Integration of QKD Channels to Classical High-speed Optical Communication Networks

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***Abstract*—Integrating Quantum Key Distribution service with classical high-speed optical data transmission using a dense wavelength division multiplexing technique in a fiber is a cost-effective solution to improve the network's security. In this multichannel system, several noise sources degrade the quality of the quantum channel. The dominant degradation effect is determined by modeling in different cases. Optical filtering cannot decrease spontaneous Raman Scattering caused by the classical optical channels. So this nonlinear optical effect is investigated in detail with different system parameter setups. The optimal channel allocation and the required bandgap between the classical and quantum channels are determined.**

***Index Terms*—Optical fiber communication, Quantum communication, Quantum key distribution, Wavelength division multiplexing, Optical fiber networks, Optical fibers, Raman scattering**

I. Introduction

QUANTUM key distribution (QKD) enables more secure, quantum-safe information transmission and sharing using quantum mechanical effects. Suppose quantum communication is applied to share and generate a secret symmetric key between two parties. In that case, it is theoretically impossible for an eavesdropper to learn about the key. The technique ensures the safety of the transmitted data from all kinds of hacking and attacks, including quantum computers [1, 22]. Fiber-based QKD experiments are typically established via dedicated dark optical fibers for point-to-point applications [10, 19].

The quantum internet vision requires a full-day working, cost-effective solution, and the QKD services must be extended from point-to-point links to network configurations. Using dedicated optical fibers only to the quantum channel has a high cost and scalability problem. That means additional fibers are required for each service next to the existing infrastructure, which may need many cable sections to be swapped or built. QKD would be transmitted through the existing fiber network together with classical optical communication signals to avoid extra investments in the optical infrastructure [2] for more appropriate operation. Network integration of QKD is essential for QKD's future deployment when the quantum key distribution link successfully generates secret keys over standard single-mode fiber with co-propagating classical high-speed optical channels. Otherwise, QKD will never be a reliable and effective widespread solution outside research laboratories.

QKD integration into the existing optical fiber network infrastructure using Wavelength Division Multiplexing (WDM) is possible [3]. The main challenge of this approach is the different optical power of the different wavelength channels, as both QKD and classical communication channels are coupled to the same fiber. QKD protocols typically require a launch power of less than 1 nW. In contrast, classical signals are launched with a 1-10 mW power per channel. A small fraction of the classical signal falling to the QKD receiver is enough to decrease the quality of the quantum communication, increasing the Quantum Bit Error Rate (QBER) to a value where key extraction is impossible. In addition, the quantum communication signal cannot pass through an optical amplifier due to the no-cloning theorem. Such integration requires careful network planning [4].

Several papers related to this topic can be found in the literature, but each focuses only on its own QKD solution, primarily examining the interaction between QKD and classical channels using experimental methods. This limits the system complexity and the number of classical channels in the published studies. Therefore, the type of QKD technology most suitable for working with classical systems and which network architecture and technology can integrate the QKD channel into the network are still questions.

The typical secure communication scenarios require different expected reach lengths and serve different groups of customers. A short reach is usually between 1 and 10 km; it is mainly needed for the financial sector, typically in the access domain [8]. The 10-50 km medium reach supports the aggregation domain for public services and municipalities. Links over 50 km are called long reach, necessary for large, multinational, and industrial corporations. Different architecture solutions and different WDM techniques are required for different scenarios.

So, the feasibility of transmitting QKD with classical communication channels through the same optical fiber by employing WDM technologies at telecom wavelengths and a wide variety of scenarios is essential.

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This paper overviews the applicable WDM technologies in the different optical network segments and the possible QKD integration solutions. Next, the paper presents the degradation effects of crosstalk from high-speed classical channels. The presented mathematical model was used to calculate the crosstalk originating from optical nonlinearities, leakages, and optical noises. Finally, nonlinear Raman scattering is modeled in detail, as optical filtering cannot decrease this effect.

II. WAVELENGTH ALLOCATION

The QKD protocols need a quantum channel and two directional signaling classical channels to perform error correction and privacy amplification on the QKD channel. So, traditionally, three optical fibers are required between Alice (QKD transmitter) and Bob (QKD receiver). As a first step, the signaling and synchronization channels can be multiplexed with the classical data communication channels. Sometimes, there are some limitations for the route and the distance of the service channel related to the quantum channel. So, applying the same fiber, or at least the same optical cable, is suggested.

Exploring the most efficient channel wavelength allocation for establishing an effective and reliable communication channel for QKD and encrypted data transmission in optical communication networks is essential. I suggest the following QKD integration solutions.

