Using Quantum Technologies to Improve Fiber Optic Communication Systems

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ABSTRACT

We discuss the near future impact that recent developments of quantum technologies can have in the field of fiber optic communication systems. The ability to generate, manipulate, transmit, and detect a single or very few photon(s) may open new routes that can trigger a completely new generation of communication systems. We show that quantum technologies can address two of the more challenging problems communication engineers face nowadays: capacity and security. Indeed, by radically decreasing the number of photons used to encode each bit of information, we can more efficiently explore the full capacity to carry information of optical fibers. Moreover, by encoding information in individual or very few photons, we can take advantage of the quantum laws to add new functionalities to communication systems. Secrecy is the more obvious one, but a completely new set of functionalities can be added at the physical layer considering the peculiarities of quantum laws that rule transmission and detection.

INTRODUCTION

Quantum physics theory was developed in the first few decades of the 20th century in an endeavor to understand the fundamental properties of matter and its interaction with electromagnetic radiation. Despite quantum theory's ability to predict the results of some of the more intriguing experiments of the time, some of the peculiarities of the theory (e.g., Heisenberg's uncertainty principle or the existence of entangled states) caused serious skepticism in the scientific community. Therefore, it came as no surprise that the first efforts and developments were carried out envisioning validation of the theoretical predictions rather than looking for practical applications. These efforts gave the theory very solid foundations, and quantum theory is now widely accepted as a complete and accurate physical theory.

In the second half of the 20th century, quantum theory led to some technological materialization through the invention of the solid-state transistor, the laser, and the optical amplifier. Despite the huge impact these devices had on communication and information systems, quantum theory is still only timidly addressed in most engineering schools. However, micro- and nanotechnologies have also evolved rapidly, and nowadays, it is possible to manipulate quantum systems quite easily. This has prompted physicists and engineers to look for quantum effects that can be usefully employed for high-performance communications and computing.

Quantum key distribution (QKD) systems are the first commercial communication systems to explore the laws of quantum mechanics to provide new functionalities [1]. The underlying principle of QKD is that nature prohibits the gain of information on the state of a quantum system without disturbing it, which can be used to provide unconditionally secure distribution of secret keys. In 1984, Bennett and Brassard developed the first QKD protocol; five years later, the first QKD experiment using a 32-cm free-space transmission system was reported. Since that pioneering work, several new experiments have been reported by the scientific community, and nowadays some companies are providing commercial solutions of QKD systems operating up to 100 km.

Animated by the advances of new technological developments at quantum scales, quantum engineering is gaining increasing importance in communication and information sciences. The development of a fully quantum computer providing huge parallel processing seems to be a medium-term achievable goal. Efficient manipulation, transmission, and detection of single photons, quantum memories, quantum repeaters, and quantum routers are examples of techniques and devices able to support the practical development of a future quantum Internet.

This article discusses and clarifies how actual quantum technologies can be used to improve fiber optic communication systems. First, we review the classical limits on carrying information of fiber optic communications systems, and discuss how encoding information in single or a few photons can increase this capacity. Then we describe new functionalities that can be added to communication systems by exploring the quantum nature of the photons.

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INCREASING THE TRANSMISSION CAPACITY

The widespread deployment of fiber to the home, broadband Internet connections, and online video and gaming is increasing substantially the amount of traffic in core networks. To cope with this increasing amount of traffic, operators have been increasing the bit rate per channel and the number of optical channels per fiber. In this section, we review the capacity limits of classical fiber optic communication systems, and analyze how the encoding of information in single or very few photons can allow us to go beyond the classical limits.

