Quantum Key Distribution Over Optical Access Networks

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***Abstract*—It is well known that optical access networks are able to provide high data rates over long distances and to a reasonable number of users. Security and privacy are always a challenge for public accessible network infrastructures. Especially in time-division multiplexing passive optical networks (TDM-PONs), in which the downstream signal is broadcasted to all users connected via the same wavelength channel in a shared fiber link, privacy can be a critical concern. Although encryption at the application layer can provide a high level of security, this can be achieved only if the encryption key distribution is perfectly save. On the other hand, encryption on the physical layer such as quantum cryptography or, more precisely, quantum key distribution (QKD) is a very promising approach to achieve secure communication. However, there remain several issues that have to be solved before the quantum cryptography reaches the maturity level needed for a cost effective implementation in practical networks.**

In this paper, we address quantum key distribution (QKD) over passive optical access networks, which is an enabling technology required to cost efficiently deploy practical quantum encrypted data communication in the access area. We study different methods to integrate QKD systems in conventional optical access networks and quantitatively evaluate their suitability for a potential implementation.

I. Introduction

Nowadays, in the era of omnipresent information technology, high-speed, reliable and secure communication has become increasingly important and essential. Various theoretical and practical concepts for encryption and secure transfer of data have been developed to be implemented at both the network and application layers. Traditionally, the encryption strength relates to the computational complexity of revealing the key from the encrypted data. Although some of the approaches promise a very high security because the current key detection algorithms and the available computational power do not suffice to decipher the encrypted message in reasonable time, the problem of secure distribution of cryptographic keys is still under discussion. The cryptographic keys are commonly distributed using either a symmetric or a public key exchange technique. If this exchange is hacked, encrypted communication is no more secure. In addition, it is a matter of time only when computers will reach the high computation speeds required to decipher encrypted messages within sufficiently short time.

Quantum cryptography (QC) or more precisely quantum key distribution (QKD) [1] relies on principles of quantum physics and do not depend on mathematical and computational assumptions of the potential adversary. The main benefit of using QKD is that eavesdropping can be easily detected since any attempt to yield information about the key will unavoidably disturb the quantum bits carried by single photons. Moreover, the no-cloning theorem only valid for quantum systems prevents a leaking of quantum information without an increase in the quantum bit error rate (QBER).

First attempts to realize practical QKD systems were concentrated on transmitting QKD channels over a dedicated fiber, while classical (traditional) communication channels, and the key distillation channel, the latter needed to perform error correction and privacy amplification on the QKD channel, were transmitted over a separate fiber [2 - 5]. Although this approach is simple and allows maximum isolation between the comparatively strong classical communication signals and weak QKD signals, it is bound to higher capital expenditures because of the high cost of installing (or leasing) additional fibers. Since recently, some studies concentrated on implementing and characterizing systems with coexisting QKD and classical communication channels within a shared fiber medium [6 - 11]. The main goal of these studies was to evaluate and mitigate the impairments of strong classical signals on the weak QKD channel in a point-to-point link and to achieve large transmission distances. Recently, transmission of QKD signals together with classical signals over more than 50 km of standard single-mode fibers was experimentally demonstrated [6], which has proven the applicability of QKD to metropolitan areas.

The use of QKD in optical access networks has also been addressed by several groups [4]. However, as in the case of point-to-point transmission experiments, the main focus has been put on systems using a dedicated network for the distribution of quantum keys. Only a few studies considered coexisting classical and QKD channels in a fiber [9, 11], mainly using the 1.5 μm window for both QKD and classical channels. Even these works assume the use of two separate feeder fibers, i.e. the fibers reaching from the central offices of network providers to the remote nodes that are placed close

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to the end users. Moreover, the experiments did not prove applicability of QKD in standard networks under specified maximum conditions such as the maximum number of users, high signal powers and large number of wavelength channels. Instead, simple implementations with only a few users and a low number of wavelength channels were used, in which the powers of classical signals were minimized in order to mitigate the impairments on the QKD channel.

In this paper, we evaluate different possibilities for accommodating QKD channels together with data communication channels over a shared fiber infrastructure in the access area. We look for an option that is able to provide a clear migration path to highly secure, next generation optical access networks and, at the same time, is capable of providing a reliable transmission of quantum signals under all conditions. The paper is structured as follows. The next section briefly reviews current and future trends in optical access networks. An estimation of the accepted background noise level of a typical QKD system is given in Section III. Afterwards, we discuss different possibilities of integrating QKD systems in conventional optical access networks in Section IV and look for a suitable band for transmitting QKD signals in presence of strong data communication channels in Section V. Finally, conclusions are drawn in Section VI.

