq S(\rho A) - \Sigma_i \, piS(\rho i) \equiv \chi$$

where χ is called the Holevo quantity, and known as the Holevo bound.

In classical information theory and classical communication systems, the mutual information I(A:B) is bounded only by the classical entropy of H(A), hence I(A:B) ≤ H(A). The mutual information I(A:B) is bounded by the classical entropy of H(A), hence I(A:B) ≤ H(A). On the other hand, for mixed states and pure non-orthogonal states the Holevo quantity χ can be greater than the mutual information I(A:B), however, it is still bounded by H(A), which is the bound for the pure orthogonal states

$$I(A:B) \leq \chi \leq H(A).$$

The Holevo bound highlights the important fact that one qubit can contain at most one classical bit, i.e., cbit of information. Hence using these bounds and entropies we can calculate the capacity of quantum channels for different situations. These calculations are very complex unlike the classical channel capacities as the involve various factors such as entanglement , qubit's state etc. Also, there are two types of capacities-Classical channel capacities where the classical information (un entangled photons) is sent over a quantum channel and the other is the Private channel capacity which has deep relevance in secret quantum communications and quantum cryptography. It describes the rate at which Alice is able to send classical information through the channel in secure manner.

Quantum channels extend the possibilities of classical communication channels allowing us to transmit classical information, entanglement assisted classical information, private classical information and quantum information. Contrary to classical channels, quantum channels can be used to construct more advanced communication primitives. Quantum entanglement or the superposed states carry quantum information, which cannot be described classically. Quantum channels can be implemented in practice easily, e.g., via optical fiber networks or by wireless optical channels, and make it possible to send various types of information. The errors are a natural interference from the noisy environment, and the can be much diverse due to the extended set of quantum channel models. In the near future, advanced quantum communication and networking technologies driven by quantum information processing will revolutionize the traditional methods. Quantum information will help to resolve still open scientific and technical problems, as well as expand the boundaries of classical computation and communication systems. Hence the channel capacity of optical links and quantum channels have been described in a brief manner.

CHAPTER 6
SELF EVALUATION

I consider myself honoured to have done my internship in Indian Institute of Science, under Dr. T. Srinivas, Associate Professor, ECE Department. This Internship was based on the Domain of Quantum Communication and Optical Communication. The course of Internship was about 40 days, from 10 June, 2019 to 20 July 2019.

During the course of the Internship I was introduced to a lot of new topics such as Photonics and Quantum Information and Communication. My knowledge of these topics was very brief before I began my internship. I knew Optical communication topics such as fiber optic communication, but the domain of Quantum communication and Qubits that is the Quantum Information was new to me and this increased my interest to learn more about them.

The first week of the internship was to gain information and knowledge by studying various IEEE published papers and other journals. So, during the first week I went through a lot of publications and learnt about these fundamental concepts of photonics, optical communication in detail. From the second week onwards, I was assigned a particular topic – "Quantum Communication and channel Capacity of Optical links". From second week onwards I did a case study on the topic and created a report at the end of the internship duration. At the end of every week I gave a presentation on the week's learning progress and clarified doubts if we had any. Following are topics that were studied by me during the course of internship-

Optical communication, Photonic Integrated Circuits, optical waveguides , Quantum Information theory, Quantum communication and its different schemes, quantum entanglement, optical channels and their capacity.

I also had the opportunity to visit the National Nanofabrication Centre in the CeNSE and learn about the various procedures of fabrication of CMOS, MEMS devices. Also, during the internship, I got the opportunity to visit talks given by distinguished professors of the Photonics and Optical communication field.

I once again express my sincere gratitude to Dr T Srinivas for giving me the opportunity to learn under his guidance and enhance my knowledge.