Quantum communication using code division multiple access network

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Abstract
For combining different single photon channels into a single path, we use an effective and reliable technique which is known as quantum multiple access. We take advantage of an add-drop multiplexer capable of pushing and withdrawing a single photon into an optical fiber cable which carries quantum bits from multiusers. In addition to this, spreading the channel noise at receiver side and use of filters stop the overlapping of adjacent channels, which helps in reducing the noise level and improved signal-to-noise ratio. In this way, we obtain enhanced performance of code division multiple access-based QKD links with a single photon without necessity of amplifiers and modulators.

Keywords Direct sequence spread spectrum · Code division multiple access · Secure quantum communication · Optical fiber communication · Quantum networks

1 Introduction

Photons are appropriate carrierers for a variety of quantum communication protocols, such as quantum teleportation, quantum key distribution, and other quantum information networks (Nielsen and Chuang 2001). As the encoded quantum states typically do not decohere notably over a transmission path, photons are suitable information carriers for the timely transmission of quantum states. Considerable progress has been made in producing entangled photonic quantum states required for performing different quantum communication protocols (Kok et al. 2007). These provide the base for development of photon-based quantum communication and lead to future quantum-based network technologies.

The fully developed quantum communication, out of the laboratory, will entail methods for handling quantum channel access and fidelity. Quantum-based communication systems may be afflicted with both losses and interference effects generated from secondary absorbers and emitters functioning within the same communication environment. These may comprise of unauthorised receivers, such as eavesdroppers and permeable impurities
in the communication channel, as well as unintentional and intentional emitters, such as transmitters and jammers.

Quantum communication with significant reduced information loss using error-correction methods, will enhance capacity of the quantum channel by correcting errors at the receiver end after prudent encoding in a photon-environment (Nielsen and Chuang 2001). Auxiliary methods are likely required for controlling the losses and impinging, present in an asynchronous quantum communication network. Specifically, techniques for allowing concurrent but uncoordinated quantum communication among multiple parties retrieving the identical transmission channel would be practical for upgrading the design of quantum communication network.

Spread spectrum is an effective technique to monitor the quantum channel access and quality of service. This approach helps to improve channel capacity in multiuser narrowband communication systems (Torrieri 2005). It increases the photons spreading bandwidth, resulting in a lower signal-to-noise ratio (SNR). A uniform channel capacity is kept by a competing gain in the channel bandwidth. A gain in signal-to-noise ratio against narrowband interference is obtained by despreading the incoming signal at the receiver end. Hence, spread-spectrum is mostly deployed for multi-user channel access, i.e., as a multi-user channel access technique for multiplexing communication systems. An important example is radio communications which make use of either DSSS (Direct-Sequence Spread Spectrum) or FHSS(Frequency-Hopping Spread-Spectrum) to provide bandwidth between multi-user transmitters.

Nodes in quantum communication network are an important part which help in achieving long distance communication and are also responsible for distributed computing. In addition to this, these are well connected with each other through photonic channels and are helpful for storage and processing of various quantum based data transfer (Kimble 2008; Felinto et al. 2006; Chou et al. 2007). Recent advancements in quantum information (Luksin 2003; Sangouard et al. 2011; You and Nori 2006, 2011; Clarke and Wilhelm 2008; Buluta et al. 2011; Blatt and Wineland 2008) have brought quantum-based networking much closer to real field applications. Quantum-based communication networks reveal many advantages when sending classical and quantum data with intelligent encoding into and decoding from those quantum states (Smith and Yard 2008; Czekaj and Horodecki 2009; Heurs et al. 2010; Aparicio et al. 2011; Gisin et al. 2002; Wang et al. 2007; Pan et al. 2012). The data transfer with accuracy and high efficiency, which is desired for large quantum communication networks is still a challenging task using such nodes (Cirac et al. 1997; Maitre et al. 1997; Phillips et al. 2001; Duan et al. 2001; Matsukevich and Kuzmich 2004; Acín et al. 2007; Lü et al. 2008). Spread-spectrum as a multiple access technique provides a practical and feasible solution to this problem.

The various approved multiple-access techniques in classical networks comprise time-division multiple-access (TDMA), frequency-division multiple-access (FDMA), and code-division multiple-access (CDMA). In time-division multiple access, distinct users share the same frequency but communicate on different time slots, but timing synchronization and delays become major issues in large-scale quantum communication networks. In frequency-division multiple-access, distinct users share identical time slots but work on dissimilar frequency bands. Only a restricted band of the data transmission line has a limited amount of leakage and the bands allocated to distinct parties should be abundantly unconnected to conquer interference. In contrast to time-division multiple access and frequency-division multiple access, code-division multiple access method makes use of the whole spectrum and time slots to encode useful information for all users, which separates distinct users with their own unique codes. Therefore, code-division multiple-access is the
Quantum communication using code division multiple access...

desirable technology of the current third generation mobile communication systems, and can assist increased number of bits per channel use (Cover and Thomas 1991) in comparison to time-division multiple access and frequency-division multiple access.