A. Separated QKD and classical DWDM networks

In this approach, wavelength multiplexed quantum channels are directed to a separate fiber, and the high-speed DWDM classical channels are transmitted via other fibers in the same optical cable. The solution is easy and performs well, as there is no shared transmission media for classical and quantum channels. It will be helpful if the QKD technology is widespread and many QKD channels are required in the network.

Uncoupled multicore fibers (MCFs) are also suitable for integrating the quantum channel into the classical communication network. The QKD performance may improve as the inter-core crosstalk is lower [11]. However, multicore fibers are not widely used in current telecommunication systems.

This QKD integration solution now requires additional fibers for quantum channels next to the existing infrastructure.

B. Coarse Wavelength Division Multiplexing (CWDM)

The classical and quantum channels coexist based on a two-directional Coarse Wavelength Division Multiplexing standard with a 20 nm channel grid (Fig. 1). The topology may include more optical filters to decrease the crosstalk and defend the quantum channel. The advantage is the lower crosstalk from the classical channels, but CWDM is less and less used in current and especially future optical communication networks.

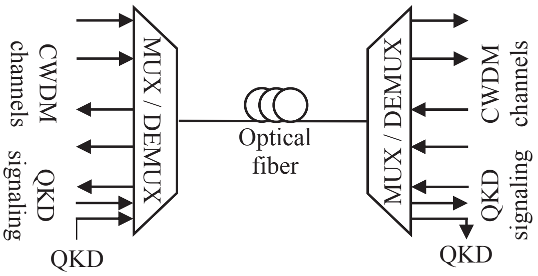

Fig. 1. CWDM Scenario, duplex communication

Nowadays, this solution may be applied in a metropolitan network, but the spread of this multicarrier standard is decreasing as the lack of an optical amplifier limits it.

C. Dense Wavelength Division Multiplexing (DWDM)

The classical and quantum channels coexist based on the Dense Wavelength Division Multiplexing standard with 0.4 or 0.8 nm channel grid (Fig. 2). The DWDM technique is applied in the core and mainly in metropolitan networks, which uses the C-band between 1530 and 1565 nm wavelength. If the QKD channel is placed in the C-band, the QKD link has low attenuation to achieve a maximum key rate and link length. However, the quantum channel is then spectrally close to the classical channels and strongly affected by stimulated Raman scattering (SRS) and four-wave mixing (FWM) in a network. A guard band between classical and quantum channels may be applied to decrease the degradation effect of FWM.

It is essential to determine the optimal position of the quantum channel in the DWDM channel allocation (lower wavelength, upper wavelength, or middle wavelength) and the required bandwidth of the guardband between the quantum and classical channels. We expected in advance that all the classical channels should be placed at wavelengths longer than the quantum channel since the Spontaneous anti-Stokes Raman scattering (SASRS) is typically weaker than the Spontaneous Stokes Raman scattering (SSRS, SRS in the following).

Additionally, amplifying quantum signals is impossible, as the quantum state can not be cloned based on the non-cloning theorem. The integrated QKD has to bypass optical amplifiers, requiring a separate multiplexer. The optical noise originating from the amplified spontaneous emission (ASE) of an erbium-doped optical amplifier (EDFA) still affects the quantum channel as it has components at the wavelength of the quantum channel. An optical notch filter can be applied to decrease the ASE noise in the QKD channel.

An optical isolator saves Alice's transmitter from the strong reflected or the backward signals. It guarantees the stable operation of the QKD transmitter.

Before Bob's receiver, an optical bandpass filter in the QKD channel is necessary for out-of-band noise reduction.

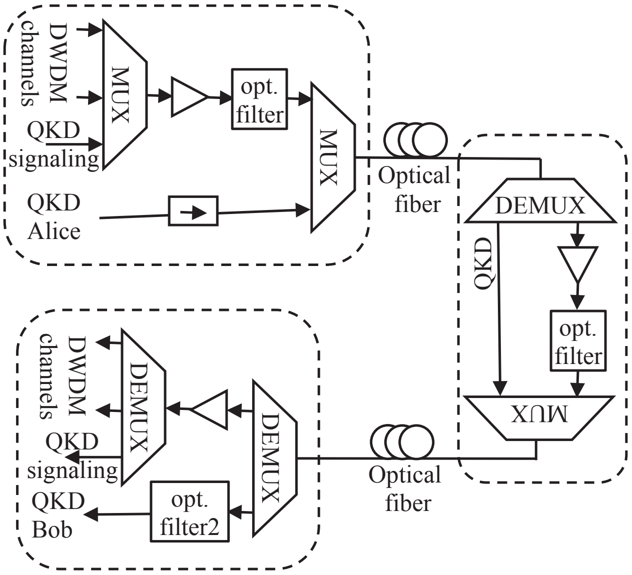

Fig. 2. One direction DWDM Scenario, simplex communication on a fiber. Duplex communication requires two fibers.
MUX: DWDM multiplexer, DEMUX: DWDM demultiplexer, opt. filter: optical notch filter for filtering out the ASE noise from the quantum DWDM channel, opt. filter2: bandpass filer for quantum channel

