IET Quantum Communication

Review Article

Quantum key distribution integration with optical dense wavelength division multiplexing: a review

eISSN 2632-8925
Received on 7th November 2019
Revised 21st December 2019
Accepted on 2nd March 2020
E-First on 27th April 2020
doi: 10.1049/iet-qtc.2019.0005
www.ietdl.org

Arash Bahrami[1] ✉, Andrew Lord[2], Timothy Spiller[1]
[1]Physics Department, University of York, York, UK
[2]British Telecom (BT), BT Research Centre, Martlesham Heath, Ipswich, Suffolk, UK
✉ *E-mail: bahramiarash@yahoo.co.uk*

Abstract: Quantum key distribution (QKD) can ensure information security between two remote parties. To commercialise QKD technology successfully, it should be integrated with dense wavelength division multiplexing optical transport. However, various challenges limit the QKD's performance in terms of the quantum key rate, quantum bit error rates, and maximum achievable distance. In this study, the authors discuss some of the major practical limiting factors for QKD performance such as spontaneous Raman scattering, four-wave mixing, and amplified spontaneous emission.

1 Introduction

Making use of the quantum properties of light, the field of quantum cryptography was first introduced by Charles Bennett and Gilles Brassard in 1984 under the name quantum key distribution (QKD) [1].

The QKD technology is based on the generation of the single photons in which one photon represents a symbol. The security is based on the laws of quantum mechanics and no-cloning theorem [2].

One major practical challenge for QKD commercialisation is its integration with dense wavelength division multiplexing (DWDM) optical transport. The difficulty arises in the co-propagation of the QKD channel with classical DWDM channels over the same fibre [3].

The ability of DWDM technology to incorporate multiple wavelengths has made it the core functioning mechanism of optical networks world-wide for many years [4], and it is still in widespread use in current optical networks [5–7]. A block diagram of the DWDM topology is presented in Fig. 1. As is shown, multiple wavelengths can be incorporated into the system, thereby increasing the data throughput of the fibre optic channel. In the conventional DWDM topology, up to 90 channels can be used across the C-band. In addition, erbium-doped fibre amplifiers (EDFAs) can be deployed across optical links to increase the transmission distance [8, 9]. Since DWDM offers multi-wavelength transmission over a single fibre for each direction (a fibre pair), it provides a clear and evolutionary option for incorporating QKD links into existing networks operating on a national scale.

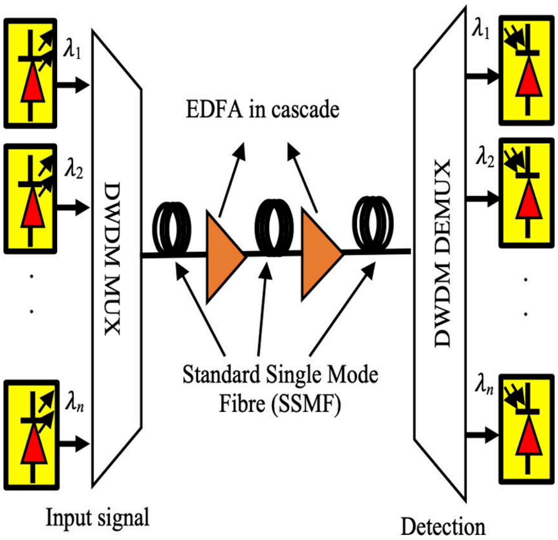

Fig. 1 *Wavelength division multiplexing (WDM)/DWDM block diagram. DWDM MUX: DWDM multiplexer; EDFA: erbium-doped fibre amplifier; DWDM DEMUX: DWDM demultiplexer*

The foci of this review paper are on core optical networks and practical challenges that limit QKD performance. The remainder of this paper has been organised as follows: Section 2 describes point-to-point QKD–DWDM links and Section 3 focuses on the challenges that limit the performance of QKD with DWDM. Next, Section 4 highlights research contributions made with regard to some of the challenges previously reported in the literature, focusing on spontaneous Raman scattering (SRS), four-wave mixing (FWM), and amplified spontaneous emission (ASE). Section 5 reports on the issues discussed in the literature in relation to a continuous variable (CV)–QKD/DWDM. Finally, Section 6 concludes the paper.