Quantum communication protocols, for e.g., quantum key distribution (Bennett and Brassard 1984; Ekert 1991), quantum dense coding (Bennett and Wiesner 1992) or quantum teleportation (Bennett et al. 1993) enhance the opportunities of classical data transmission. Frequency division multiple access approach has been deployed in quantum key distribution communication networks (Yoshino et al. 2012; Brassard et al. 2004; Ortigosa-Blanch and Capmany 2006; Brassard et al. 2003; Townsend 1997). A quantum code-division multiple access network would necessitate that the quantum states transmitted by every transmitting node of the quantum communication network are encoded into their consistent superposition before being sent to the common channel, and the quantum information for each of the intended receiving node is coherently and efficiently recovered by a suitable decoding scheme at the end of the shared channel.

The paper is organized as follows. The problem statement is made in Sect. 2. Section 3 briefly discusses related work while in Sect. 4, system architecture is shown. In Sect. 5, the simulation for multi-users is described. A plausible experimental verification is discussed in Sect. 6. Discussions are then made and we conclude in Sect. 7.

2 Problem statement

An important open issue in complex quantum communication networks is how to effectively send quantum data among a number of users through a shared channel. We propose a method by constructing a quantum code division multiple access (CDMA) technique in which the quantum state is randomly encoded to extend its frequency content, and further decoded through mix-up synchronization to extract distinct sender-receiver matches. In comparison to the frequency division multiple access, the proposed quantum code division multiple access method can enhance the quantum information data transfer per channel used.

The quantum states of light are most suited for implementing the quantum communication protocols. There are successful optical implementations of quantum key distribution systems that transmit single photons via the best available optical fiber channels (Gisin et al. 2002). As the number of customers increase, there arises the issue of communication channel access. Various customers might intend to deploy similar resources at the same time. Classical communication networks resolve this issue with a number of multiple access techniques (Sklar 1983, 2001). Quantum communication networks have used frequency and wavelength division multiple access techniques where each customer transmits data at distinct frequencies (Brassard et al. 2003; Yoshino et al. 2012; Chapuran et al. 2009; Qi et al. 2010; Tanaka et al. 2008; Patel et al. 2014; Ortigosa-Blanch and Capmany 2006; Mora et al. 2012; Ciurana et al. 2014; Eriksson et al. 2019), and time division multiple access where different users wait for their chance (Choi et al. 2011).

Here, we present a spread spectrum multiple access approach. This is tuned towards optical fiber quantum communication, but could also be used to free-space quantum data transmission. Our communication system is constructed from extensively used quantum optical elements and devices. It transmits the photons of multiple customers through the shared optical fiber channel so that they split their typical communication path, spectral band and allotted time slot. Earlier, the spread spectrum multiple access approaches for
quantum optical communication suffered massive losses when they integrated and isolated the communication data from each customer (Razavi 2012; Zhang et al. 2013). The present approach can realize perfect destinism operation. It acquires an add-drop building block with simple merger and extraction points and it has been constructed to follow classical spread spectrum techniques. The system can reiterate existing code structures and conventional classical approaches. The customers only need to append the multiplexer and demultiplexer, as discussed below.

We present a quantum-based multiple access technique which can accept distinct single photon communication channels and add all of them in the shared common communication path. We describe an add-drop multiplexer method that can push or take out a single photon information carrier into a quantum optical communication fiber bringing the quantum bits of all the users. This complete setup works on the postulate of code division multiple access, which is known as spread spectrum approach, deployed in cellular communication networks.

3 Related work

The successful transmission of classical data is achieved by various quantum key distribution schemes (Bennett and Brassard 1984; Boaron et al. 2018; Ekert 1991; Sharma and Banerjee 2019; Sharma et al. 2016; Sharma 2016; Sharma and Banerjee 2018; Thapliyal et al. 2017), and other quantum communication protocols (Bennett and Wiesner 1992; Bennett et al. 1993; Sharma et al. 2015). In a number of these protocols, photons are the preferred information carriers through various optical fiber links (Gisin et al. 2002; Hiskett et al. 2006; Olmschenk et al. 2009; Townsend and Thompson 1994; Hughes et al. 2000; Takesue et al. 2015).

In case of high traffic density, where more than one user wants access to the channel at the same time, multiple access schemes (Sklar 1983, 2001; Benslama et al. 2016; Belavkin et al. 2013) come into picture. As far as quantum networks are concerned, wavelength and frequency division multiple access schemes play an effective role in which each user transmits information at different frequencies (Brassard et al. 2003; Yoshino et al. 2012; Chapuran et al. 2009; Qi et al. 2010; Tanaka et al. 2008; Patel et al. 2014; Ortigosa-Blanch and Capmany 2006; Mora et al. 2012; Ciurana et al. 2014; Eriksson et al. 2019), and each user wait for its chance (Choi et al. 2011).

Here, we use concepts of multiple access, based on spread-spectrum methods (Sharma and Sharma 2014). Most of our discussions are based on optical fiber based data transmission, but they would be useful for free-space communication as well. In our scheme we deploy optical devices, useful for transmitting photons of multiple users via the same optical fiber. In this way, the multiple users share their time window, path, and frequency band. Hence, this quantum optical communication approach is based on spread-spectrum multiple access methods, and eliminates heavy losses, which were present in previous schemes (Razavi 2012; Zhang et al. 2013). In our scheme, along with add-drop architecture, we adopt classical spread-spectrum techniques (Sharma and Sharma 2014).