II. Optical Access Networks

Currently, fiber-based optical technologies are already widely deployed or at least considered to be deployed shortly within the access network area. Optical access networks are generally named Fiber-To-The-x (FTTx). The different options for FTTx differ basically in how near to the subscriber the fiber reaches, but also in the multiplexing technique applied and the wavelength bands used to carry the up- and downstream signals. Typical cases are: the Fiber-To-The-Home (FTTH), which means that the optical signals reach the end subscriber's equipment situated in the subscriber's home. Other examples are Fiber-To-The-Building (FTTB), Fiber-To-The-Curb (FTTC) and Fiber-To-The-Node (FTTN), where the final section into the subscribers home is realized by copper or radio. The usual network topology is either of ring or tree type or a combination of those two [12]. The downstream (DS, in the direction towards end users) and upstream (US, from end users to the network) signals can be transmitted over the same fiber or two separate fibers can be used for two directions. Particularly, extended reach passive optical networks (ER-PONs) with high optical loss budget typically follow the approach of dedicating a dual-feeder to avoid impairments caused by the strong downstream signals and affecting the weak upstream signal, while laying out the drop segment of the optical distribution network using a single-feeder design in order to preserve a simple and low-cost optical network terminal (OLT) with single fiber pigtail [12].

Here, we consider both Point-to-Point (P-t-P) and Point-to-Multipoint (P-t-MP) optical access options and analyze their suitability for integrating quantum key distribution. We choose the following options: P-t-P Ethernet, P-t-P 10G Ethernet, Ethernet PON (1G-EPON) [13], Gigabit Passive Optical Network (GPON) [14], asymmetric 10 Gbit/s Ethernet PON (10G-EPON) [15], XG-PON [16], wavelength-division multiplexing PON (WDM PON) [17] and the hybrid wavelength-division multiplexing and time-division multiplexing (WDM-TDM) PON [12, 18, 19], the latter envisioned as wavelength-stacked 10 Gbps TDM-PON for the second phase of the next-generation PON evolution (NG-PON2) [20]. An overview of different access technologies and their corresponding energy consumptions is given in [21 - 23].

Table I shows that different standards use different wavelengths and data rates to transmit upstream and downstream signals in co-existence with legacy PON standards. Also specified minimum and maximum transmitter (Tx) powers, i.e. optical powers launched into the fiber, differ among options. Both the transmitter power and its center wavelength have a strong influence on the level of background noise in the QKD channel. The main mechanisms that cause increased background noise in case of transmitting classical and QKD channels over the same fiber are briefly addressed in Section IV. Since WDM PON and WDM/TDM PON are not standardized yet, we assume for these two options the use of arrayed waveguide gratings (AWGs) operational in the C-band as available today, in conjunction with standard WDM certified transceiver technology.

III. QKD Systems

The architecture of a typical QKD-system is similar to a classical communication link, where a transmitter generates a signal which should be measured by a receiver. The largest difference between the quantum key distribution (QKD) and the data transmission is the signal power and the method used for encoding the information. The quantum information (in most cases the difference in phase between two pulses) is encoded on quantum signals with only one photon per bit corresponding to a pulse energy of 1.28×10^{-19} J at 1550 nm. Any signal with two or more photons per bit is a security risk, because even a second photon could carry the same quantum information and could subsequently be used by an adversary without being noticed. Decoy-states and other methods have been implemented to lower this risk. With quantum-dots single photons can be generated without a partner photon, but this technology is not mature enough nowadays and is currently under development. Therefore, strongly attenuated pulses are used with the drawback that not only a precise attenuation in the order of 70 dB must be applied in order to reduce the relatively high power of 1-ns-pulses (about 1 mW) to the level of 1 photon/pulse, but also the number of photons are not constant and follow a Poisson statistics, which can finally lead to generating more than 1 photon/pulse. A solution to avoid this double-photons is to increase the attenuation by 10 dB more to yield an average photon number of 0.1 photons/pulse, so only every 10th photon carries an unwanted partner with it (according to the Poisson statistics). A typical pulse repetition rate of a nowadays QKD-systems is 10 MHz, which is limited by the single-photon detectors, but is already reduced in the source to 1 MHz by attenuating the generated signal by 10 dB as discussed above. Each absorbed photon before detection causes the loss of the overall quantum information carried in this time slot and, subsequently, the secure key rate at the end is reduced. Recently, an increase to the GHz-level was achieved using better detection schemes [3].

After transmission through the quantum channel with a loss of typically 15 dB only approximately 30.000 photons per second arrive at the receiver having a typical quantum system in mind. The detectors are expecting photons during the time of the original 10 MHz pulse train, so the detectors need to be opened accordingly. A typical opening time of the InGaAs avalanche detector is about 5 ns. Such avalanche diodes are operated in Geiger mode, so after each detected photon the detector need to rest for approximately 10 μs, which is referred to as detector dead time. For the sake of simplicity, we do not consider the effect of the detector dead time here, so we can assume an overall opening time of 50 ms (10 million openings of 5 ns duration) in each second. In this time also in-band background noise photons can generate detector signals which are not distinguishable from the original quantum signals. In order to achieve a reliable exchange of quantum keys, the required signal to noise ratio must be greater than 10 (SNR $>$ 10), so within this 50 ms only 3000 background photons are allowed, which corresponds to 600,000 photons per second. The numbers presented here are rough estimations taking the principle operation of QKD-system into account. The resistance of QKD-systems against background photons is typically not evaluated in research papers [2, 4 - 6] because dedicated fibres are usually assumed for QKD.

