



# Quantum Technology Fueling the Next Generation Optical Communication: Challenges and Pathways

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**Abstract.** Information transmission through light has attained significant advancements in the fields of both optical fiber communication (OFC) and optical wireless communication (OWC) systems. These advancements have been examined by numerous researchers by employing pioneering modulation schemes, adaptive optics, advanced signal processing algorithms, advancement in materials, and employing sophisticated network architectures for wide variety of applications such as: military; defense; healthcare; satellite; internet of things; and telecommunications. However, the primary factors which affecting the OFC systems are signal attenuation, dispersion, reliability, robustness, and security even though there exists a predominant development. In addition, atmospheric attenuation (due to absorption and scattering), turbulences, climate conditions (fog, rain, snow, dense fog *etc.*), alignment and tracking, interference, range constraints, and security are the major challenges in OWC systems in spite of having advanced approaches from past few decades. Hence, these challenges are need to be addressed in order to achieve reliable and high-speed data transmission. This could be possible with the integration of OFC and OWC with emerging quantum communication technologies (quantum key distribution, quantum entanglement, quantum repeaters, quantum sensing, and quantum secured OWC links). Therefore, this work presents the recent advancements in the fields of OFC and OWC systems with the state-of-art-of techniques and approaches. The primary research challenges related to security, speed, range, capacity and adaptability of both OWC and OFC are outlined. In addition, the possible integration of these systems with quantum communication technologies and the recent progression have been outlined. Finally, the possibility of future research direction towards the quantum OFC, quantum OWC have been discussed for ensuring and revealing the full potential of quantum enhanced optical communication systems.

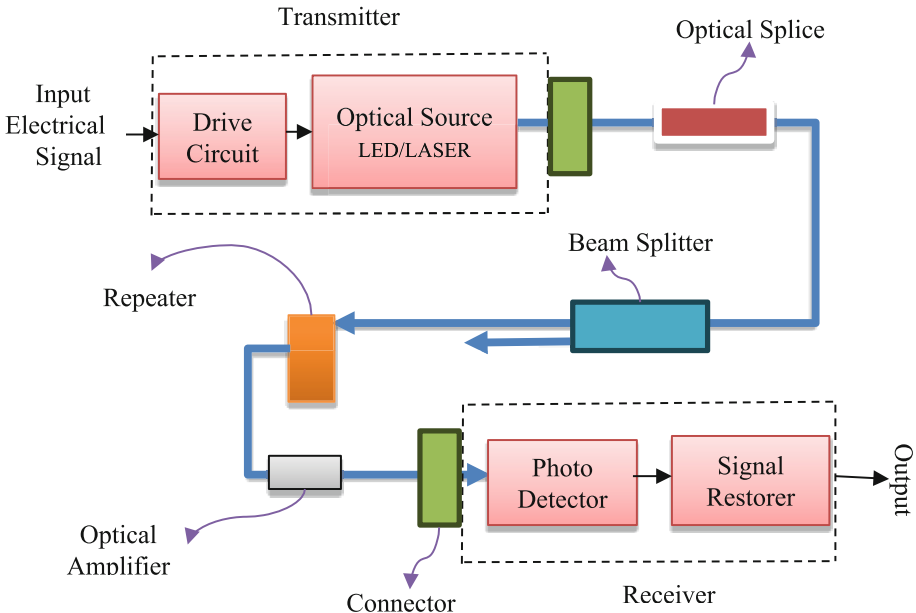
**Keywords:** Optical Fiber Communication · Optical Wireless Communication · Quantum Communication · Quantum Key Distribution · Attenuation Security · Reliability

# 1 Introduction

In the digital era, optical communication ensures the revolutionary leap in information transmission over long distances. Optical communication relies on principals of optics and light for efficient, reliable and high-speed data transmission [1]. Based on the transmission medium, the optical communication is broadly classified into two types such as OFC (utilizes the optical fiber cables) and OWC (utilizes free space). As the advancement in technology is growing rapidly, these systems need to address the channelings posed by various applications and also should ensure even more data transfer speed, improved efficiency, and security.