2 Basic point-to-point QKD–DWDM

The QKD link consists of the quantum channel and the authenticated discussion channel between Alice (transmitter) and Bob (receiver). The quantum channel sends quantum signals that are used to generate keys and the discussion channel is used to communicate securely in order to establish the keys [10]. Within the classical channel (discussion channel), Alice and Bob exchange information for clock synchronisation/recovery and data processing [11, 12]. The quantum discussion channel, however, is not assumed secure and can be monitored by an eavesdropper (Eve).

Multiplexing a QKD channel with classical data traffic over single-mode fibre (SMF) offers a practical solution to the question of QKD deployment using existing infrastructure. However, as amplification of quantum signals would introduce noise at an unavoidable, fundamental level [13], the integrated QKD then has to by-pass optical amplifiers. Therefore, a separate multiplexer is required (Fig. 2) [14].

One consideration when integrating the QKD channel with DWDM is whether or not to assign the QKD a wavelength at different frequency bands, such as O-band. Some papers report implementing the QKD channel in the C-band to achieve a maximum key rate [15]. To minimise the effect of the ASE, contributed by the EDFA, and the effect of SRS, the QKD channel can be placed in the O-band at 1310 nm to create a separation

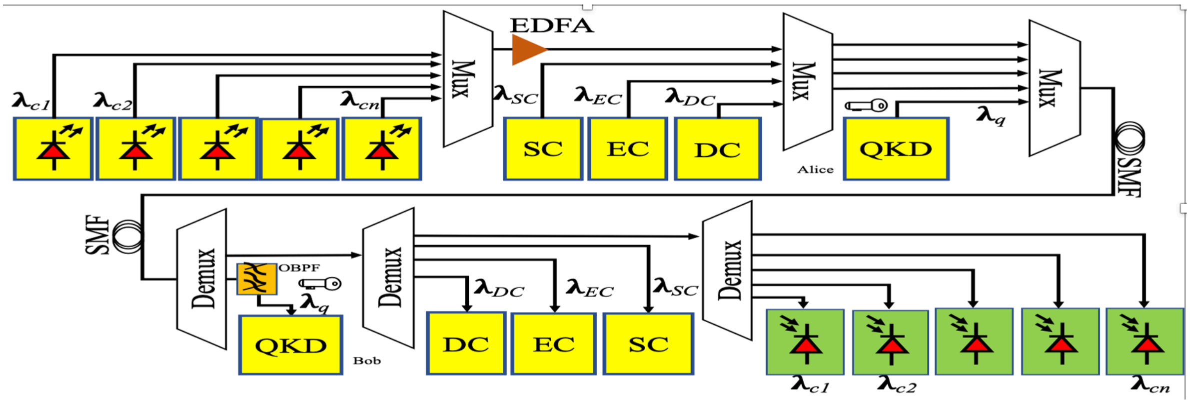

Fig. 2 *General block diagram of the QKD–DWDM; λ_C: classical channel; EDFA: erbium-doped fibre amplifier; λ_{SC}: service channel; λ_{DC}: quantum discussion channel; λ_{MC}: monitoring channel; λ_q: quantum channel; SMF, single-mode fibre; OBPF: optical bandpass filter*

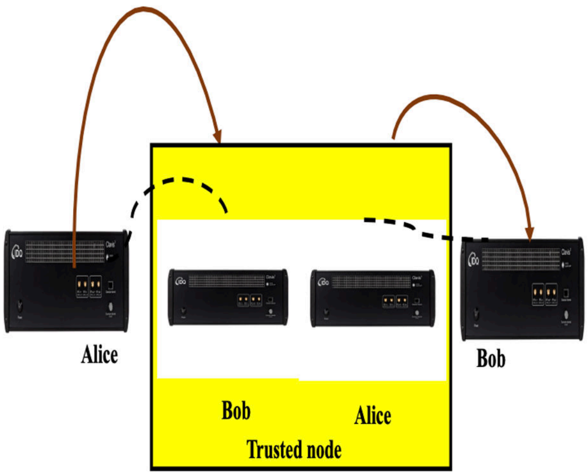

Fig. 3 *QKD link via trusted nodes*

>200 nm between the QKD channel and the C-band/classical channels [16].