TABLE I
WAVELENGTH PLAN AND DATA RATES IN STANDARD OPTICAL ACCESS NETWORKS. DS: DOWNSTREAM, US: UPSTREAM.

	P-t-P GbE		P-t-P 10 GbE	
	DS	US	DS	US
wavelength [nm]	1550	1310	1330	1270
data rate [Gbps]	1.25	1.25	10.3125	10.3125
Tx power [dBm]	-8 .. -2	-8 .. -2	-5 .. 2	-5 .. 2
	EPON		**GPON**	
	DS	US	DS	US
wavelength [nm]	1490 1550(Video)	1310	1490 1550(Video)	1310
data rate [Gbps]	1.25	1.25	2.488	1.244
Tx power [dBm]	2.5 .. 7	-1 .. 4	3 .. 7	0.5 .. 5
	10G-EPON		**XG-PON**	
	DS	US	DS	US
wavelength [nm]	1577	1270	1577	1270
data rate [Gbps]	10.3125	1.25	9.953	2.488
Tx power [dBm]	2 .. 6	2 .. 6	2 .. 6	2 .. 6
	WDM PON		**WDM-TDM PON**	
	DS	US	DS	US
wavelength [nm]	1548-1577	1520-1547	1548 - 1577	1520 - 1547
data rate [Gbps]	10.3125	1.25	10.312	1.25
Tx power [dBm]	2 .. 5	1 .. 4	2 .. 5	1 .. 4

IV. QKD IN OPTICAL ACCESS NETWORKS

In order to enable a widespread adaption of any QKD technology more research effort should be undertaken in the access area. Standard passive optical networks (PONs) are especially eligible for QKD transmission as no optical amplification is needed for standard reaches up to 20 km. The limited range potentially supports higher secure key rates and the possibility to place the quantum channel at wavelengths outside of the minimum-attenuation bands commonly used in standard single mode fibers.

A. Impairments on QKD channels

Strong conventional signals in optical access networks are causing nonlinear effects in optical fibers. These effects can constitute severe problems for the weak QKD signals and need to be addressed individually and in combination. Additionally, imperfections of optical filters also contribute to an increase in background noise. Several studies have shown that coexistence architectures are in principle possible [6, 8, 11] , but impairments are strongly limiting the performance of QKD systems. In order to find the wavelength regions in which QKD operation is feasible, all sources of background noise have to be analyzed and modeled [6, 11, 24].

Attenuation: Depending on the fiber type used for transmission, a characteristic curve describes the wavelength dependent attenuation of optical signals along the fiber length. Standard Single-Mode Fibers (SSMF) exhibit a broad water peak around 1383 nm, making this wavelength range impractical for effective transmission. The 1.5 μm C-band transmission window is most widely used for modern long-range optical signal transmission due to the low attenuation down to 0.2 dB/km. The low attenuation makes this band also attractive for QKD systems, but the co-existing classical signals within the same band cause serious impairments. The band about 1.3 μm (O-band) has a higher attenuation of $\approx$ 0.3 dB/km. It is often used for short- and middle-range transmission and may be appropriate for accommodating a quantum channel in some cases because of the large spectral offset to signals in the C-band.

Spontaneous Raman scattering: Inelastic photon scattering causes frequency shifts of incident photons. Acoustic phonon-photon scattering (Brillouin scattering) can be neglected because it's maximal offset by 10 GHz in backward direction does not overlap with adjacent channels in the 100 GHz ITU-grid, whereas Raman scattering, in which optical phonons are involved, introduces large spectral shifts covering the entire C-band with a maximum at 13 THz offset from the pump. In the case of Stokes scattering, part of the photons energy is absorbed by the fiber resulting in a lower frequency. When a photon is scattered off an exited phonon energy is transferred to the photon in an anti-Stokes process resulting in a higher frequency. The anti-Stokes scattering is less effective as it requires the preexistence of vibrational modes. Thus, the quantum channel wavelength should preferably be chosen below the pump wavelength to minimize the Raman scattering effects.

Four-wave mixing: When dealing with multiple signals at different wavelengths or frequencies $f_1, f_2, ..f_n$, as it is the case in WDM transmission systems, the effect of four-wave mixing has to be considered. Here, no energy is transferred to or from the fiber but the scattering of incident photons produces another photon at a different wavelength. The efficiency of four-wave mixing depends on the coherence of the incident photons and decrease due to chromatic dispersion. Around zero-dispersion wavelengths, the quantum channel should not be placed at frequencies corresponding to $f_{ijk} = f_i + f_j - f_k$, where $i, j, k = 1, 2, ..., n$ and $i, j \neq k$.

