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Modeling and Minimizing Spontaneous Raman Scattering for QKD Secured DWDM Networks

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***Abstract*—Quantum key distribution (QKD) provides information-theoretic security based on quantum mechanics. Integrating QKD with classical data traffic by using wavelength division multiplexing (WDM) techniques in a single fibre is a cost-efficient way to improve security in legacy infrastructure. In such a system, the main noise source to the quantum channel is spontaneous Raman scattering (SRS) caused by the classical channels. In this letter we introduce a channel allocation strategy for both quantum and classical signals to minimize the SRS noise. A use case that quantum and classical channels co-exist in a dense WDM system is investigated. The results show >26% increase of achievable transmission distance for the QKD system when implementing the introduced channel allocation strategy. Moreover, a network updating plan is proposed, which provides a guideline to light the new wavelengths for classical communications while minimizing the SRS noise to quantum channels.**

***Index Terms*—Optical fibre communication, Optical fibre network, Quantum key distribution (QKD).**

I. Introduction

COMBINED with conventional symmetric encryption, e.g., advanced encryption standard, a quantum key distribution (QKD) protocol protects the encrypted data by detecting any eavesdropping event with quantum mechanics instead of computational difficulty [1]. An QKD secured wavelength division multiplexing (WDM) network architecture (see Fig. 1(a)) consists of two layers, namely a QKD layer and a data layer. The QKD layer has both quantum and authentic signals for key generation that allows the data layer to run data encryption for the selected services. Such a WDM network integrated with QKD shares the same fibre infrastructure and assigns spectrum for two types of channels: 1) quantum channels only for quantum signals and 2) classical channels for both data transmission and QKD authentication.

A few implementations of QKD networks have been carried out in field, including SECOQC [2] in Spain, the Tokyo QKD network [3], and the QKD connection between Beijing and Shanghai [4] with trusted nodes in between. Despite the latest progress of QKD, the key rate over long distances that can only be achieved is still low even with the state-of-art commercialized QKD equipment. Paralleling multiple QKD systems to enable a high aggregated secret key rate (SKR) has been realized in spectrum and spatial dimensions [5], [6]. Confronting the potential massive deployment, sharing infrastructure with conventional WDM system is the cost-efficient way avoiding the high cost of the dedicated fibre

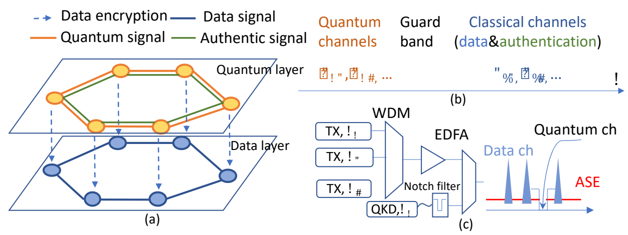

Fig. 1. (a) A QKD secured WDM network architecture, (b) the benchmark channel allocation strategy [11], and (c) multiplexing QKD with classical channels. WDM: wavelength division multiplexer; EDFA: erbium doped fibre amplifier

assigned to the QKD. The classical and quantum channels can be in different wavebands (e.g., O-band for quantum channels and C-band for classical channels [7]) or in the same waveband (e.g., C-band for both channels [4]). Using C-band for quantum channels is beneficial for QKD since the low insertion loss can facilitate high secret key rate (SKR) and long transmission distance. There are a few modelling and demonstrations of QKD and classical communication co-existing in C-band, where different QKD protocols [8]–[12] are implemented.

Given the increasing security demand, more than one QKD channel might be needed to provide enough keys for data encryption. A general co-existence scenario is needed, where several quantum channels can be integrated with multiple classical channels in a single fibre. A typical approach is to separate quantum and classical channels by guard band, and place the quantum channels in shorter wavelengths [13], see Fig. 1(b), which is later being used as benchmark. In [14], the best wavelength assignment to the quantum signals and classical signals varies when the number of running classical channels increases. The wavelengths are chosen based on the evaluation of spontaneous Raman scattering (SRS) from classical to quantum wavelengths, which is the main noise source to the quantum channels. However, in network planning, the spectrum resources are typically allocated gradually rather than all at once from the scratch. Moreover, since the QKD channels needs wavelength sensitive filtering devices, changing the wavelengths of the quantum channels is complicated and not recommended during the network update.