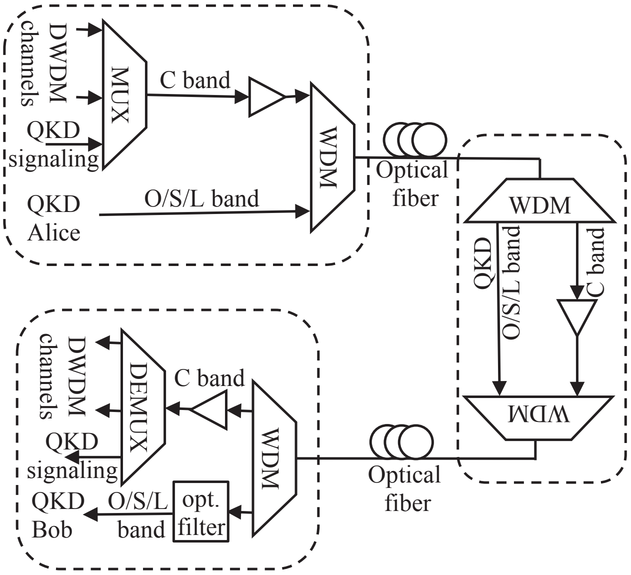

Fig. 3. Hybrid system, O/L/S-band QKD Scenario.
MUX: DWDM multiplexer, DEMUX: DWDM demultiplexer, opt. filter: bandpass filer for quantum channel, WDM: WDM coupler for separate and add the two optical bands

D. *Hybrid system*

In this solution, the quantum channel wavelength is placed in the O-band at 1310 nm (between 1260 and 1360 nm), and DWDM classical channels are set in the C-band (Fig. 3). In this approach, the separation is more significant than 200 nm between the QKD and C-band classical channels. By applying an optical bandpass filter on the receiver side, the effect of the crosstalk can be reduced.

The integrated QKD channel can also be placed in the S-band or L-band when the separation is smaller, but the same advantages can be realized.

The main disadvantage of this approach is that the QKD optical link loss is higher, which limits the quality of the quantum channel. However, in the current practical metropolitan optical networks, the excess loss due to fiber connections, patches, routing devices, or other passive components dominates the total loss of a link. In such an environment, the quantum channel in the O-band may be helpful since the optical loss approaches that of the C-band channels, but the noise is reduced.

E. *QKD in Optical Access Networks*

The optical access network is a special segment of communication networks. The access networks are short-span, point-to-multipoint, passive optical networks with a time or wavelength division multiplexing approach connecting to the end user [7]. A particular segment of optical networks consists of the optical links and systems used in mobile networks, where security is a critical issue [9]. Security and privacy are a challenge for time division multiplexing passive optical networks (TDM-PONs), where the same wavelength channel in a shared fiber link is used for broadcasting the downstream signal to all users [12].

Although time division multiplexing is used for resource sharing between classic users, integrating the QKD channel in time multiplexing is not practical and challenging. Typically, wavelength multiplexing can be used here as well. We have to apply a different wavelength allocation strategy than other network segments. The typical architecture of the access network is tree topology. A passive network requires power dividers, and the high insertion loss of the dividers dominates the optical loss over the attenuation of the optical fiber.

Different optical access standards use different wavelengths, minimum and maximum transmitter powers, and data rates to transmit upstream and downstream signals. The optical powers launched into the fiber and its center wavelength strongly influence the background noise level in the QKD channel. We assume the typical PON reaches a maximum of 20 km, of which 15 km is dedicated to the feeder fiber. QKD channels should be ideally placed spectrally far away from classical signals to avoid strong interactions and degradation. Therefore, wavelength ranges below 1310 nm are suitable.

F. *Review of the published demonstrations*

Table 1 summarizes the recent research published for different QKD protocols implemented in telecommunication networks. The main concept of each scenario is the same as the principles I presented in the previous subsections. But the quality-improving additional elements that I propose are not included, and usually only a connection between two points is examined, without the intermediate node. Nevertheless, it is clear that the number of channels and the link length are limited, and it is difficult to find a comprehensive simulation and experimental study in the literature.