## 1.1 Optical Fiber Communication

OFC systems are widely popular around the globe and lead the communication field in the forefront by means of its unique and versatile data transmission techniques. These systems transmit the data through pulses of light using optical fibers (plastic, or glass), ultimately archives enhanced data rates, bandwidth, and reliability when compared to conventional copper-based systems. The primary components of an OFC systems include: optical transmitter; optical fiber; and optical receiver. A typical block schematic of OFC system has been depicted in Fig. 1.



**Fig. 1.** Block diagram of OFC system [2].

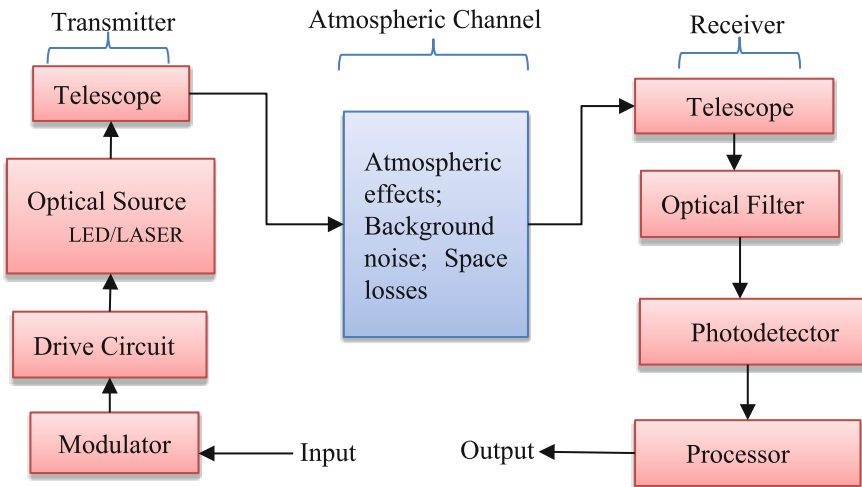
In the transmitter section, the input electrical signal is converted to optical signal using LED or LASER in order to ensure transmission through optical fiber cables.

Optical fiber cable acted as a medium in OFC systems which are made up of glass or plastic. In order to maintain the signal integrity, the connectors and splices are responsible for join different sections of OFC system [3]. During the transmission, the data need to be monitored for ensuring better capacity, for that the beam splitter has been utilized. For an extend fiber cables, the lost signal strength can be restored by using repeaters. In order to overcome the signal attenuation, the optical amplifiers are used in OFC systems [4]. Finally, at the receiver end the optical signal is converted into electrical signal through photodetectors. For high speed and reliable data transfer, these OFC systems are stated as a primary choice of preference [5, 6]. These systems offering abundant opportunities to researchers by enabling numerous recompenses such as:

- Providing extremely high bandwidths
- Less attenuation when compared to copper-based systems
- Highly immune to interference
- Enhances the security
- Offers long range
- Environment resistance, supports multiplexing, and low maintenance cost

## 1.2 Optical Wireless Communication

Unlike OFC, the OWC systems has utilized air or vacuum as a medium for transmitting optical signals over long distances. OWC systems are often referred as free space optics (FSO) as they use free space medium between transmitter and receiver. The typical block diagram for OWC comprises of transmitter, receiver, and atmospheric channel which is depicted using Fig. 2.