B. Integration of QKD in Optical Access Networks

The considered options for integrating quantum cryptography systems in optical access networks are shown in Fig. 1. We assume here a maximum PON reach of 20 km, of which 15 km is dedicated to the feeder fiber. For the two active P-t-P Ethernet options, we assume bi-directional operation over two different wavelengths for downstream and upstream. The point-to-point networks are shown in Fig. 1(a), while single channel passive optical networks (PONs) and wavelength-division multiplexing (WDM) PONs are, respectively, depicted in Fig. 1(b) and (c). Note that there are a number of other proposals for high-performance optical access networks that can be found in the research literature, which we do not address in this correspondence because they are neither standardized nor widely deployed yet. Even if WDM PON and WDM/TDM PON are also not standardized yet, we consider these two technologies because they are widely considered to be a natural extension of the standard PONs. Not considered are methods for reach extension [12, 25] , because these demand optical amplification or optical-electrical-optical conversion, which both strongly affect or even hinder the integration of a QKD channel.

As already mentioned in Section IV-A, strong classical signals can cause a serious degradation of the QKD signals or even make it impossible to exchange quantum keys. Therefore, the selection of an appropriate wavelength band for transmitting QKD signals is essential. To avoid strong interactions, QKD channels should be ideally placed spectrally far away from classical signals. Due to the fact that the Stokes scattering is stronger than the anti-Stokes, placing the quantum channel at shorter wavelengths than the classical channels is advantageous. Additional to the scattered waves also the total path loss, the spectral shape and adjacent channel isolation of filters as well as spectral characteristics of sources and other active components such as amplifiers play a very important role. Fig. 2 shows the attenuation spectrum for standard single-mode fibers (SSMF) and low water peak single-mode fibers as well as the wavelength plan for the considered access technologies. The dark blue bars depict the classical signals for upstream (US) and downstream (DS) directions while the bands indicated with dashed lines represent the allocated

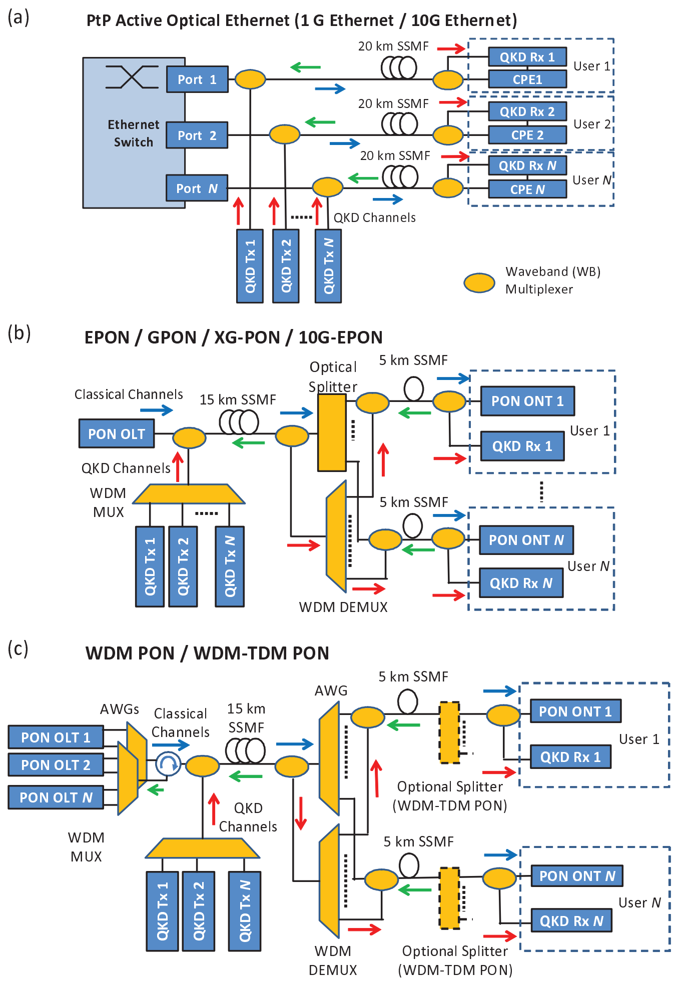

Fig. 1. Implementation options for quantum cryptography in optical access networks: (a) point-to-point topologies (1G and 10G active Ethernet), (b) single channel passive optical networks (EPON, GPON, XG-PON and 10G-EPON) and (c) wavelength-division multiplexing (WDM) passive optical networks (WDM PON and WDM/TDM PON). SSMF: Standard Single-Mode Fiber, QKD: Quantum Key Distribution, PON: Passive Optical Network, TDM: Time-Division Multiplexing, Rx: Receiver, Tx: Transmitter, AWG: Arrayed Waveguide Grating-based multiplexer.