With all these in mind, we investigate a wavelength assignment approach for the QKD secured WDM network that minimize SRS noise added to the quantum channel(s) along with the practical network updating solution to light the new wavelengths for the classical communications. This paper extends our previous work [15] by bringing up the quantum

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channels performance in a counter-propagation case as well as a guideline to light new wavelengths given the best channel allocation to minimize the SRS in quantum channels.

II. SYSTEM DESCRIPTION

Sharing the same fibre, quantum channels are easily contaminated by the data channels. The noise can be divided into the out-of-band noise and in-band noise. The first category includes inter-channel crosstalk and amplified spontaneous emission (ASE) noise, which can be mitigated by putting a notch filter [16]with high a rejection level, centering at quantum channels before multiplexing QKD with classical channels, as shown in Fig. 1(c). In-band noise may come from a nonlinear process in the fibre, including four-wave-mixing and SRS noise. The SRS is often identified as the main noise source for quantum channels [17], [18] and hence is concentrated on in this letter.

A. SRS modeling

Considering L equally spaced spectrum channels in the WDM system, each of the channel λ_i can be noted as:

$$\lambda_i = \lambda_1 + \Delta \cdot (i-1), 1 \leq i \leq L \quad (1)$$

where i is the number of the channel wavelength and Δ is the spacing between two adjacent channels. When a classical channel with a launch power of P_0 is co-propagating with the quantum channel i_q, the SRS noise SRS_{co} generated by the classical channel is:

$$SRS_{co} = P_0 z \beta(i_q) \exp(-\alpha z)\, \eta \frac{\tau}{hv}, \quad (2)$$

where z is the fibre length, α is the average fibre attenuation coefficient over the considered wavelength range of data and quantum channels, η is the detection efficiency, τ is the detection gate length, and hv is the average energy of the photons from the classical channels. $\beta(i_q)$ denotes the effective SRS coefficient. Throughout the whole band, SRS noise is given by a Stokes or anti-Stokes coefficient, depending on the spectrum difference of the quantum and classical channels and displaying a V-shape distribution along the C-band.

The SRS noise can be reflected by $\beta(i_q)$, expressed as:

$$\beta(i_q) = \begin{cases} k_1(i_q - i_c), i_q \geq i_c \\ k_2(i_c - i_q), i_q \leq i_c \end{cases} \quad (3)$$

where k_1 and k_2 are the slopes of the frequency-dependent Stokes and anti-Stokes coefficient, and i_c represents the classical channel, respectively.

When there are multiple classical channels, the overall co-propagation SRS noise ($SRS_{co_{all}}$) can be obtained by summing up SRS noise from each individual channel:

$$SRS_{co_{all}} = z\exp(-\alpha z)\, \eta\tau / hv \sum_j P_{0,i} \beta(i_{q,j}). \quad (4)$$

Similarly, the SRS noise to the quantum channel i_q in counter-propagation case for the single channel ($SRS_{counter}$) and multiple channels ($SRS_{counter_{all}}$) can be expressed as:

$$SRS_{counter} = \frac{P_0}{2\alpha} \beta(i_q) \left[1 - \exp(-2\alpha z)\right] \eta \frac{\tau}{hv}, \quad (5)$$

$$SRS_{counter_{all}} = \frac{1}{2\alpha} \left[1 - \exp(-2\alpha z)\right] \eta \frac{\tau}{hv} \sum_j P_{0,i} \beta(i_{q,j}) \quad (6)$$

Assuming all the classical channels launch with the same power, the SRS noise level is determined by the last term, i.e., the accumulated SRS coefficient $\sum_j \beta(i_{q,j})$. When there are n quantum channels, each is denoted by $i_{q,j}$ ($1 \leq j \leq n$ and $i_{q,1}$<... $< i_{q,j} < \cdots i_{q,n}$). Then, $\sum_j \beta(i_{q,j})$can be expressed as:

$$\sum_j \beta(i_{q,j}) = \sum_j [\sum_{i_c=1}^{i_{q,j}-1} k_1(i_{q,j} - i_c) + \sum_{i_c = i_{q,j}+1}^{L} k_2(i_c - i_{q,j}) - k_1 \sum_1^{j-1} (i_{q,j} - i_{q,i}) - k_2 \sum_{j+1}^{n} (i_{q,i} - i_{q,j})] \quad (7)$$