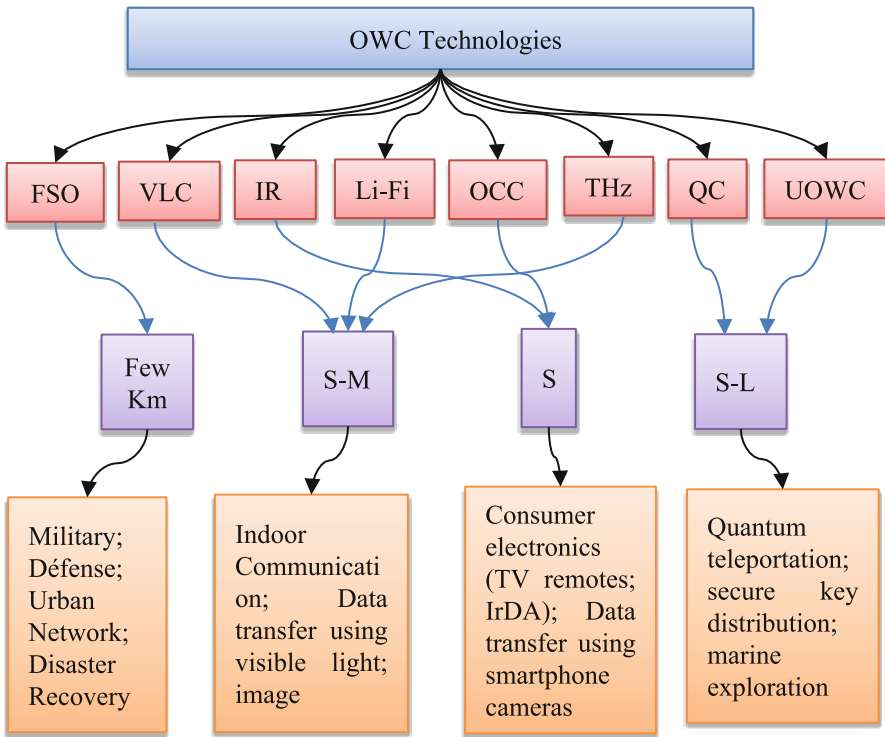
**Fig. 2.** Block diagram of OWC system [7].

These systems have acquired massive attentions from research community because of their versatility especially where the traditional systems are unfeasible [8]. OWC

systems has offered numerous applications ranging from short range indoor to long range point-to-point links and also lead the foundation for various key communication technologies [9] such as:

- Free space optics (FSO)
- Visible light communication (VLC)
- Infrared communication (IR)
- Light fidelity (Li-Fi)
- Optical camera communication (OCC)
- Terahertz communication (THz)
- Quantum communication (QC)
- Underwater Optical Communication (UOWC)

For a specific application and scenario, these OWC technologies ensures unique and enhanced solutions there by enabling the cutting-edge advances in the field of OWC technology and improving the range of applications [10]. The range and application areas of these OWC technologies has been outlined in Fig. 3. However, these ranges are highly influenced by the atmospheric conditions (fog, snow, rain), communication medium, and implementation of specific technology [11, 12].



**Fig. 3.** OWC technologies.

Unlike OFC, the OWC systems has offered versatile solutions for diverse applications [13–17] ranging from military to defense, satellite, point-to-point, consumer electronics, long distance, indoor, marine exploration *etc.* Depending up on the application requirements, environmental conditions, the OWC systems enables numerous advantages such as:

- OWC systems offers high bandwidths with high speed
- Enhances the security for data
- OWC systems are immune to Electromagnetic Interference
- No licensed spectrum requirements
- Offers real time communication
- Application specific

## 2 Research Challenges

While OFC and OWC systems have many benefits, their broad and smooth implementation is hampered by a number of obstacles such as: huge cost associated with deployment; requirements of sophisticated maintenance; interference and compatibility; alignment; weather resistance capabilities. In order to progress the fields of OFC and OWC and realize its full potential for a range of applications, such as last-mile connectivity, disaster recovery, and high-speed data transmission, the research society need to address these research challenges and develop the strategies which are tackled with these uncertainties.

### 2.1 Explorative Obstacles in OFC

Here, the major research problems facing by scientific research society in the processes of advancing the field of OFC have been summarized.

- OFC systems should ensure high capacity and bandwidth in accordance to rise in data traffics which requires advanced modulation schemes, advanced fibre types, and improved WDM techniques [18].
- Implementing innovative signal processing, fiber design, and novel materials for tackle non-linear effects in OFC system in order to improve the system performance and signal quality [19].
- To minimize signal deterioration and maximize the reach of OFC systems, better fiber designs and compensatory techniques are essential [20].
- Developing low power components and materials for reducing power consumption on OFC systems [21].
- Deploying hybrid systems and protocols for effective integration [22].
- Ensuring security, reliability and robustness [23].
- Acquiring Cost effective components to reduce the deployment cost [24].