Theoretical modelling of the QKD channel in the integrated QKD–DWDM channel has been reported in [17] in which the optimum locations of the QKD in C-band has been investigated in a particular scenario.

The industry investigates the possibility of placing QKD in the O-band and applying optical bandpass filter (OBPF) on the receiver side (Bob) to further reduce noise introduced into the quantum channel from ASE and SRS generated by classical data traffic at DWDM [18]. Although, the possibility of placing the QKD channel in the S-band or L-band in integrated QKD–DWDM is being taken into consideration, which requires further investigations [18].

Fig. 2 depicts a topology of the QKD–DWDM network in which DWDM and QKD channels are combined on the fibre using a multiplexer following the EDFA.

According to Fig. 2, classical channels ($\lambda_{c_1,\ldots,c_n}$) are sent to the multiplexer prior to the quantum channel. A separate multiplexer is used to add a supervisory channel (λ_{SC}) for the control and monitoring purposes of the classical channels, ethernet channel (λ_{EC}) and discussion channel (λ_{DC}). The final multiplexer is used to add the quantum channel, Alice (λ_q), to the SMF. At the receiver (Bob) end, the same number of de-multiplexers are utilised to drop those same channels added at the transmitter. For instance, in Fig. 2, QKD is the last wavelength multiplexed at the transmitter and is the first to be dropped at the receiver end.

The network of the integrated QKD–DWDM can be realised using trusted nodes. In this implementation, quantum keys are not directly exchanged between the communicating partners.

Trusted nodes are effectively repeaters which connect a two-party QKD system and relay a secret key step-by-step [19]. This architecture can be used to build a long-distance QKD network [20] and Fig. 3 illustrates the block diagram of a QKD network linked via trusted nodes. Based on the QKD trusted-node network (Fig. 3), a secure path between Alice and Bob is established through the trusted nodes. The trusted node combines (e.g. by using XOR function) these separate keys to form an end-to-end key between node [21–23].

3 Primary QKD–DWDM challenges

3.1 Amplified spontaneous emission (ASE)

In principle, even the ideal EDFA generates noise which limits the performance of the systems [24]. The source of the fundamental noise in EDFA, is known as ASE, and occurs due to the spontaneous emission. The optical bandwidth of the generated ASE noise is on the order of tens of nm and the average ASE photon number per Hz of bandwidth is given as follows [25]:

$$\langle N_{\rm ASE}\rangle = 2n_{\rm sp}(G-1), \tag{1}$$

In the above equation, the factor of 2 addresses the two perpendicular polarisation modes, G is the linear gain of the EDFA, and $n_{\rm sp} \geq 1$ is the spontaneous emission factor. If the only noise source is spontaneous emission in the system, then $n_{\rm sp} = 1$.

The noise generated by an EDFA is defined by its noise figure (NF), which is related to $n_{\rm sp}$ as follows [25]:

$$\text{NF (dB)} = 10\log\left(\frac{1 + 2n_{\rm sp}(G-1)}{G}\right). \tag{2}$$

In the high gain range of $G \gg 1$, $\text{NF(dB)} \simeq 10\log 2n_{\rm sp}$.

The quantum channel cannot be propagated through the EDFA, as each quantum state of light used subsequently to generate the key information will be irreversibly distorted by the action of amplification. The practical solution for this is to utilise an additional multiplexer to by-pass the EDFA [26]. Fig. 4 depicts the add–drop mechanism proposed for bypassing the ASE noise. Fig. 4, allows the EDFA to be applied in either form of the advance amplification or in-line amplification for the classical channel in integrated QKD–DWDM systems. The OBPF is placed after the EDFA is used to reduce the ASE noise, which can hinder the QKD performance significantly.