TABLE I
REFERENCE WORKS

ref. number	QKD	Scenario	distance	channels	e/s
[12]	BB84	DWDM	80km	40	s
[13]	CV	DWDM	50km	5	s
[14]	CV	hybrid	60km	5-40	s
[15]	CV	DWDM	10km	100	e
[16]	BB84	hybrid	50km	32	e
[17]	BB84	DWDM	50km	1-4	e
[18]	BB84	hybrid	70km	9	e

channels.: number of classical channels
e/s: experiments/simulations

III. NOISE CONTRIBUTIONS

Crosstalk between channels in multichannel optical networks and optical nonlinear phenomena occurring in optical waveguides are not new or unknown. They also happen in purely classical optical networks, and we know their description [3]. However, the specialties of the quantum channel have repeatedly drawn attention to their quality degradation effects and require a specific examination of the phenomena.

The impact of classical channels on the quantum channel has been investigated. Two main sources can contribute to the noise photons in the quantum channel. The leakage of photons from classical channels is due to the imperfect isolation of WDM multiplexers and demultiplexers. The in-band noise photons are generated in optical fibers from nonlinear processes, such as four-wave mixing (FWM) and spontaneous Raman scattering (SRS). In the DWDM system, the in-band ASE photons generated by optical amplifiers are also considered. These optical noises heavily determine the quality of the QKD channel.

Suitable, cascaded optical filters can easily increase channel isolation, but the applied optical filters also increase the insertion loss.

However, nonlinear processes can create photons at the same wavelength as the quantum signal, which cannot be spectrally filtered. Depending on the wavelength of the classical and quantum channels, Raman scattering and four-wave mixing are the dominant nonlinear processes. FWM is a narrow-band effect that can be minimized by carefully choosing the quantum channel's wavelength. However, the fixed channel grid of the DWDM standard limits this opportunity. Raman noise has a broad spectrum; classical channels in the C-band create a Raman noise spectrum covering the whole band. Temporal filtering may help to reduce the impact of noise photons at the quantum channel's band. The quality of Raman noise rejection depends on the time-bandwidth product of the quantum signal and on how tight the time and spectral filtering can be implemented.

A. *Leakage from the classical channels*

Multiplexing and demultiplexing (MUX and DEMUX) provide filtering between the QKD and conventional signal [18]. However, photons from the classical signals will be at the quantum channel because of the finite isolation of the applied MUX/DEMUX. Two types can be distinguished. The leakage noise component can be in the quantum channel's wavelength band, called in-band noise. This happens because the signal arriving on the classical channel also has components in the QKD band, which cannot be separated with a filter after multiplexing since they fall within the wavelength range of the quantum channel.

The origin of the out-of-band leakage noise is the component at the classical channel wavelength range, attenuated by the non-infinitive isolation of the demultiplexer. That is, the attenuated signal level of the classical channel is still comparable to the unattenuated signal of the quantum channel, which is detected by a sensitive QKD receiver in the entire wavelength range. The out-of-band leakage noise component can be further reduced using spectral filters at the receiver's side.

Typically, the value of the in-band leakage noise is lower than that of the out-of-band leakage noise; because the original value of the in-band leakage noise is lower, and the multiplexer filters it out.

The typical adjacent channel isolation of a CWDM DEMUX or MUX is higher than 30dB, the non-adjacent channel isolation is higher than 45 dB, and the insertion loss is less than 3 dB. For DWDM DEMUX and MUX, these parameters are typically a bit worse, but they can also reach these values using modern technology. The average leakage photon number can be calculated from the leakage power, which is determined by the classical channel power and the isolation.

$$\langle \mathrm{N}_{\mathrm{leakage}} \rangle = \frac{\mathrm{P}_{\mathrm{leakage}} \cdot \Delta t}{\mathrm{h} \cdot \nu} = \frac{\mathrm{P}_{fiber\_out} \cdot \mathrm{a}_{\mathrm{DEMUX\_ISO}} \cdot \Delta t}{\mathrm{h} \cdot \nu} \quad (1)$$

where h is the Planck constant, v is the frequency of the classical optical channel, a_{DEMUX_ISO} is the demultiplexer isolation, Δt is the time window, P_{fiber_out} is the classical channel power at the output of the fiber.

B. *Amplified Spontaneous Emission (ASE)*

The ASE is generated from a typical optical amplifier (EDFA or SOA). It can be considered a broadband noise source with a flat spectral power density within the spectral bandwidth of the quantum channel, as it has a broad bandwidth of tens of nm.