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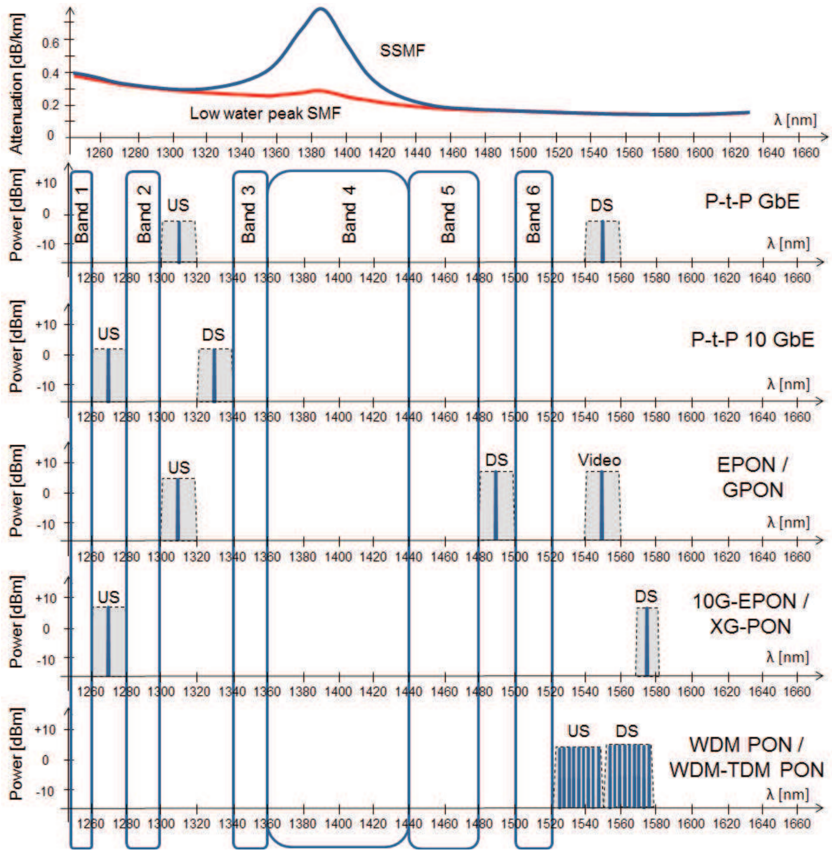

Fig. 2. Attenuation of optical fiber and wavelength plan for the considered optical access options. The marked wavelength regions (Band 1 - Band 6) are not used for classical communications and can thus be potentially used for QKD. Note that Band 4 can only be considered when using the low water peak fiber.

wavelength range for uncooled operation of the respective transmitters thereof. Since the attenuation of optical fibers is wavelength dependent and the weak QKD systems are susceptible to losses, the wavelengths for which the fiber attenuation is high should be avoided. Particulary, the OH peak region within the E-band in standard single-mode fibers (SSMFs) and the wavelengths smaller than 1240 nm (see Fig. 2) likely would not be a good choice. As can be seen from the figure, the differences among new and legacy PON standards leads to quite some occupied spectral ranges due to reserved wavebands for DS and US signals. This makes it difficult to define a unique wavelength band for QKD that suits all access technologies and deployment scenarios. The bands that are currently not used by classical signals are indicated in Fig. 2 and evaluated for their suitability for QKD in the next section.

V. Band selection for QKD in access networks

To qualitatively assess the impairments on QKD signals in different wavelength bands and to find out which bands could be used to implement QKD in optical access networks, we simulated the systems depicted in Fig. 1 using the VPI System's TransmissionMaker software tool [26]. For this purpose, we modified the existing bidirectional model of optical fiber to cover a large spectrum of more than 400 nm, which is particulary important to correctly model effects occurring across several wavelength bands such as the Raman scattering. We used the values for the launched powers and the central wavelengths as listed in Table I. The number of users, N, was set to 32 (except for WDM/TDM PON where 128 are assumed because of the 4-port splitters used per wavelength) and the launched powers to the maximum specified values (see Table I), which corresponds to a worst-case scenario.

The measured photon counts per second within a bandwidth of 0.1 nm that occur due to combined effects of Raman scattering, Rayleigh backscattering, four-wave mixing (FWM) and amplified spontaneous emission (ASE) are shown in Fig. 3. These photons represent the background noise for QKD systems, which is highly undesirable. If the number of these background counts together with the dark counts of the receiver is comparable to or higher than the number of QKD counts, a reliable key distribution becomes impossible.