3.2 Spontaneous Raman scattering (SRS)

SRS occurs when a photon is scattered to generate/absorb a photon with leading/lagging frequency shifts, respectively [27]. Photons from the classical channels can propagate into the quantum channel due to the Raman scattering. The magnitude of power the generated Raman effect on the quantum channel is proportional to the power of all classical channels and the fibre span [28].

The magnitude of SRS is smaller at wavelengths less than that of the pump laser in the link (i.e. classical channels). Therefore, to reduce SRS it is suggested that the QKD channel propagates at a

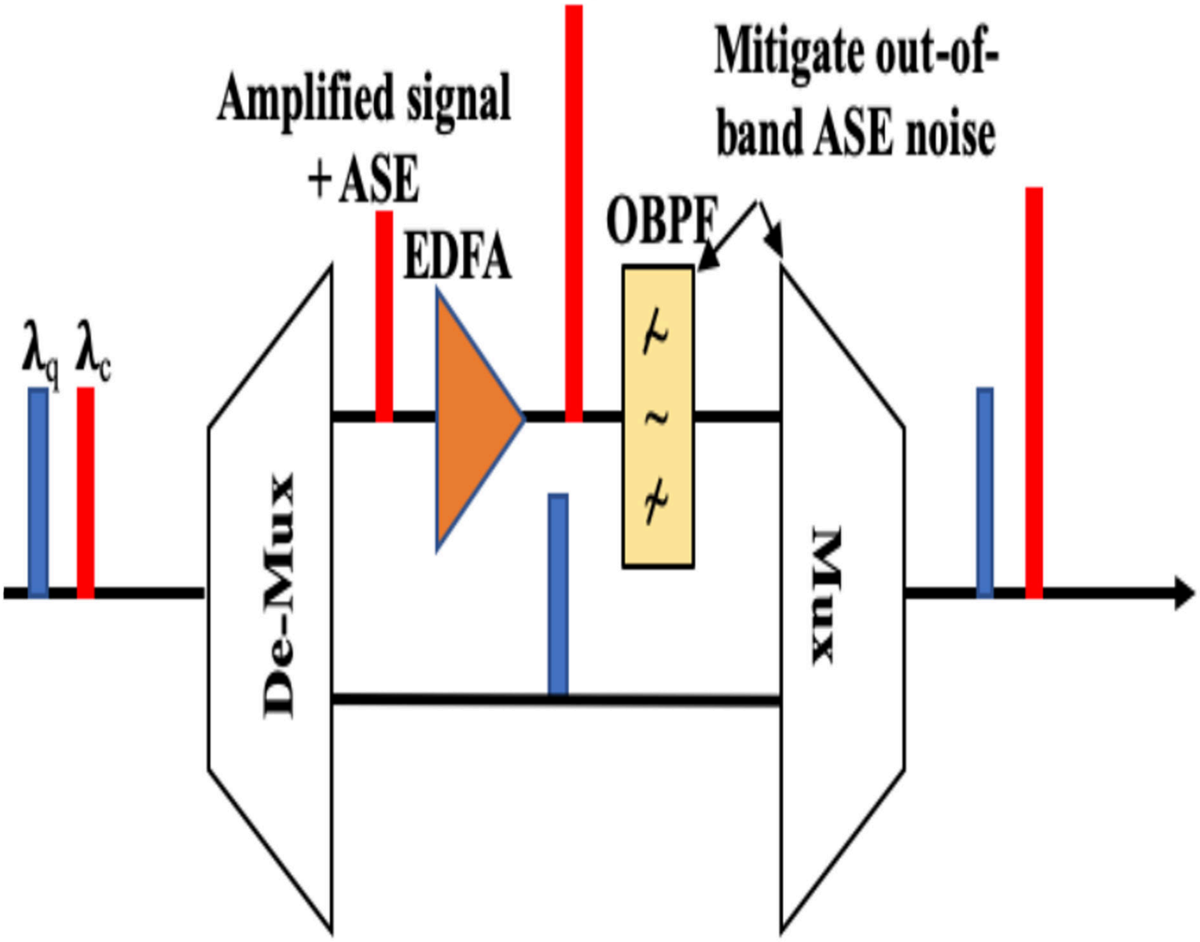

Fig. 4 *QKD-WDM adds/drops multiplexers to by-pass the EDFA to mitigate the ASE noise it generates. OBPF: optical band-pass filter; De-MUX: demultiplexer, MUX: multiplexer*