In spread spectrum techniques Sharma and Sharma (2014), bandwidth $B$ of a modulated signal $D(t)$ is spread by $RB$, where $R$ is the spreading factor Pickholtz et al. (1982). The received signal $S(t)$, after spreading operation, is a larger bandwidth signal, as compared to the original modulated data signal $D(t)$.
In the current work, we are using Direct sequence spread-spectrum (DSSS) method, in the Code division multiple access (CDMA) technology. In CDMA, a code \( c_p \) (1 or \(-1\) as a vector) is assigned to each user \( U_p \). The basic and essential condition while assigning \( c_p \) to each user is that, \( c_p c_q^T = \delta_{pq} \) or \( c_p c_q^T \leq r \), for \( p \neq q \), where value of integer \( r \) must be as small as possible. During spreading process, signal is multiplied by \( c_p \). Despreading can be achieved at the receiver side by again multiplying the signal by the same value of \( c_p \).

To separate the signals from all the users, who share the bandwidth at the same time, it is essential that the codes be chosen appropriately. The operations of spreading diminishes the effect of noise and permits the enhancement of multiple users with improved separation. In this task, an appropriate length of orthogonal codes is chosen.

Direct-sequence spread spectrum (DSSS) techniques are employed to single photons (Belthangady et al. 2010). First, the photon’s wave function is spread and then despread at the receiver side. In despreading operation, we get back the photon’s wavefunction in original form. If some noise exists, filters are used to remove the noise part from photon’s wavefunction.

Here, we highlight the advantages of using single photon spreading for photon’s channels where improved performance is obtained alongwith multiple access systems.

### 4 System architecture

We incorporate three optical fiber elements as the basic building blocks of the working system, namely: fiber Bragg gratings (FBG), circulators, and modulators. A signal’s wavefunction is altered by a control signal (Saleh et al. 1991), present in the electro-optic modulators. The same approach can be adapted in the quantum domain (Capmany and Fernández-Pousa 2010). The photon’s phase are modulated using optical modulators. For this a phase shift of \( \pm \frac{\pi}{2} \) can be applied (Belthangady et al. 2010) to various time bins of the photon’s wave function. Use is made of a wavefunction of time length \( T \) to segment it into \( S \) different segments. The corresponding code element \( C_p \) approves phase shift \( \frac{\pi}{2} \) (if the element is 1), or \(-\frac{\pi}{2}\) (if the element is \(-1\)). In addition to this, to make the phase 0 (for element 1) or \( \pi \) (for element \(-1\)), we use an additional optical modulator. At the end, the total phase change by both the modulations are \( \pm \frac{\pi}{2} \) or \( 0/\pi \).

In order to add the spread photons of multiusers in the same fiber use is made of two important optical elements: fiber Bragg gratings and circulators. Circulators are non-reciprocal optical devices that redirect incoming optical signals to the successive output ports (as shown in Figs. 1 and 2). To increase the bandwidth over optical fiber transmission, a multiplexing technology known as dense wavelength division multiplexing (DWDM) is used. This is an optical multiplexing approach, which transmits various signals at different wavelengths on the same fiber.

Optical circulators are three-port devices which are used in a wide range of optical set-ups. These are non-reciprocating and polarization-maintaining (PM) optical circulators with a center wavelength of 1310 nm, 1550 nm, and 1064 nm. The optical circulators have many significant properties which are required in communication systems such as very low insertion loss and high isolation. Because of these unique properties, these are used as chromatic dispersion compensation devices, add-drop multiplexers, and bi-directional pumps.

Figure 1 describes the operation of circulators with Fiber Bragg Grating (FBG). Circulators drop an optical signal using a dense wavelength division multiplexing (DWDM)
technique with the use of FBG. The Port 1 is coupled to the input of DWDM with Port 2 connected to FBG. The FBG reflects the single wavelength, which then reenters the circulator in Port 2 and finally reaches Port 3. The rest of the signals travel through FBG and reach the top fiber.

Figure 3 explains the operation of the two circulators deployed at the end of the fiber. They add signals in one direction and remove in the other direction. Hence, this kind of
arrangement is used to transmit optical signals in two different directions down a single fiber.

Fiber Bragg gratings allow many of the incoming signals to pass without altering their properties, when a special frequency band is reflected. Hence, FBGs are called reflectors for some specific frequencies (as shown in Fig. 4).

We make use of qubits as information carrier with different encodings. In classical communication frequency modulation is one of the most common approaches, among different modulation schemes, to deal with such kind of transmissions. Following the same approach in the quantum regime, $|0\rangle$ and $|1\rangle$ can be considered as wavefunctions at different frequencies (Capmany and Fernandez-Pousa 2012). In addition to this, for getting phase information, at sidebands of carriers, we can use phase modulation (Guerreau et al. 2003).