The ASE noise of the optical amplifier is characterized by the noise figure (NF)

$$NF = \frac{1 + 2 \cdot n_{sp}(G-1)}{G} \quad (2)$$

where n_{sp} is the spontaneous emission factor ($n_{sp} \geq 1$), G is the gain of the optical amplifier, and the two orthogonal polarization modes are described by factor 2. In the high gain range, the noise figure can be calculated directly, $NF \approx 2 \cdot n_{sp}^2$.

ASE has a broad bandwidth and components in the quantum channel. So, it will contribute to in-band noise after the demultiplexer, but the isolation of the demultiplexer attenuates it. The in-band ASE photon number per spatiotemporal mode originating from the transmitter side optical amplifier, at the input of the quantum receiver, is given by

$$\langle N_{ASE} \rangle = 2 \cdot n_{sp} \cdot (G-1) \cdot a_{MUX\_ISO} \cdot a_{fiber} \cdot a_{DEMUX} \quad (3)$$

where a_{MUX_ISO} is the multiplexer isolation, a_{fiber} is the attenuation of the optical fiber between the optical amplifier and the QKD detector, a_{DEMUX} is the attenuation of the demultiplexer.

In practical cases, the value of n_{sp} is often unknown, but optical noise power can be measured. The mean number of the noise photon for a narrow optical band can be calculated from the measured optical noise power (P_{opt}):

$$\langle \mathrm{N} \rangle = \frac{P_{opt} \cdot \Delta t}{\frac{h \cdot \nu}{\lambda}} \tag{4}$$

and

$$\langle N_{ASE} \rangle = \frac{P_{ASE} \cdot \lambda \cdot \Delta t}{h \cdot \nu} \cdot a_{Notch} \cdot a_{MUX\_ISO} \cdot a_{fiber} \cdot a_{DEMUX} \tag{5}$$

where a_{Notch} is the attenuation of the optical notch filter, P_{ASE} is the ASE optical noise power.

The laser diode has similar broadband optical noise, which can be modeled with the same approach. However, the noise level is lower in the in-band leakage noise analysis.

C. *Optical nonlinearities*

As the strong classical signals propagate along the optical fiber, various nonlinear optical processes will generate noise photons at different wavelengths. If the wavelength of the noise photons falls into the wavelength band of the quantum channel, it is in-band noise that can not be filtered at the side of the receiver.

1) *Spontaneous Stokes Raman scattering (SRS)*

The level of the SRS effect depends on the propagation direction of the classical and quantum channels. If the signal counter-propagates to the quantum signal, the Raman noise level is higher than the co-propagating channels because of the isotropic nature of Raman scattering and the higher power at the receiver.

The SRS noise power within $\Delta\lambda$ optical bandwidth at the output of the optical fiber is given by

$$P_{SRS} = P_{fiber_{out}} \cdot \beta_{SRS} \cdot z \cdot \Delta\lambda = P_{fiber\_in} \cdot \beta_{SRS} \cdot z \cdot \Delta\lambda \cdot a_{fiber} \tag{6}$$

where β_{SRS} is the spontaneous Raman scattering coefficient depending on the optical wavelengths, P_{fiber_in} is the classical channel power at the input of the fiber, P_{fiber_out} is the classical channel power at the output of the fiber, z is the fiber length, and a_{fiber} is the loss of the optical link.

The average SRS photon number can be calculated from the SRS noise power within a bandwidth of $\Delta\lambda$. However, the mode number corresponding to the $\Delta\lambda$ optical bandwidth and a time window (Δt) must be considered [3].

$$N_{mode} = |\Delta\nu \cdot \Delta t| = \frac{c}{\lambda^2} \Delta\lambda \cdot \Delta t \tag{7}$$

where c is the speed of light in a vacuum.

The average SRS photon number at the output of the optical fiber can be calculated.

$$\langle N_{SRS\_fiber\_out} \rangle = \frac{P_{SRS} \cdot \Delta t}{h \cdot \nu \cdot N_{mode}} \tag{8}$$

The SRS signal goes via the DEMUX; the insertion loss of the DEMUX attenuates the average SRS photon number at the input of the optical receiver.

$$\langle N_{SRS} \rangle = \frac{P_{SRS} \cdot \Delta t}{h \cdot \nu \cdot N_{mode}} \cdot a_{DEMUX} \tag{9}$$

So, the average SRS photon number at the output of the optical fiber is given by

$$\langle N_{SRS} \rangle = \frac{\lambda^3}{h \cdot c^2} \cdot P_{fiber_{out}} \cdot \beta_{SRS}(\lambda) \cdot z \cdot a_{DEMUX} \tag{10}$$

2) *Four Wave Mixing (FWM)*

FWM is a third-order nonlinear optical process, which can be observed during two or more optical signal propagation through an optical fiber and originates from the Kerr effect.