lower wavelength than those of the classical channels [29, 30]. Typically, SRS is measurable at optical launch power (OLP) around 22 mW (∼13.4 dBm) [31]. At OLPs of <22 mW, the Stokes and anti-Stokes which are the frequencies generated due to the interaction between the photons emitting from the laser source and the phonons (mechanical vibration in atoms of the fibre), become very challenging to measure, particularly at OLPs < 0 dBm. Hence, by maintaining classical DWDM channels OLP far less than ∼22 mW (∼13.4 dBm), the effect of the SRS on the quantum channel can be negligible. The SRS effects have been reported over different fibre spans ranging from 2.7 km [31] to 50 km [32].

3.3 Leakage from the classical channel

Moving the classical channels away from the QKD channel in QKD–DWDM systems does not completely prevent photon leakage into the quantum channel limited isolation provided by the de-multiplexer. The average photon leakage number per second is

$$\left\langle N_{\text{leak}}^{(C)} \right\rangle = \frac{\xi_2 P_{\text{out}}}{h\upsilon}, \tag{3}$$

where ξ_2 is the de-multiplexer isolation factor, P_{out} is the fibre output power related to the classical channels, h is Planck's constant, and v is the frequency of the classical signal.

As discussed in [33], to extract the QKD at 1310 nm optical filtering is required before Bob. Multiplexing/demultiplexing provide filtering between the QKD and conventional signal. Normally the filter isolation rate varying from 30 to 40 dB is required for the QKD–DWDM system to provide sufficient isolation between the quantum channel and classical channels. A double-stage thin-film 1.3/1.5 μm band multiplexer is to provide >67 dB before filtering at Alice, and demultiplexer to obtain >110 dB rejection of the signals while separating the quantum and Bob detector before Bob [33].

3.4 Four-wave mixing (FWM)

The FWM process occurs when two or more wavelengths exist in the link [30, 34, 35]. In the case of two lasers operating at frequencies v_1 and v_2 transmitting data through a single-mode fibre, the non-linear Kerr effect occurring in the fibre due to the change in the refractive index would result in FWM. As a consequence, undesired frequency harmonics at $(2v_2 - v_1)$ and $(2v_1 - v_2)$ will be generated [36]. As outlined in [34], FWM can be challenging to QKD in QKD–DWDM networks, and the use of a simple filtering technique will not eliminate the FWM effect on the QKD channel. It is known that the non-linearity of the Kerr effect can manifest itself in the form of self-phase modulation, cross-phase modulation (XPM), and FWM. Such a non-linear coefficient is considerably weak and is comprised between 2.1 and 3.2×10^{-20} m^2/W. However, it cannot be ignored, particularly in long-haul transmission and noise from EDFA and increase the FWM effect [37] provided that the QKD is not integrated with the DWDM. Depending on the channel allocations of the classical wavelengths in QKD–DWDM systems (50, 100 or 200 GHz channel spacing) and the periodic spacing of the classical channels, FWM can occur in the same grid that is allocated to a specific classical wavelength. Such a grid can be either on, below, or above the DWDM channel frequencies. Several investigations have highlighted the significance of channel allocations in QKD–DWDM networks in terms of further mitigating the FWM effect on the QKD channel [17, 38–40]. According to [41], the separation between the QKD channel and classical channels would mitigate the crosstalk effect, which occurs due to FWM.

Toliver *et al*. [42] outlined the selection of the QKD wavelength is critical in the FWM effect on the QKD channel. When the QKD is operating at 1550 nm, the presence of two neighbouring DWDM channels strongly influences the performance of the QKD channel. In such a scenario, the effect of the FWM cannot be easily suppressed because the generated harmonics can occur in the QKD frequency spectrum. Available thin-film filters are not sufficient to suppress the FWM effect on the QKD receiver. The proposed solutions [42] including the selection of QKD wavelength away from the classical channel wavelengths, minimising DWDM optical channel power, or unequal distribution of the classical channel in DWDM. The other method of compensating the FWM effect is the implementation of highly non-linear fibre to maximise the bandwidth of the proposed FWM compensator [43].