Combining the similar terms with respect $to\, i_{q,j}$,

$$\sum_j \beta(i_{q,j}) = \sum_j \frac{i_{q,j}^2 (k_1 + k_2)}{2} + i_{q,j}\left[(k_1 - k_2(2L+1))/2 - k_1(j-1) + k_2(n-j)\right] + k_2[L(L+1) - (i_{q,j+1} + i_{q,n})(n-j)]/2 + ((i_{q,j-1} + i_{q,1})(j-1)k_1)/2 \quad (8)$$

which is a quadrature function of $i_{q,j}$. To minimize $\sum_j \beta(i_{q,j})$, the optimal channel number assigned to quantum signal should belong to a set of integers $\{i_{opt,j}, 1 \leq j \leq n\}$, which can be expressed as:

$$i_{opt,j} = round\left(\frac{\left(\frac{k_1 - k_2(2L+1)}{2}\right) - k_1(j-1) + k_2(n-j)}{k_1 + k_2}\right) \quad (9)$$

where $round(\cdot)$ returns the nearest integer. Note that the average fibre attenuation and average photon energy of the classical channels is used, which may result in slightly higher SRS noise than the real value for the shorter wavelengths and lower SRS noise for the longer wavelengths part. Such difference may lead to small variance in the SKR performance evaluation result in a minor way.

B. Secret key rate

The SKR for practical decoy state protocols can be expressed as [19]

$$SKR \geq Q_1\left[1 - H_2(e_1)\right] - Qf(E) H_2(E) \quad (10)$$

where Q_1 and Q are the probability of a single-photon pulse and all-photon states sent by Alice and being detected by Bob, respectively. e_1 is the error probability for the single-photon state. $H_2(\cdot)$ is the Shannon binary entropy function, and $f(\cdot)$ is the error correction inefficiency factor function. E represents the total QBER, which can be calculated as[20]:

$$E = \frac{1}{Q}\left[\frac{1}{2} Y_0 + \gamma\left(1 - e^{-\mu\eta}\right)\right] \quad (11)$$

For a BB84 system with two SPDs, $\frac{1}{2}Y_0$ denotes the split system noise, which is composed by dark counts of the SPD and the split SRS noise between the two SPDs. γ denotes the alignment of the optical system. μ is the average photon flux set by Alice,

TABLE I: KEY PARAMETERS FOR THE QKD SYSTM [21]

Parameter	Symbol	Value
Attenuation coefficient	α	0.21 dB/km
Detection gate length	τ	1 ns
System noise	Y_0	1.7e-6
Average photon flux	μ	0.48
Detection efficiency	η	0.045
Error correction inefficiency	$f(E)$	1.22
Optical system alignment	γ	0.033

η is the detection efficiency. The key parameters used for the QKD performance evaluation are listed in Table I [21].

III. Performance Evaluation

In this section, we first simulate quantum channel performance with all other wavelength channels occupied by classical signal transmission. Then a roll-up plan for increasing the number of classical channels is sketched with the goal of maintaining the quantum channel(s) running as well as possible.

A 40-channel DWDM system is considered with the wavelengths ranging from 1529.55 nm (i.e., Channel 1) to 1560.61 nm (i.e., Channel 40) [22], where n channels are assigned to quantum and the remaining (40-n) channels are assigned to classical communications. The wavelength allocation strategy in [13] is referred to as the benchmark (see Fig. 1(b)), where the n shortest wavelengths are assigned to the quantum channels. The SRS coefficient slopes are set 6.9e-12 and 11.5e-12 per 100GHz per km for co-propagation, and, 6.8e-12 and 10.8e-12 per 100GHz per km for counter-propagation, respectively [18]. Fig. 2 shows the value of accumulated SRS coefficient $\beta(i_q)$ when only one of the 40 channels is assigned for quantum signal (i.e., n=1). The accumulated SRS coefficient gives the lowest value at Channel 15, which indicates the minimum impact of the SRS if it is assigned to the quantum channel for both co- and counter-propagation cases, i.e., i_{opt} is Ch 15 when n=1. If requesting 2 quantum channels, the solution with the minimized SRS is to allocate Ch 14 ($i_{opt,1}$) and Ch 15 ($i_{opt,2}$) to quantum signals. To maintain the quantum channels, the launch power of the classical signals needs to be attenuated sharply, which is set to -20dBm for each classical channel.