Time-bin encoding is another approach where wavefunction is bounded within $(0, T_0)$ for encoding the quantum state $|0\rangle$, and $|1\rangle$ is encoded by introducing delay in wavefunction to start from $(T_0, 2T_0)$ (Brendel et al. 1999). Time-bin quantum bits transmission scheme is mostly used in quantum key distribution and optical fiber communication. In a time-bin qubit encoding scheme, codes are designed for a fixed time interval say $T_0$. After code design, these are applied twice within that time interval $T_0$, so that interference between the generated spread signals by different users can be avoided. In this way, two orthogonal codes which produce similar spread signals will never overlap with each other and effect of the noise is diminished.

We now discuss transmitter unit of each user which combine incoming signals with $|\psi_s\rangle$. This $|\psi_s\rangle$ is a superposition state, and it has all the photons of the previous users. The multiplexing operation is shown in Fig. 5. The add-drop multiplexing is used in optical fiber which helps in combining different frequencies from different channels. Here, we use add-drop multiplexers in both the operations of multiplexing and demultiplexing.

An optical add-drop multiplexer (OADM) is used for multiplexing light in single mode fiber (SMF). This is useful in wavelength-division multiplexing and in routing various channels of light into or out of a SMF. For designing various optical telecommunication networks, OADM acts as an optical node. Add and Drop terms are used here to add and remove the wavelengths according to the desired operations taking place during the transmission in a particular network. Hence, OADM is also known as an optical cross-connect.

For adding individual photons of different quantum states, classical methods fail. The main reason is that classical methods doesn’t follow the reversible operation of quantum states. Y-junction, star couplers are some well-known classical methods but they

![Operation of fibre-Bragg-grating](https://scaime.com/fibre-bragg-grating-technology)
introduces high losses and fail to maintain quantum coherence (Razavi 2012; Zhang et al. 2013; Salehi 1989; Fouli and Maier 2007). In our current add-drop multiplexer technique, photon loss is minimized.

In Fig. 5, the multiplexing operation is shown. The code $c_p$ is multiplied to the input superposition $U_p$. This multiplied signal is passed through fiber Bragg grating (FBG). The main function of FBG is to reflect those frequency bands which have the photon signal. This operation of frequency reflection is achieved before the spreading operation. Along with the above operations, the modulated signals, $d_p(t)$, are transmitted in the opposite direction without spreading as a data signal for the next user via a circulator which reaches FBG simultaneously as a superposition signal. The new photon and other spreaded superposition signals are present in the circulator, where some of the signals come from FBG. The new photons are reflected by the grating into port 2 and some part of the spread superposition returns to the optical fiber it arrived from. The signal with previous photons and the incoming new photon arrive at the circulator, and is pointed to the next modulator in port 3. At port 3, one more code $c_p$ is used for multiplication. At this stage, photon from $U_p$ is spread with the input superposition to its original form. The final result is the combination of the previous wavefunction, and the incoming new photon. In principle, the photons don’t interact with each other and are less interactive with the external environment. Hence, this final result is similar to the tensor product of orthogonal wavefunction which lies in the same frequency range.

Fiber Bragg grating reflects some part of the photon’s wavefunction. For larger $S$ (spreading factor), the reflection probability is $\frac{1}{S}$ and loss will be small. This small value indicates very low value of channel loss. Further, for multiusers, this loss limits the channel access. For security reasons, different codes are used to spread the wavefunction at each multiplexer unit. The section of the wavefunction, which is in the spectrum as an ending part, is different for every extra photon added. The resulting effect can be thought of as a uniform loss, and is the effect of the second modulation.

If we perform the multiplexing operation for the $N$ users, we get qubits from all the users, where a fiber carries $N$ photons. At the receivers end, these photons are separated using demultiplexing operation, as shown in Fig. 6. As the circulator is a non-reciprocal
device, we cannot use multiplexing circuit in reverse order in the demultiplexing operation. Hence, we have to perform slight modification in the circuit sequence.

As shown in Fig. 6, the incoming superposition signal is modulated with the help of a code $c_p$, which results in spreading of the signal. This spreaded signal is now despread by the modulator at the other end. The final wavefunction is concentrated in the original spectrum $W$.

The new signal is further sent into a Fiber Bragg Grating. The FBG reflects the intended photon back to that circulator which forwards it to its intended receiver. In this process, some part of the noise is added in the form of a fraction $\frac{1}{5}$ of the wavefunction of the other photons. To recover all the incoming photons, we need to run the experiment $N$ times.

### 5 Simulation for multi-users

When we go for the practical implementation of these ideas, it is pertinent to keep in mind that photon losses become larger as compared to ideal case, where losses are $\frac{1}{5}$. Here, we show the extra benefits of the add-drop architecture in the quantum spread spectrum. To nullify the effects of losses, and crosstalk between users, we use long length codes for obtaining better results.

#### 5.1 Photon shape and its analysis

We perform multiplexing operation on single photons of length $T$, which are in the time domain. These single photons can carry an empty or a Gaussian wave packet. These time bin encoding schemes are similar to the COW (coherent one-way) protocol (Stucki et al. 2005; Grosshans et al. 2003; Stucki et al. 2009), and Ekert protocol (Ekert 1991), which are entangled in time-energy form (Tittel et al. 2000). The two same length time bins exist in a COW protocols, with a mean photon number smaller than one. Here the Gaussian pulse is used to denote the time bin in the coherent one-way protocol. Out of the two time bins, the first and the second correspond to $|0\rangle$ and $|1\rangle$, respectively.