Three optical channels at frequencies f_x, f_y, f_z mix through the fiber's third-order susceptibility, generating a new optical carrier at $f_{xyz}=f_x+f_y-f_z$ frequency.

The effect requires phase matching. So, the level is high at sort fiber length or zero-dispersion optical fiber. However, it is weaker in long-distance standard single-mode fiber due to the chromatic dispersion. The effect can be decreased by applying a guard band between the classical and quantum channels. Also, FWM can be minimized by channel wavelength optimization in a flex grid system. Polarization multiplexing also suppresses this effect. Based on it, 2-2 channel guardbands were applied, and FWM was neglected in this investigation.

3) *Cross-Phase Modulation (XPM)*

Cross-phase modulation also originates from the Kerr effect in optical fibers, where intensity modulation of one optical carrier can modulate the phases of other transmitting optical carriers in the same fiber. Phase noise is not a direct source of performance degradation in intensity modulation and direct detection systems. However, together with the dispersion, it already has a negative effect. In addition, the quality-deteriorating effect is also direct in a coherent optical system.

When integrating a quantum channel, its effect strongly depends on the applied QKD technology. It is more significant for Phase-modulated quantum information, especially in the case of CV-QKD [5]. In this case, the QKD structure is similar to classical coherent detection; but the noise level must be kept sufficiently low so that the effect of quantum phenomena can be observed. Therefore, its effect must be examined independently of the other noise components.

IV. SIMULATION RESULTS

Optical scattering and crosstalk between classical and quantum channels are critical in the one-direction DWDM scenario (Chapter II.C). I investigated the noise and crosstalk from the classical channels in this topology because it is the more challenging scenario. During the detailed noise analysis, a simplified system structure is used, where we implement classical and quantum communication between two points, and the classical channels are amplified (Fig. 4).

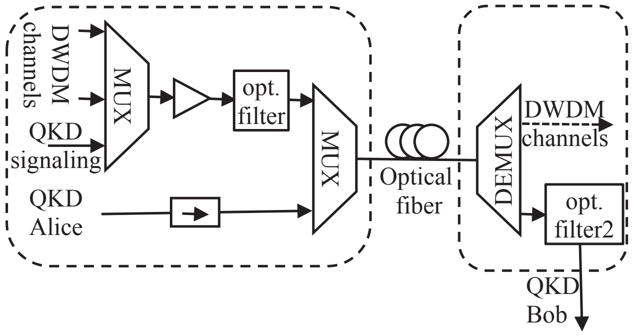

Fig. 4. One direction DWDM simulation setup. Simplex communication is used on a fiber, Duplex communication requires two fibers.
MUX: DWDM multiplexer, DEMUX: DWDM demultiplexer, opt. filter: optical notch filter for filtering out the ASE noise from the quantum DWDM channel, opt. filter2: bandpass filer for quantum channel

This topology includes every important effect, and the main conclusions can be drawn from it. The level of crosstalk from the classical to the quantum channel, practically the number of noise photons, is determined. The out-of-band classical signal leakage noise, the nonlinear Raman scattering, the ASE noise of the optical amplifier, and the laser noise were taken into account; I presented all of them in detail in the previous chapter. Filtering the QKD channel from DWDM channels is performed by both the multiplexer and the demultiplexer [18]. So, the in-band leakage noise was neglected, as the multiplexer filters it out, and the value is lower than the out-of-band leakage noise.

Table II summarizes the applied simulation parameters.

TABLE II
SIMULATION PARAMETERS

Symbol	Parameter name	Value
P	Classical transmitter output optical power	0dBm
RIN	Laser relative intensity noise	-160dBc/Hz
a_{MUX}	Multiplexer insertion loss	3dB
$a_{MUX\ ISO}$	Multiplexer isolation	40dB
a_{filter}	Notch optical filter insertion loss	1dB
NF	Optical amplifier noise figure	5dB
α_{fiber}	Fiber attenuation	0.2dB/km
β_{SRS}	Nonlinear Raman scattering coefficient	$2\cdot10^{-9}$/km/nm
a_{DEMUX}	Demultiplexer insertion loss	3dB
a_{DEMUX_ISO}	Demultiplexer isolation + optical bandpass filter	85dB
a_{filter}	Optical bandpass filter insertion loss	1dB
$\Delta\lambda$	Channel bandwidth	0.4nm
Δt	Gating time window	1ns

Fig. 5 presents the noise photons in the quantum channel. Similar to practical optical systems, in this first simulation, the optical gain is adaptive, compensating for the attenuation of the channel, and therefore, has a variable value depending on the length of the connection. The dominant noise type depends on the system parameters and varies over the communication link.