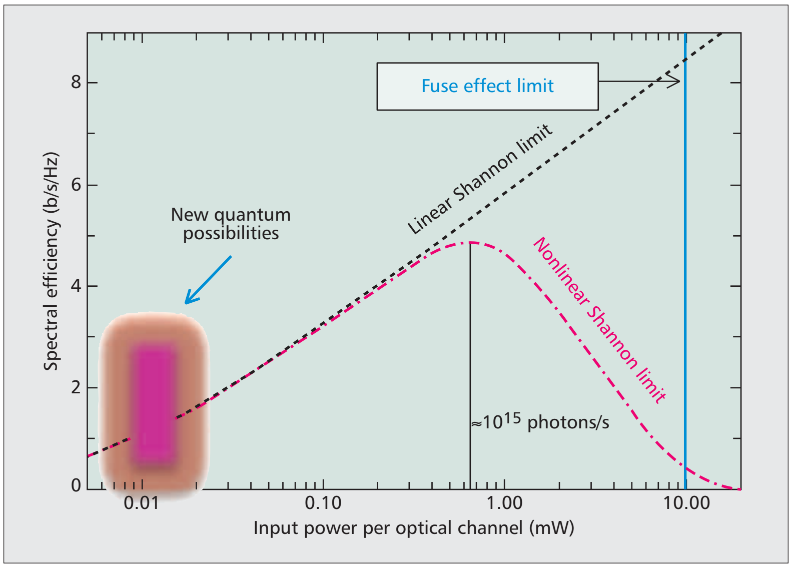

Figure 1. *Spectral efficiency limits for a 2000-km-long dense wavelength-division multiplexing system, with 100 optical channels separated by 50 GHz. Spectral efficiency is a measure of the transmission capacity per spectral bandwidth. We are assuming 25 fiber spans; between each fiber span there is an optical amplification module that completely compensates for fiber losses, the noise figure of each amplification stage is 4.2 dB, and fiber losses are assumed to be 0.2 dB/km.*

TRANSMISSION CAPACITY LIMITS

A classical receiver is a device that receives a classical signal (typically an electromagnetic field, current, or voltage) and extracts information from that signal. In a pass-band digital transmission system, at the emitter the signal is modulated in order to generate symbols at a constant symbol rate. Each symbol carries a certain amount of information. Assuming equiprobable symbols, the maximum number of symbols (i.e., the cardinal of the set of symbols) a receiver can discern is proportional to the symbols' average energy, and the amount of information carried by each symbol is just the logarithm base two of the cardinal of the set of symbols, assuming that information is measured in bits. Therefore, the maximum amount of information that the receiver can extract from the signal is proportional to the symbols' average energy. At the emitter, during transmission and even at the receiver, noise is added to the signal, which means that part of the extracted information is meaningless because it is generated by the added noise. Therefore, in order to calculate the maximum amount of information that can be transmitted, we have to calculate the maximum amount of information that can be extracted from the signal with noise and then subtract the information generated only by the noise. As the subtraction of two logarithms is equivalent to the logarithm of the ratio of their arguments, we end up with the logarithm of the ratio between the signal plus noise and the noise. Considering that the maximum number of independent symbols that can be transmitted over a pass-band channel equals its bandwidth, we obtain the well-known linear Shannon limit for the maximum capacity of a communication system [2],

$$C = B\log_2\left(1+\frac{S}{N}\right), \tag{1}$$

where S and N are the average signal and noise energy per symbol, respectively, and B is the channel bandwidth (Fig. 1). As the average energy equals the average power multiplied by a constant, the constant being the integration time, we can replace the average energy by the average signal and noise power, respectively. In the derivation of the linear Shannon limit, it is generally assumed that the signal power can be increased indefinitely and that the noise power is independent of the signal power. If this were the case, the capacity of the channel could be increased as much as desired just by continuously increasing the signal power, and in that way the signal-to-noise ratio (SNR, i.e., S/N) could be continuously improved. This can be seen in Fig. 1, where the spectral efficiency (i.e., the transmission capacity per unit of spectral bandwidth) is presented as a function of the input power per channel for a 2000-km-long fiber optic communication system. As can be seen, the linear Shannon limit increases continuously with the signal power. However, this is not realistic. In fact, an optical fiver is a very tiny waveguide, which leads to strong confinement of the electromagnetic field in the core region. Even for moderate optical powers, this originates very high optical intensities that could lead to a catastrophic damage of the fiber, known as the fuse effect [3]. The fuse effect is usually ignited by small particles of dust in optical connectors or narrow bends in the fiber, which lead to a localized increase of temperature sufficient to burn the fiber core. Once ignited, the process propagates toward the light source, permanently damaging the optical fiber. Fuse effect events have been reported for optical powers as low as ~1 W. This puts a hard limit on the maximum amount of optical power that can be transmitted and, consequently, on the maximum amount of information that can be carried by an optical fiber. In Fig. 1, the fuse effect limit is represented as a straight vertical line, indicating that there is a maximum amount of optical power a fiber can handle, after which the fuse effect is ignited and the fiber is permanently damaged. In fiber optic communication systems, this value tends to be quite small, ~1 W, due to the presence of several connectors and narrow bends in the fiber. However, even before the fuse effect is reached, the optical noise starts to show signifi-