We apply the multiplexing operation in a time-energy quantum key distribution protocol. This multiplexing technique helps in the distribution of entangled pairs, which were initially shared between each of the communicating users. Specially, in a time-energy QKD method we allow the entangled photons to be shared between the authenticate users. These entangled photons were emitted from a spontaneous parametric down-conversion (Fedorov et al. 2009). Continuous-variable (CV) quantum key distribution is not similar to the standard QKD from the perspective of weak optical signal detection (Hirano et al...
Gaussian wave packets are used for analyzing the results. These Gaussian packets have a $\sigma$ (standard deviation) = 0.1 T, with a centered time bin. We analyzed our results with in phase and random phase wave packets. The in phase and random phase patterns are similar.

Let $\phi(x, t)$ is the photon’s wave function. This is a complex valued function of two real variables $x$ and $t$. Considering the wave function as a probability amplitude, the square modulus of the wave function will be a positive real number:

$$|\phi(x, t)|^2 = \phi^*(x, t)\phi(x, t) = \rho(x, t),$$

where asterisk (*) denotes complex conjugation. If the particle’s position is measured, it’s location cannot be determined from the wave function, but is determined by a probability distribution. The probability that its position $x$ will be in the interval $a \leq x \leq b$ is the integral of the density over this interval

$$P_{a \leq x \leq b}(t) = \int_a^b |\phi(x, t)|^2 dx,$$

where $t$ is the time at which the particle was measured. This leads to the normalization condition

$$\int_{-\infty}^{\infty} |\phi(x, t)|^2 dx = 1.$$  \hspace{1cm} (2)

Here, we have considered photon pulse as a Gaussian wave packet. The normalized wave packet centered on $x = x_0$, and of characteristic width $\sigma$ is

$$\phi(x) = \phi_0 e^{-i(x-x_0)^2/(4\sigma^2)}.$$ 

The normalization constant $\phi_0$ is

$$|\phi_0|^2 = (1/2\pi\sigma^2)^{1/2}.$$ 

Hence, the general form of normalized Gaussian wavefunction is

$$\phi(x) = \frac{e^{i\varphi}}{(2\pi\sigma^2)^{1/4}}e^{-(x-x_0)^2/(4\sigma^2)},$$ \hspace{1cm} (3)

where $\varphi$ is an arbitrary real phase-angle. This is used for calculating photon loss and cross-talk probabilities in the coming sections.

### 5.2 Codes for multiplexing-demultiplexing operations

The linear feedback shift registers (LFSR) are used to generate a unique code for each user which are then used in the spread spectrum techniques. A long sequence of pseudo-random binary sequences are desired for high speed data transfer as well for scrambling the message signals. The Pseudo noise (PN) sequences are generated by Exclusive-OR (X-OR) gates and shift registers. They depend on the value of $n$ (number of registers) and proper feedback, $2^n - 1$, as a periodic output is received, which is also known as maximum-length sequence (m-sequence). These $m$-sequences follow particular type of properties. These
\(m\)-sequences generate random signal statistics with a low value of the autocorrelation function Golomb and Gong (2005), a parameter to measure the similarity or dissimilarity between the input and output data. To analyze our results for performance evaluation, the shifted version of the various \(m\)-sequences with the right feedback are chosen from the table in Mutagi (1996). The code value \(c_p\) denotes a cyclic shift by \(p^{th}\) position. Following these codes from 1 to \(2^n - 1\) with binary data as \(\pm 1\), the expression, \(c_p c_q^T = -1\), is valid if and only if, \(p \neq q\). In the other case, the expression \(c_p c_q^T = 2^n - 1\), is valid if and only if, both the indices are equal, i.e., \(p = q\).

We need proper synchronization between the modulators. In addition to this, deploying a classical side channel can coordinate the nodes, which helps in maintaining the start and end timings of the bit stream, and also codes will be orthogonal. These issues are discussed in QKD networks Stucki et al. (2005), Tanaka et al. (2008). Without proper synchronization between the multiplexer and demultiplexer units many undesirable effects such as interference and change in code families may occur, which further leads to different sensitivities to time shifts.

5.3 Noise removing filters and signal modulators

We are considering FBG filter of spectral width \(\sigma_{\text{filt}}\). This is similar to the Gaussian filter. If we compare this spectral width with the spectral width of the Gaussian wave packet of the photons, we find that it is \(8g\) times the spectral width of the FBG filter. Specially for FBG, we have chosen Gaussian shapes, the reason being that the properties of the Gaussian shapes are quite suitable and come close to the transfer function of apodized gratings.

We are using an ideal modulator, which provides a 0 or a \(\pi\) phase shift. In the interval of length \(T_S\), the modulator introduces variable phase shift, which are determined by the binary values of the code used. These code elements are generated at regular intervals of \(T\) seconds. We receive \(S\) elements after \(T\) seconds. There will be no phase shift introduced by the modulator, in the case the code element is 1 and if the code is \(-1\), \(\pi\) shift occurs.