As can be seen from Fig. 3, the background photon count is higher than 10^6 for almost the whole spectrum range between 1240 nm and 1660 nm throughout the considered single channel network options. A typical QKD system designed for a quantum channel implemented on dark fibers as discussed in Section III will not accept such high background photon rates. Note that to obtain the results presented in Fig. 3 we used a narrow bandwidth filter (0.1 nm) to filter the

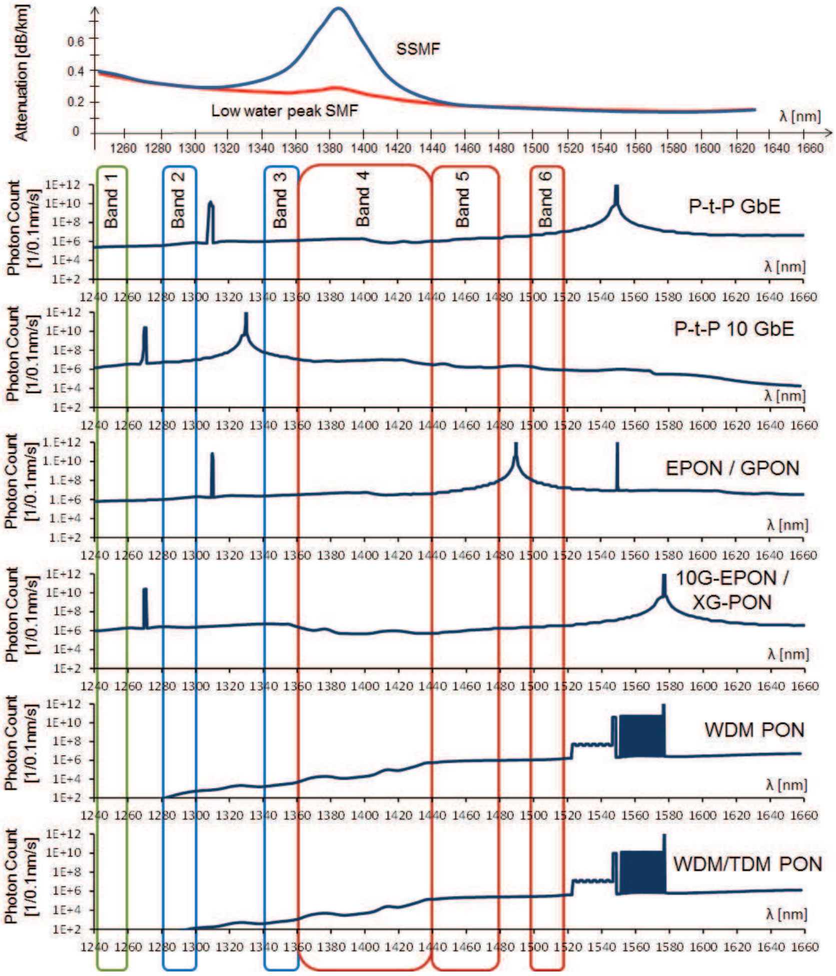

Fig. 3. Downstream photon counts (background noise) measured just before the network termination point for maximum launched power at the classic transmitters and a 32-user PON. The selected resolution bandwidth is 0.1 nm.

broadband background noise out. With a 1 nm filter, the background photon rate would be about 10 times higher. Thus, a potential QKD system would need to implement very tight spectral filtering with sub-0.1 nm resolution as well as a good capability to distinguish the noise photon and the signal photons by accurate time information. The latter could be achieved by using adequate single photon detectors with low timing jitter, which could lead to a reduced time window in the order of 500 ps (instead of 5 ns as stated in Section III) for expected signal photons. Our current interpretation of the achieved results is that the integration of QKD in optical access networks is far from trivial. There seems to be no free band for QKD-systems suitable for all the different schemes we compared. Some of the considered PON-systems foresee a wide wavelength gap between upstream and downstream signals, such that the entire space across all bands is flood by Stokes and anti-Stokes Raman photons. A slight reduction of background counts to about or even below 10^6 is observable for wavelengths shorter than 1250 nm only.

In case of WDM PON and WDM/TDM PON with all channels allocated in the C-band, the background noise falls below 10^4 photons per second in the 1.3 μm wavelength region, which is low enough to allow the exchange of quantum keys. These two technologies support an integration of currently available QKD systems. Since the level of the background noise within Band 1 (1240 - 1260 nm) is the lowest for all considered optical access options, this band seems to be a possible candidate for allocating a PON technology independently usable QKD channel. However, the performance of QKD systems needs to be improved and the noise power generated by classical transmitters decreased where possible. In addition, the fiber attenuation is higher at this wavelength than at 1310 nm or 1550 nm, which leads to a reduction of the secure data rate that the quantum channel can provide. For example, a QKD signal transmitted at 1240 nm instead of 1310 nm (or 1550 nm) experiences about 3 dB (or 5 dB) higher end-to-end loss in case of an 20-km optical access network (see Fig. 4). To compensate for this loss a QKD system with a higher pulse rate is needed.