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cant dependence on the optical signal power. In the linear regime this is mostly due to intra- and interchannel crosstalk, mainly due to imperfect filtering, reflection, and scattering. In the linear regime a proper design of the system could in principle eliminate most of this noise. However, for high power levels the optical fields at the fiber output can no longer be described as a linear combination of the input fields, because mixing terms start to appear, giving rise to new optical spectral components. In this regime, known as the nonlinear regime, the noise dependence on the signal power is mostly due to the fiber nonlinear response, which generates different types of nonlinear interactions between signals co-propagating in the fiber, and between signals and noise. Due to the random nature of the noise and the unpredictable nature of the signals, it is not possible to eliminate the excess growth of the noise due to these nonlinear interactions. This excess growth of noise leads to a decrease of the transmission capacity after a certain level of signal power [4]. This evolution of the maximum transmission capacity as a function of the signal power is known as the nonlinear Shannon limit (Fig. 1). In present-day fiber optic communication systems, this nonlinear degradation of the transmission capacity tends to occur before the fuse effect limit is reached, as can be seen in Fig. 1. Also note that chromatic dispersion, which can severely degrade the signal in high-speed fiber optic communication systems, is not usually considered a fundamental limit due to its deterministic behavior, which, in principle, makes it possible to fully compensate for it.

For decades, telecommunication engineers have been concerned about spectral efficiency. Clever methods have been engineered to increase the amount of information transmitted per spectral bandwidth. In current classical communication systems, the spectral efficiency can be larger than 5 b/s/Hz. Nevertheless, the amount of information sent by photons remains on the order of 10^{-5} bit/photon, which is several orders of magnitude below the 1.44 b/photon pointed out as the fundamental limit [5]. Increasing the optical power efficiency seems to be mandatory to substantially increase the transmission capacity of next generation fiber optic communication systems.

Recently, a quantum receiver based on an avalanche photodiode in conjunction with digital post-processing for optimum state discrimination was proposed and experimentally validated, approaching the fundamental limit [6]. Using a quadrature phase shift keying (QPSK) modulation scheme, a symbol error rate smaller than 10^{-3} was achieved using an average of 8 photons/symbol. Note that in a QPSK modulation scheme, each symbol carries 2 bits of information; therefore, a ratio of 0.25 b/photon was obtained.

ENGINEERING SINGLE OR FEW PHOTONS TRANSMISSION SYSTEMS

In order to increase the power efficiency of next generation fiber optic communication systems (i.e., in order to increase the number of bits carried per photon), we have to be able to generate, manipulate, transmit, and detect single or very few photons. This requires quantum sources and receivers. Quantum sources and receivers can explore the different degrees of freedom of a photon to carry information.

Quantum Sources — True single photon sources (typically known as on-demand sources or photon guns) are still quite complex to realize since must of them demand cryogenic temperatures or only operate in a vacuum. Typically, these single photon sources use an external control system, such as a laser, to put a quantum system in an excited state, which is going to emit a single photon during the relaxation process. Examples of quantum systems used in single photon sources are single atoms or molecules, single ions, color centers, quantum dots, and quantum wells [7]. Although this kind of source allows us to obtain true single photons, they also demand the manipulation of very complex systems, usually involving complex free-space optical alignment systems. Thus, these sources are difficult to implement and not easily integrated with other components of the communication system.

A different approach to obtain single photons is based on the generation of time correlated photon pairs in a nonlinear material. In this case, one photon of the pair signals (heralds) the presence of the other photon. These sources are known as heralded single photon sources, and are based on a pump laser and a nonlinear medium. Due to a nonlinear process, typically spontaneous four-wave mixing in optical fibers, two photons from the pump laser are annihilated and two photons are created in symmetrical frequencies around the pump laser such that the net energy and momentum are conserved. The nonlinear medium can be an optical fiber, and in this case the photon pair is already generated inside the fiber, which greatly facilitates the integration of the source with the rest of the communication system. Note that these photons are easily distinguishable due to their distinct frequencies. Due to the probabilistic nature of the nonlinear process, these sources are not usually classified as on-demand sources. However, they are much simpler to implement than true single photon sources.