5.4 Sources for insertion losses and noise

In the simulation, we assume the circulators, modulators and all the connections are ideal and have no losses. The aim of this simulation is to model intrinsic losses due to the spreading. The effect of other sources of loss is commented upon in the discussion. Likewise, we have not included noise or other effects that could degrade the signal.

5.5 Simulation results

Here, we consider two different sources of errors: one due to crosstalk and the other due to photon loss. These values vary with the value of spreading factor (5) and the number of users. Our results suggest that overall performance can be enhanced with larger value of spreading factor, but as the number of users participating in the communication process increases, the channel performance degrades. Hence larger value of spreading factor helps in increased system performance, but each additional user degrades the system performance. There is a trade off between the two factors.

In our analysis, we consider five users who transmit eight bit random sequence, in which empty time bin is denoted by 0, and one photon Gaussian pulse is represented by
Here, we are considering two different values of the spreading factor $S = 2^8 - 1$ and $S = 2^{15} - 1$, as shown in the Figs. 7 and 8, respectively. The result is shown in the form of density of the average photon number. Moreover, the output is in the form of probability density $|\phi(t)|^2$. These outputs indicate the losses, probability of photon loss, i.e.
less than one information carrier (photon) in a time bin, and crosstalk, i.e. probability of finding a photon in an empty time bin, or more photons in a time bin, instead of one.

These problems are addressed in Fig. 7, where pulse distortion occurs during multiplexing operation. The pulses of different heights are indicated to represent the loss during transmission. Other than these, the residual pulses are indicated by 0, in which some portion of the information carrier photons in adjacent channels reach a user that must receive zero photons.

Improved results without any losses and crosstalk, are depicted in Figs. 8, 9, and 10. From Fig. 7, photon loss, crosstalk, and adjacent Gaussian photon pulse interference can be seen, which give a lower value of SNR (signal to noise ratio). Moreover, losses present in these signals are a major hurdle, and make reproduction of the original signal (meaningful information or initial wavefunction) difficult at the receiver end. Contrary to high value of losses present in Fig. 7, comparatively high values of SNR or negligible losses (photon loss and crosstalk) are seen in Figs. 8, 9, and 10. These high values of SNR are desirable for various applications of quantum communication. These parameters also serve to compare various losses or the photon transmission in a wrong channel. These results indicate that a perfect high value of spreading factor, $S$, eliminates the various losses described earlier, and correspondingly the density of the average photon number, particularly in these cases, is close to $|\psi(t)|^2$. In these cases, the integration of the Gaussian pulse (area under the curve) is one.

Here we have computed probability of photon loss for the cases where only one channel transmits a Gaussian single photon pulse. This channel selection is randomly allotted. The results have been shown in Table 1, representing average photon loss probability for 200 different tests. The values depicted in the Table 1 are computed from the probability density, which denotes the availability of the photon in its original channel.

It is observed that losses become effective in the communication system, as the number of users grow. Each multiplexer and demultiplexer stage introduce additional losses. Larger

![Number of Registers (n) = 13; Spreading Factor (S) = 8191](image-url)

**Fig. 9** Example of transmission in a system with $S = 2^{13} - 1$ (with a code from an LFSR with $n = 13$ registers) and five users.
value of spreading factor helps in the filtering process, and becomes more selective for higher values of $S$. Thus, more the spreading factor $S$, more the photon spread, hence larger bandwidth results in less losses making it more acceptable for practical applications.

Other source of error is crosstalk. Here, in such a case, we have calculated the photon probability appearing in a channel which is empty. The transmitted single photon is random in phase. In these calculations, we randomly allocated empty channel and investigated the photon availability at the output. The area under the Gaussian photon pulse (integrating average photon number density in the considered channel), gives the value of the crosstalk for 128 runs where each user transmits 8 bits, as shown in Table 2. The considered channel should be empty in such cases, while calculating crosstalk.

As the number of users increase, losses (crosstalk and probability of photon loss), also increase. On the other side, to avoid channel interference, we need to select longer codes. To make it practically acceptable and feasible in a realistic scenario, there must be fine tuning between the number of users and code selection.

A characteristic of a quantum system is that it follows the principal of superposition and is the key property behind quantum communication applications, as required in coherent one-way (COW) QKD protocols (Walenta et al. 2014; Stucki et al. 2005; Sibson et al. 2017). In the present study, we are considering four different quantum states $|0\rangle$, $|1\rangle$, $|+\rangle$, $|−\rangle$. 

![Fig. 10 Example of transmission in a system with $S = 2^14 − 1$ (with a code from an LFSR with n = 14 registers) and five users](image)

| Value of spreading factor | Five users | Twenty users | Fifty users |
|---------------------------|------------|--------------|-------------|
| $S = 2^8 − 1$             | 0.1197     | 0.3720       | 0.6727      |
| $S = 2^{12} − 1$          | 0.0583     | 0.1337       | 0.2640      |
| $S = 2^{14} − 1$          | 0.0424     | 0.0618       | 0.0996      |
and \( |\rangle \) which serve as single photon information carriers. We have defined these quantum states, depicted in Fig. 11. A state with photon present in the first time bin, but empty in the second time bin, is denoted by \( |0\rangle \). While if the photon is present in the second time bin, but empty in the first time bin, is represented by the state \( |1\rangle \). Here each of the time bins is of duration \( T \). Following the same pattern, the superposition of the quantum states, \( |0\rangle \) and \( |1\rangle \) are written as \( |+\rangle = \frac{|0\rangle + |1\rangle}{\sqrt{2}} \) and \( |-\rangle = \frac{|0\rangle - |1\rangle}{\sqrt{2}} \). These superposition states span the time duration from 0 to \( 2T \), as seen in Fig. 11.