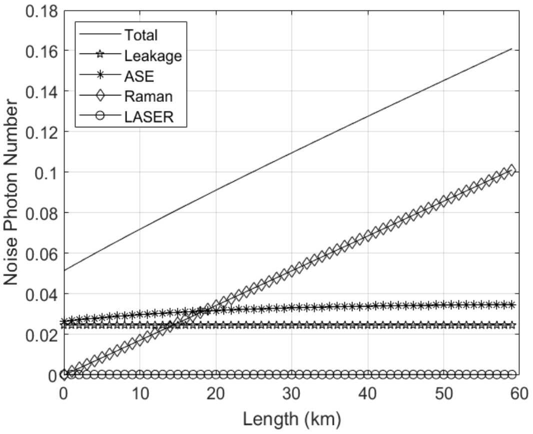

Fig. 5. Noise contributions versus optical fiber. Adaptive optical amplification, it compensates the optical channel loss.

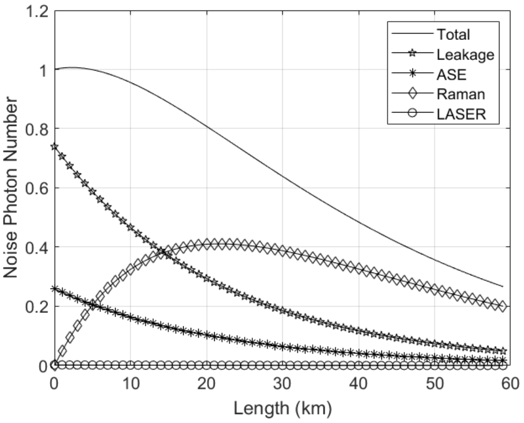

Fig. 6. Noise contributions versus optical fiber. Constant optical amplification.

The situation changes somewhat if the optical gain is not adaptive, but has a constant value regardless of the connection length (Fig. 6). The level of different types of noise changes differently along the connection length. Therefore, the dominant noise type in the total noise level may differ from section to section. But typically, the Raman scattering exceeds the value of the other noise components for longer lengths.

Correctly setting the parameters makes it possible to make one type of noise dominant in the total noise value. The broad-spectrum noise level of the optical amplifier and laser source can be reduced with better isolation of the multiplexer and better suppression of the optical notch filter (Fig. 7). The isolation of the multiplexer and the characteristic of the proposed optical notch filter have similar effects. The isolation of the multiplexer decreases the in-band leakage from the classical channels, including also the ASE noise photons at the input of the second multiplexer. The suggested optical notch filter decreases the ASE noise in the QKD band, but it simultaneously decreases all the in-band noises at the optical amplifier output. Fig. 7. represents the consequences of these elements, which mainly decrease the ASE noise in the QKD channel as in-band leakage noise is much less than ASE noise.

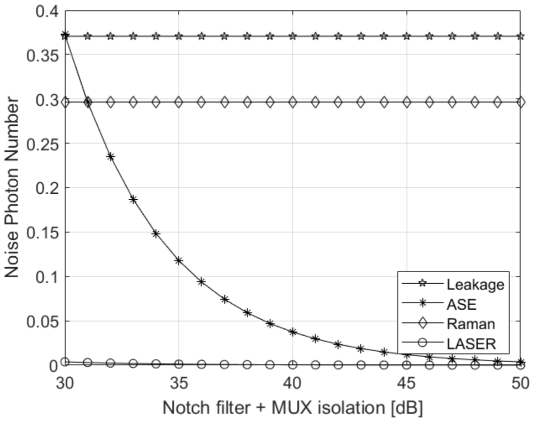

Fig. 7. Noise contributions versus the isolation of the multiplexer and suppression of the optical notch filter. Fiber length is 40km.

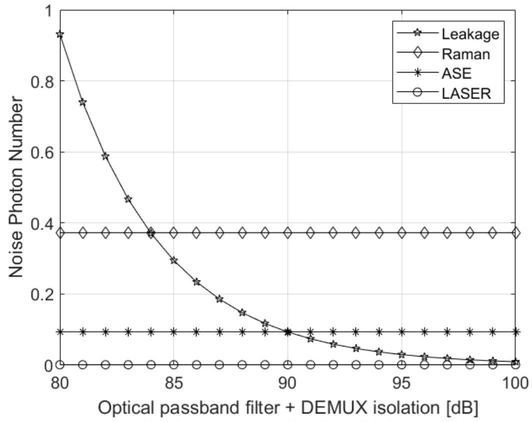

Fig. 8. Noise contributions versus the demultiplexer isolation and the suppression of the optical bandpass filter. Fiber length is 20km.