## 3 Quantum Approaches: A Potential Solution

Quantum communication (QC) is a field of study that utilize the ideologies of quantum mechanics to enable the secure transmission of information. The quantum is usually describing as a packet of energy. A distinctive particle known as an entangled photon

shares quantum states with other particles. Hence, the quantum communication operates on quantum bits or qubits rather than classical bits in conventional communication systems (0 and 1). A solitary qubit can embody the value of two classical bits. In a broader context, a collection of  $n$  qubits can collectively represent the values of  $2^n$  classical bits [25]. Conversely, in QC systems, detecting branches becomes exceedingly challenging due to the presence of entangled particles and quantum states. The overview of basic secure QC systems has been represented using Fig. 4.

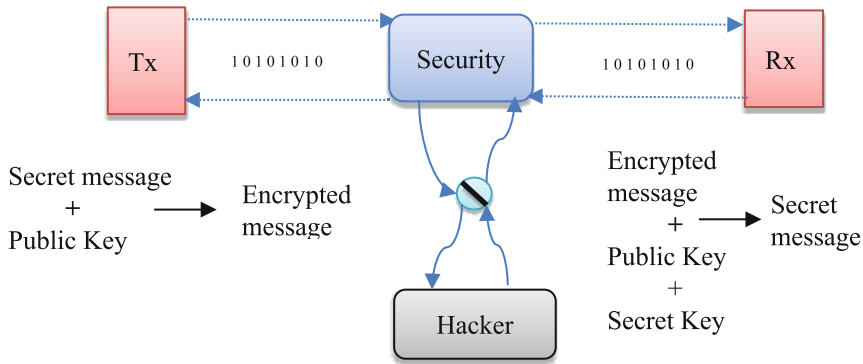


Fig. 4. Basic representation of secure quantum communication [25].

In order to enhance or integrate the conventional communication system through QC system it is important to understand the preliminaries such as: quantum bits (qubits), superposition, entanglement, quantum states and measurements, quantum key distribution (QDK), quantum teleportation, and quantum cryptography.

### 3.1 Quantum Bits and Superposition

Quantum bits, or qubits, are the fundamental units of quantum information, representing the quantum analogue of classical bits. Unlike classical bits, which can only exist in one of two states (0 or 1), qubits can exist in a superposition of both 0 and 1 states simultaneously [26]. This unique property enables qubits to process information in parallel, providing a significant advantage in certain computational tasks. The state of a qubit can be expressed as a linear combination of its basis states  $|0\rangle$  and  $|1\rangle$ . The qubits are represented using (1), where  $|\Psi\rangle$  is the state of the qubit and  $\alpha$  and  $\beta$  are complex numbers representing probability amplitudes [27].

$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle \tag{1}$$

The probabilities of measuring the qubit in the states  $|0\rangle$  and  $|1\rangle$  are given by the squared magnitudes of the probability amplitudes and are represented using (2) and (3) respectively.

$$P|0\rangle = |\alpha|^2|0\rangle = |\alpha|^2 \tag{2}$$

$$P|1\rangle = |\beta|^2|1\rangle = |\beta|^2 \tag{3}$$

### 3.2 Quantum Entanglement

In quantum mechanics, entanglement is a special case of a non-classical phenomena in which two or more particles become linked to the point that their states are directly related to one another, independent of their distance from one another. Joint states can be superposed to represent the entangled state of two qubits [28]. The Bell state is the most well-known entangled state which is represented using (4), where  $|\Phi^+\rangle$  is the entangled state and the joint states  $|00\rangle$ ,  $|11\rangle$  indicates both qubits are in state  $|0\rangle$  and  $|1\rangle$  respectively.

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) \quad (4)$$

### 3.3 Quantum Measurement

Making an observation in order to derive information about a quantum system is known as quantum measurement [29]. A measurement collapses the quantum state to one of the basic states and produces a probabilistic result. The Born rule explains how likely it is to measure a specific result and is represented using (5), where  $|\Psi_i\rangle$  is the conjugate transpose of the vector representing the state associated with outcome  $i$  and  $|\Psi\rangle$  is the initial state.

$$P_{\text{outcome}(i)} = |\langle\Psi_i|\Psi\rangle| \quad (5)$$

### 3.4 Quantum Key Distribution (QKD)

A cutting-edge cryptographic mechanism called QKD makes use of quantum mechanics to facilitate safe communication between two parties. By ensuring that any attempt to listen in on the conversation is detectable, QKD offers a safe method for exchanging cryptographic keys [30].