Although some applications in the field of quantum information demand single photon sources, there are other applications that require only weak coherent light fields. In that case, a highly attenuated laser can be used as a source of a few photons. That source follows Poisson statistics, which means that if the laser light is highly attenuated in order to obtain one or less photon per symbol, there is still a non-negligible probability of generating symbols with two or more photons. Nevertheless, that probabilistic source has the advantage of being fully integratable with today's communication technologies and can operate at very high speeds. A particular implementation of QKD, known as continuous-variable QKD (CVQKD), can be obtained with standard telecommunications components (i.e., a standard semiconductor laser diode and a PIN photodiode). This scheme is based on randomly encoding information in the phase and amplitude of a highly attenuated optical field, and a homodyne detection scheme. The main idea behind CVQKD is to operate in such a low SNR regime that any malicious attempt to eavesdrop the information gets noticed due to the inevitable degradation of the SNR induced by a quantum measurement in two non-commuting variables (amplitude and phase in this case).

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Quantum Receivers — Extracting information from single or very few photons is still quite challenging. The difficulty arises from the fact that the photon energy is on the order of 10^{-19} J, and the detector, after receiving a photon, typically has to convert that energy (or that click) in a macroscopic current. Single photon detectors are typically divided in two main categories, depending on whether or not they are capable of discriminating the number of photons that arrive at the detector in a certain time window.

Nowadays, there are commercially available non-resolving single photon detectors using different technologies, such as photomultiplier tubes, quantum dots with field effect transistors, superconduction nano-wires, up-conversion processes, and avalanche photodiodes [7]. The most common single photon detector for QKD applications at telecom wavelengths is the avalanche photodiode working in the Geiger mode. The outcome of this detector is a macroscopic pulse of current if one or more photons reach the detector. This kind of detector works at temperatures of 210°K to 250°K, with a detection efficiency of around 75 percent in the visible spectral region and 10 percent in the infrared. One of the major advantages of the avalanche photodiode detector is that it can operate with a thermoelectric cooler. This makes it possible to integrate the detector in a compact, quiet, and user-friendly device.

Although non-resolving single photon detectors can be used in some applications, others demand photon number resolving (PNR) detectors. The most common PNR detectors are based on super-conducting tunnel junctions, quantum dots with field effect transistors, parallel super-conducting nano-wires, super-conducting transition edge sensors, visible light photon counters, space- or time-multiplexed avalanche photodiodes, or avalanche photodiodes with self-differencing circuits [7]. The self-differencing circuit allows precise measurement of the avalanche current, and from that an estimation of the number of photons that have impinged on the detector can be obtained. Since photo-detection based on avalanche photodiodes is a very mature technology, this approach to PNR detectors seems to be quite promising for practical implementations.

INTRODUCTION TO NEW FUNCTIONALITIES

Using very few photons per symbol means that the photon's quantum nature gains more relevance in the design of the communication system. As quantum laws are substantially different from classical laws, they can be explored to give new functionalities to systems. In this section, we analyze this aspect, reviewing some advances in the field of quantum random number generation and key distribution, quantum repeaters and memories, and quantum Internet and computing.

RANDOM NUMBER GENERATION AND KEY DISTRIBUTION

True random numbers are hard to generate. Indeed, any random number generator based on a classical system should be as predictable as the underlying theory is predictable. Nevertheless, despite the deterministic nature of classical physics, it is possible to build complex classical systems with such a large number of degrees of freedom that the future behavior of the system is almost unpredictable. However, if we wish to go further and obtain a "perfect" random number generator, we have to base it on a quantum system: a system described by quantum laws that are probabilistic by nature. This underlying quantum system can be as simple as a beam-splitter, in which an incoming photon has equal probability to leave at one or the other of the two output ports. Indeed, there are already commercially available compact quantum random number generators based precisely on this underlying quantum system, targeting markets as diverse as gambling, lotteries, and scientific research.