Fig. 3 shows the SKR performance for n=1, 2, 3, i.e., one, two and three wavelengths are used for quantum signal while other channels in the DWDM system are used for classical signal transmission, respectively. It can be observed that a much better performance can be achieved if the quantum channel is placed at the SRS noise optimized point rather than in the benchmark in terms of SKR and achievable transmission distance both in co-propagation and counter-propagation case. The total SKR increases slightly faster than a linear change since the accumulated SRS noise decreases due to the reduction of classical channels. More than 26% improvement in achievable transmission distance by the proposed SRS minimized wavelength allocation compared to the benchmark. As shown in Fig. 4, more than 50% SKR improvement can be found in most cases when quantum channel(s) are co-propagating with the classical channels. Over 60 km, only the SRS minimized allocation can enable non-zero SKR in some cases, so that 100% improvement can be observed. A higher accumulated counter-propagation SRS noise results in a shorter reachable distance for the quantum channels, nevertheless, the SRS minimized allocation increases the SKR substantially.

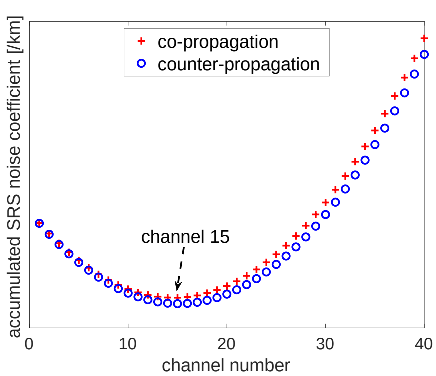
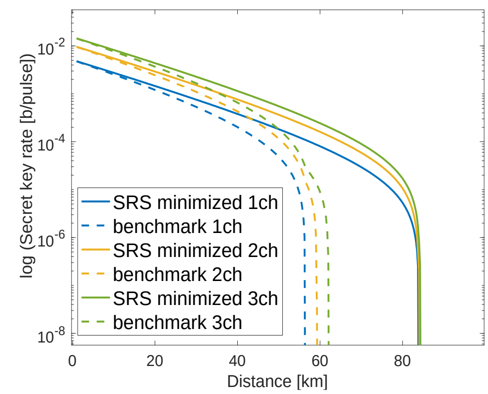
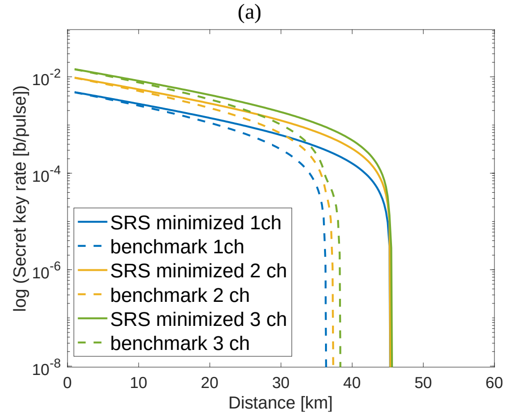


Fig. 2. Accumulated SRS coefficient on a single quantum channel.

With the knowledge of quantum channel location, in Fig. 5 we present the roll-up plan for the classical wavelengths co-propagating with the quantum channels. The wavelength assignment of quantum channels is marked by red labels. The

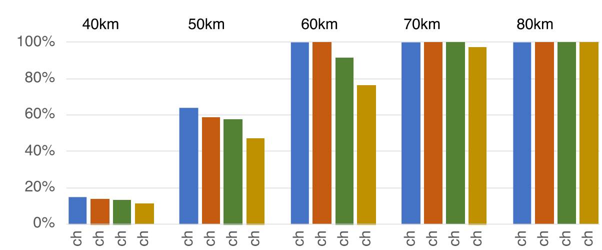


(a)

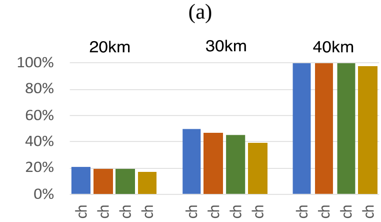


(b)

Fig. 3. The total SKR as a function of transmission distance under the case of 1, 2, and 3 quantum channels when (a) co-propagating and (b) counter-propagating with classical channels in the 40 channels DWDM system.