Let \( \phi(t) \) is the initial wavefunction, which travels through the optical channel. At the receiver end, we get a distorted wavefunction \( \tilde{\phi}(t) \). Fidelity, \( F \), is used to compare between the input and output states and can be defined from the overlap integral

\[
F = \left| \int \tilde{\phi^*}(t)\phi(t)dt \right|^2, \tag{4}
\]

where \( \phi(t) \) denotes the original photon’s wavefunction at the input side, and \( \tilde{\phi^*}(t) \) is the complex conjugate of the distorted wavefunction at the receiver end. The asterik (*) indicates complex conjugation. Here we have not taken the effect of the time of flight, which is the photons travel time taken through the optical network.

The average fidelity is computed between the input and normalized output state. The four quantum states with different number of users and their corresponding fidelity values are calculated with the help of Eqs. (1) to (4). They are depicted in Table 3, in the form of a complementary factor \( 1 - F \). They are computed for the spreading factor, \( S = 2^{10} - 1 \) and indicate that the average fidelity \( (F) \) is approximately one. We have used Gaussian wave packets centered in the middle of the time bin and a pulse width of \( \sigma = 0.1 \) \( T \). Here, \( \sigma \) represents standard deviation, as discussed in Sect. 5.1. The modulator uses the code once in each time bin of length \( T \) and photons with wavefunctions in the order of microsecond length range (and photon rates in the order of MHz range) are used. The modulators, as shown in Fig. 12 have modulation rates around 10–100 Gbps. Here, we have shown

| Value of spreading factor | Five users | Twenty users | Fifty users |
|--------------------------|-----------|--------------|-------------|
| \( S = 2^{8} - 1 \)     | 0.0632    | 0.2240       | 0.3888      |
| \( S = 2^{10} - 1 \)    | 0.0183    | 0.0728       | 0.1677      |
| \( S = 2^{12} - 1 \)    | 0.0041    | 0.0184       | 0.0480      |
| \( S = 2^{14} - 1 \)    | 0.0010    | 0.0050       | 0.0124      |

| Probability of Crosstalk | Five users | Twenty users | Fifty users |
|--------------------------|-----------|--------------|-------------|
| \( S = 2^{8} - 1 \)     | 0.0632    | 0.2240       | 0.3888      |
| \( S = 2^{10} - 1 \)    | 0.0183    | 0.0728       | 0.1677      |
| \( S = 2^{12} - 1 \)    | 0.0041    | 0.0184       | 0.0480      |
| \( S = 2^{14} - 1 \)    | 0.0010    | 0.0050       | 0.0124      |

| Average Fidelity values in complementary form \((1 - F)\) for different users | Single photon as an information carrier | Five users | Twenty users | Fifty users |
|-----------------------------------------------------------------------------------------------|----------------------------------------|------------|--------------|-------------|
| \( |0\rangle \)                                                                         | 1.077 \times 10^{-3}                    | 2.330 \times 10^{-3} | 5.624 \times 10^{-3} |
| \( |1\rangle \)                                                                         | 1.077 \times 10^{-3}                    | 2.330 \times 10^{-3} | 5.620 \times 10^{-3} |
| \( |+\rangle \)                                                                         | 1.077 \times 10^{-3}                    | 2.340 \times 10^{-3} | 5.630 \times 10^{-3} |
| \( |−\rangle \)                                                                         | 1.076 \times 10^{-3}                    | 2.332 \times 10^{-3} | 5.605 \times 10^{-3} |
a quantum communication approach using CDMA which accepts photon rate in order to have an adjustable and appropriate add-drop multiple access technique.

### 6 Experimental verification

Continuous-variable (CV) quantum key distribution is different from the standard quantum key distribution method for detecting weak optical signals (Hirano et al. 2003; Grosshans et al. 2003; Jouguet et al. 2013; Wang et al. 2015; Huang et al. 2016; Imre and Gyongyosi 2012; Hanzo et al. 2012). Here, optical fiber channel is used as a transmission medium in which codes are deployed from code division multiple access. A significant parameter is the spreading factor $S$, which helps in reducing noise effects on system performance, and at the same time allows more users to share the channel. For adequate separation, $N \leq S$ is the condition giving appropriate number of orthogonal codes. The acceptable experimental value of $S$ is $2^{15} - 1$, which is practically possible without further overlap (Belthangady et al. 2010).