The figure emphasizes the importance of the proposed notch filter. A MUX's typical adjacent channel isolation is higher than 30 dB. This is why the graph starts from 30dB (MUX isolation) and presents the additional effect of the proposed notch filter.

By improving the demultiplexer isolation and the suppression of the optical bandpass filter, out-band leakage noise (typically leakage) can be reduced (Fig. 8). The demultiplexer and the proposed bandpass optical filter for the QKD band have similar effects. They decrease the out-of-band classical channels. 30dB typically MUX's adjacent channel isolation is insufficient; the bandpass filter can never be omitted. Therefore, the figure concentrates on the essential operating range above 80 dB.

However, optical filtering cannot remove the noise components due to nonlinear phenomena, even using an ideal filter. Therefore, the nonlinear Raman scattering effect is investigated in detail.

Actually, the Raman scattering coefficient is not constant depending on the wavelengths of the applied quantum and classical channels. For more accurate calculations, the wavelength of the channels must be known and the exact coefficient determined. Based on the measurement results found in the literature, this coefficient is a non-symmetrical V-shaped function versus the wavelength [21]. In addition, the coefficient is different in the case of Stokes and anti-Stokes, as in the case of co- and counter propagation. If there are several classical channels in the DWDM system, then the effect of their Raman scattering is added. It is worth using at least 2 guard bands in addition to the quantum channel to reduce the impact of four-wave mixing.

Fig. 9 represents the Raman scattering-originated noise photon number versus the position of the quantum channel. One quantum channel and 93 classical channels were considered in the C Telecommunication band, with 2-2 channel wide guardbands before and after the quantum channel. The ITU DWDM standard determines the IDs of the DWDM channels in this paper. Namely, ID 1 means optical carrier with a wavelength of 1567.13nm, ID 96 means 1529.16nm, and the channel spacing is 0.4nm. The optimal quantum channel position is the DWDM channel with ID 61-62. The Raman noise photon number can be halved by carefully choosing the wavelengths. It can improve the connection length or the quantum key rate.

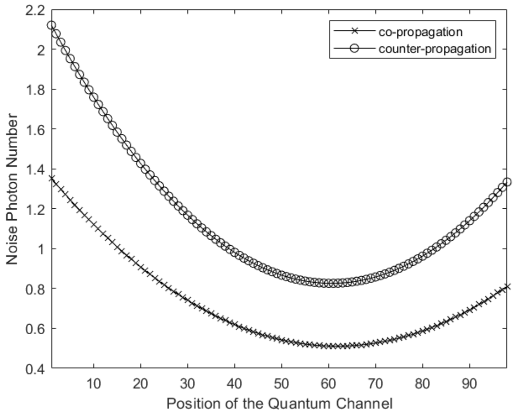

Fig. 9. Noise Photon Number originating from the Nonlinear Raman Scattering versus the DWDM ID of the quantum channel. One quantum channel with 2-2 guardbands, in case of co- and counter propagation, 40km fiber length

V. CONCLUSION

This paper deals with the sensitive QKD channel integration to classical high-speed optical communication networks for improving network security.

The first part of the paper overviews the typical technologies in the different optical network segments. It also suggests effective QKD integration solutions, which differ from segment to segment. The main ideas of the system structures are presented using the same optical fiber for QKD and classical channels. The paper recommends additional elements to maintain the quality of the QKD channel, such as optical bandpass filter, optical notch filter, and optical isolator.

The second part of the paper presents the optical noise calculations and simulations. In the proposed multichannel system, several noise sources degrade the quality of the quantum channel. The dominant degradation effect was determined by modeling in adaptive and fixed optical amplification depending on the system parameters. The results show that the broadband optical noise of the laser source has a negligible effect compared to other noise sources. The broad-spectrum noise level of the optical amplifier and laser source can be reduced with better isolation of the multiplexer and better suppression of the optical notch filter. Improving the demultiplexer isolation and suppressing the optical bandpass filter can reduce out-band leakage noise (typically leakage). Optical filtering cannot decrease spontaneous Raman Scattering caused by the classical optical channels. So this nonlinear optical effect was investigated in detail with different system parameter setups. The optimal channel allocation and the required bandgap between the classical and quantum channels were determined.

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