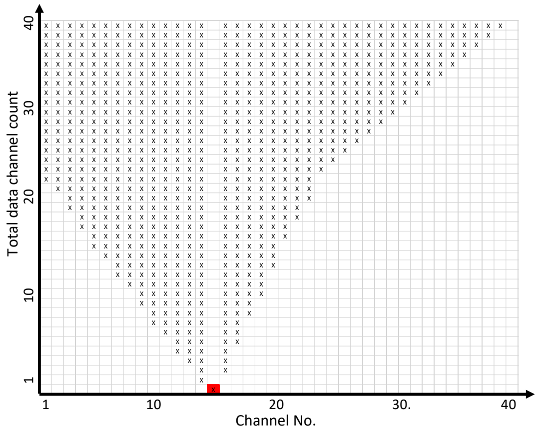


(a)

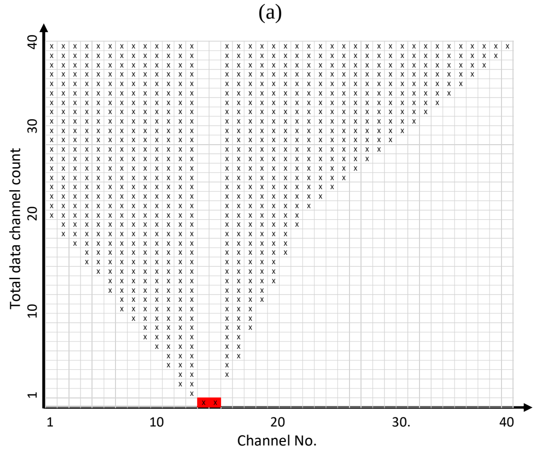


(b)

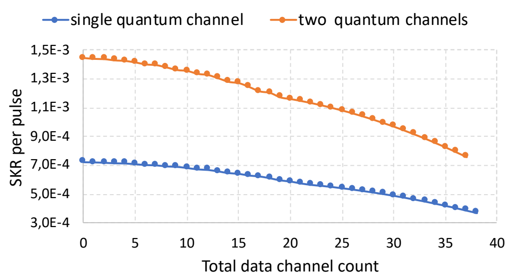
Fig. 4. SKR improvement in (a) co-propagation and (b) counter-propagation case.



(a)



(b)



(c)

Fig. 5 the data channel roll-up plan with (a) a single quantum channel and (b) two quantum channels, and (c) total SKR per pulse as data channel count

X-axis shows the channel number while the Y-axis shows the total channels count used for classical signals. The principle to determine the spectrum for the coming classical traffic is to pick the wavelength that minimizes the additional SRS noise to the existing quantum channel(s). For instance, for the case that only one quantum channel is put on Ch 15 while 4 wavelengths are to be occupied by data transmission, i.e., Ch 12, Ch 13, Ch 14 and Ch 16. The SKR performance degradation for one and two quantum channels cases with the increasing of data wavelengths over 40 km fibre transmission are shown in Fig. 5(c). Due to the accumulated SRS noise, the total SKR degrades to about half of the case when the fibre is dedicated to the quantum channel, i.e., the starting point.

IV. Conclusion

In this letter, we model the SRS noise in QKD secured WDM network with co-existence of the quantum and classical signals and propose an analytical model for the least SRS contaminated quantum channels when all other wavelengths are all occupied with classical signals. A case study in C-band is carried out. By minimizing SRS noise, the total SKR is improved by at least 50% for most cases when quantum and classical signals are propagating along the same direction and the reachable distance increases 26% compared to the benchmark. We also carry out a wavelength occupation plan to assign the increasing classical traffic demand. A guideline is provided to light the new wavelengths with the minimized SRS noise to quantum channels for updating the network.

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