Another important application of quantum random number generators is quantum key distribution. QKD is nothing more than the synchronous continuous generation of random numbers at two distant locations. Both numbers generated, one in each location, are indeed the same random number that is going to be used as an encryption key. Quantum entanglement can be used to generate pairs of random numbers at two different locations. A pair of entangled photons is a pair of photons described by the same wave function. A wave function that cannot be factorized into two independent wave functions, one for each photon, no matter how far apart the photons are. This means that the pair is generated, the photons are separated and sent to two different locations, and measurements are performed. In one location a measurement is performed on one of the photons of the pair. The result of this measurement is completely random. Subsequently, another measurement is performed at a distant location on the second photon. To a local observer, the result of this second measurement is also completely random. However, it turns out that both results are perfectly correlated, despite being obtained in two distant locations and being completely random, and despite the absence of any interaction between the photons after the initial generation of the pair. This is the kind of resource classical systems cannot provide. Entanglement does not exist in classical physics.

A different approach to QKD is based on the generation of a random number in one location and subsequently the transfer of that number to a different location, making sure that it is impossible to gain any relevant information about the generated number between the two locations. In these systems, which are already commercially available, quantum laws are explored to detect

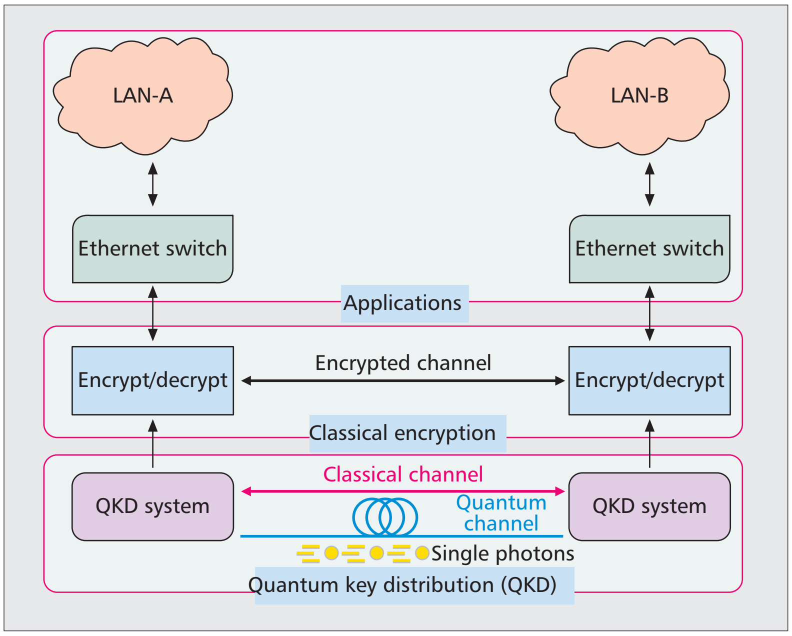

Figure 2. *An example of a layer 2 encrypted point-to-point link in which QKD is used to continuously generate new encryption keys. The frequent and continuous change of keys makes it virtually impossible to break the classical encryption code. There are already QKD systems in the market that allow a change of encryption keys every minute.*

the presence of an eavesdropper, or, better put, quantum laws are used to quantify the amount of leaked information between the two locations. Then privacy amplification is applied to guarantee that even with all the leaked information, it is not possible to obtain any relevant information about the purified random number (i.e., about the key). This quantification of the leaked information is only possible due to the noncloning theorem, which forbids the gain of information about a quantum unknown system without inducing a perturbation in the system. From the amount of perturbation, the leaked information is quantified, and privacy amplification is applied. If the amount of leaked information is below a certain threshold, privacy amplification guarantees perfect secrecy on the link. In Fig. 2 a layer 2 encryption system is presented in which QKD is used to allow a continuous exchange of the encryption keys. Note that in QKD systems classical cryptographic protocols are still in use, like AES-256 or any other (Fig. 2). The add-on provided by QKD is the possibility to change the keys continuously, typically every minute or less. This frequent change of keys strongly limits the time a malicious attacker has to break the classical cryptographic code, making the code virtually inviolable.