However, the FWM in the integrated QKD–DWDM is regarded to be negligible as it has been highlighted in [44].

However, the method seems to be more acceptable to mitigate the effect of FWM, is the careful selection of the wavelengths in DWDM bands to make sure avoiding the resultant FWM frequency harmonics fall within the proximity to the QKD channel. Such wavelength selection in DWDM wavelengths can become critical when the QKD operates at C-band closer to the classical wavelengths of the DWDM.

3.5 Cross-phase modulation (XPM)

The variation in the optical intensity of classical data leads to a variation in the refractive index of the fibre. When different wavelengths are transmitted through the fibre, each wavelength's optical phase can be influenced by other wavelengths. Such a phenomenon is referred to as XPM.

The challenge posed to the quantum channel in QKD–DWDM has been previously discussed in [45–47]. The effect of XPM exists without the presence of QKD and a recent investigation of the XPM effect proves that coherent communication is more vulnerable to the XPM effect than non-coherent communication [47, 48]. In this regard, XPM is one of the main impairments to coherent quadrature phase-shift keying (QPSK) in QPSK–on–off keying hybrid systems. Such findings [49, 50] are significant because two quadratures of a carrier also carry information in CV–QKD protocol, which is similar to the QPSK structure. As reported in [48], the maximum transmission span has achieved ∼38 km with a secure key rate $\sim 10^{-3}$ and although the existence of XPM has been acknowledged, no significant excess noise [48].

3.6 Key management in QKD–DWDM network

Generally, a QKD–DWDM system consists of a QKD layer that deals with the key management and is also known as the key management layer and the application layer that is used by the user end to encrypt their information with the classical encryptor [51]. As outlined in [51], the key management layer is located in the physical medium and the application layer. The application layer itself is using the produced quantum keys to secure communications.

Usually, a QKD network requires a distributed key management process. Such a process is often known as a client–server operation. The client–server topology reconcile and verify the keys reservation and their subsequent distribution for their business need and data encryption [52]. In addition, the key management layer in the QKD–DWDM network should be designed in such a way as to be able to support multi-point to multi-point communication. In such a scenario, the generated quantum keys should be distributed to individual users in the network [53]. Various topologies have been proposed for the key management layer in order to deliver quantum keys to these users more effectively and any key management layers must address the network connection failure and an alternative routing mechanism for key delivery [54, 55].

3.7 Key authentication in QKD–DWDM network

Key authentication, as part of key management in QKD networks, is important as it is a major procedure in the integration of the QKD into the DWDM network [56]. The standard is to use the Wegman–Carter authentication algorithm, which incorporates the hash functions [57]. The final step is to authenticate the message exchanged between Alice and Bob on the classical channel to avoid any eavesdropping attempt on the communication channel.

The process involves Alice utilised the bits in the key within the previous message to generate a verifying tag. After using the bits for generating a tag, the bit will be discarded. The generated tag by the sender will be sent with the transmitting message and the recipient uses his copy of the key to generate a new tag from the received message. If the two tags are identical then the message will be regarded as the authentic. In case the two tags are not matched, the message will not be authenticated [58]. However, as it has been outlined in [59], the process of generating authentication key based on the bits left from the previous key causes a problem for the very first authentication key as there is no previous key to use the left bits. In this regard, asymmetric key ciphers are used only for the initial step. In the case of the eavesdropping occurring in the system the key cannot be hacked by the Eve in the initial stage, then the system operation is secure. This is due to the fact, as Jain *et al*. [59] highlight, subsequent key verification would be implemented based on the incorporation of the part of the key obtained from the QKD protocol.

4 Review of QKD–DWDM progress

Investigations carried out on the performance of QKD–DWDM networks can be classified according to different criteria, including maximum key rate, maximum achievable distance, ASE noise from EDFA and FWM contributed by the classical channels. In addition, the QKD operating wavelength in a QKD–DWDM network is a fundamental issue that can alter the QKD performance significantly.