### 3.5 Quantum Teleportation

A phenomenon known as quantum teleportation in quantum mechanics enables the transfer of quantum information between locations without the need for actual particle movement. It is predicated on quantum measurement and entanglement. Instead of using the traditional concept of teleporting stuff, quantum teleportation involves moving a particle's quantum state from one place to another [31].

### 3.6 Leveraging the Limits of Conventional Communication Systems with Quantum Approaches

With the advancements in quantum communication, the integration of conventional communication systems (OFC, OWC, UWOC, satellite, MIMO, NOMA, and OFDM) with the quantum principles has conquered rapid attention from the research society for

utilizing the full strength of these communication technologies. In addition, the quantum communication has emerging towards the graphene based plasmonic [32–34] in order to develop unique optical devices. Table 1 provides the overview of recent studies that integrates quantum technology with conventional communication systems for enhancing security, speed, range and capacity.

**Table 1.** Major integrations of quantum approaches.

Ref	Year	Key Findings	QC Integration
[35]	2022	A prototype for the acquisition and tracking of a SWaP-efficient (Size, Weight, and Power) system has been developed specifically for creating an airborne QKD link.	UAVs and FSO
[36]	2020	A novel method for multiplexing coherent polarization states, rooted in the three-dimensional rotation group, is introduced.	Free space QC system
[37]	2018	Development of various tracking strategies for testing and correcting wavefront tilt.	FSO
[38]	2020	An analysis has been conducted on the security performance of HAP-based relay-assisted satellite systems that integrate FSO and QKD.	Satellite FSO and vehicular networks
[39]	2021	Explored the application of a CV teleportation channel, established between a LEO- satellite and a ground station on earth, to improve the effectiveness of quantum communication	Uplink satellite communication
[40]	2006	A unique mathematical model has been developed to assess the impact of crosstalk and interference on the performance of the MIMO-QKD system.	MIMO
[41]	2009	Explored the utilization of LDPC coded M-array PSK in optical coherent state quantum communication, particularly in scenarios with and without background radiation.	Optical communication

## 4 Future Research Directions

The integration of OFC and OWC systems with the quantum principles can enable the doors for cutting edge areas of research towards the high speed, high secure, and high-capacity data transmissions. Using the principles of quantum machines the two future revolutionary technologies such as: quantum optical fiber communication (QOFC) and quantum optical wireless communication (QOWC) would set the standards of optical communication in the forefront of research across the globe. The following sections highlight the possible research areas where the researchers can implement the integration of quantum principles with ongoing developments related to optical components, and systems.

### 4.1 Quantum Optical Fiber Communication (QOFC)

- By integrating classical and quantum communication channels for the development of enhanced functionality there by enabling the hybrid system approaches.
- Optimize the errors due to repeater spacing, error correction, and synchronization in OFC systems by employing quantum repeaters.
- Developing quantum error correction methods, protocols, and efficient modulation and demodulation schemes.
- Investigate the approaches for enhancement of efficiency of quantum repeaters through quantum memory.
- Developing a novel QDK techniques for enhancing security

### 4.2 Quantum Optical Wireless Communication (QOWC)

- Analyzing the effects on quantum signal transmission in outdoor environment in order to develop secure QDK protocols
- Improving the security of satellite communication links through quantum signal processing
- Addressing the mobility of the users in mobile environment via quantum coherence
- Exploring the possibilities of deploying quantum relays in order to improve the coverage and reliability

## 5 Conclusion

This work focuses on fundamentals of OFC and OWC systems in the prospects of their capabilities in modern era communication systems by analyzing their challenges. The explorative barriers in the field of OFC and OWC systems have been outlined. Then, the principles of quantum communication have been addressed. The possibilities of integrating OFC and OWC technologies with quantum communication has been discussed. Finally, the future research directions towards QOFC and QOWC have been outlined.

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