In the QKD research community, efforts have been made to engineer a worldwide QKD network. This worldwide QKD network could provide secure keys between any two locations, adding almost perfect security to telecommunication networks at the physical level. Note that the major threats to the security of actual telecommunications networks came about not due to the inadequacy of the algorithms used in classical cryptography but because secret keys are kept for too long. The way in which this QKD worldwide network will be engineered is still quite vague, but a more promising solution consists in some terrestrial QKD networks that behave like QKD islands which are interconnected through secure links with low-orbit satellites.

QUANTUM REPEATERS AND MEMORIES

Quantum communications consists in the transfer of quantum states from one location to a distant one. In order to explore all the resources provided by quantum laws, such as superposition and entanglement, the transferred state must remain unknown during transmission. This forbids the creation of a copy of the state during transmission, which precludes its regeneration or amplification. Although optical fiber losses are quite low, around 0.2 dB/km at a wavelength of 1550 nm, they still represent an effective bottleneck for long distance quantum communications. For instance, if one assumes an ideal single-photon source generating 10^{10} photons/s, the photon rate after 500 km of fiber propagation will drop to around 1 photon/s due to fiber losses. This simple calculation shows that without quantum repeaters, it is not possible to extend quantum communications for distances longer than a few hundred kilometers.

A quantum repeater is a device that is able to extend the reach of a quantum communication system, preserving the transmitted quantum state. This is possible through a technique known as entanglement swapping, which is represented in Fig. 3a. Consider, for instance, that one has two pairs of entangled photons (A entangled with B, and C entangled with D, Fig. 3a) and that each photon is launched into four different optical fibers. Because A is entangled with B, both photons are perfectly correlated, that is, a measurement in one of the photons reveals the state of both. The same happens between C and D. Now, photons B and C are received at a quantum measurement device that asks these photons if they are identical. Note that the device does not measure (reveal) the state of B or the state of C; it just measures (reveals) their relative state. If the measurement succeeds (i.e., if the two photons carry the same quantum state), the quantum repeater establishes an entanglement between photons A and D without any previous interaction between these two photons, and without revealing their states. This entanglement swapping allows the distance over which one can wnsure the entanglement to be doubled. It allows the reach of the quantum communication system to be doubled. Note that after entanglement swapping, photons A and D carry the same quantum state. If the measurement fails (i.e., photons, B and C do not carry the same quantum state), another measurement must be performed. However, if that were to happen, new pairs of entangled photons must be readily available, which implies the availability of a device able to store quantum states (i.e., a quantum memory). Quantum memories are related to the capability to transfer quantum information in a reversible way between light and matter. Moreover, one must be able to store and recall (after a certain storage time) the quantum states on demand. To achieve long-distance quantum communications, several quan-