Consider the experimental setup in Fig. 12 (Belthangady et al. 2010). The spread spectrum technology at the level of single photons is presented in Scholtz (1977). In Belthangady et al. (2010), it was shown that a single photon with a temporal waveform can be transmitted via a noisy environment, generated by a narrow band of thermal photons. In addition to this, the noisy medium can be produced by an interfering laser beam which
has an average power equivalent to thousand times larger than the average power of the beam of single photons (Belthangady et al. 2010). In Fig. 12a, the same can be achieved by deploying two synchronously operated electro-optic phase modulators. The modulator in Fig. 12a, at the transmitter $M_1$, broadens the frequency spectrum of the incident photon beam from $10^6$ to $10^{10}$ Hz, hence diminishing the power spectral density by a factor of $10^4$. In contrast to this, the demodulator $M_2$, used at the receiver end, operates in antiphase to modulator $M_1$, demodulating the photon beam and minimizing it to the original bandwidth $10^6$ Hz. Finally, this is now transmitted through a narrow bandpass filter $F_2$. Further, a significant “processing gain” is achieved by following the setup shown in Fig. 12a. If we transmit the single photon beam via a medium of thermal photons with a linewidth comparable to the original beam, the noise generated from such an arrangement, when injected just after the first modulator, as shown in Fig. 12a, will be further broadened in frequency domain by the second modulator. This results in a low power transmission through a narrow band filter used at the receiver side. At the end, all these operations, enhance the ‘Signal to Noise Ratio (SNR)’ in the ratio of modulation bandwidth to the bandwidth of the final filter. This effect is known as “processing gain” (Belthangady et al. 2010). There are practical limits on modulators. Modulation rate of 10–100 Gbps can be achieved. Exceeding the modulation rate, enhanced smooth transition occurs in the codes. These smooth transitions are undesirable and degrade the overall performance of the multiplexing stages.

![Diagram](image-url)
These effects lead to limits on the modulation rates and code length. Photons with spreading factor values; $S = 2^{13} - 1$ or $2^{14} - 1$, and with wavefunctions in microsecond length (photons in MHz range) are practically possible.

7 Discussion and conclusion

Considering a single optical fiber as a channel, we studied the spread spectrum technique, in which multiple users transmit their qubits. A unique code is deployed for each user to spread the original message signal. The original message signal is obtained by considering the wavefunction of each photon. The unique advantage of the spread spectrum approach is that, this technology offers extended bandwidth. For example, CDMA (code division multiple access) is a type of spread-spectrum technique, where $N$ different qubits are encoded in $N$ different photons and only a single optical fiber is used as a transmission channel.

During successive multiplexing stages, a new qubit is added in the channel corresponding to each new user. The photon loss probability of each “old” photon is $\frac{1}{S}$. This is similar to that of demultiplexing operation. There are $2N - 2$ lossy stages for a photon while passing from various multiplexing-demultiplexing stages. Here $N$ represents the number of users sharing a particular channel. The maximum probability of photon loss is $\frac{2N - 2}{S}$, which can be further reduced by the proper selection of addition and extraction of qubits of each user. The Figs. 5 and 6 will add coupling losses that should in principle be taken into account.

Coupling losses at the optical elements are also likely to be a major limitation. In many QKD networks, losses limit the maximum communication distance, but spreading provides certain protection against noise that reduces the strength of losses, enhancing the signal-to-noise ratio of the data link. The noise that has been picked up in the channel (Sharma et al. 2018) is spread at the receiver and the filter that rejects adjacent channels also stops a greater proportion of the energy of the noise. This is an independent effect of spreading and can be used to extend the reach of QKD links with a single photon. In that case, the photon need not be spread with a modulator. An interesting alternative is using spread spectral teleportation, a teleportation protocol that can stretch or shrink the wavefunction in frequency (Humble 2010). This kind of teleportation could extend the applicability of spread spectrum methods to quantum repeater networks (Briegel et al. 1998).

We have discussed the trade off between spreading factor $S$, and the number of users, $N$. The only solution of this problem is that, the number of users accessing the channel during communication can be restricted, resulting in lower losses ($\frac{1}{S}$).

The deployment of integrated optical elements, such as integrated microring structures with discrete elements are a substitute for fiber Bragg-Grating and circulators. These microring structures perform as frequency selective filters and routing devices, thereby eliminating the requirement of amplifiers and giving birth to energy-efficient quantum optical code division multiple access (Little et al. 1998; Xiao et al. 2008).

The present study of the multiplexing method can also be used to combine classical and quantum data. Most QKD networks send photons through what are called dark fibers, which are reserved for quantum use and carry no classical data. Classical and quantum information channels can share the same fiber if they are assigned different frequency bands, but Raman scattering and other processes triggered by the classical optical signal introduce noise into the photon channel. The present study of add-drop architecture offers a new way to introduce a single photon into an optical fiber that carries classical signals. The
method allows insertion in already deployed optical networks and spreading helps to fight the noise in the communication channel.

By proper adjustment with an antiphased modulator, the biphoton waveform may be regenerated at a long distance. Although antiphased operation of the modulators may be an issue at long distances, irregular transmission of synchronizing signals could be deployed to reduce it. Since the spread spectrum technique makes the time-frequency entanglement properties of the photons flawless, dispersion in the anti-Stokes channel may be rejected nonlocally by dispersion in the Stokes channel (Franson 1977). The implementations may incorporate an extra level of classical security for quantum key distribution.

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