For simplicity, in this review, we have classified the QKD–DWDM topology as follows:

a. Discrete variable (DV) QKD–DWDM (QKD@C-band)
b. DV QKD–DWDM (QKD@O-band)
c. CV–QKD–DWDM (CV–QKD@C-band)

Within each category (a, b or c), research contributions associated with specific challenges have been highlighted accordingly. Table 1 summarises the results of our classifications of some of the recently published articles.

As shown in Table 1, considerable research has been implemented recently with a focus on a QKD–DWDM with the QKD operating in the C-band (wavelength ‘a’ in the table). Three articles were found to have addressed limiting factors, such as SRS, FWM or ASE mitigation [3, 47, 74] and only two papers discussed trusted nodes [71, 72]. Hence, the overall picture for the majority of the conducted research is incomplete and is focused on the main aspect of integrating QKD with the optical network.

The longest transmission distance was reported in [30] with an implemented QKD in the C-band (a), in line with the majority of published articles. Such results are expected as the attenuation of the fibre is less in the C-band compared to the O-band.

Very few investigations have adopted trusted nodes to extend the maximum achievable distance in a QKD–DWDM network even though trusted nodes are utilised for point-to-point communication and have been adopted by industry.

The longest fibre-based point-to-point QKD link has been implemented in China from Beijing to Shanghai achieving over 2000 km and comprised 32 trusted nodes [80]. However, no conventional telecom data have been transmitted with the QKD channel concurrently over the same fibre in Beijing to Shanghai QKD link.

A systematic investigation into the effects of SRS, FWM, and XPM on QKD can be found in [60]. To mitigate such effects, Eraerds *et al*. [60] proposed the deployment of the QKD in the O-band, while classical channels (e.g. DWDM or passive optical network (PON)) are operated in the C-band. In addition, an OBPF is recommended for the receiver side (Bob) to mitigate the SRS effect further, thus improving quantum bit error rates.

Table 1 Summary of contributions

Ref no.	QKD wavelength	Distance, km	Key rate	Data rate	Trusted nodes	SRS	ASE mitigation	FWM
[60]	b	10–14	varies	—	—	yes	yes	—
[61]	a	25–70	∼445 kb/s to ∼2.38 Mb/s	10 Gb/s	—	—	—	—
[30]	a	90	∼2.5 Mb/s	—	—	—	—	—
[62]	a	12–25–45	∼20–10–3 kb/s	—	—	yes	—	—
[63]	a	40–90	7.6 kb/s	10 Gb/s (@40 km)	—	yes	—	—
[64]	a	90	1.1 kb/s	—	—	—	—	—
[65]	a	—	—	—	—	yes	—	—
[66]	b	80	1.0–14.8 kb/s	6.3 Tb/s	—	yes	yes	—
[67]	b	∼10	1.3 kb/s	1.25 Gb/s	—	—	—	—
[33]	b	10–25–50–75–100	∼700–800 b/s	—	—	yes	—	yes
[68]	a	101	1.2–1.9 Mb/s	200 Gb/s	—	—	—	—
[61]	b	70	2.38 Mb/s	10 Gb/s	—	—	—	—
[69]	c	20–40–60–80	—	100 Gb/s	—	—	—	—
[70]	a	404	3 kb/s	—	—	—	—	—
[71]	a	45–12–13	81.7 kb/s	—	6	—	—	—
[72]	a	3.7–17.1–14.4	256 b/day	10 Gb/s	3	—	—	—
[73]	b	28	—	1.2 Gb/s	—	—	—	—
[47]	c	25–50–75	12–8–9 b/s	—	—	yes	yes	yes
[3]	c	10	27.2–28.9 kbit/s	18.3 Tb/s	—	yes	yes	yes
[74]	a	10	—	—	—	yes	yes	yes
[75]	a	40	10.9 ± 0.55 kb/s	—	—	—	—	—
[76]	a	∼4–12	696 kb/s to 1.3 Mb/s	10 Gb/s	—	yes	yes	—
[77]	a	10–20–30–40–50–60	∼0.2–1.5	—	—	—	—	—
[78]	a	10	—	—	—	—	—	—
[14]	b	2–5–13–14–21–25	—	—	—	yes	—	—
[79]	c	10,…, 80	—	—	—	—	—	—
[16]	b	16	—	—	—	yes	—	—