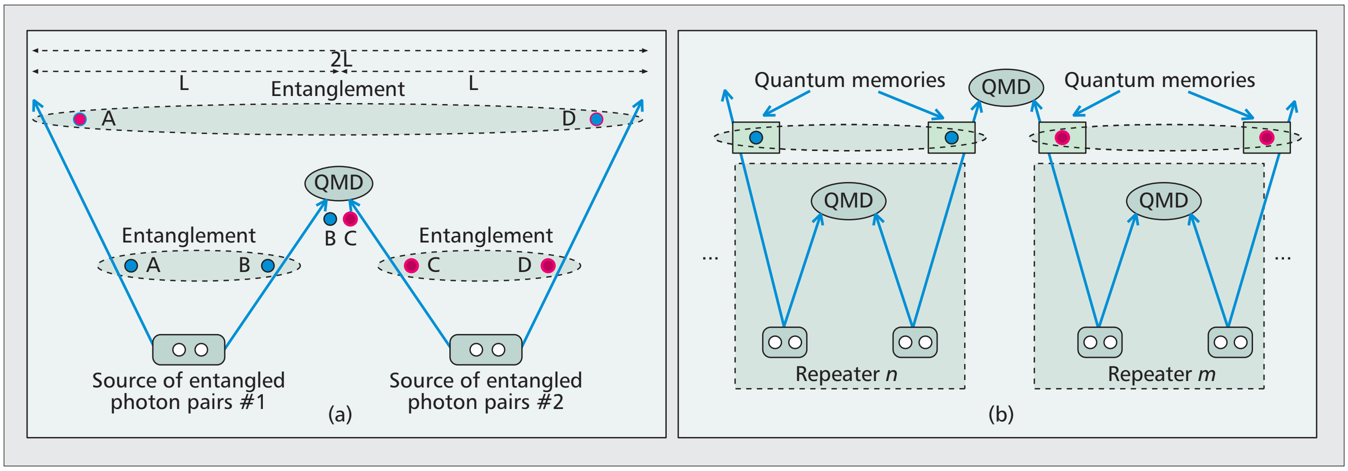

Figure 3. *Schematic representation of the quantum repeater concept: a) quantum repeater establishes entanglement between photons A and D; photons B and C, initially entangled with A and D, respectively, are received at a quantum measurement device (QMD) responsible for further entanglement between A and D; b) entanglement swapping between neighboring quantum repeaters. Quantum memories store quantum states to allow entanglement swapping.*

tum repeaters can be interconnected (Fig. 3b). However, this requires quantum memories with large storage times to perform entanglement swapping between long chains of quantum regenerators.

Over the past few years there have been a large number of experiments demonstrating the feasibility of quantum repeaters; nevertheless, the technology is still quite far from being mature [8]. Recently, some results have been reported in which it is demonstrated that it is possible to engineer room-temperature easy-to-operate quantum memories [9].

QUANTUM INTERNET AND COMPUTERS

QKD was the first commercially available product in the field of quantum information science. It can be implemented with single, entangled, or weak coherent fields, and enables two parties, usually named Alice and Bob, to create a secure key. However, the increasing ability to manipulate single and entangled photons opens the door to a new set of applications in the field of quantum information science. In that sense, it is natural to consider the expansion of actual two-party systems to a more complex architecture, the quantum Internet [10], which combines several quantum technologies. A quantum network could be implemented connecting individual quantum systems, the nodes of the network, via quantum channels (i.e., fiber optical links). Quantum nodes that behave as quantum routers are currently under strong investigation efforts.

Quantum routers are essential elements in a future quantum Internet. Typically, a router uses a control signal (packet header) to determine the output port. However, at the quantum level, if we read (measure) the packet header of the signal, we will destroy its quantum state. To overcome that, an optical router capable of routing photons without disturbing their quantum state was proposed recently based on polarization entangled photon-pairs. In that case, one of the photons works as the control signal, and its measurement addresses the second photon to the intended destination. Quantum routers can in principle be implemented with several different material systems, with their major requirement being a quantum memory with a very long coherence time.

CONCLUSIONS

In this article, we have identified two major problems in today's fiber optic communication systems: capacity and security. A possible solution for both problems can be found in the use of a very low number of photons per symbol. In that regime, the communication system is governed by quantum laws. The peculiarities of quantum laws can be used to add new functionalities. There are already commercially available products that explore quantum laws to add new functionalities, such as QKD systems and quantum random number generators. Nevertheless, most of the more disruptive technologies still remain only in the laboratory domain, such as quantum repeaters, quantum memories, quantum routers, and quantum computers. If these systems can be materialized in some practical devices, a fully functional quantum Internet can start to emerge.

It is clear that there are many exciting prospects for further development of quantum-based technologies, and certainly, these developments are going to shape future communication networks.

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BIOGRAPHIES

ARMANDO NOLASCO PINTO [SM] (anp@ua.pt) graduated in electronic and telecommunications engineering in 1994, and received his Ph.D. degree in electrical engineering in 1999, both from the University of Aveiro, Portugal. He joined the Instituto de Telecomunicações as a researcher in the Optical Communications and Photonics Group, and the Electronic, Telecommunications, and Informatics Department of the University of Aveiro as a lecturer, in 1995 and 1997, respectively. In 2006 and 2007, he was a visiting professor with the Institute of Optics, University of Rochester. He is now an associate professor at the Electronic, Telecommunications and Informatics Department of the University of Aveiro and leads the Optical Communications and Photonics Group at the Aveiro site of the Instituto de Telecomunicações. His research interests are focused on quantum and nonlinear effects on high-speed optical communication systems and networks. He has authored or co-authored more than 100 scientific papers in international journals and conferences. He is a member of the OSA and SPIE. He has served on the Technical Committees of various scientific international conferences. He is currently an Editorial Board member of the *International Journal of Optics*.

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