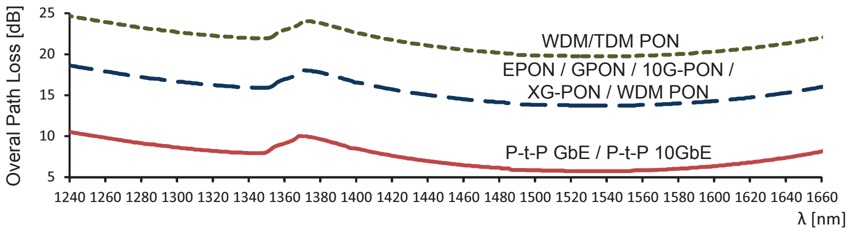

Fig. 4. Overall loss in the QKD signal path.

VI. Conclusions

We studied a possible integration of quantum key distribution (QKD) systems in optical access networks. The considered options include legacy networks such as point-to-point 1G and 10G active optical Ethernet, Gigabit Passive Optical Network (GPON) and Ethernet PON (EPON) as well high-capacity PONs such as 10G-PON, XG-PON, WDM PON and WDM/TDM PON. Particular attention was paid to find a favorable allocation of the QKD channels, intended to minimize impairments and provide a clear, still open migration path to highly secure, next generation optical access networks.

We evaluated by physical layer simulations the noise components generated by spontaneous Raman scattering along optical fibers for different PON realization options. We also included Rayleigh backscattering to obtain an overview of the deployment of QKD in such structures. The entire wavelength region between 1240 nm and 1660 nm was considered, in order to cover all the important telecommunication bands. The performed simulation study for networks with 32 ONTs (128 in case of WDM/TDM PON) and high transmit powers show a background noise level likely prohibiting the use of typical QKD systems, but also confirm principle design guidelines to overcome these difficulties. To integrate currently available QKD systems in optical access networks the transmitters for data channels have to be operated at lower power levels and narrow-band optical filters in the sub-0.1 nm range should be used in front of QKD receivers to efficiently suppress background noise. Further, developments towards background-noise resistant QKD-systems are needed in order to mitigate the found restrictions on a successful general integration of QKD into any modern optical access network technology.

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References

[1] C. H. Bennett, G. Brassard, et al., "Quantum cryptography: Public key distribution and coin tossing", IEEE International Conference on Computers, Systems and Signal Processing, Bangalore, India, December 1984, pp. 175-179.

[2] D. Stucki, N. Gisin, O. Guinnard, G. Ribordy, and H. Zbinden, "Quantum key distribution over 67 km with a plug&play system", New Journal of Physics, vol. 4, 2002, pp. 41.141.8.

[3] A. J. Shields, C. Gobby and Z. L. Yuan, "Quantum key distribution over 122 km of standard telecom fiber", Applied Physics Letters, Vol. 84, 2004, pp. 3762-3764.

[4] A. Treiber, A. Poppe, M. Hentschel, D. Ferrini, T. Lorünser, E. Querasser, T. Matyus, H. Hübel and A. Zeilinger, "A Fully Automated Quantum Cryptography System Based on Entanglement for Optical Fibre Networks", New Journal of Physics, Vol. 11, 2009, paper 045013.

[5] A. Tanaka, M. Fujiwara, S. W. Nam, Y. Nambu, S. Takahashi, W. Maeda, K. Yoshino, S. Miki, B. Baek, Z. Wang, A. Tajima, M. Sasaki and A. Tomita, "Ultra fast quantum key distribution over a 97 km installed telecom fiber with wavelength division multiplexing clock synchronization", Optics Express, Vol. 16, Issue 15, 2008, pp. 11354-11360.

[6] P. Eraerds, N. Walenta, M. Legre, N. Gisin and H. Zbinden, "Quantum key distribution and 1 Gbps data encryption over a single fibre", New Journal of Physics, Vol. 12, No. 6, 2010, paper 063027.

[7] R. J. Runser, T. E. Chapuran, P. Toliver, M. S. Goodman, J. Jackel, N.Nweke, S. R. McNown, R. J. Hughes, C.G. Peterson, K. McCabe, J. E. Nordholt, K. Tyagi, P. Hiskett, and N. Dallmann,"Demonstration of 1.3 μm Quantum Key Distribution (QKD) Compatibility with 1.5 μm Metropolitan WDM", Optical Fiber Communication Conference (OFC 2005) Anaheim, California, March 2005, paper OW12.

[8] T. J. Xia, D. Z: Chen, G. A. Wellbrock, A. Zavriyev, A. C. Beal and K. M. Lee, "In-band quantum key distribution (QKD) on fiber populated by high-speed classical data channels", Optical Fiber Communication Conference (OFC 2006), Anaheim, CA, USA, March 2006, paper OTuJ7.