Six papers have suggested practical solutions for reducing the effect of the ASE noise generated by the EDFA on the QKD channel in QKD–DWDM. Some solutions mention high isolation of out-of-band noise which is the probability of classical photons being detected by the single-photon detectors at the QKD receiver site. Therefore, the combination of wavelength selection and sharp optical filtering are cost-effective methods to reduce the ASE effect on the QKD channel.

In almost all articles reviewed, the key rates for the QKD–DWDM networks are limited to Mb/s in the range at the highest, and it, therefore, seems that significant improvements in the design of the QKD transmitter and receiver, and single-photon detector are required. Two major challenges have been identified by Boaron *et al*. [81] as detector noise and the time required to collect all the generated keys. By detector noise, the authors refer to the gradual decrease of the signal power that inevitably results in the domination of the noise. On the other hand, in low detector noise, considering the limited key, incapacitate the system to use the key with a high degree of confidence.

Classical channels in a QKD–DWDM network have been shown to achieve a data rate on the order of Tb/s in the case of at least one article [3]. Importantly, the upper limit of classical data transmission in QKD–DWDM systems is not yet known and is still under investigation.

5 Continuous variable (CV)–QKD/DWDM

CV–QKD protocols modulate the information on the quadrature of the quantised electromagnetic field which is then recovered by coherent detection such as in the case of homodyne (or heterodyne) quadrature detection [82–85].

The co-propagation of CV–QKD in the DWDM has been reported in [47], demonstrating impressive resilience to the noise generated by the classical channels while the quantum channel was in the C-band (1530.12 nm) [74]. In [47], the system was able to achieve a key rate of 0.49 kbits/s over a 75 km transmission span. The literature reports that the higher resilience of CV–QKD is because photons representing symbols are prepared in an orthogonal mode which is separated from the local oscillator polarisation state and in such case modulated photons not matching with local oscillator are filtered at the receiver using the homodyne method [86, 87]. The homodyne measurement used in CV–QKD involves superposing the signal with a strong (coherent state) local oscillator (LO), with the phase of the latter dictating the quadrature of the quantum signal that is measured through the difference in photocurrents of the two detectors. This detection naturally excludes noise in the quantum signal that does not match the LO mode.

The significance of CV–QKD co-propagation in the DWDM is that, unlike DV–QKD which requires a finely tuned optical filter on Bob's side to maintain performance, CV–QKD does not require such a filtering mechanism.

6 Conclusion

Some of the major challenges of QKD–DWDM systems have been discussed in this review.

The overall conclusion to be drawn from the practical implementation of point-to-point QKD–DWDM systems is that the separation of the QKD channel from the classical channel (usually in the C-band) when combined with OBPF at the receiver end (Bob) provides a practical solution for the challenges associated with the current technology. Moreover, it seems that ASE noise from EDFAs in point-to-point QKD–DWDM systems is the dominant NF affecting the QKD channel, with SRS the second most relevant, so these are the challenges requiring most effort to address.

When the QKD channel is located at C-band, closer to the DWDM channels, the allocation of DWDM wavelengths is more critical since FWM generated by adjacent channels can inject noise and degrade the QKD channel.

Furthermore, the structure of the trusted nodes in point-to-point QKD–DWDM systems is critical in extending point-to-point QKD–DWDM to more involved and dynamic network configurations. Of course it is anticipated that future QKD implementations in fibre optic networks will incorporate quantum entanglement and quantum repeaters [88, 89] that could eventually eliminate the need for trusted nodes. However, these technologies are still in their development stages, so it would seem that the next practical developments will focus on continued improvement of trusted node approaches.

7 Acknowledgments

This work was supported by the UK Engineering and Physical Sciences Research Council (grant numbers EP/M013472/1, EP/N015207/1).

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