[9] T. E. Chapuran, P. Toliver, N. A. Peters, J. Jackel, M. S. Goodman, R. J. Runser, S. R: McNown, N. Dallmann, R. J. Hughes, K. P. McCabe, J. E. Nordholt, C. G. Peterson, K. T. Tyagi, L. Mercer and H. Dardy,"Optical networking for quantum key distribution and quantum communications", New Journal of Physics, 2009, Vol. 11, No. 10, paper 105001.

[10] P. D. Townsend, "Simultaneous quantum cryptographic key distribution and conventional data transmission over installed fibre using wavelength-division multiplexing", Electronics Letters, Vol. 33, No. 3, 1996, pp. 188 - 190.

[11] S. Aleksic, D. Winkler, A. Poppe, G. Franzl, B. Schrenk and F. Hipp, "Distribution of Quantum Keys in Optically Transparent Networks: Perspectives, Limitations and Challenges", invited, 15th International Conference on Transparent Optical Networks (ICTON 2013), Cartagena, Spain, July 2013, pp. 1-6.

[12] B. Schrenk, J.A. Lazaro, D. Klonidis, F. Bonada, F. Saliou, V. Polo, E. Lopez, Q.T. Le, P. Chanclou, L. Costa, A. Teixeira, S. Chatzi, I. Tomkos, G. Tosi Beleffi, D. Leino, R. Soila, S. Spirou, G. de Valicourt, R. Brenot, C. Kazmierski and J. Prat, "Demonstration of a Remotely Dual-Pumped Long-Reach PON for Flexible Deployment, IEEE/OSA J. Lightwave Technol., Vol. 30, April 2012, pp. 953-961.

[13] IEEE P802.3ah, "Ethernet in the First Mile Standard", 2008, http://www.ieee802.org/3/efm/.

[14] ITU-T, Recommendation G.984.1, "Gigabit-capable Passive Optical Networks (GPON): General characteristics", 2008, http://www.itu.int/rec/T-REC-G.984.1/en.

[15] IEEE 802.3av 10G-EPON (Ethernet Passive Optical Network) Task Force, http://www.ieee802.org/3/av/.

[16] ITU-T G.987, 10-Gigabit-capable passive optical network (XG-PON) systems: Definitions, abbreviations and acronyms, 2012, http://www.itu.int/rec/T-REC-G.987-201206-I.

[17] M. Maier, "WDM passive optical networks and beyond: The road ahead", invited, J. Opt. Commun. Netw., Vol. 1, No. 4, pp. C1-C16.
[18] A. Lovric, S. Aleksic, J. A. Lazaro, G. M. Tosi-Beleffi, F. Bonada and J. Prat, "Influence of Broadcast Traffic on Energy Efficiency of Long-Reach SARDANA Access Network", Optical Fiber Communication Conference (OFC 2011), Los Angeles, CA, USA, March 2011, paper OThB5.
[19] A. Lovric and S. Aleksic, "Power Efficiency of Extended Reach 10G-EPON and TDM/WDM PON", National Fiber Optic Engineers Conference (NFOEC 2010), San Diego, CA, USA, March 2010, paper MMC4.
[20] ITU-T Recom. G.989.1: 40-Gigabit-capable passive optical networks (NG-PON2): General requirements, 2012, http://www.itu.int/itu-t/.
[21] S. Aleksic, A. Lovric "Energy Consumption and Environmental Implications of Wired Access Networks", American Journal of Engineering and Applied Sciences, Vol. 4, No. 4, 2012, pp. 531 - 539.
[22] S. Aleksic, "Energy Efficiency of Electronic and Optical Network Elements", IEEE Journal of Selected Topics in Quantum Electronics, Vol. 17, No. 3, 2011, pp. 296-308.
[23] S. Aleksic and A. Lovric, "Power Consumption of Wired Access Network Technologies", 7th IEEE/IET International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP 2010), Newcastle, UK, July 2010, pp. 146-151.
[24] H. Rohde, S. Smolorz, P. Poppe, H. Huebel, "Quantum key distribution integrated into commercial WDM systems", Optical Fiber Communication Conference (OFC 2008), San Diego CA, USA, February 2008, paper OTuP1.
[25] P. Ossieur, C. Antony, A. M. Clarke, A.Naughton, H.-G. Krimmel, Y. Chang, C. Ford, A. Borghesani, D. G. Moodie, A. Poustie, R.Wyatt, B. Harmon, I. Lealman, G. Maxwell, D. Rogers, D. W. Smith, D. Nesset, R. P. Davey and P. D. Townsend, "A 135-km 8192-Split Carrier Distributed DWDM-TDMA PON With $2 \times 32 \times 10$ Gb/s Capacity, J. Lightw. Technol., VOl. 29, No. 4, February 2011, pp. 463-474.
[26] VPI Systems, VPItransmissionMaker Optical Systems, http://www.vpiphotonics.com/.